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NM5507

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL COVER SHEET
Complete Only Applicable Items

1. QA: QA

Page: 1 of: 41

2. ☒ Analysis — Check all that apply

Type of Analysis:
- ☐ Engineering
- ☒ Performance Assessment
- ☐ Scientific

Intended Use of Analysis:
- ☐ Input to Calculation
- ☒ Input to another Analysis or Model
- ☐ Input to Technical Document
- ☐ Input to other Technical Products

Describe use:
Provide input to waste package and drip shield degradation analysis.

3. ☒ Model — Check all that apply

Type of Model:
- ☐ Conceptual Model
- ☒ Abstraction Model
- ☐ Mathematical Model
- ☐ System Model
- ☐ Process Model

Intended Use of Model:
- ☐ Input to Calculation
- ☒ Input to another Model or Analysis
- ☐ Input to Technical Document
- ☐ Input to other Technical Products

Describe use:
Provide input to waste package and drip shield degradation analysis.

4. Title:
Abstraction of Models of Stress Corrosion Cracking of Drip Shield and Waste Package Outer Barrier and Hydrogen Induced Corrosion of Drip Shield

5. Document Identifier (including Rev. No. and Change No., if applicable):
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For TSPA-SR.

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD
Complete Only Applicable Items

2. Analysis or Model Title:

Abstraction of Models of Stress Corrosion Cracking of Drip Shield and Waste Package Outer Barrier and Hydrogen Induced Corrosion of Drip Shield

3. Document Identifier (including Rev. No. and Change No., if applicable):

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4. Revision/Change No.	5. Description of Revision/Change
00	Initial Issue

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1. PURPOSE

As directed by a written development plan (CRWMS M&O 1999a), an analysis for the degradation of drip shield and waste package in the engineered barrier system (EBS) is conducted. The purpose of this analysis is to assist Performance Assessment Department (PAD) and its EBS Performance Section in analyzing process models of stress corrosion cracking (SCC) of waste package (CRWMS M&O 2000a) and hydrogen induced cracking (HIC) of drip shield (CRWMS M&O 2000d), and develop abstractions of the models, which are used as input to the WAste Package DEGradation (WAPDEG) model (CRWMS M&O 2000b, Section 3.2.5). The WAPDEG model is used in the total system performance assessment (TSPA) for waste package and drip shield degradation analysis. This analysis will allow PAD to provide a more detailed and complete waste package and drip shield degradation abstraction and to answer the key technical issues (KTI) raised in the U.S. Nuclear Regulatory Commission (NRC) Issue Resolution Status Report (IRSR) for the Container Lifetime and Source Term (CLST) Revision 2 (NRC 1999).

The scope of the current abstraction analysis is limited to the SCC and HIC processes (and their process models and parameters) that significantly affect the performance of waste packages and drip shields in the repository (CRWMS M&O 2000a). The processes that do not have significant impact on the drip shield and waste package performance are not considered. Also, the model abstractions documented in this AMR are based on the process models and their parameters documented in the associated AMR (CRWMS M&O 2000a). The abstraction analyses documented in this AMR are for the Enhanced Design Alternative II (EDA II) design (CRWMS M&O 1999d). In this design, a drip shield is placed over the waste package with backfill emplaced over the drip shield (see Design Constraint 2.2.1.1.9 of CRWMS M&O 1999d). The output from the abstraction analyses is used as input to the WAPDEG analysis for waste package and drip shield degradation.

Alternative approaches to representing the uncertainty and variability of the stress state and stress intensity factor in the closure-lid welds of waste package are also being evaluated. Those analyses will be documented in future revision of this AMR.

2. QUALITY ASSURANCE

The Quality Assurance (QA) program applies to the development of this documentation for the abstraction analyses of stress corrosion cracking (SCC) of waste package outer barrier and drip shield and hydrogen induced cracking (HIC) of drip shield. The Performance Assessment Operations responsible manager has evaluated the technical document development activity in accordance with QAP-2-0, *Conduct of Activities*. The QAP-2-0 activity evaluation, *Conduct of Performance Assessment* (CRWMS M&O 1999b), has determined that the preparation and review of this technical document is subject to *Quality Assurance Requirements and Description* (QARD) DOE/RW-0333P (DOE 2000) requirements. Preparation of this analysis did not require the classification of items in accordance with QAP-2-3, *Classification of Permanent Items*. This activity is not a field activity. Therefore, an evaluation in accordance with NLP-2-0, *Determination of Importance Evaluations* was not required.

3. COMPUTER SOFTWARE AND MODEL USAGE

3.1 COMPUTER SOFTWARE

3.1.1 Mathcad 2000 Professional

Mathcad 2000 Professional is a commercially available software used in this analysis. This software, in accordance with AP-SI.1Q, *Software Management*, is appropriate for this application as it offers all of the mathematical and graphical functionality necessary to perform and document the numerical manipulations used in this analysis. Mathcad 2000 Professional was executed on a DELL PowerEdge 2200 Workstation equipped with two Pentium II 266 MHz processors (CRWMS M&O tag 112371) in the Windows NT 4.0 operating system. Details of the Mathcad numerical manipulations performed in support of this analysis are discussed throughout this analysis and included in Section 3.3 of Attachment I.

3.1.2 Excel 97 SR-2

Excel 97 SR-2 is a commercially available software used in this calculation. This software, in accordance with AP-SI.1Q, *Software Management*, is appropriate for this application as it offers all of the mathematical and graphical functionality necessary to perform and document the numerical manipulations used in this calculation. No macros were used and no numerical manipulations of sufficient complexity to qualify as a software routine (as defined by the AP-SI.1Q *Software Management* procedure) were implemented within Excel. Excel 97 SR-2 was executed on a DELL PowerEdge 2200 Workstation equipped with two Pentium II 266 MHz processors (CRWMS M&O tag 112371) in the Windows NT 4.0 operating system. Details of the Excel manipulations performed are discussed throughout this calculation.

3.1.3 SCCD 1.01

Software routine, Stress Corrosion Cracking Dissolution (SCCD), was also developed, in accordance with AP-SI.1Q, *Software Management*, to implement the results of this analysis. This software is appropriate for this application as it was developed to implement the results of this analysis. Details of the software routine verification are presented in Attachment I. The SCCD software routine is typically compiled as a windows Dynamic Link Library (DLL) and called by other programs. This routine was developed using Microsoft Developer Studio 97 Visual FORTRAN 5.0D, Standard Edition, a commercially available software. The SCCD software routine is identified as follows:

Name and Version Number: SCCD, Version 1.01

SRR Document Identification Number: N/A

SRR Media Number (if applicable): N/A

3.2 MODELS USED

3.2.1 Manufacturing Defect Abstraction Model

This model abstraction is to calculate the probability of the occurrence and size of manufacturing defects in waste package closure-lid welds. This model is discussed in Sections 5.1 and 6.2. All of the data and parameters used in this model are documented in the calculation entitled *Calculation of Probability and Size of Defect Flaws in Waste Package Closure Welds to Support WAPDEG Analysis* (CRWMS M&O 2000c) and are tracked by DTN: MO0001SPASUP03.001.

3.2.2 Stress and Stress Intensity Factor Profile Abstraction Model

This model abstraction is to calculate the stress state and stress intensity factor versus depth and their uncertainty and variability in the closure-lid welds of waste package. The abstraction approach and results are discussed in Sections 5.2 and 6.3. This model is implemented partly in the SCCD software routine (see Section 3.1.3 and Attachment I).

3.2.3 Slip Dissolution Abstraction Model

The theory of slip dissolution (or film rupture) has been successfully applied to assess the SCC crack propagation for light water reactors at high temperature (CRWMS M&O 2000a). The description of the SCC model based on the theory of slip dissolution and film rupture is discussed in the upstream process model analysis (CRWMS M&O 2000a). The adaptation of the slip dissolution model to assess the stress corrosion cracking capability of the waste package outer barrier (Alloy 22) requires the determination of two parameters, "A" and "n", in an equation which relates the crack growth rate to the crack tip strain rate. A mathematical formula that relates "A" to "n" for stainless steels is adopted for Alloy 22 to determine "A" from "n" (CRWMS M&O 2000a). This model abstraction is discussed in Sections 5.3 and 6.4.

3.2.4 Threshold Stress Intensity Factor Abstraction Model

The concept of threshold stress intensity factor (K_{ISCC}) has been commonly used to assess the susceptibility of material to SCC. A description of this concept is discussed in the upstream process model analysis (CRWMS M&O 2000a). According to the threshold model, there exists a threshold value (K_{ISCC}) for the stress intensity factor such that no growth occurs in a pre-existing crack having a stress intensity factor less than the threshold value. Pre-existing cracks are usually caused by manufacturing processes (especially welding processes). The adaptation of the threshold model to Alloy 22 (the material for the waste package outer shell) requires the determination of (1) the threshold stress intensity factor for Alloy 22, which has been experimentally observed by Roy et al. (1998); and (2) the stress intensity factor for the given stress state and pre-existing crack size in the waste package.

4. INPUTS

4.1 DATA AND PARAMETERS

Data and parameters that are input to this analysis include stress and stress intensity profiles (stress or stress intensity versus depth), threshold stress, incipient crack densities, and crack growth rate model and model parameters appropriate for both the outer and inner closure lids of the waste package outer barrier. These data were acquired or developed under quality assurance procedures and are being qualified. Some of the data are preliminary and require verification. Those data carry "To Be Verified (TBV)," and will be verified in subsequent revision of this report. Table 1 summarizes these data, their sources, data tracking numbers (DTNs), and other associated information.

Table 1. Data and Parameters and Their Sources.

Parameter	Source	DTN	Where Documented in this Document
Stress Intensity Factor Profiles of WP Closure-Lid Welds	CRWMS M&O 2000a Sections 6.2.2.4 & 6.2.2.5 Attachment I	LL000316005924.140 (TBV) LL000316105924.141 (TBV)	Table 2
Coefficients for Stress Profile Equation of WP Closure-Lid Welds	CRWMS M&O 2000a Sections 6.2.2.2 Attachment I	LL000316005924.140 (TBV) LL000316105924.141 (TBV)	Table 3
Yield Strength of Alloy 22 at 125 °C	CRWMS M&O 1999c Section 5.7, p. 33	Accepted Data	Table 4
Various Fractions of Yield Stress to account for Uncertainty and Variability of Stress and Stress Intensity Factor of WP Closure-Lid Welds	CRWMS M&O 2000a Section 6.2.2.5	N/A	Table 4
Threshold Stress Intensity Factor	CRWMS M&O 2000a Section 6.3.2	N/A	Section 6.5
Threshold Stress	CRWMS M&O 2000a Section 6.5.2	N/A	Section 6.4.3
Incipient Crack Density	CRWMS M&O 2000a Section 6.5.2	N/A	Section 6.4.4
Slip Dissolution Model and Model Parameters	CRWMS M&O 2000a Section 6.4 Equations 22 to 24	N/A	Equations 2 to 4 Section 4.1 Section 6.4.2
Probability and Size of Manufacturing Defect Flaws in Waste Package Closure-Lid Welds	CRWMS M&O 2000c	MO0001SPASUP03.001 (TBV)	Section 6.2

Parameter	Source	DTN	Where Documented in this Document
Time to Failure of Drip Shield by Hydrogen Induced Cracking	CRWMS M&O 2000d Section 6.2 Case 1: Conservative Estimate Case 2: Best Estimate	N/A	Section 6.1

Table 2. Stress Intensity Factor (K_I) vs. Depth Tables for the Outer and Inner Closure-Lids of Waste Package Outer Barrier.

Outer Lid		Inner Lid	
KI (MPa*m½)	Depth (mm)	KI (MPa*m½)	Depth (mm)
-8.096912553	0.3988	-7.201806034	0.3277
-11.08864448	0.8001	-10.05117186	0.6579
-13.12743778	1.1989	-12.14661052	0.9855
-14.62395207	1.6002	-13.83718048	1.3132
-15.74125563	1.9990	-15.26051182	1.6408
-16.56494834	2.4003	-16.48813922	1.971
-17.16634511	2.7991	-17.60873931	2.2987
-17.5702798	3.2004	-18.62418012	2.6264
-17.79521296	3.5992	-19.34568044	2.954
-17.85960516	3.9980	-18.27353932	3.2842
-17.77785124	4.3993	-17.05876838	3.6119
-17.56148906	4.7981	-15.73543176	3.9395
-17.22755067	5.1994	-14.40693057	4.2697
-16.78515648	5.5982	-13.09502192	4.5974
-16.23441637	5.9995	-11.74410433	4.9251
-15.58159374	6.3983	-10.37129779	5.2527
-14.83251247	6.7970	-8.992063026	5.5829
-13.99233711	7.1984	-7.619959749	5.9106
-13.06249616	7.5971	-6.28349195	6.2382
-12.03771518	7.9985	-5.021547684	6.5659
-10.93137807	8.3972	-3.791766552	6.8961
-9.747286832	8.7986	-2.602642611	7.2238
-8.489320377	9.1973	-1.461856773	7.5514
-7.161148843	9.5987	-0.376262524	7.8791
-5.7664094	9.9974	0.6479086	8.2093
-4.327309665	10.3962	1.602739435	8.5369
-2.830795383	10.7975	2.489890331	8.8646
-1.280437794	11.1963	3.304704392	9.1948
0.320255595	11.5976	4.043027992	9.5225
1.967753102	11.9964	4.701256926	9.8501
3.658542826	12.3977	5.276226526	10.1778
5.415098304	12.7965	5.809253288	10.508
7.218783158	13.1978	6.267459831	10.8356
9.05768593	13.5966	6.633989902	11.1633
10.92825736	13.9954	6.907239191	11.491
12.82690422	14.3967	7.086141819	11.8212
14.74987947	14.7955	7.170016506	12.1488
16.73175271	15.1968	7.171796631	12.4765
18.7698867	15.5956	7.082153019	12.8067
20.82285508	15.9969	6.8851964	13.1343

22.88648224	16.3957	6.581695963	13.462
24.95692222	16.7945	6.173014275	13.7897
27.03021919	17.1958	5.661052333	14.1199
29.13461342	17.5946	5.214086954	14.4475
31.33328838	17.9959	5.185517036	14.7752
33.52559005	18.3947	5.092620849	15.1028
35.70701317	18.7960	4.940639873	15.433
37.87294261	19.1948	4.735255128	15.7607
40.01865333	19.5961	4.482741007	16.0884
42.13953021	19.9949	4.18995429	16.4186

Note: The outer lid data from p. A-29, Attachment I, CRWMS M&O 2000a (also DTN: LL000316005924.140). The inner lid data from p. A-46, Attachment I, CRWMS M&O 2000a (also DTN: LL000316105924.141).

Stress State

Stress (σ_s in ksi) as a function of depth (x in inches) in the closure-lid welds of the waste package outer barrier is given by a third order polynomial equation of the form (CRWMS M&O 2000a, p. 27):

$$\sigma_s(x) = A_0 + A_1 \cdot x + A_2 \cdot x^2 + A_3 \cdot x^3 \qquad \text{(Eq. 1)}$$

where the values of the coefficients (A_i's) are given in Table 3.

Table 3. Values of the Coefficients in Equation 1 for the Stress Profiles of the Outer and Inner Closure-Lid Welds of the Waste Package Outer Barrier.

Coefficient	Outer Lid	Inner Lid
A_0	-51.6723	-63.49
A_1	136.9724	651.94
A_2	134.4068	-1460.30
A_3	-155.158	872.50

Note: The outer lid coefficients are from Excel File S&K_OL_Anne (DTN: LL000316005924.140), and the inner lid coefficients are from Excel File S&K_IL_Peen (DTN: LL000316105924.141).

Stress State Uncertainty

The uncertainty in the stress state of the closure-lid welds is calculated using the yield strength (*YS*) and fraction of the yield strength (*F*) of the lid materials (Alloy 22) as discussed in Section 6.3. The data are given in Table 4.

Table 4. Yield Strength and Fraction of the Yield Strength for the Uncertainty of the Stress State in the Closure-Lid Welds of the Outer Barrier (CRWMS M&O 2000a, p. 36).

	Outer Lid	Inner Lid
Yield Strength (*YS*) at 125 °C	46.72 ksi	46.72 ksi
Fraction of Yield Strength (*F*) for Annealed Lid	0.05	0.05

Note: The fraction of the yield strength represents the bounds at three standard deviations around the mean of normal distribution.

Stress State Variability

The variability of the mean stress along the circumference of the waste-package outer-barrier closure lid is represented with a sinusoidal variation with a range of 5 ksi about the mean stress (CRWMS M&O 2000a, p. 40).

Slip Dissolution Model for Crack Initiation and Growth

Once crack growth initiates the crack(s) grow at a velocity given by (CRWMS M&O 2000a, Section 6.4.4):

$$V_t = \bar{A}(K_I)^{\bar{n}} \qquad \text{(Eq. 2)}$$

where V is the crack growth rate in mm/s, and K_I is the stress intensity factor in Mpa·m$^{1/2}$. Parameters, $\bar{A}$ *and* $\bar{n}$, in the above equation are expressed as follows (CRWMS M&O 2000a, Section 6.4.4).

$$\bar{A} = 7.8x10^{-2}\, n^{3.6}\left(4.1x10^{-14}\right)^{n} \qquad \text{(Eq. 3)}$$

$$\bar{n} = 4n \qquad \text{(Eq. 4)}$$

The uncertainty in the model parameter n is represented by a uniform distribution with an upper bound of 0.84 and a lower bound of 0.75 (CRWMS M&O 2000a, Section 6.4.4).

4.2 CRITERIA

This section provides a summary of the NRC acceptance criteria outlined in the Issue Resolution Status Report (IRSR) that applies to the Container Life and Source Term Key Technical Issues (KTIs) (NRC 1999). The following six sub-issues are identified in the IRSR (NRC 1999, Section 2.2).

(1) Consider the effects of corrosion processes on the lifetime of the containers (NRC 1999, Section 2.2).

(2) Consider the effects of phase instability of materials and initial defects on the mechanical failure and lifetime of the containers (NRC 1999, Section 2.2).

(3) Evaluate the rate at which radionuclides in spent nuclear fuel (SNF) are released from the Engineered Barrier System (EBS) through the oxidation and dissolution of spent fuel (NRC 1999, Section 2.2).

(4) Evaluate the rate at which radionuclides in high-level waste (HLW) glass are leached and released from the EBS (NRC 1999, Section 2.2).

(5) Consider the effect of in-package criticality on waste package (WP) and EBS performance (NRC 1999, Section 2.2).

(6) Analyze the effects of alternate EBS design features on container lifetime and radionuclide release from the EBS (NRC 1999, Section 2.2).

Of these sub-issues, only sub-issues (1) and (2) are relevant to this analysis.

4.2.1 Acceptance Criteria Applicable To All Six Sub-Issues

(1) The collection and documentation of data, as well as development and documentation of analyses, methods, models, and codes, are accomplished under approved quality assurance and control procedures and standards (NRC 1999, Section 4.0).

(2) Expert elicitations, when used, are conducted and documented in accordance with the guidance provided in NUREG-1563 (Kotra, et. al., 1996) or other acceptable approaches (NRC 1999, Section 4.0).

(3) Sufficient data (field, laboratory, and natural analog) are obtained to adequately define relevant parameters for the models used to evaluate performance aspects of the sub-issues (NRC 1999, Section 4.0).

(4) Sensitivity and uncertainty analyses (including consideration of alternative conceptual models) are used to determine whether additional data would be needed to better define ranges of input parameters (NRC 1999, Section 4.0).

(5) Parameter values, assumed ranges, test data, probability distributions, and bounding assumptions used in the models are technically defensible and can reasonably account for known uncertainties (NRC 1999, Section 4.0).

(6) Mathematical model limitations and uncertainties in modeling are defined and documented (NRC 1999, Section 4.0).

(7) Primary and alternative modeling approaches consistent with available data and current scientific understanding are investigated and their results and limitations considered in evaluating the sub-issue (NRC 1999, Section 4.0).

(8) Model outputs are validated through comparisons with outputs of detailed process models, empirical observations, or both (NRC 1999, Section 4.0).

(9) The structure and organization of process and abstracted models adequately incorporate important design features, physical phenomena, and coupled processes (NRC 1999, Section 4.0).

4.2.2 Acceptance Criteria For Sub-Issue 1

(1) Identify and consider likely modes of corrosion for container materials, including dry-air oxidation, humid-air corrosion, and aqueous corrosion processes, such as general corrosion, localized corrosion, microbial-induced corrosion (MIC), stress corrosion cracking (SCC), and hydrogen embrittlement, as well as the effect of galvanic coupling (NRC 1999, Section 4.1.1).

(2) Identify the broad range of environmental conditions within the WP emplacement drifts that may promote the corrosion processes listed previously, taking into account the possibility of irregular wet and dry cycles that may enhance the rate of container degradation (NRC 1999, Section 4.1.1).

(3) Demonstrate that the numerical corrosion models used are adequate representations, taking into consideration associated uncertainties, of the expected long-term behaviors and are not likely to underestimate the actual degradation of the containers as a result of corrosion in the repository environment (NRC 1999, Section 4.1.1).

(4) Consider the compatibility of container materials, the range of material conditions, and the variability in container fabrication processes, including welding, in assessing the performance expected in the container's intended waste isolation function (NRC 1999, Section 4.1.1).

(5) Justify the use of data collected in corrosion tests not specifically designed or performed for the Yucca Mountain repository program for the environmental conditions expected to prevail at the Yucca Mountain site (NRC 1999, Section 4.1.1).

(6) Conduct a consistent, sufficient, and suitable corrosion testing program at the time of the LA submittal. In addition, DOE shall identify specific plans for further testing to reduce any significant area(s) of uncertainty as part of the performance confirmation program (NRC 1999, Section 4.1.1).

(7) Establish a defensible program of corrosion monitoring and testing of the engineered subsystems components during the performance confirmation period to assure they are functioning as intended and anticipated (NRC 1999, Section 4.1.1).

4.2.3 Acceptance Criteria for Sub-Issue 2

(1) Identify and consider the relevant mechanical failure processes that may affect the performance of the proposed container materials (NRC 1999, Section 4.2.1).

(2) Identify and consider the effect of material stability on mechanical failure processes for the various container materials as a result of prolonged exposure to the expected range of temperatures and stresses, including the effects of chemical composition, microstructure, thermal treatments, and fabrication processes (NRC 1999, Section 4.2.1).

(3) Demonstrate that the numerical models used for container materials stability and mechanical failures are effective representations, taking into consideration associated uncertainties, of the expected materials behavior and are not likely to underestimate the actual rate of failure in the repository environment (NRC 1999, Section 4.2.1).

(4) Consider the compatibility of container materials and the variability in container manufacturing processes, including welding, in its WP failure analyses and in the evaluation of radionuclide release (NRC 1999, Section 4.2.1).

(5) Identify the most appropriate methods for nondestructive examination of fabricated containers to detect and evaluate fabrication defects in general and, particularly, in seam and closure welds (NRC 1999, Section 4.2.1).

(6) Justify the use of material test results not specifically designed or performed for the Yucca Mountain repository program for environmental conditions (i.e., temperature, stress, and time) expected to prevail at the proposed Yucca Mountain repository (NRC 1999, Section 4.2.1).

(7) Conduct a consistent, sufficient, and suitable materials testing program at the time of the License Application submittal. In addition, DOE has identified specific plans for further testing to reduce any significant area(s) of uncertainty as part of the performance confirmation program (NRC 1999, Section 4.2.1).

(8) Establish a defensible program of monitoring and mechanical testing of the engineered subsystems components, during the performance confirmation period, to assure they are functioning as intended and anticipated, in the presence of thermal and stress perturbations (NRC 1999, Section 4.2.1).

4.3 CODES AND STANDARDS

No codes and standards are used in this analysis.

5. ASSUMPTIONS

The following assumptions were made. None of the following assumptions require confirmation prior to the use of the parameters developed in this document. All of the assumptions document accepted scientific practice and are consistent with assumptions made in the supporting AMRs.

5.1 MANUFACTURING DEFECTS IN CLOSURE-LID WELDS

Assumptions used to develop the abstraction for the probability and size of manufacturing defects in the waste package closure-lid welds are described in detail in the abstraction calculation (CRWMS M&O 2000c). The major assumptions that are important to the effect of the manufacturing defects on SCC are listed below.

5.1.1 Only surface breaking defects are considered, since these are the types of flaws that may potentially lead to stress corrosion cracking (SCC). Note that there is uncertainty associated with this assumption because, as general corrosion propagates, some of the pre-existing surface-breaking defects may disappear, and embedded defects would become surface-breaking defects. This evolution of the surface-breaking defects was not considered. This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.1.2 Only the closure-lid weld of the waste package develops residual stresses high enough to cause stress corrosion cracking (if corrosive environment is also present). Other fabrication welds used in waste package fabrication are fully annealed prior to waste emplacement, and thus do not develop residual stress high enough for stress corrosion cracking to occur (CRWMS M&O 2000a, Section 5, Assumption 1). This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.1.3 Flaws are assumed to occur randomly as represented by a Poisson process (CRWMS M&O 2000c). This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.1.4 The mean flaw density (Poisson distribution parameter) of the closure weld is assumed to be 0.6839 flaws per meter of one inch thick weld as given in the process model analysis (CRWMS M&O, 2000g) (DTN: MO9910SPAFWPWF.001). This is a reasonable value based on the literature reviewed for the process model analysis (CRWMS M&O 2000g). This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.1.5 The fraction of surface breaking flaws is assumed to be uniformly distributed between the minimum and maximum fractions (0.13% and 0.49%) used to determine the average fraction quoted in the process model analysis (CRWMS M&O 2000c) (DTN: MO0001SPASUP03.001). The basis of this assumption is that the three values (0.13%, 0.40% and 0.49%) quoted in the process model analysis are not sufficient to determine a single representative average value (CRWMS M&O 2000c). The use of the uniform distribution is a reasonable representation of the uncertainty in expressing this value. This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.1.6 Pre-inspection flaw sizes are assumed to be lognormally distributed, with distribution parameters (dependent on the weld thickness) as given in the process model analysis (CRWMS M&O 2000g) (DTN: MO9910SPAFWPWF.001). The assumption is employed because it provided the best fit to the flaw size data used in the upstream process model analysis (CRWMS M&O 2000g, Section 6.2.1). This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.1.7 The probability of non-detection is given as a function of flaw size as discussed in the process model analysis (CRWMS M&O 2000g) (DTN: MO9910SPAFWPWF.001). The model is dependent on the following parameters: the detection threshold (*p*), the location parameter (*b*), and a scale parameter (*v*). The *b* and *v* parameters are taken to be uncertain with a uniform distribution. The ranges for these distributions are determined from the values identified in the literature quoted in the process model analysis (CRWMS M&O 2000g) (DTN: MO9910SPAFWPWF.001). This is a reasonable assumption, as the manufacturing and detection processes for welds on the waste container are not specified to date. The values are based on similar industrial manufacturing practices as reviewed in the process model analysis. The basis for this assumption should be checked as data is developed on actual welds. This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.1.8 It is assumed that all flaws detected are repaired to specified acceptance criteria or removed in such a manner that they are eliminated from consideration for further failure analysis. This assumption is used in the abstraction analysis of manufacturing defects in waste package closure-lid welds in Section 6.2.

5.2 STRESS AND STRESS INTENSITY FACTOR PROFILES IN CLOSURE-LID WELDS

The following assumptions were used to develop abstractions for stress and stress intensity factor profiles in the closure-lid welds (outer and inner lids) of the outer barrier of waste package.

5.2.1 It is assumed that all fabrication welds of waste package, except the welds for closure lids, are fully annealed before the waste packages are loaded with waste and not subject to SCC (CRWMS M&O 2000a, Section 5, Assumption 1). This assumption is used in the abstraction analysis of stress and stress intensity factor profiles in waste package closure-lid welds in Section 6.3.

5.2.2 The hoop stress (and the corresponding stress intensity factor for radial cracks) is the prevailing stress in the closure-lid welds that fail the waste packages by SCC if it occurs. Thus, the current abstraction is limited to the profiles for the hoop stress and corresponding stress intensity factor for radial cracks (CRWMS M&O 2000a). This assumption is used in the abstraction analysis of stress and stress intensity factor profiles in waste package closure-lid welds in Section 6.3.

5.2.3 The hoop stress and corresponding stress intensity factor profiles in the inner lid welds from the process model analysis are for a plane that is inclined at about 37.5° from a plane normal to the outer surface of the inner lid (CRWMS M&O 2000a). Because the SCC analysis in the integrated waste package degradation model (WAPDEG) assumes that cracks propagate in the direction normal to the lid surface, the profiles from the process model analysis were projected to the plane normal to the outer surface of the lid. The SCC analysis with the projected profiles properly represents the hoop stress and stress intensity factor profiles for the inclined plane. This assumption is used in the abstraction analysis of stress and stress intensity factor profiles in waste package closure-lid welds in Section 6.3.

5.2.4 The hoop stress and corresponding stress intensity factor profiles versus depth in the closure-lid welds from the process model analyses represent the mean profiles (CRWMS M&O 2000a). The uncertainties in the hoop stress and corresponding stress intensity factor profiles are represented with normal distribution, and the uncertainty range is bounded at three standard deviations (± 3 s.d's) around the mean profiles (CRWMS M&O 2000a, Section 6.2.2.5) (DTN: LL000316005924.140, LL000316105924.141). This assumption is used in the abstraction analysis of stress and stress intensity factor profiles in waste package closure-lid welds in Section 6.3.

5.2.5 The hoop stress and stress intensity factor profiles vary along the circumference of the closure-lid welds, and this represents the variability in the profiles on a given waste package. The same degree of the profile variability is applied equally to all the waste packages in the repository, and there is no variability in the profiles among waste packages. This assumption is used in the abstraction analysis of stress and stress intensity factor profiles in waste package closure-lid welds in Section 6.3.

5.2.6 As a crack propagates in the closure lid welds or the welds corrode by corrosion, stresses in the welds may re-distribute in such a way to mitigate the SCC initiation and crack growth (CRWMS M&O 2000a). Such stress re-distribution or relaxation is not considered in the current abstraction. This is a conservative bounding condition such that additional confirmation is not needed. This assumption is used in the abstraction analysis of stress and stress intensity factor profiles in waste package closure-lid welds in Section 6.3.

5.3 SLIP DISSOLUTION MODEL

The following assumptions were used to develop abstraction for the slip dissolution model for the SCC crack growth.

5.3.1 Induction-heating solution annealing is used to mitigate residual stress in the outer closure-lid welds, and laser peening in the inner closure-lid welds (CRWMS M&O 2000a, Section 6.2.2.4). The process-model manufacturing defect analyses (CRWMS M&O 2000g) and the abstraction calculation (CRWMS M&O 2000c) are assumed applicable to the closure-lid welds after the stress annealing processes. This assumption is used in the abstraction analysis of the Slip Dissolution Model and model parameters in Section 6.4.

5.3.2 It is assumed that the analyses for incipient cracks reported in the process model analysis (CRWMS M&O 2000a) are applicable to the closure-lid welds after the stress mitigation process. This assumption is used in the abstraction analysis of the Slip Dissolution Model and model parameters in Section 6.4.

5.4 THRESHOLD STRESS INTENSITY FACTOR (K_{ISCC}) MODEL

The following assumption was employed in the SCC analysis with the threshold stress intensity factor (K_{ISCC}) model.

5.4.1 As recommended in the process model analysis (CRWMS M&O 2000a), the threshold stress intensity factor (K_{ISCC}) model is applied to pre-existing flaws such as manufacturing defects in the closure-lid welds. This assumption is used in the abstraction analysis of the Threshold Stress Intensity Factor Model and model parameters in Section 6.5. The effect of different exposure conditions (including applied stress) on the K_{ISCC} value, and improved characterization of its uncertainty and variability under those varying exposure conditions will be made as additional data and analysis are developed (CRWMS M&O 2000a, Section 6.3.2).

6. ANALYSIS/MODEL

This section documents analyses to develop abstractions for models and parameters for stress corrosion cracking (SCC) of waste package and drip shield and hydrogen induced cracking (HIC) of drip shield. As discussed in Section 6.1 below, SCC and HIC of drip shield would not affect the drip shield performance under the repository conditions. No further analysis was conducted for model abstraction of SCC and HIC of the drip shield. The results of the abstraction analyses documented in this AMR are tracked by DTN: MO0004SPASDA04.003 .

In order for SCC to occur in a susceptible material, three factors must be present: a flaw (or crack-initiation site), a stress state, and a corrosive environment (CRWMS M&O 2000a, Section 6.1). Except the welds for the closure lids (for example, outer and inner lids of the outer barrier of waste package), all the fabrication welds in the waste packages are assumed fully annealed and not subject to SCC. Also, the major sources of stresses in the drip shield induced by backfill and earthquakes are insignificant to SCC (CRWMS M&O 2000a, Section 5, Assumption 1). Therefore, the abstractions for the SCC model discussed in this section are for the closure-lid welds in the waste package. The current abstraction analysis does not address detailed potential effects of microstructure-scale processes on SCC such as dislocation, aging, noble element enrichment, etc.

In the current waste package degradation analysis, two alternative SCC models, the Slip Dissolution (or Film Rupture) Model and the Threshold Stress Intensity Factor (K_{ISCC}) Model, are considered (CRWMS M&O 2000a, Section 3.2). In the Threshold Stress Intensity Factor Model, the threshold stress intensity factor (K_{ISCC}) is used to determine when SCC will occur. Provided that an initial flaw and corrosive environment is present, a SCC failure will occur when the applied stress intensity factor K_I is greater than or equal to the threshold stress intensity factor K_{ISCC} (i.e., $K_I \geq K_{ISCC}$). The Slip Dissolution Model assumes that incipient cracks or defects grow continuously when the oxidation reaction that occurs at the crack tip ruptures the protective film via an applied strain in the underlying matrix. The rate at which the crack grows is a function of the crack tip strain rate and environmental and material chemistries. The theory and fundamentals of the SCC models are described in detail in the process model analysis (CRWMS M&O 2000a). This section documents the model abstractions for the two alternative SCC models.

6.1 STRESS CORROSION CRACKING AND HYDROGEN INDUCED CRACKING OF DRIP SHIELD

As discussed in the process model analysis report (CRWMS M&O 2000a), the drip shield is assumed fully annealed before it is placed in the emplacement drift and assumed not subject to SCC under the conditions anticipated in the repository. Therefore, no additional analysis was conducted for SCC of drip shield.

Hydrogen induced cracking (HIC) of drip shield is a potential degradation mechanism that could cause catastrophic failure of drip shield if the hydrogen uptake in the titanium drip shield is greater than the critical hydrogen concentration (CRWMS M&O 2000d). In the current design with backfill placed over the drip shield, crevice corrosion and passive general corrosion of the drip shield are two feasible processes in the repository that could lead HIC failure of the drip shield. Hydrogen is produced as a result of the corrosion processes. Some of the hydrogen produced can be absorbed by the titanium metal and then transported into the metal by diffusion. Because the drip shield will not be subject to crevice corrosion under the exposure conditions anticipated in the repository (CRWMS M&O 2000e), general corrosion is the only mechanism that could cause HIC in the drip shield. Results of the bounding analyses have shown that the time that the hydrogen uptake concentration reaches the critical hydrogen concentration under the exposure conditions anticipated in the repository (CRWMS M&O 2000d) is greater than the time required to initiate the drip shield breach by general corrosion (about 20,000 years) (CRWMS M&O 2000b, Section 3.2.5). Therefore it is concluded that HIC is not a limiting degradation process that could significantly affect the drip shield performance in the repository, and no additional analysis was conducted.

6.2 MANUFACTURING DEFECTS IN CLOSURE-LID WELDS

6.2.1 Abstraction Methodology

In addition to other factors affecting SCC such as residual stress and corrosive environment, pre-existing manufacturing defects in the waste package closure welds have significant effects on the initiation of and failure by SCC of waste packages. Therefore, a separate analysis was conducted to quantify the probability of the occurrence and size of the defects in the waste package closure-lid welds and their uncertainty and variability (CRWMS M&O 2000c). This section summarizes the abstraction analyses. Initial (pre-inspection) mean flaw densities and flaw sizes used in the abstraction were from the upstream process model analysis (CRWMS M&O 2000g) (DTN: MO9910SPAFWPWF.001). Calculation of the outer surface-breaking mean flaw density begins with the base mean flaw density of 0.6839 flaws/meter of weld for a one inch thick stainless steel Tungsten Inert Gas (TIG) weld (this density was measured from an actual weld performed under shop conditions) subject to radiographic (RT) and dye-penetrant (PT) tests (DTN:

MO9910SPAFWPWF.001). To convert this value to a flaw density for an uninspected weld, the base flaw density is increased by the sum of the flaw reduction factors provided for the RT and PT tests. The adjustment for the RT exam increases the total flaw density by a factor of 12.8 while the PT exam, which detects only surface-breaking flaws, increases the density of only the surface-breaking flaws by a factor of 31.4 (DTN: MO9910SPAFWPWF.001). Next the effect of weld thickness on flaw density is used to adjust for the actual weld thickness on the closure welds. For the 25-mm thick outer closure-lid weld, the flaw reduction factor is 97.3% (865 divided by 889) (DTN: MO9910SPAFWPWF.001). Multiplying this result by the circumference of the closure weld results in the flaw density per closure weld (or per waste container). A final multiplication by the fraction of surface breaking flaws results in the final mean flaw density of surface breaking flaws per closure weld. Details of the abstraction approach are given in CRWMS M&O 2000c.

The resulting cumulative probability for defects for the outer (25-mm thick) and inner (10-mm thick) closure weld lids of the outer barrier are shown in Figure 1 (CRWMS M&O 2000c). Each of the cumulative probabilities in the figure is from 100 realizations with random sampling of parameters the location parameter (b) and the scale parameter (ν) and represent the defect flaw probability used in the waste package SCC analysis. Figure 2 shows several probability density functions (pdf's) for defect flaw sizes in the closure-lid welds for various combinations of parameter values for the location parameter (b) and a scale parameter (ν). The pdf's are used for both the outer and inner lid welds (CRWMS M&O 2000c).

6.2.2 Implementation of Closure-Lid Weld Defect Flaw Abstraction Results in Waste Package Degradation Analysis

The number of flaws that appear on a patch is sampled stochastically as a Poisson random variable as suggested in the process model analysis (CRWMS M&O 2000g). For each flaw that occurs (i.e., when the number of flaws is not equal to zero), a flaw size is randomly assigned to it by sampling from the calculated flaw size cumulative distribution function (Figure 2). This flaw (with sampled location and size) is then used in the SCC analysis. The abstracted results are then input to the integrated waste package degradation model (WAPDEG) to analyze its effect on waste package performance (CRWMS M&O 2000b, Section 3.2.5).

The main approach in this abstraction is that, as these distributions treat the variability observed in flaws occurrence and size, some of the parameters that determine these distributions may need to be treated as uncertain. The instances of where uncertainty is included are for the parameters of 1) the flaw detection distribution (b and ν) and 2) the fraction of surface breaking flaws (ψ). The parameters are treated as follows. The b and v parameters of the detection distribution are allowed to uniformly range between 1.6 to 5 mm and 1 to 3, respectively (CRWMS M&O 2000c). The fraction of surface breaking flaws (ψ) in the upstream process model analysis (CRWMS M&O 2000g) (DTN: MO9910SPAFWPWF.001) is an average of three observations (average (0.49%, 0.40%, 0.13%) = 0.34%). Instead of using a single value (i.e., 0.34%), it is allowed to uniformly range from 0.13% to 0.49% (CRWMS M&O 2000c). The model parameters are varied independently. Sensitivity analyses with the proposed distributions of the parameters need to be conducted to analyze the affect of not knowing the correct (deterministic) value of the parameters.

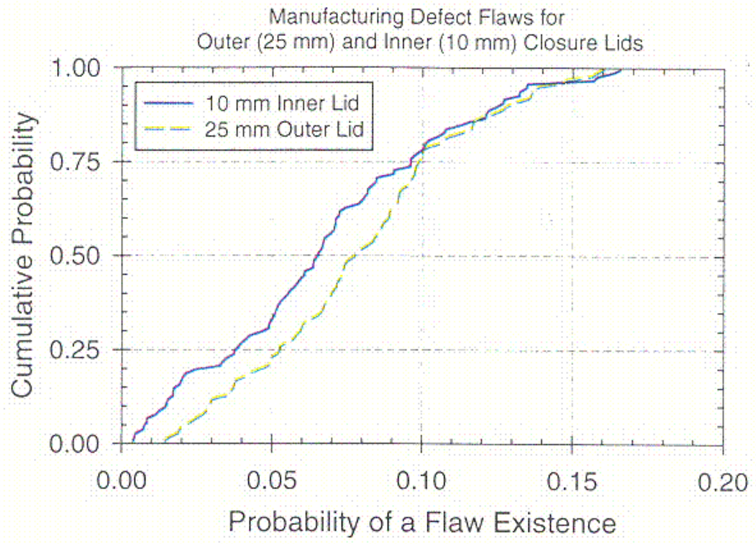

Figure 1. Cumulative probability for the occurrence of defect flaws in the welds of the outer (25-mm thick) and inner (10-mm thick) lids of waste package outer barrier (Source: CRWMS M&O 2000c; DTN: MO0001SPASUP03.001).

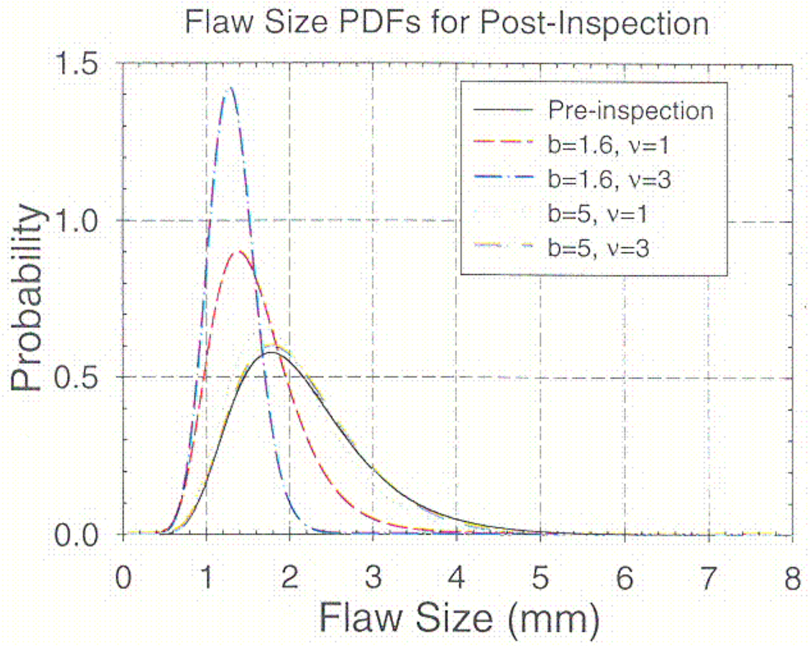

Figure 2. Conditional probability density functions of defect flaw sizes in the closure lid welds for various combinations of values for parameters, *b* and *ν* (Source: CRWMS M&O 2000c; DTN: MO0001SPASUP03.001).

6.3 STRESS AND STRESS INTENSITY FACTOR PROFILE IN CLOSURE-LID WELDS

6.3.1 Abstraction Methodology

The hoop stress (and the corresponding stress intensity factor for radial cracks) is the prevailing stress in the closure lid welds that fail the waste packages by SCC if it occurs (CRWMS M&O 2000a). Thus, the current abstraction is limited to the profiles for the hoop stress and corresponding stress intensity factor for radial cracks.

The outer lid of the waste package outer barrier is 25-mm thick and composed of Alloy 22. The inner lid of the outer barrier is 10-mm thick and composed of Alloy 22. Details of the abstraction and analysis process are presented in Attachment I. The coefficients for the polynomial equation to calculate the stress versus depth (given in Table 3) were first converted from English units (i.e., ksi and inches) to metric units (i.e., MPa and milimeters). The resulting coefficients are shown in Table 5.

Table 5. Coefficients of the Polynomial Equation to Calculate the Stress State versus Depth for the outer and inner lids in Attachment I (converted to metric units relative to those in Table 3).

Coefficient	Outer Lid	Inner Lid
A_0	-356.26778	-437.720543
A_1	37.180767	176.967239
A_2	1.436391	-15.606072
A_3	-0.065282	0.367099

The provided hoop stress state was determined to vary with angle (θ) around the circumference of the waste package closure-lid welds ($\theta = 0$ for a reference point arbitrarily chosen) according to the following functional form (CRWMS M&O 2000a, Section 6.2.2.5):

$$\sigma_t = \sigma_s(x) - (2.5 \cdot 6.894757) \cdot (1 - \cos(\theta)) \qquad \text{(Eq. 5)}$$

Note that σ_s (defined in Equation 1) should use the stress coefficients (A_i) defined in Table 5 with x in units of milimeters, and *6.894757* is a conversion factor between ksi and MPa. Based on the angular stress variation in Equation 5, the stress intensity (K_I) variation with angle is given by

$$K_t(x,\theta) = K_s(x) \cdot \left(\frac{\sigma_t(Thck,\theta)}{\sigma_t(Thck,0)} \right) \qquad \text{(Eq. 6)}$$

where *Thck* is the lid thickness (CRWMS M&O 2000a, Section 6.2.2.5). The uncertainty in the stress state and stress intensity factor is introduced through a scaling factor, $rscale(\theta,s)$, where s represents the number of standard deviations away from the median value. The scaling factor is also a function of the yield strength (YS) and yield strength scaling factor (F),

$$rscale(\theta, s) = \frac{\sigma_t(Thck,\theta) + s \cdot \left(\frac{YS \cdot F}{3}\right)}{\sigma_t(Thck,\theta)} \qquad \text{(Eq. 7)}$$

The elicited radial crack path for the outer lid (driven by the hoop stress) is in a direction normal to the outer surface (CRWMS M&O 2000a), thus, the crack length corresponds to the crack depth for the outer lid. However, the elicited crack path for the inner lid is at an angle to the normal of the lid surface (CRWMS M&O 2000a, p. A-60 and A-61), and the depth of the crack with respect to the surface is determined by projecting the crack length onto the lid surface normal. The angle of projection (37.5 degrees) was estimated from the length of the hoop stress plane and the thickness of the inner lid (see CRWMS M&O 2000a, Figure AI-1). Thus the *sine* of the angle multiplied by the crack length results in the crack depth with respect to the inner lid surface (i.e., in a direction normal to the inner lid outer surface).

6.3.2 Abstraction Results and Discussion

The abstraction results for the uncertainty range of the hoop stress at the weld centerline plane as a function of depth in the outer closure-lid welds (25-mm thick) are given in Figure 3. With respect to potential susceptibility to SCC, this path through Alloy 22 weld metal is very likely to be the most vulnerable as observed in other high nickel alloys (CRWMS M&O 2000a). The stress profiles in Figure 3 are at a reference location (*0°* angle) on the circumference of the lid welds. As will be shown later (Figure 5), the reference location on the lid weld circumference was selected in such a way that it has the largest hoop stress. The figure shows that the hoop stress in the outer-lid welds is compressive at the surface (from stress mitigation with the induction-heating solution annealing technique) and becomes tensile at a depth of about 8 mm. The uncertainty range becomes larger with the weld depth. This is because the stress uncertainty is obtained by multiplying the mean stress by the uncertainty scaling factor in Equation (7) and the mean stress increases with the depth. The corresponding stress intensity factor profiles as a function of radial crack depth are shown in Figure 4. The stress intensity factor is negative at the surface, consistent with the compressive stress at the surface shown in Figure 3, and becomes positive at a depth of about 12-mm. Therefore no SCC crack will initiate until the 12-mm thick layer is removed. As with the hoop stress, the uncertainty range of the stress intensity factor increases with the weld depth. Figures 5 and 6 show respectively the hoop stress as a function of depth and the corresponding stress intensity factor as a function of radial crack depth, both at *0°*, *90°*, and *180°* angle along the circumference of the outer-lid welds. The reference location designated at 0° angle has the largest hoop stress, and the location at *180°* angle has the least hoop stress. As shown in the figures, the variability of the both profiles along the weld circumference is minor.

The abstraction results for the uncertainty range of the hoop stress as a function of the projected depth for the inner closure-lid welds (10-mm thick) are given in Figure 7. The stress profiles are at a reference location (*0°* angle) on the circumference of the lid welds. The hoop stress in the inner-lid welds is compressive at the surface (from stress mitigation with the laser peening technique), transits to tensile state at a projected depth of about 2-mm, and then back to compressive state at a projected depth of about 8.5-mm. The uncertainty range in the profiles is larger for the tensile region of the weld depth. The corresponding stress intensity factor profiles as a function of the projected radial crack depth are shown in Figure 8. The stress intensity factor is negative at the surface and becomes positive at a projected depth of about 5-mm. Therefore no SCC crack will initiate until the (projected) 5-mm thick layer is removed. The uncertainty of the stress intensity factor increases slightly with the weld depth beyond the depth at which it becomes positive. Figures 9 and 10 show respectively the hoop stress as a function of the projected depth and the corresponding stress intensity factor as a function of the projected radial crack depth, both at *0*°, *90*°, and *180*° angle along the circumference of the inner-lid welds. As for the outer-lid welds, the variability of the both profiles along the weld circumference of the inner lid is minor.

6.3.3 Implementation of the Abstraction Results

The abstraction processes that are described above and detailed in Attachment I were implemented as a software routine (SCCD Version 1.01) written in Fortran. The software routine is called by the integrated waste package degradation model (WAPDEG) (CRWMS M&O 2000b). Details of the software routine verification are documented in Attachment I. The software routine was tested and validated for the range of the parameters used in the waste package degradation analysis as documented in Attachment I.

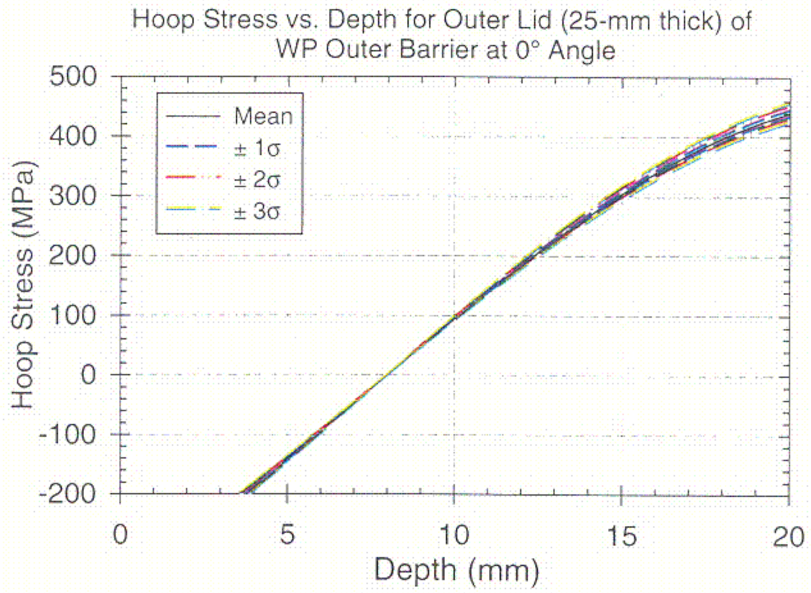

Figure 3. Hoop stress as a function of depth in the outer-lid welds (25-mm thick) at the reference location on the outer-lid weld circumference and the uncertainty range.

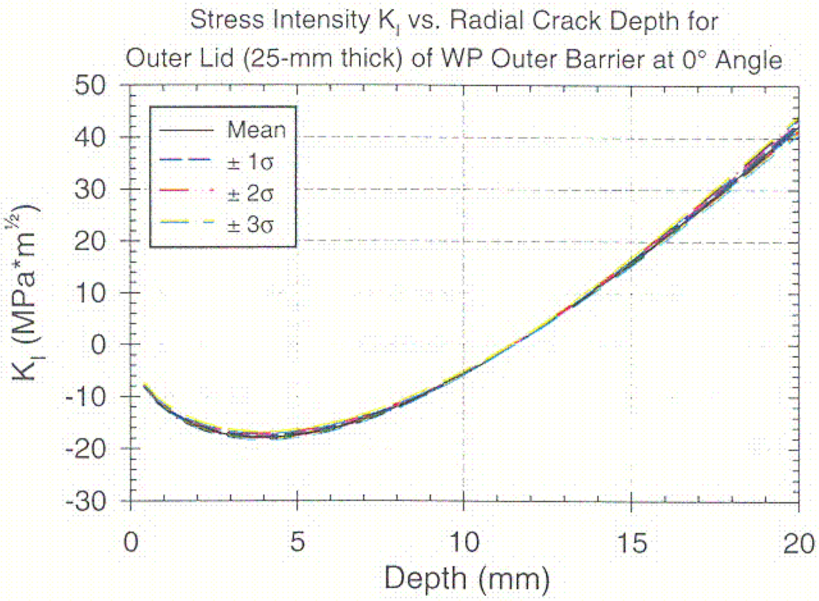

Figure 4. Stress intensity factor as a function of radial crack in the outer-lid welds (25-mm thick) at the reference location on the outer lid weld circumference and the uncertainty range.

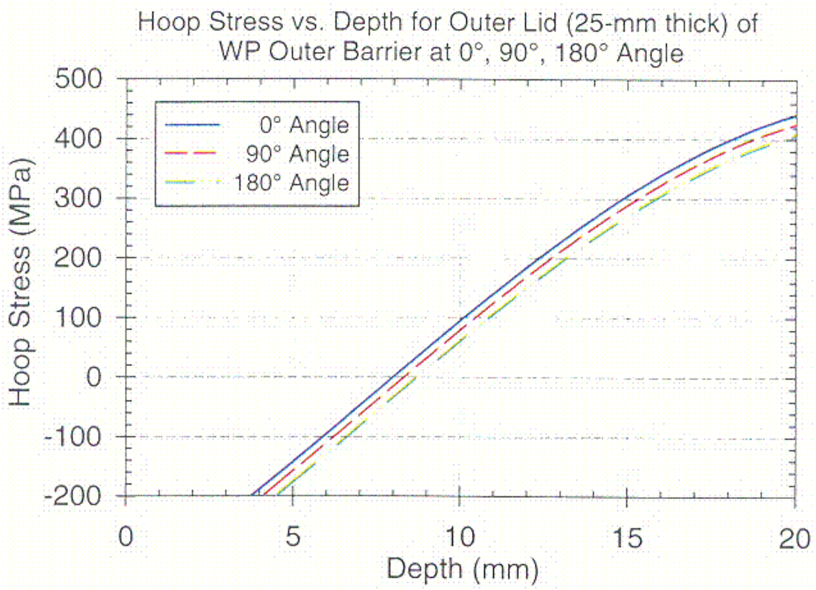

Figure 5. Hoop stress as a function of depth in the outer-lid welds (25-mm thick) at 0°, 90° and 180° angles along the circumference of the outer-lid weld.

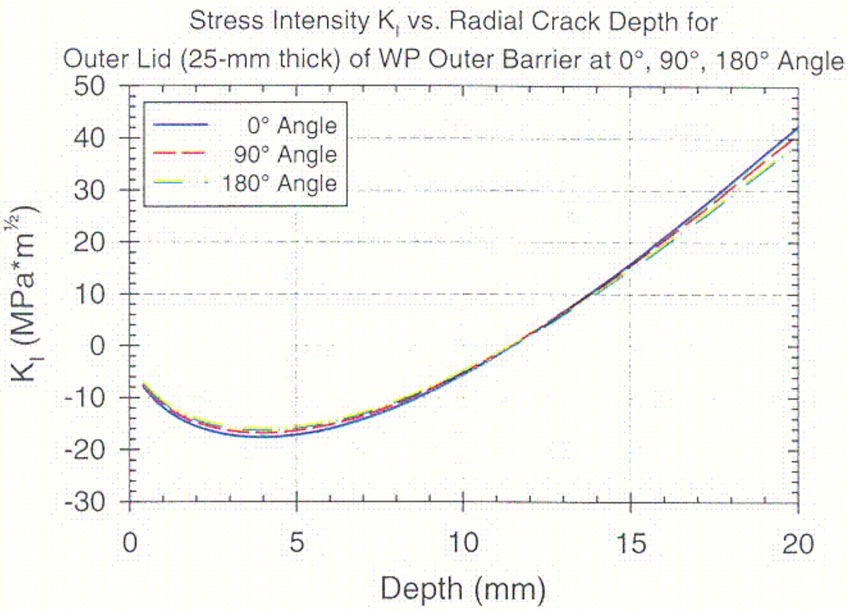

Figure 6. Stress intensity factor as a function of radial crack in the outer-lid welds (25-mm thick) at 0°, 90° and 180° angles along the outer lid weld circumference.

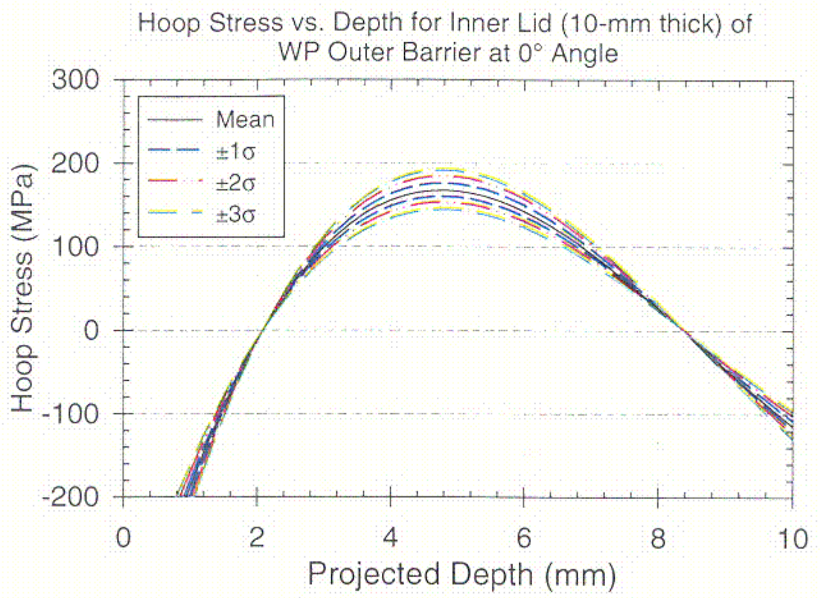

Figure 7. Hoop stress as a function of the projected depth in the inner-lid welds (10-mm thick) at the reference location on the inner-lid weld circumference and the uncertainty range.

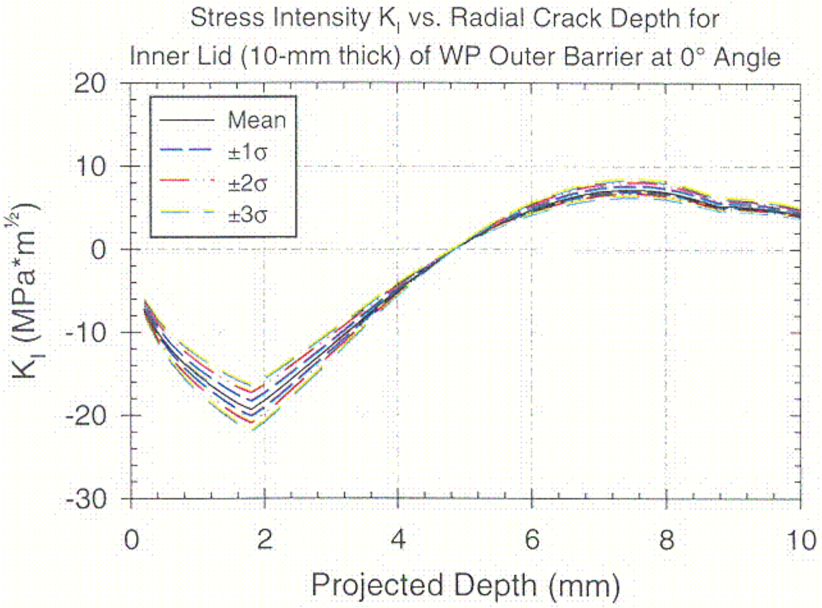

Figure 8. Stress intensity factor as a function of the projected radial crack depth in the inner-lid welds (10-mm thick) at the reference location on the inner-lid weld circumference and the uncertainty range.

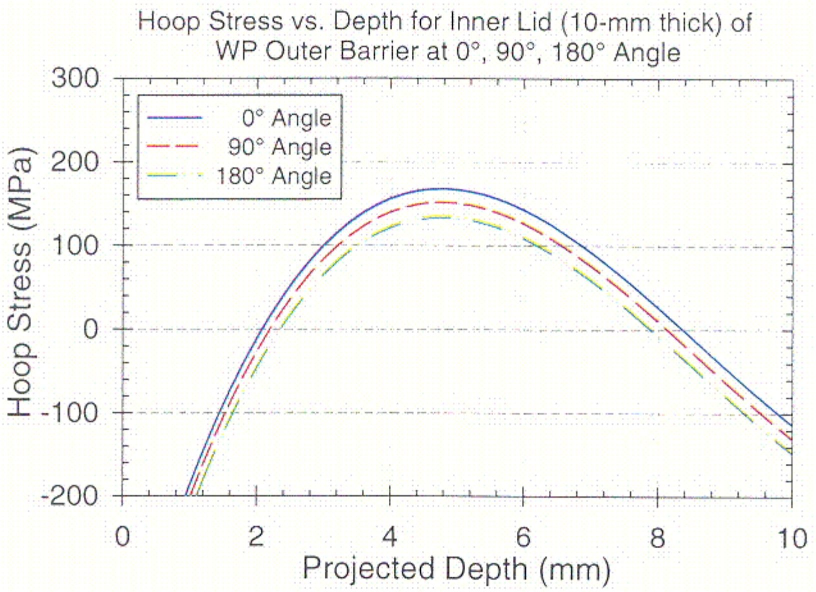

Figure 9. Hoop stress as a function of the projected depth in the inner-lid welds (10-mm thick) at 0°, 90° and 180° angles along the circumference of the inner-lid weld.

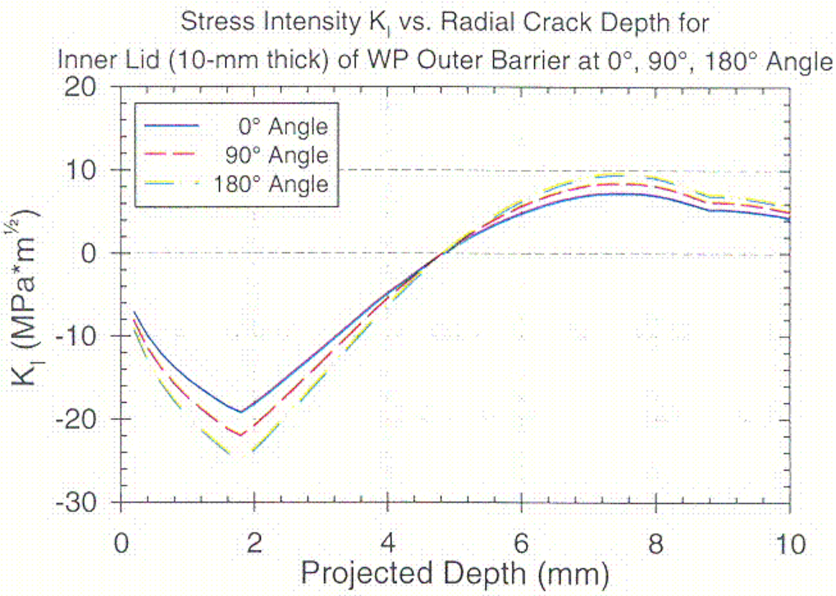

Figure 10. Stress intensity factor as a function of the projected radial crack depth in the inner-lid welds (10-mm thick) at 0°, 90° and 180° angles along the inner-lid weld circumference.

6.4 SLIP DISSOLUTION MODEL

This section discusses the approach and methodology used in the abstraction development for the slip dissolution model. This section also discusses the abstraction results and their implementation in the integrated waste package degradation model (WAPDEG) (CRWMS M&O 2000b).

6.4.1 Abstraction Approach and Methodology

The purpose of this analysis is to develop abstractions for the parameters that are associated with the Slip Dissolution model. In the waste package degradation (WAPDEG) analysis this model is employed to calculate the growth rate of cracks initiated by stress corrosion cracking (SCC). The theory and fundamentals of the model are discussed in detail in the process model analysis (CRWMS M&O 2000a). The waste package degradation analysis employs a stochastic approach to model the initiation and propagation of SCC cracks. The major efforts in the abstraction discussed in this section are to develop an approach to represent the uncertainty and variability associated with the SCC initiation and crack propagation processes, and to implement them in the waste package degradation analysis. As discussed in the following section, the associated parameters in the model include two model parameters (*A* and *n*), stress intensity factor (K_I), threshold stress, and incipient crack density and size. The nominal-case SCC analysis also includes pre-existing manufacturing defects in the closure-lid welds. Abstractions for the manufacturing defects and the residual stress and stress intensity factor in the closure-lid welds are discussed in Sections 6.2 and 6.3, respectively. The current abstractions for the model parameters (*A* and *n*), threshold stress, and incipient cracks expand the process model analysis results to represent and quantify the uncertainty and variability associated with the parameters (CRWMS M&O 2000a). The abstraction assumes that statistical sampling of the associated model parameter values within their probable range capture the effects of the complex processes affecting the SCC crack initiation and growth rate.

6.4.2 Crack Growth Rate Model

The crack growth rate in the slip dissolution model is determined by the following expression (CRWMS M&O 2000a, Section 6.4.4).

$$V_t = \overline{A}(K_I)^{\overline{n}} \qquad \text{(Eq. 2)}$$

where *V* is the crack growth rate in mm/s, and K_I is the stress intensity factor in $MPa(m)^{1/2}$. Parameters, $\overline{A}$ *and* $\overline{n}$, in the above equation are expressed as follows (CRWMS M&O 2000a, Section 6.4.4).

$$\overline{A} = 7.8\text{x}10^{-2} n^{3.6}\left(4.1\text{x}10^{-14}\right)^{n} \qquad \text{(Eq. 3)}$$

$$\overline{n} = 4n \qquad \text{(Eq. 4)}$$

Parameter "n" (referred to also as the repassivation potential slope) is a function of environmental and materials parameters such as solution conductivity, corrosion potential, and alloy composition (i.e., chromium depletion in the grain boundary) (CRWMS M&O 2000a). The variability in the crack growth rate may be represented with potentially varying exposure conditions (n) and stress intensity factor (K_I) among waste packages and also on different locations over a single waste package. However, due to a lack of data, n is considered independent of exposure conditions and alloy composition. In the waste package degradation analysis (CRWMS M&O 2000b, Section 3.2.5), the value of the parameter is sampled from a range (i.e., from 0.75 to 0.84 discussed in the next paragraph). Impact of this approach needs to be assessed as additional data and analysis is developed. However, the effect of n on the failure time by SCC is less than the stress intensity factor (K_I) (see Section 6.4.5). As discussed in Section 6.3, the stress intensity factor profile (as a function of depth in the closure-lid weld) varies along the circumference of the closure-lid welds, but the variability is not significant. It is assumed that there is no variability in the profile among waste packages.

The uncertainty associated with the crack growth rate is represented with the uncertainties in the model parameters, i.e., n and K_I. As discussed in Section 6.3, the uncertainties associated with the K_I profiles are represented with normal distribution bounded at three standard deviations from the mean profile. Because of a lack of data, the uncertainty associated with n is coarsely defined: uniform distribution between the lower bound 0.75 and the upper bound 0.84 (CRWMS M&O 2000a, Section 6.4.4). The lower bound value for n will be verified from the on-going work (CRWMS M&O 2000a, Section 3.2).

6.4.3 Threshold Stress for Crack Growth Initiation

The threshold stress is defined as the minimum stress at which cracks start growing at a rate determined by Equation (2). The threshold stress may be represented as a fraction of the yield strength of the material, which varies with temperature (CRWMS M&O 1999c, p. 33). Because the upper limit of the temperature at which corrosion initiates (or stable liquid water can form) is 120.59 °C (CRWMS M&O 2000f, Section 4.1.8, Table 7), the yield strength of Alloy 22 at 125 °C is used. The yield strength was calculated by linearly interpolating the yield strengths at 93 °C (338 MPa) and 204 °C (283 MPa) (CRWMS M&O 1999c, p. 33). The resulting yield strength used for the threshold stress is 322.3 MPa (46.72 ksi). Although the yield strength increases as temperature decreases, the value at 125 °C is used for all the waste package temperatures after corrosion initiates in the repository. This is because there is only a small change in the yield strength of Alloy 22 from 125 °C to the ambient temperature. Potentially marginal variability in the yield strength and thus the threshold stress are ignored in the current analysis.

As suggested in the process model analysis (CRWMS M&O 2000a, Section 6.5.2), the uncertainty in the threshold stress is conservatively represented as 20 to 30 percent of the yield strength, and uniform distribution is assumed for the uncertainty range. Thus, the resulting uncertainty range for the threshold stress is 64.46 to 96.60 MPa with the assumed uniform distribution between the two values. In the SCC analysis of waste package closure-lid weld with WAPDEG, for each realization (or each run), the threshold stress is sampled from the range with the assumed uniform distribution, and the sampled threshold stress is used for all the closure-lid weld patches of the waste packages under consideration.

6.4.4 Incipient Cracks and Manufacturing Defects

In the SCC process the crack initiation is associated with microscopic crack formation at localized corrosion or mechanical defect sites that are associated with pitting, intergranular attack, scratches, weld defects, planar dislocations, secondary phase precipitates, or design notches. The crack growth rate increases as the microscopic cracks coalesce, and approaches a steady-state value when a crack can be detected (CRWMS M&O 2000a, Section 6.4.1). The current analysis assumes that a crack depth range of about 20 μm to 50 μm represents the minimum crack depth for which the Slip Dissolution model can be applied. Those cracks are referred to as "incipient" cracks. Exponential distribution with a maximum size of 50 μm and a medium size of 20 μm was suggested for the incipient crack size distribution (CRWMS M&O 2000a, Section 6.5.2). Because the effect of differing incipient crack sizes within the suggested range on crack growth rate is much less than the model parameters (n and K_I), the medium crack size (20 μm) is used for all the incipient cracks considered in the SCC analysis.

The SCC analysis using the Slip Dissolution model also considers manufacturing defects in the closure-lid welds. As discussed in Section 6.2, in the WAPDEG analysis, the size of the manufacturing defects are sampled for the closure-lid weld patches, and the sampled defect flaws are included in the Slip Dissolution model. Because manufacturing defects are much larger than the incipient cracks, the closure-lid weld patches with manufacturing defects are likely to fail initially by SCC.

6.4.5 Slip Dissolution Model Analysis

Bounding analyses were performed to examine the model responses for the SCC failure time of the outer lid (25-mm thick) and inner lid (10-mm thick) as a function of the model parameters (n and K_I). The analyses considered two bounding values (0.75 and 0.84) for n (CRWMS M&O 2000a, Sections 3.2 and 6.4.4) and a range of values for the stress intensity factor, which may be expected in the closure-lid welds (CRWMS M&O 2000a, Attachment I). The lower bound value for n will be verified from the future work (CRWMS M&O 2000a, Section 3.2). The threshold stress for crack growth initiation and pre-existing manufacturing defect were not considered in this bounding analysis. The results are shown in Figure 11. As shown in the figure, the stress intensity factor is the dominant parameter in the model, and the time to failure by SCC increases exponentially as the stress intensity factor decreases. The failure time by SCC is less than 100 years for the stress intensity factors greater than 20 MPa($m^{1/2}$). The failure time increases to well above 1,000 years if the stress intensity factor is kept below 6 MPa($m^{1/2}$). The analysis demonstrates that, once a SCC crack initiates, it penetrates the closure-lid thickness fast. It also demonstrates importance of stress mitigation in the closure-lid welds to avoid premature failures of waste packages by SCC.

6.5 THRESHOLD STRESS INTENSITY FACTOR MODEL

The concept of threshold stress intensity factor (K_{ISCC}) has been commonly used to assess the susceptibility of material to SCC (CRWMS M&O 2000a, Section 3.2). The applicability of this model to the waste package outer barrier (Alloy 22) has been studied experimentally and estimates of K_{ISCC} have been obtained. A reasonable mean value of 30 Mpa·$m^{1/2}$ was estimated using load controlled compact tension specimens exposed to 110°C basic saturated water (BSW) (CRWMS M&O 2000a, Section 6.3.2). This mean value was corroborated (Roy et al. 1998) along with an experimental basis for establishing a basis for the expected degree of uncertainty. In this latter study the susceptibility of Alloy 22 and Ti GR-12 to SCC is evaluated by using wedge-loaded pre-cracked double-cantilever-beam (DCB) specimens in de-aerated acidic brine (pH ≈ 2.7) at 90°C. Details of the testing and model are described by Roy et al. (1998).

In this model failure is assumed to occur for crack sizes a where $K_I \geq K_{ISCC}$. In applying the Threshold Stress Intensity Factor model, it is necessary to obtain information on (1) stress intensity factor $K_I(a, \sigma)$ as a function of crack size correspondent to the stress state at and near the crack site and (2) the threshold value of the stress intensity factor K_{ISCC}. This method is considered to be conservative if the threshold K_{ISCC} can be accurately determined experimentally. This method is conservative because it ignores the fact that the crack growth does not necessarily lead to a failure state in cases where the stress intensity factor exceeds the threshold.

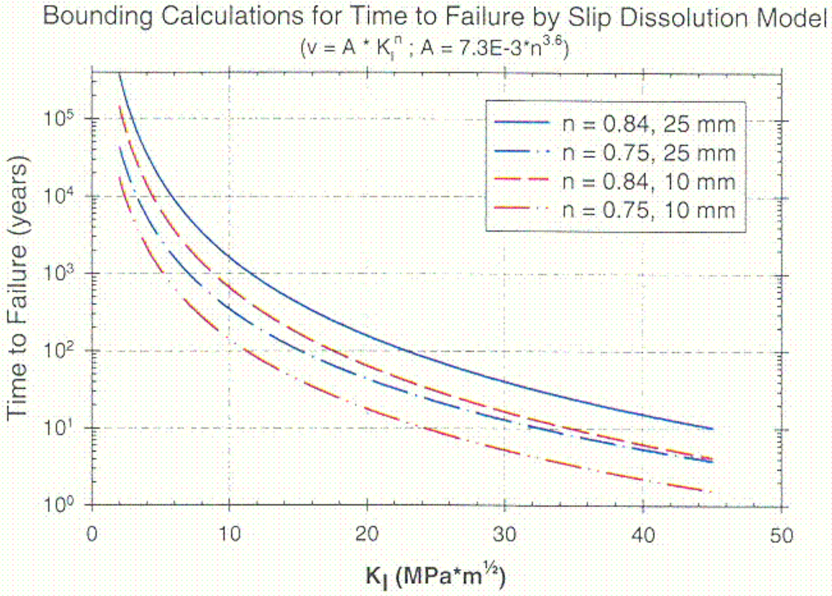

Figure 11. Bounding calculations for the model responses for the time to failure of the outer and inner closure lids by SCC calculated with the slip dissolution model using the bounding values for parameter n for a range of the stress intensity factor values.

As suggested in the process model analysis (CRWMS M&O 2000a, Section 6.3), the K_{ISCC} of the waste package outer barrier (Alloy 22) is characterized assuming a normal distribution with a mean of 30 ksi·in$^{1/2}$ (or 33 MPa·m$^{1/2}$) and a standard deviation of 1.6 ksi·in$^{1/2}$ (or 1.8 MPa·m$^{1/2}$). It is assumed the distribution is bounded at ± 4 standard deviations. The entire variance of the K_{ISCC} is considered as uncertainty. The probability density function for the K_{ISCC} is shown in Figure 12. The lower limit of the parameter is 23.5 ksi·in$^{1/2}$ (or 25.9 MPa·m$^{1/2}$), and the upper limit is 36.5 ksi·in$^{1/2}$ (or 40.2 MPa·m$^{1/2}$). Additional data are needed for the effect of different exposure conditions (including applied stress) on the K_{ISCC} value, and to better quantify its uncertainty and variability under those varying exposure conditions (CRWMS M&O 2000a, Section 6.3.2).

As shown in Figure 2, the possible maximum manufacturing defect flaw size in the closure-lid welds is about 6-mm. Assuming this defect flaw is a radial crack, the maximum stress intensity factor at the tip of the crack in the outer closure-lid is about –15 MPa·m$^{1/2}$ (Figure 4), and that in the inner closure-lid is about 5 MPa·m$^{1/2}$ (Figure 8). Because these are less than the minimum K_{ISCC} (25.9 MPa·m$^{1/2}$) for SCC to occur, no SCC failure is predicted for both of the waste package closure-lid welds. Therefore no further abstraction analysis was conducted using the Threshold Stress Intensity Factor model.

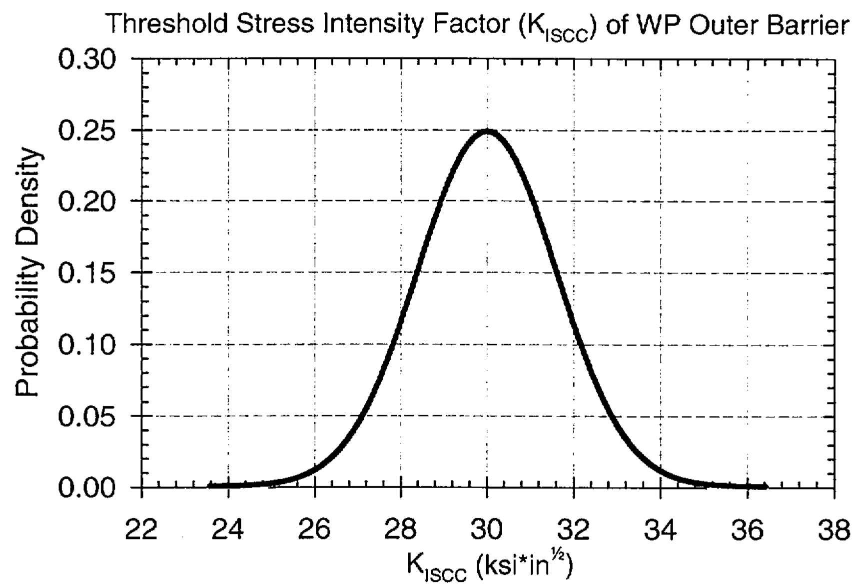

Figure 12. Probability density function of the threshold stress intensity factor of the waste package outer barrier (Alloy 22).

7. CONCLUSIONS

Hydrogen induced cracking (HIC) of drip shield is a potential degradation mechanism that could cause catastrophic failure of drip shield if the hydrogen uptake in the titanium drip shield is greater than the critical hydrogen concentration (CRWMS M&O 2000d). In the current design of backfill placed over the drip shield, crevice corrosion and passive general corrosion of the drip shield are two feasible processes in the repository that could lead HIC of the drip shield. Hydrogen is produced as a result of the corrosion processes and some of the produced hydrogen can be absorbed by and transport into the titanium drip shield (CRWMS M&O 2000d). Because the drip shield will not be subject to crevice corrosion under the exposure conditions anticipated in the repository (CRWMS M&O 2000e), general corrosion is the only mechanism that could cause HIC in the drip shield. Results of the bounding analyses have shown that the time that the hydrogen uptake concentration reaches the critical hydrogen concentration from passive corrosion under the repository exposure conditions is far greater than the time required to breach the drip shield by general corrosion (CRWMS M&O 2000b, Section 3.2.5). Therefore it is concluded that HIC is not a degradation process that could significantly affect the drip shield performance in the repository, and no additional abstraction analysis was conducted.

In order for stress corrosion cracking (SCC) to occur, the following three factors must be present: a flaw (or crack-initiation site), a stress state, and a corrosive environment (CRWMS M&O 2000a, .Section 6.1). Drip shield is assumed fully annealed before it is placed in the emplacement drift and assumed not subject to SCC in the repository. Also, stresses that are relevant to SCC are insignificant in the drip shield in the repository (CRWMS M&O 2000a, Section 5, Assumption 1). Therefore no additional abstraction analysis was conducted for SCC of drip shield. For SCC of waste package, except the welds for the closure (outer and inner) lids, all the fabrication welds in the waste packages are assumed fully annealed and not subject to SCC. Accordingly, analyses were conduced to develop abstractions for the SCC models and parameters for the waste-package closure-lid welds. The abstractions developed in the current analyses are: 1) stress and stress intensity factor profiles as a function of depth, 2) threshold stress intensity factor, 3) threshold stress to initiate crack growth, 4) parameters A and n of the Slip Dissolution model, 5) incipient crack density and size used with the Slip Dissolution Model, and 6) probability for the occurrence and size of manufacturing defects in the closure-lid welds. Major efforts of the abstraction were given to develop approach to represent uncertainty and variability of the model parameters. As identified in Section 1, alternative approaches to representing uncertainty and variability of the stress and stress intensity factor versus depth in the closure-lid welds are also being evaluated.

In the current waste package degradation analysis, two alternative SCC models, the Slip Dissolution (or Film Rupture) Model and the Threshold Stress Intensity Factor (K_{ISCC}) Model, are considered (CRWMS M&O 2000a, Section 3.2). In the Threshold Stress Intensity Factor Model, the threshold stress intensity factor ($K_{\rm ISCC}$) is used to determine when SCC will occur. Provided that an initial flaw and corrosive environment is present, a SCC failure will occur when the applied stress intensity factor K_I is greater than or equal to the threshold stress intensity factor $K_{\rm ISCC}$ (i.e., $K_I \geq K_{\rm ISCC}$). The Slip Dissolution Model assumes that incipient cracks and manufacturing defects grow continuously when the oxidation reaction that occurs at the crack tip ruptures the protective film via an applied strain in the underlying matrix. The rate at which the crack grows is a function of the crack tip strain rate and environmental and material chemistries.

The possible maximum manufacturing defect size in the closure-lid welds is about 6-mm (Figure 2). Assuming this defect flaw is a radial crack, the maximum stress intensity factor at the tip of the manufacturing defect in the outer closure-lid is about –15 MPa·m$^{1/2}$ (Figure 4), and that in the inner closure-lid is about 5 MPa·m$^{1/2}$ (Figure 8). Because these are less than the minimum K_{ISCC} (25.9 MPa·m$^{1/2}$) for SCC to occur, no SCC failure occurs for both of the waste package closure-lid welds. Therefore no further abstraction analysis was conducted using the Threshold Stress Intensity Factor model. Effect of different exposure conditions (including applied stress) on the K_{ISCC} value, and its uncertainty and variability under those varying exposure conditions will be evaluated as additional and and/or analysis is developed (CRWMS M&O 2000a, Section 6.3.2).

The Slip Dissolution model assumes that SCC cracks grow continuously in the presence of stress. Analyses were conducted to develop abstractions for the parameters that are associated with the Slip Dissolution model. The major efforts in the abstractions were to develop an approach to represent the uncertainty and variability associated with the SCC initiation and crack propagation processes, and to implement them in the integrated waste package degradation model (WAPDEG model) (CRWMS M&O 2000b, Section 3.2.5). Utilizing the data and models from the process model analyses, abstractions were developed for the parameters associated with the model. Those parameters include two model parameters (A and n), stress intensity factor (K_I), threshold stress, incipient crack density and size, and pre-existing manufacturing defects in the closure-lid welds. The abstraction processes for the stress and stress intensity factor versus depth in the welds were implemented as a software routine (SCCD (Stress Corrosion Cracking Dissolution), Version 1.01) written in Fortran (see Attachment I). The software routine is used as part of the integrated waste package degradation model (WAPDEG) (CRWMS M&O 2000b, section 3.2.5).

Bounding analyses were performed to examine the responses of the Slip Dissolution model for the SCC failure time of the outer lid (25-mm thick) and inner lid (10-mm thick) as a function of the model parameters (n and K_I). It was shown in the analyses that the stress intensity factor is the dominant parameter in the model, and the time to failure by SCC increases exponentially as the stress intensity factor decreases. Once a SCC crack initiates, it penetrates the closure-lid thickness fast. The analysis also demonstrated importance of stress mitigation in the closure-lid welds to avoid premature failures of waste packages by SCC.

The analyses documented in this AMR are for the Enhanced Design Alternative II (EDA II) design (CRWMS M&O 1999d). In this design, a drip shield is placed over the waste package with backfill emplaced over the drip shield (see Design Constraint 2.2.1.1.9 of CRWMS M&O 1999d). The current analysis results in this AMR may not be applicable to a no-backfill design.

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the input information quality may be confirmed by review of the Document Input Reference System database.

8. INPUTS AND REFERENCES

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QAP-2-3, Rev. 10, *Classification of Permanent Items*, Las Vegas, Nevada: CRWMS M&O. MOL 19990316.006.

8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

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MO0001SPASUP03.001: Data to Support Calculation of Probability and Size of Defect Flaws in Waste Package Closure Welds to Support WAPDEG Analysis. CAL-EBS-PA-000003 REV00. Submittal date: 01/31/2000.

LL000316005924.140: Stress Corrosion Cracking Of The Drip Shield, The Waste Package Outer Barrier And The Stainless Steel Structural Material (Excel file S&K_OL_Anne for stress and stress intensity factor profiles in the outer lid of the waste package outer barrier after stress mitigation with the induction heating solution annealing technique). Submittal date: 3/22/2000.

LL000316105924.141: Stress Corrosion Cracking Of The Drip Shield, The Waste Package Outer Barrier And The Stainless Steel Structural Material (Excel file S&K_IL_Peen for stress and stress intensity factor profiles in the inner lid of the waste package outer barrier after stress mitigation with the laser peening technique). Submittal date: 3/22/2000. Submit to RPC URN 0260.

Note: Additional references are identified in Attachment I.

9. ATTACHMENTS

I - SCCD Software Routine Report

ATTACHMENT I

SCCD SOFTWARE ROUTINE REPORT

1. SOFTWARE ROUTINE IDENTIFICATION

Name and Version Number: SCCD (Stress Corrosion Cracking Dissolution), Version 1.01

This routine was developed using Microsoft Developer Studio 97 with Visual Fortran 5.0, Standard Edition.

SRR Document Identification Number: N/A

SRR Media Number (if applicable): N/A

2. DESCRIPTION AND TESTING

The software routine SCCD calculates the stress state and corresponding stress intensity factor versus depth in the closure-lid welds of waste package. The calculation results are input to stress corrosion cracking (SCC) analysis of waste package. The stress state and corresponding stress intensity factor tables are calculated for a user-specified number of angles (in the range 0 to pi radians) along the circumference of the waste package closure-lid welds. Uncertainty is included via an input standard normal random number that describes the deviation from the median residual stress in the closure-lid welds. Variability is included via the input amplitude for the angular variation of the stress. These calculations are based on the abstraction of the hoop stress and corresponding stress intensity factor versus depth as discussed in the upstream process model analysis AMR (CRWMS M&O 2000a) and Section 6.3 of this AMR. The outputs of SCCD are:

- A text file in WAPDEG table format for the user specified number of angles of tables for stress state versus depth, and
- A text file in WAPDEG table format for the user specified number of angles of tables for the corresponding stress intensity factor versus depth.

2.1 DESCRIPTION OF SOFTWARE ROUTINE AND THE EXECUTION ENVIRONMENT

SCCD is a FORTRAN program 308 lines in extent. It conforms to the FORTRAN 90 standard and is thus highly portable. SCCD was developed and tested in the Windows NT 4.0 operating system, and has been compiled with Digital FORTRAN 5.0 in the Windows/PC environments. SCCD is designed to be compiled as a DLL (SCCD.dll) and be executed within GoldSim, with input parameters specified by inserting them as data elements in the GoldSim environment (Golder Associates 2000). SCCD was developed to run with GoldSim to determine the stress state versus depth at various angles around the waste package closure lid circumference. The output stress tables are used by the WAPDEG DLL to generate distributions for waste package failures in GoldSim (CRWMS M&O 1999e).

WAPDEG tables are formatted so that lines proceeded by a "!" are comment lines. The first line proceeded by a "#" contains two numbers: the first number indicates the number of tables, and the second number indicates the number of columns in each table. The number in the next line proceeded by a "#"indicates the number of rows in the lookup table. The number (fraction) in the next line proceeded by a "#"indicates that the fraction of the waste packages/drip shields to be simulated, to which this look-up table corresponds . This is followed by one more comment line (proceeded by a "!") which is used to specify column headers. The following rows consist of the first table with subsequent tables preceded by the latter three line entries of number of rows, fraction applied, and header line.

Compilation of SCCD requires the module modDefaultSize.f to be present from the WAPDEG library (CRWMS M&O 1999f).

The bulk of SCCD's coding is devoted to computing and scaling the stress state and corresponding stress intensity factor at various angles along the circumference of waste package closure-lid welds, given the stress state and corresponding stress intensity factor versus depth at a reference point (i.e., zero angle). The inputs are read as part of the argument list of SCCD, as the elements of array in(*):

in(1)	z	Uncertain deviation from median yield strength (sampled from N(0,1))
in(2)	sinf	Sine of stress plane angle
in(3)	a(1)	Zero order regression coefficient from model abstraction for stress vs. depth at zero degree
in(4)	a(2)	First order regression coefficient from model abstraction for stress vs. depth at zero degree
in(5)	a(3)	Second order regression coefficient from model abstraction for stress vs. depth at zero degree
in(6)	a(4)	Third order regression coefficient from model abstraction for stress vs. depth at zero degree
in(7)	nangle	number of angles in the range of zero to π radians to compute tables of stress and KI versus depth
in(8)	ys	Expected yield strength [Mpa]
in(9)	fys	Fraction yield strength range
in(10)	amp	Angular amplitude for the equation of angular variation of stress [Mpa]
in(11)	idxinp	File index for input table of stress intensity factor v. depth
in(12)	idxkin	File index for output stress intensity factor v. depth at nangle angles
in(13)	idxstr	File index for output stress v. depth at nangle angles

The first output table file consists of nangle tables of stress intensity factor versus depth, written to the file referenced by index in(12). The second output table file consists of nangle tables of stress versus depth, written to the file referenced by index in(13). Like all GoldSim DLL's, the project coding standards require all DLL's to accept as input a 'method' variable which controls the operation of the program (see Figure 1) (Golder Associates 2000). If a DLL is called with the following values of 'method', the following will occur (Golder Associates 2000):

Method = 0 the DLL is initialized (SCCD requires no initialization, thus nothing happens).

Method = 1 run the DLL's calculations (for SCCD, compute the stress tables and stress intensity factor tables).

Method = 2 the DLL returns the version number as out(1).

Method = 3 report the number of input and output arguments as out(1) and out(2), respectively (for SCCD, this should yield the values 13 and 1, respectively).

Method = 99 the DLL closes all files and processes.

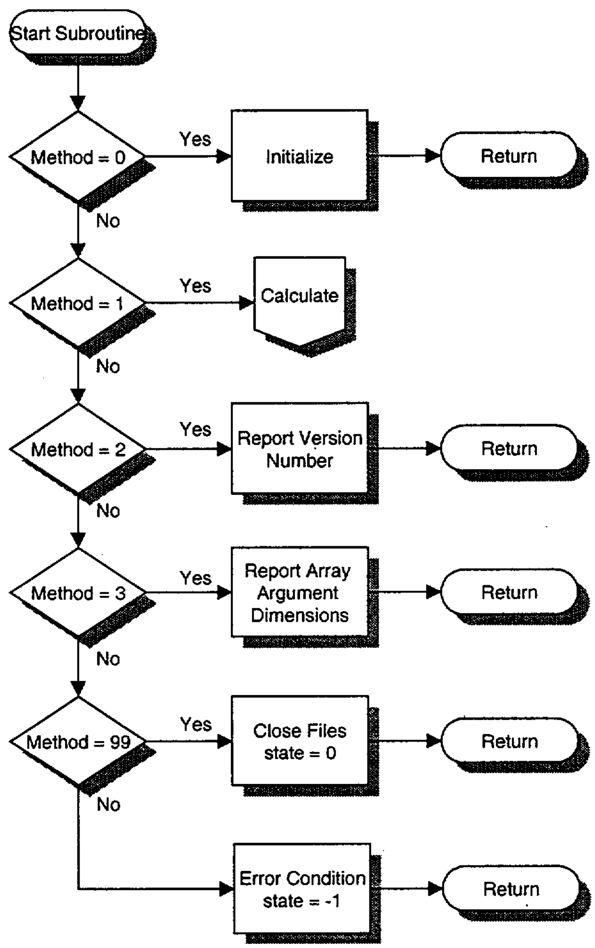

Figure I-1. Method calling structure for DLLs in GoldSim.

2.2 DESCRIPTION OF THE ALGORITHM

SCCD receives the input parameters from the argument list, and then follows the algorithm presented in the upstream analysis (CRWMS M&O 2000a) and Section 6.3 of this report. Specifically, the following steps are performed:

1. Read from an external file the stress intensity factor versus depth at reference point (i.e., zero angle in the current analysis).

   kin, depth *nrows* values of stress intensity factor K_I and depth.

2. Based on the equation for stress versus depth at a reference point (zero angle) (see Equation (1), Section 4.1 of this report) and the input look-up table for the stress intensity factor versus depth at the same reference point (see Table 2, Section 4.1 of this report),

   a. calculate stress and stress intensity factor versus depth at each of the *nangle* angles (for the variability on a single waste package), and

   b. re-scale the output tables from (a) to the yield strength (*ys*) range for the random deviate *z* (for the uncertainty).

3. Output:

   a. stress intensity factor versus depth for *nangle* angles

   b. stress versus. depth for *nangle* angles

2.3 DESCRIPTION OF TEST CASES

The testing approach involves comparing the results of SCCD with the example calculations presented in the Mathcad worksheets (see Section 3.3 of this attachment). The specific test cases calculate, for various angles, the hoop stress and corresponding stress intensity factor versus depth, given a random variate and a table of stress intensity factor versus depth at zero angle. The output tables are checked to match the results for the test cases evaluated for two set of calculations, one set of test runs to evaluate the (10-mm thick) Alloy 22 inner lid, and a second set of test runs to evaluate the (25-mm thick) Alloy 22 outer lid.

2.3.1 Alloy 22 Inner Lid Test Case

Running in the GoldSim environment as a DLL creates the first fourteen test files (seven executions), where the following values are inserted as data elements in the SCCD input stream where values for in(1), in(12), and in(13) were varied as indicated.

Z	in(1) =	0, 1, -1, 2, -2, 3, -3
Sinf	in(2) =	0.60887
a(1)	in(3) =	-437.72054
a(2)	in(4) =	176.96724
a(3)	in(5) =	-15.60607
a(4)	in(6) =	0.36710
nangle	in(7) =	1
ys	in(8) =	322.12305
fys	in(9) =	0.05
amp	in(10) =	17.23689

The remaining inputs are indices of the locations within the GoldSim file for output filenames

Inputidx	in(11) =	1
Outputidxk	in(12) =	10, 11, 12, 13, 14, 15, 16
Outputidxs	in(13) =	3, 4, 5, 6, 7, 8, 9

The last test run is produced with the following input stream where in(7) = 3:

Z	in(1) =	0
sinf	in(2) =	0.60887
a(1)	in(3) =	-437.72054
a(2)	in(4) =	176.96724
a(3)	in(5) =	-15.60607
a(4)	in(6) =	0.36710
nangle	in(7) =	3.00000
ys	in(8) =	322.12305
fys	in(9) =	0.05
amp	in(10) =	17.23689
inputidx	in(11) =	1.00000
outputidxk	in(12) =	18.00000
outputidxs	in(13) =	17.00000

The test case requires, as input, a text file WD4DLL.wap, which is a list of filenames to be read by SCCD. The names of files used by SCCD for the input and output tables are found in this file by their line index. The input table of stress intensity factor versus depth at the zero angle, KIinM.fil, is given in Section 3.0 of this SRR. Each execution of the routine produces two output files that are the resulting tables of stress intensity factor versus depth and stress versus depth, respectively.

2.3.2 Alloy 22 Outer Lid Test Case

Running in the GoldSim environment as a DLL creates the first fourteen test files (seven executions), where the following values are inserted as data elements in the SCCD input stream where values for in(1), in(12), and in(13) were varied as indicated.

Z	in(1) =	0, 1, -1, 2, -2, 3, -3
Sinf	in(2) =	1.0
a(1)	in(3) =	-356.26778
a(2)	in(4) =	37.18077
a(3)	in(5) =	1.43639
a(4)	in(6) =	-0.06528
nangle	in(7) =	1
ys	in(8) =	322.12305
fys	in(9) =	0.05
amp	in(10) =	17.23689

The remaining inputs are indices of the locations within the WD4DLL.wap file for input and output filenames

Inputidx	in(11) =	2
Outputidxk	in(12) =	19, 20, 21, 22, 23, 24, 25
Outputidxs	in(13) =	26, 27, 28, 29, 30, 31, 32

The last test run is produced with the following input stream where in(7) = 3:

Z	in(1) =	0.00000
Sinf	in(2) =	1.00000
a(1)	in(3) =	-356.26778
a(2)	in(4) =	37.18077
a(3)	in(5) =	1.43639
a(4)	in(6) =	-0.06528
nangle	in(7) =	3.00000
ys	in(8) =	322.12305
fys	in(9) =	0.05
amp	in(10) =	17.23689
inputidx	in(11) =	2.00000
outputidxk	in(12) =	34.00000
outputidxs	in(13) =	33.00000

The test case requires as input a text file WD4DLL.wap, which is a list of filenames to be read by SCCD. The names of files used by SCCD for the input and output tables are found in this file by their line index. The input table of stress intensity factor versus depth at zero angle, KIinO.fil, is given in Section 3.0 of this SRR. Each execution of the routine produces two output files which are the resulting tables of stress intensity factor versus depth and stress versus depth, respectively.

2.4 DESCRIPTION OF TEST RESULTS

The test results for the Alloy 22 inner lid test case should be compared to the results of the output file, data10.txt, from the Mathcad worksheet SCCD_10SR. The test results for the Alloy 22 outer lid test case should be compared to the output file, data25.txt, from the Mathcad worksheet SCCD_25SR. Visual comparison of the test-case output files with the appropriate rows and columns of the above-named worksheets confirms that SCCD gives the anticipated results (DTN: MO0004SPASDA04.003). The output tables match the results for these cases, thus the tests are considered successful.

2.5 RANGE OF INPUT PARAMETER VALUES OVER WHICH RESULTS WERE VERIFIED

The preceding test case evaluates SCCD for a typical set of parameters as observed from the study of stress corrosion cracking discussed in the upstream process model analysis AMR (CRWMS M&O 2000a) and Section 6.3 of this AMR. The software routine was validated with the range of the input parameter values documented in the following table. Therefore, SCCD will execute properly if the input parameters are used within their respective ranges and types given in the table.

Variable	Type and Range	Description
z	real	Uncertain deviation from median yield strength
sinf	real [0,1]	sine of stress plane angle
0 order regression coefficient	real	Regression coefficient from model abstraction for stress v. Depth at 0 degrees
1 order regression coefficient	real	Regression coefficient from model abstraction for stress v. Depth at 0 degrees
2 order regression coefficient	real	Regression coefficient from model abstraction for stress v. Depth at 0 degrees
3 order regression coefficient	real	Regression coefficient from model abstraction for stress v. Depth at 0 degrees
Number of angles	positive integer	Divisions of the range 0 to π radians to compute tables of stress and KI versus depth
Yield stress	positive real	Expected yield strength
Fraction yield stress range	real [0,1]	Fraction of yield strength range
Amplitude	real	Angular amplitude for the equation of angular variation of stress along the circumference of closure-lid welds
File index 1	integer	File index for input table of stress intensity factor v. depth
File index 2	integer	File index for output stress intensity factor v. depth at various angles
File index 3	integer	File index for output stress v. depth at various angles

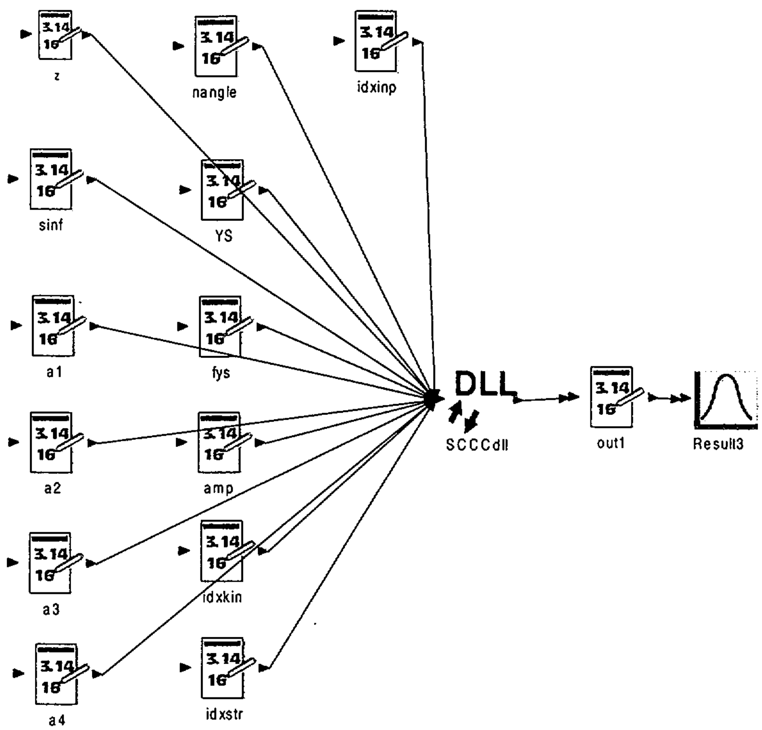

Figure I-2. Representative GoldSim SCCD Container Element.

Note: The term "Container" in the above figure caption is used to indicate a component model element implemented for the GoldSim analysis. It should not be confused with the waste disposal container.

2.6 IDENTIFICATION OF LIMITATIONS ON SOFTWARE ROUTINE OR VALIDITY

None.

3. SUPPORTING INFORMATION

3.1 DIRECTORY LISTING OF EXECUTABLE AND DATA FILES

```
Directory of SRRdir

Program files:
02/04/00  11:10a              12,288 SCCD.dll
04/12/00  10:18a             606,130 SCCDtestv2.gsm

Mathcad files:
04/11/00  04:44p              23,541 SCCD_10revC.mcd
04/11/00  04:49p              22,857 SCCD_25revC.mcd
04/12/00  09:43a              16,900 data10.txt
04/12/00  09:44a              16,900 data25.txt

Input files:
02/10/00  01:57p                 586 WD4DLL.wap
01/14/00  02:06p               1,436 WDKIinM.fil
01/14/00  09:26p               1,439 WDKIinO.fil

Output files:
```

```
04/12/00  10:17a               3,126 WDdata10c01.fil
04/12/00  10:17a               3,126 WDdata10c02.fil
04/12/00  10:17a               3,126 WDdata10c03.fil
04/12/00  10:17a               3,126 WDdata10c04.fil
04/12/00  10:17a               3,126 WDdata10c05.fil
04/12/00  10:17a               3,126 WDdata10c06.fil
04/12/00  10:17a               3,126 WDdata10c07.fil
04/12/00  10:17a               3,136 WDdata10c08.fil
04/12/00  10:17a               3,136 WDdata10c09.fil
04/12/00  10:17a               3,136 WDdata10c10.fil
04/12/00  10:17a               3,136 WDdata10c11.fil
04/12/00  10:17a               3,136 WDdata10c12.fil
04/12/00  10:17a               3,136 WDdata10c13.fil
04/12/00  10:17a               3,136 WDdata10c14.fil
04/12/00  10:17a               8,270 WDdata10c15to17.fil
04/12/00  10:17a               8,280 WDdata10c18to20.fil
04/12/00  10:17a               3,126 WDdata25c01.fil
04/12/00  10:17a               3,126 WDdata25c02.fil
04/12/00  10:17a               3,126 WDdata25c03.fil
04/12/00  10:17a               3,126 WDdata25c04.fil
04/12/00  10:17a               3,126 WDdata25c05.fil
04/12/00  10:17a               3,126 WDdata25c06.fil
04/12/00  10:17a               3,126 WDdata25c07.fil
04/12/00  10:17a               3,136 WDdata25c08.fil
04/12/00  10:17a               3,136 WDdata25c09.fil
04/12/00  10:17a               3,136 WDdata25c10.fil
04/12/00  10:17a               3,136 WDdata25c11.fil
04/12/00  10:17a               3,136 WDdata25c12.fil
04/12/00  10:17a               3,136 WDdata25c13.fil
04/12/00  10:17a               3,136 WDdata25c14.fil
04/12/00  10:17a               8,270 WDdata25c15to17.fil
04/12/00  10:17a               8,280 WDdata25c18to20.fil
```

3.2 COMPUTER LISTING OF SOURCE CODE

```
subroutine sccd(method, state, in, out)
!
!  Subroutine to calculate stress vs. depth and stress intensity
!  vs depth for n tables corresponding to n angles from 0 to pi.
!
!  1. From argument list:
!     z              a deviate of a standard normal.
!     sinf           sin of fracture angle.
!     a(1),...,a(4)  coeffecients for stress vs. depth equation
!     nangle         number of angles to calculate tables
!     ys             yield stress
!     fys            fraction of yeild stress range
!     amp            angular amplitude
!     idxinp       integer location of input file name for KI
!     idxkin     integer location of output file name for k v. depth
!     idxstr     integer location of output file name for s v. depth
!  2. Read from external table\file:
!        kin       nrows values of stress intensity KI
!        depth     nrows values of depth, corresponding to KI.
!  3. Calculate:
!     a. calculate hoop stress and hoop stress intensity vs. depth at
!        nangle's
!     b. rescale tables to YS range for RV z.
!  4. Output:
!     a. ki vs. depth for nangle's
!     b. stress vs. depth for nangles's
!
!DEC$ ATTRIBUTES dllexport,c :: sccd
!DEC$ ATTRIBUTES value       :: method
!DEC$ ATTRIBUTES reference   :: state
!DEC$ ATTRIBUTES reference   :: in
!DEC$ ATTRIBUTES reference   :: out
      USE ModDefaultsize
      IMPLICIT NONE
```

```
      integer(IKind) method    ! input, tells sccd what to do
      integer(IKind) state     ! return, 0 = OK
      real(RKind)    in(*)     ! input arguments
      real(RKind)    out(*)    ! output arguments
      real(RKind),PARAMETER :: VERSION = 1.01
      integer(IKind),PARAMETER :: NUMIN = 13, NUMOUT = 1
      real(RKind),PARAMETER :: PI = 3.141592653589793
      integer(IKind) :: kinunit , strunit, errunit
      integer(IKind) :: idxinp, idxkin, idxstr
      character(LEN = 80) :: inptab, kintab, strtab, line1
      real(RKind), ALLOCATABLE, DIMENSION(:) :: kin
      real(RKind), ALLOCATABLE, DIMENSION(:) :: depth
      real(RKind) a(4)
      integer(IKind) n, i, j, nangle, nrows, nsets, ncol
      real(RKind) ys, fys, amp, angle, dangle, rscale, ki, z, thick
      real(RKind) str, strta, strt0, sinf
      logical(LKind) :: OK
!
!**********************************************************************
!
      if (method .eq. 0) then        ! Initialize
        state = 0
        return
      elseif (method .eq. 2) then    ! Report code version
        out(1) = VERSION
        state = 0
        return
      elseif (method .eq. 3) then    ! Report number of arguments
        out(1) = NUMIN
        out(2) = NUMOUT
        state = 0
        return
      elseif (method .eq. 1) then    ! Calculate
        z      = in(1)
        sinf   = in(2)
        a(1)   = in(3)
        a(2)   = in(4)
        a(3)   = in(5)
        a(4)   = in(6)
        nangle = in(7)
        ys     = in(8)
        fys    = in(9)
        amp    = in(10)
        idxinp = in(11)
        idxkin = in(12)
        idxstr = in(13)
        out(1) = z
        if (nangle .le. 1) then
          nangle = 1
          dangle = 0.
        else
          dangle = PI/(nangle - 1)  !delta angle increment
        end if
!
!  Open the file list and find the I/O filenames
!
        kinunit = nextfreeunit()
        open(unit = kinunit, file = 'WD4DLL.wap')
        n = max(idxinp, idxkin, idxstr)
        do i = 1, n
           read(kinunit,*) line1
           if (i .eq. idxinp) inptab = line1
           if (i .eq. idxkin) kintab = line1
           if (i .eq. idxstr) strtab = line1
        end do
        close(unit = kinunit)
!
!  Open Input KI vs. Depth table and read contents
!  Read in values for: nrows, ncol, kin(1:nrows), depth(1:nrows)
!  Mainly dealing with file formating here.
!
```

```
      inquire(file = inptab, exist = OK)
      if (.not. OK) then
        state = 1
        errunit = nextfreeunit()
        open(unit = errunit,file = 'sccderror.log')
        write(errunit,*) 'input file not found'
        close(unit = errunit)
        return
      end if
      kinunit = nextfreeunit()
      open(kinunit, file = inptab)
!  Scroll through the preliminary comments
      line1 = '!'
      do while (line1(1:1) .eq. '!' .or. line1(1:1) .eq. ' ')
        read(kinunit, 9000) line1
9000    format(a80)
      end do
!  First noncomment line must be #-character, then
!  number of data sets (nsets), number of columns (ncols).
      if (line1(1:1) .ne. '#') then
        state = 1
        errunit = nextfreeunit()
        open(unit = errunit,file = 'sccderror.log')
        write(errunit,*) 'format error in input file, 123'
        close(unit = errunit)
        return
      end if
      read(line1(2: 79), *) nsets, ncol
      if (nsets .le. 0) then
        state = 1
        errunit = nextfreeunit()
        open(unit = errunit, file = 'sccderror.log')
        write(errunit,*) 'nsets = 0 in input file'
        close(unit = errunit)
        return
      end if
      if (ncol .lt. 2) then
        state = 1
        errunit = nextfreeunit()
        open(unit = errunit,file = 'sccderror.log')
        write(errunit,*) 'ncol < 2 in input file'
        close(unit = errunit)
        return
      end if
!  Read the number of rows (nrows) (begins the set)
      read(kinunit, 9000) line1
      if (line1(1:1) .ne. '#') then
        state = 1
        errunit = nextfreeunit()
        open(unit = errunit, file = 'sccderror.log')
        write(errunit,*) 'format error in input file, 147'
        close(unit = errunit)
        return
      end if
      read(line1(2:79), *) nrows
      if (nrows .le. 0) then
        state = 1
        errunit = nextfreeunit()
        open(unit = errunit, file = 'sccderror.log')
        write(errunit,*) 'error, number of rows in input file'
        close(unit = errunit)
        return
      end if
!  Read the fraction and discard
      read(kinunit, 9000) line1
      if (line1(1:1) .ne. '#') then
        state = 1
        errunit = nextfreeunit()
        open(unit = errunit,file = 'sccderror.log')
        write(errunit,*) 'format error in input file, 164'
        close(unit = errunit)
```

```
          return
        end if
!   Read the column header and discard
        read(kinunit, 9000) line1        !Column header line
!   Read the nrows rows in the set
        ALLOCATE(depth(nrows))
        ALLOCATE(kin(nrows))
        do j = 1, nrows
          read(kinunit,*) kin(j), depth(j)
        end do
        close(kinunit)
!
!   Write headers to output files*******
!
        kinunit = nextfreeunit()
        open(kinunit, file = kintab)
        strunit = nextfreeunit()
        open(strunit, file = strtab)
        write(kinunit,3330) VERSION
        write(kinunit,3331) out(1)
        write(kinunit,3334) !title3334
        write(kinunit,3338) ( i, in(i), i = 1, NUMIN )
        write(kinunit,3332) nangle, ncol
        write(strunit,3330) VERSION
        write(strunit,3331) out(1)
        write(strunit,3335) !title3335
        write(strunit,3338) ( i, in(i), i = 1, NUMIN )
        write(strunit,3332) nangle, ncol
 3330   format('! Output from sccd version ',F4.2)
 3331   format('! For sampled random variable z =',F9.5)
 3332   format('#',1x,I5,I5)
 3333   format('#',1x,F9.5)
 3334   format('! Stress Intensity vs. Depth ')
 3335   format('! Stress vs. Depth ')
 3336   format('! KI vs. Depth        (angle = ',f9.5,' radians)')
 3337   format('! Stress vs. Depth    (angle = ',f9.5,' radians)')
 3338   format('! argument in(',I2,') = ',f12.5)
!
! Perform Calculations*********************************************
!   For nangle's from 0 to pi, calculate:
!   scaled stress table  str(depth,angle)*rscale
!   scaled ki table      ki(depth,angle)*rscale
!
        thick = depth(nrows)
        angle = 0.0_RKind
        do i = 1, nangle
          write(kinunit,3332) nrows
          write(kinunit,3333) 1.0/nangle
          write(kinunit,3336) angle
          write(strunit,3332) nrows
          write(strunit,3333) 1.0/nangle
          write(strunit,3337) angle
          strta = stress(a,amp,thick,angle)
          strt0 = stress(a,amp,thick,0.0_RKind)
          rscale = (strta + ((z*ys*fys)/3.0))/strta
          do j = 1, nrows
            ki = kin(j)*(strta/strt0)*rscale
            str  = stress(a,amp,depth(j),angle)*rscale
            write(kinunit,*) ki,  depth(j)*sinf
            write(strunit,*) str, depth(j)*sinf
          end do !over depths
          angle = angle + dangle
        end do !over angles
        close(unit = kinunit)
        close(unit = strunit)
        DEALLOCATE(depth, kin)
        state = 0
        return
      elseif (method .eq. 99) then   ! Shut-down
        close(unit = kinunit)
        close(unit = strunit)
```

```
        close(unit = errunit)
        state = 0
        return
      else
        errunit = nextfreeunit()
        open(unit = errunit,file = 'sccderror.log')
        write(errunit,*) 'sccd crashed method = ',method
        close(unit = errunit)
        state = 1
        return
      end if                         ! end block for method
      CONTAINS      !stress, nextfreeunit
!
! **********************************************************************
!
      real(RKind) FUNCTION stress(a, amp, x, angle)
!
!  Regression equation for stress v. depth abstracted
!  from the finite element code, adapted to angular variation
!  Input : a(*)      array of coefficients
!          amp       amplitude in MPa
!          x         depth in mm
!          angle     angle in radians
!  Output: (function value)
!
      real(RKind) :: a(*), amp, x, angle
!
      stress = a(1)+x*(a(2)+x*(a(3)+x*a(4)))-amp*(1.0-cos(angle))
      return
      END FUNCTION stress
!
!**********************************************************************
!
      integer(IKind) FUNCTION nextfreeunit()
!
!  Find the smallest unit number not currently attached and in use.
!  Avoid units 5 and 6.
!  Input : (none)
!  Output: (function value)
!  Local : i, InUse
!
!  Local variables
!
      integer(IKind) :: i
      logical InUse
!
      InUse = .true.
      i = 0
      do while (InUse)
        i = i + 1
        if(i .ne. 5 .and. i .ne. 6) then
          inquire(i, opened = InUse)
        end if
      end do
      nextfreeunit = i
      RETURN
      END FUNCTION nextfreeunit
!
!**********************************************************************
!
      END SUBROUTINE sccd
```

3.3 LISTING OF MATHCAD WORKSHEETS

Hoop Stress and Stress Intensity Factor Calculation (10-mm Inner Lid)

Conversion Factors: 1 in = 25.4 mm, 1 ksi = 6.89 MPa, 1 ksi-in^½ = 1.0988 MPa-m^½

$c0 := 25.4$

$c1 := 6.894757$

$c2 := 1.098843$

Coefficients for the third-order polynomial stress equation.

$A_0 := -63.486c1$

$A_0 = -437.720543$

$A_1 := 651.94\frac{c1}{c0}$

$A_1 = 176.967239$

$A_2 := -1460.3\frac{c1}{c0 \cdot c0}$

$A_2 = -15.606072$

$A_3 := 872.5\frac{c1}{c0 \cdot c0 \cdot c0}$

$A_3 = 0.367099$

$\sigma_s(x) := \left[A_0 + x \cdot \left[A_1 + x \cdot \left(A_2 + x \cdot A_3\right)\right]\right]$

Stress Intensity Factor Table based on hoop stress at 50 linearly spaced points out to (99.97% of length along crack) 16.42 mm.

Ktable :=

−7.201806034	0.3277
−10.05117186	0.6579
−12.14661052	0.9855
−13.83718048	1.3132
−15.26051182	1.6408
−16.48813922	1.971
−17.60873931	2.2987
−18.62418012	2.6264
−19.34568044	2.954
−18.27353932	3.2842
−17.05876838	3.6119
−15.73543176	3.9395
−14.40693057	4.2697
−13.09502192	4.5974
−11.74410433	4.9251
−10.37129779	5.2527
−8.992063026	5.5829
−7.619959749	5.9106
−6.28349195	6.2382
−5.021547684	6.5659
−3.791766552	6.8961
−2.602642611	7.2238
−1.461856773	7.5514
−0.376262524	7.8791
0.6479086	8.2093
1.602739435	8.5369
2.489890331	8.8646
3.304704392	9.1948
4.043027992	9.5225
4.701256926	9.8501
5.276226526	10.1778
5.809253288	10.508
6.267459831	10.8356
6.633989902	11.1633
6.907239191	11.491
7.086141819	11.8212
7.170016506	12.1488
7.171796631	12.4765
7.082153019	12.8067
6.8851964	13.1343
6.581695963	13.462
6.173014275	13.7897
5.661052333	14.1199
5.214086954	14.4475
5.185517036	14.7752
5.092620849	15.1028
4.940639873	15.433
4.735255128	15.7607
4.482741007	16.0884
4.18995429	16.4186

$Thck := Ktable_{49,1}$

$Thck = 16.4186$

$K_s(x) := \mathrm{linterp}\left(Ktable^{\langle 1\rangle}, Ktable^{\langle 0\rangle}, x\right)$

Functional form based on angular variation.

$\sigma_t(x,\theta) := \sigma_s(x) - (c1 \cdot 2.5) \cdot (1 - \cos(\theta))$

$$K_t(x,\theta) := K_s(x) \cdot \left(\frac{\sigma_t(Thck,\theta)}{\sigma_t(Thck,0)}\right)$$

Rescaling for uncertainty with the yield strength of 46.72 ksi.

$YS := c1 \cdot 46.72$

$YS = 322.123047$

$F := 0.05$

$$rscale(\theta,s) := \left(\frac{\sigma_t(Thck,\theta) + s \cdot \frac{YS \cdot F}{3}}{\sigma_t(Thck,\theta)}\right)$$

$\sigma_u(x,\theta,s) := \overrightarrow{\left(\sigma_t(x,\theta) \cdot rscale(\theta,s)\right)}$

$K_u(x,\theta,s) := \overrightarrow{\left(K_t(x,\theta) \cdot rscale(\theta,s)\right)}$

$$sinf := \frac{20.256 - 19.764}{\sqrt{(20.256 - 19.764)^2 + (30.641 - 30.0)^2}}$$

$sinf = 0.60887312121$

$\mathrm{asin}(sinf) = 37.508067 deg$

$xx := Ktable^{\langle 1\rangle}$

$data10^{\langle 0\rangle} := Ktable^{\langle 1\rangle} \cdot sinf$

$data10^{\langle 1\rangle} := \sigma_u(xx, 0, 0)$

$data10^{\langle 2\rangle} := \sigma_u(xx, 0, 1)$

$data10^{\langle 3\rangle} := \sigma_u(xx, 0, -1)$

$data10^{\langle 4\rangle} := \sigma_u(xx, 0, 2)$

$data10^{\langle 5\rangle} := \sigma_u(xx, 0, -2)$

$data10^{\langle 6\rangle} := \sigma_u(xx, 0, 3)$

$data10^{\langle 7\rangle} := \sigma_u(xx, 0, -3)$

$data10^{\langle 8\rangle} := K_u(xx, 0, 0)$

$data10^{\langle 9\rangle} := K_u(xx, 0, 1)$

$data10^{\langle 10\rangle} := K_u(xx, 0, -1)$

$data10^{\langle 11\rangle} := K_u(xx, 0, 2)$

$data10^{\langle 12\rangle} := K_u(xx, 0, -2)$

$data10^{\langle 13\rangle} := K_u(xx, 0, 3)$

$data10^{\langle 14\rangle} := K_u(xx, 0, -3)$

$data10^{\langle 15\rangle} := \sigma_u(xx, 0, 0)$

$data10^{\langle 16\rangle} := \sigma_u\left(xx, \frac{\pi}{2}, 0\right)$

$data10^{\langle 17\rangle} := \sigma_u(xx, \pi, 0)$

$data10^{\langle 18\rangle} := K_u(xx, 0, 0)$

$data10^{\langle 19\rangle} := K_u\left(xx, \frac{\pi}{2}, 0\right)$

$data10^{\langle 20\rangle} := K_u(xx, \pi, 0)$

WRITEPRN("data10.txt") := data10

Hoop Stress and Stress Intensity Factor Calculation (25-mm Outer lid)

Conversion Factors: 1 in = 25.4 mm, 1 ksi = 6.89 MPa, 1 ksi-in^½ = 1.0988 MPa-m^½

$c0 := 25.4$

$c1 := 6.894757$

$c2 := 1.098843$

Coefficients for the third-order polynomial stress equation.

$A_0 := -51.672275c1$

$A_0 = -356.26778$

$A_1 := 136.97241\frac{c1}{c0}$

$A_1 = 37.180767$

$$A_2 := 134.40677 \frac{c1}{c0 \cdot c0}$$

$$A_2 = 1.436391$$

$$A_3 := -155.15755 \frac{c1}{c0 \cdot c0 \cdot c0}$$

$$A_3 = -0.065282$$

$$\sigma_s(x) := \left[A_0 + x \cdot \left[A_1 + x \cdot \left(A_2 + x \cdot A_3\right)\right]\right]$$

Stress Intensity Factor Table based on hoop stress at 50 linearly spaced points out to (80% of thickness) 0.7872 inches or 19.995 mm.

Ktable :=

−8.096912553	0.3988
−11.08864448	0.8001
−13.12743778	1.1989
−14.62395207	1.6002
−15.74125563	1.999
−16.56494834	2.4003
−17.16634511	2.7991
−17.5702798	3.2004
−17.79521296	3.5992
−17.85960516	3.998
−17.77785124	4.3993
−17.56148906	4.7981
−17.22755067	5.1994
−16.78515648	5.5982
−16.23441637	5.9995
−15.58159374	6.3983
−14.83251247	6.797
−13.99233711	7.1984
−13.06249616	7.5971
−12.03771518	7.9985
−10.93137807	8.3972
−9.747286832	8.7986
−8.489320377	9.1973
−7.161148843	9.5987
−5.7664094	9.9974
−4.327309665	10.3962
−2.830795383	10.7975
−1.280437794	11.1963
0.320255595	11.5976
1.967753102	11.9964
3.658542826	12.3977
5.415098304	12.7965
7.218783158	13.1978
9.05768593	13.5966
10.92825736	13.9954
12.82690422	14.3967
14.74987947	14.7955
16.73175271	15.1968
18.7698867	15.5956
20.82285508	15.9969
22.88648224	16.3957
24.95692222	16.7945
27.03021919	17.1958
29.13461342	17.5946
31.33328838	17.9959
33.52559005	18.3947
35.70701317	18.796
37.87294261	19.1948
40.01865333	19.5961
42.13953021	19.9949

$Thck := Ktable_{49,1}$

$Thck = 19.9949$

$K_s(x) := linterp(Ktable^{\langle 1 \rangle}, Ktable^{\langle 0 \rangle}, x)$

Functional form based on angular variation.

$\sigma_t(x,\theta) := \sigma_s(x) - (c1 \cdot 2.5) \cdot (1 - \cos(\theta))$

$$K_t(x,\theta) := K_s(x) \cdot \left(\frac{\sigma_t(Thck,\theta)}{\sigma_t(Thck,0)} \right)$$

Rescaling for uncertainty with the yield strength of 46.72 ksi.

$YS := c1 \cdot 46.72$

$YS = 322.123047$

$F := 0.05$

$$rscale(\theta,s) := \left(\frac{\sigma_t(Thck,\theta) + s \cdot \frac{YS \cdot F}{3}}{\sigma_t(Thck,\theta)} \right)$$

$\sigma_u(x,\theta,s) := \overrightarrow{(\sigma_t(x,\theta) \cdot rscale(\theta,s))}$

$K_u(x,\theta,s) := \overrightarrow{(K_t(x,\theta) \cdot rscale(\theta,s))}$

$xx := Ktable^{\langle 1 \rangle}$

$data25^{\langle 0 \rangle} := Ktable^{\langle 1 \rangle}$

$data25^{\langle 1 \rangle} := \sigma_u(xx, 0, 0)$

$data25^{\langle 2 \rangle} := \sigma_u(xx, 0, 1)$

$data25^{\langle 3 \rangle} := \sigma_u(xx, 0, -1)$

$data25^{\langle 4 \rangle} := \sigma_u(xx, 0, 2)$

$data25^{\langle 5 \rangle} := \sigma_u(xx, 0, -2)$

$data25^{\langle 6 \rangle} := \sigma_u(xx, 0, 3)$

$data25^{\langle 7 \rangle} := \sigma_u(xx, 0, -3)$

$data25^{\langle 8 \rangle} := K_u(xx, 0, 0)$

$data25^{\langle 9 \rangle} := K_u(xx, 0, 1)$

$data25^{\langle 10 \rangle} := K_u(xx, 0, -1)$

$data25^{\langle 11 \rangle} := K_u(xx, 0, 2)$

$data25^{\langle 12 \rangle} := K_u(xx, 0, -2)$

$data25^{\langle 13 \rangle} := K_u(xx, 0, 3)$

$data25^{\langle 14 \rangle} := K_u(xx, 0, -3)$

$data25^{\langle 15 \rangle} := \sigma_u(xx, 0, 0)$

$data25^{\langle 16 \rangle} := \sigma_u\left(xx, \frac{\pi}{2}, 0\right)$

$data25^{\langle 17 \rangle} := \sigma_u(xx, \pi, 0)$

$data25^{\langle 18 \rangle} := K_u(xx, 0, 0)$

$data25^{\langle 19 \rangle} := K_u\left(xx, \frac{\pi}{2}, 0\right)$

$data25^{\langle 20 \rangle} := K_u(xx, \pi, 0)$

WRITEPRN("data25.txt") := data25

3.4 COMPUTER LISTING OF TEST DATA INPUT AND OUTPUT

Input master file list (WD4DLL.wap).

```
WDKIinM.fil
WDKIinO.fil
WDdata10c01.fil
WDdata10c02.fil
WDdata10c03.fil
WDdata10c04.fil
WDdata10c05.fil
WDdata10c06.fil
WDdata10c07.fil
WDdata10c08.fil
WDdata10c09.fil
WDdata10c10.fil
WDdata10c11.fil
WDdata10c12.fil
WDdata10c13.fil
WDdata10c14.fil
WDdata10c15to17.fil
WDdata10c18to20.fil
WDdata25c01.fil
WDdata25c02.fil
WDdata25c03.fil
WDdata25c04.fil
WDdata25c05.fil
WDdata25c06.fil
WDdata25c07.fil
WDdata25c08.fil
WDdata25c09.fil
WDdata25c10.fil
WDdata25c11.fil
```

```
WDdata25c12.fil
WDdata25c13.fil
WDdata25c14.fil
WDdata25c15to17.fil
WDdata25c18to20.fil
```

Listing of Input Stress Intensity Facor File (KIinM.fil) for (10-mm) Inner Lid Test Case

```
! KIinM.fil
! From Thinlid1.xls
! AO30:AO79          A89:A138
#  1  2
#  50
#  1.0
! KI (MPA*m½)       depth (mm)
-7.201806034        0.3277
-10.05117186        0.6579
-12.14661052        0.9855
-13.83718048        1.3132
-15.26051182        1.6408
-16.48813922        1.9710
-17.60873931        2.2987
-18.62418012        2.6264
-19.34568044        2.9540
-18.27353932        3.2842
-17.05876838        3.6119
-15.73543176        3.9395
-14.40693057        4.2697
-13.09502192        4.5974
-11.74410433        4.9251
-10.37129779        5.2527
-8.992063026        5.5829
-7.619959749        5.9106
-6.28349195         6.2382
-5.021547684        6.5659
-3.791766552        6.8961
-2.602642611        7.2238
-1.461856773        7.5514
-0.376262524        7.8791
0.6479086           8.2093
1.602739435         8.5369
2.489890331         8.8646
3.304704392         9.1948
4.043027992         9.5225
4.701256926         9.8501
5.276226526         10.1778
5.809253288         10.5080
6.267459831         10.8356
6.633989902         11.1633
6.907239191         11.4910
7.086141819         11.8212
7.170016506         12.1488
7.171796631         12.4765
7.082153019         12.8067
6.8851964           13.1343
6.581695963         13.4620
6.173014275         13.7897
5.661052333         14.1199
5.214086954         14.4475
5.185517036         14.7752
5.092620849         15.1028
4.940639873         15.4330
4.735255128         15.7607
4.482741007         16.0884
4.18995429          16.4186
```

Listing of Input Stress Intensity Factor File (KIinO.fil) for (25-mm) Outer Lid Test Case

```
! KIinO.fil
! From S&K_OL.xls
! AO29:AO78        A87:A136
#  1  2
#  50
#  1.0
! KI (MPA*m½)      depth (mm)
-8.096912553       0.3988
-11.08864448       0.8001
-13.12743778       1.1989
-14.62395207       1.6002
-15.74125563       1.9990
-16.56494834       2.4003
-17.16634511       2.7991
-17.5702798        3.2004
-17.79521296       3.5992
-17.85960516       3.9980
-17.77785124       4.3993
-17.56148906       4.7981
-17.22755067       5.1994
-16.78515648       5.5982
-16.23441637       5.9995
-15.58159374       6.3983
-14.83251247       6.7970
-13.99233711       7.1984
-13.06249616       7.5971
-12.03771518       7.9985
-10.93137807       8.3972
-9.747286832       8.7986
-8.489320377       9.1973
-7.161148843       9.5987
-5.7664094         9.9974
-4.327309665       10.3962
-2.830795383       10.7975
-1.280437794       11.1963
0.320255595        11.5976
1.967753102        11.9964
3.658542826        12.3977
5.415098304        12.7965
7.218783158        13.1978
9.05768593         13.5966
10.92825736        13.9954
12.82690422        14.3967
14.74987947        14.7955
16.73175271        15.1968
18.7698867         15.5956
20.82285508        15.9969
22.88648224        16.3957
24.95692222        16.7945
27.03021919        17.1958
29.13461342        17.5946
31.33328838        17.9959
33.52559005        18.3947
35.70701317        18.7960
37.87294261        19.1948
40.01865333        19.5961
42.13953021        19.9949
```

Listing of Output Stress and Stress Intensity Factor Files (WDdata10c15to17.fil and WDdata10c18to20.fil) for (10-mm) Inner Lid Test Case

```
! Output from sccd version 1.01
! For sampled random variable z =  0.00000
! Stress Intensity vs. Depth
! argument in( 1) =      0.00000
! argument in( 2) =      0.60887
! argument in( 3) =   -437.72054
! argument in( 4) =    176.96724
! argument in( 5) =    -15.60607
! argument in( 6) =      0.36710
! argument in( 7) =      3.00000
! argument in( 8) =    322.12305
! argument in( 9) =      0.05000
! argument in(10) =     17.23689
! argument in(11) =      1.00000
! argument in(12) =     18.00000
! argument in(13) =     17.00000
#     3    2
#    50
#   0.33333
! KI vs. Depth         (angle =    0.00000 radians)
  -7.20180603400000        0.199527721820517
  -10.0511718600000        0.400577626444059
  -12.1466105200000        0.600044460952455
  -13.8371804800000        0.799572182772972
  -15.2605118200000        0.999039017281368
  -16.4881392200000         1.20008892190491
  -17.6087393100000         1.39961664372543
  -18.6241801200000         1.59914436554594
  -19.3456804400000         1.79861120005434
  -18.2735393200000         1.99966110467788
  -17.0587683800000         2.19918882649840
  -15.7354317600000         2.39865566100679
  -14.4069305700000         2.59970556563034
  -13.0950219200000         2.79923328745085
  -11.7441043300000         2.99876100927137
  -10.3712977900000         3.19822784377977
  -8.99206302600000         3.39927774840331
  -7.61995974900000         3.59880547022383
  -6.28349195000000         3.79827230473222
  -5.02154768400000         3.99780002655274
  -3.79176655200000         4.19884993117628
  -2.60264261100000         4.39837765299680
  -1.46185677300000         4.59784448750519
 -0.376262524000000         4.79737220932571
  0.647908600000000         4.99842211394925
   1.60273943500000         5.19788894845765
   2.48989033100000         5.39741667027817
   3.30470439200000         5.59846657490171
   4.04302799200000         5.79799429672223
   4.70125692600000         5.99746113123062
   5.27622652600000         6.19698885305114
   5.80925328800000         6.39803875767468
   6.26745983100000         6.59750559218308
   6.63398990200000         6.79703331400359
   6.90723919100000         6.99656103582411
   7.08614181900000         7.19761094044765
   7.17001650600000         7.39707777495605
   7.17179663100000         7.59660549677657
   7.08215301900000         7.79765540140011
   6.88519640000000         7.99712223590850
   6.58169596300000         8.19664995772902
   6.17301427500000         8.39617767954954
   5.66105233300000         8.59722758417308
   5.21408695400000         8.79669441868148
   5.18551703600000         8.99622214050199
```

```
! Output from sccd version 1.01
! For sampled random variable z =  0.00000
! Stress vs. Depth
! argument in( 1) =      0.00000
! argument in( 2) =      0.60887
! argument in( 3) =   -437.72054
! argument in( 4) =    176.96724
! argument in( 5) =    -15.60607
! argument in( 6) =      0.36710
! argument in( 7) =      3.00000
! argument in( 8) =    322.12305
! argument in( 9) =      0.05000
! argument in(10) =     17.23689
! argument in(11) =      1.00000
! argument in(12) =     18.00000
! argument in(13) =     17.00000
#     3    2
#    50
#   0.33333
! Stress vs. Depth     (angle =    0.00000 radians)
  -381.391354046354        0.199527721820517
  -327.944074942598        0.400577626444059
  -278.124745432091        0.600044460952455
  -231.408411480447        0.799572182772972
  -187.746124894520        0.999039017281368
  -146.734338309176         1.20008892190491
  -108.929849460936         1.39961664372543
  -73.9334352802770         1.59914436554594
  -41.6770222269442         1.79861120005434
  -11.8475042555369         1.99966110467788
   15.1711756272377         2.19918882649840
   39.6852830645551         2.39865566100679
   61.9467878680317         2.59970556563034
   81.6887433515208         2.79923328745085
   99.1663370590975         2.99876100927137
   114.452739672944         3.19822784377977
   127.727431624854         3.39927774840331
   138.862411738665         3.59880547022383
   148.041130471831         3.79827230473222
   155.346682805888         3.99780002655274
   160.888780598165         4.19884993117628
   164.661508132565         4.39837765299680
   166.790690751384         4.59784448750519
   167.355119690056         4.79737220932571
   166.418842014631         4.99842211394925
   164.074962488104         5.19788894845765
   160.398029218561         5.39741667027817
   155.423807439792         5.59846657490171
   149.305623100921         5.79799429672223
   142.090376169171         5.99746113123062
   133.851153100029         6.19698885305114
   124.594011615931         6.39803875767468
   114.540324274169         6.59750559218308
   103.694859700931         6.79703331400359
   92.1380696224587         6.99656103582411
   79.8522271249622         7.19761094044765
   67.1053410871005         7.39707777495605
   53.8764203100514         7.59660549677657
   40.1414657033600         7.79765540140011
   26.1907609908213         7.99712223590850
   11.9907194137937         8.19664995772902
  -2.37693477679909         8.39617767954954
  -16.9451346345174         8.59722758417308
  -31.4108693340314         8.79669441868148
  -45.8155335190830         8.99622214050199
```

```
    5.09262084900000         9.19568897501039
    4.94063987300000         9.39673887963393
    4.73525512800000         9.59626660145445
    4.48274100700000         9.79579432327496
    4.18995429000000         9.99684422789851
#    50
#   0.33333
! KI vs. Depth          (angle =    1.57080 radians)
   -8.28755421267853        0.199527721820517
   -11.5664919740185        0.400577626444059
   -13.9778401014336        0.600044460952455
   -15.9232813043319        0.799572182772972
   -17.5611948481243        0.999039017281368
   -18.9739000199156         1.20008892190491
   -20.2634423864780         1.39961664372543
   -21.4319716030261         1.59914436554594
   -22.2622457020834         1.79861120005434
   -21.0284680060869         1.99966110467788
   -19.6305575411692         2.19918882649840
   -18.1077139755280         2.39865566100679
   -16.5789272265161         2.59970556563034
   -15.0692345178223         2.79923328745085
   -13.5146518602042         2.99876100927137
   -11.9348802626275         3.19822784377977
   -10.3477113185186         3.39927774840331
   -8.76874900825270         3.59880547022383
   -7.23079459995272         3.79827230473222
   -5.77859893285489         3.99780002655274
   -4.36341533126066         4.19884993117628
   -2.99501842080432         4.39837765299680
   -1.68224709193949         4.59784448750519
  -0.432988065927861        4.79737220932571
   0.745587651487789        4.99842211394925
    1.84436930037434         5.19788894845765
    2.86526754599714         5.39741667027817
    3.80292341619275         5.59846657490171
    4.65255708205551         5.79799429672223
    5.41002096668734         5.99746113123062
    6.07167329502636         6.19698885305114
    6.68505946038938         6.39803875767468
    7.21234547000819         6.59750559218308
    7.63413381305000         6.79703331400359
    7.94857831287022         6.99656103582411
    8.15445239797345         7.19761094044765
    8.25097207821786         7.39707777495605
    8.25302057582710         7.59660549677657
    8.14986224432484         7.79765540140011
    7.92321233875917         7.99712223590850
    7.57395601148037         8.19664995772902
    7.10366125082743         8.39617767954954
    6.51451564913777         8.59722758417308
    6.00016552749258         8.79669441868148
    5.96728839317947         8.99622214050199
    5.86038712670840         9.19568897501039
    5.68549341644331         9.39673887963393
    5.44914475603662         9.59626660145445
    5.15856146937568         9.79579432327496
    4.82163406832737         9.99684422789851
#    50
#   0.33333
! KI vs. Depth          (angle =    3.14159 radians)
   -9.37330239135706        0.199527721820517
   -13.0818120880370        0.400577626444059
   -15.8090696828671        0.600044460952455
   -18.0093821286639        0.799572182772972
   -19.8618778762487        0.999039017281368
   -21.4596608198313         1.20008892190491
   -22.9181454629560         1.39961664372543
   -24.2397630860521         1.59914436554594
   -25.1788109641668         1.79861120005434
   -23.7833966921739         1.99966110467788
```

```
   -60.0728759766058         9.19568897501039
   -74.2201822011426         9.39673887963393
   -87.9608464820539         9.59626660145445
   -101.325410484862         9.79579432327496
   -114.332917016722         9.99684422789851
#    50
#   0.33333
! Stress vs. Depth      (angle =    1.57080 radians)
   -398.628246546354        0.199527721820517
   -345.180967442598        0.400577626444059
   -295.361637932091        0.600044460952455
   -248.645303980447        0.799572182772972
   -204.983017394520        0.999039017281368
   -163.971230809176         1.20008892190491
   -126.166741960936         1.39961664372543
   -91.1703277802770         1.59914436554594
   -58.9139147269442         1.79861120005434
   -29.0843967555369         1.99966110467788
   -2.06571687276231         2.19918882649840
    22.4483905645551         2.39865566100679
    44.7098953680317         2.59970556563034
    64.4518508515208         2.79923328745085
    81.9294445590975         2.99876100927137
    97.2158471729440         3.19822784377977
    110.490539124854         3.39927774840331
    121.625519238665         3.59880547022383
    130.804237971831         3.79827230473222
    138.109790305888         3.99780002655274
    143.651888098165         4.19884993117628
    147.424615632565         4.39837765299680
    149.553798251384         4.59784448750519
    150.118227190056         4.79737220932571
    149.181949514631         4.99842211394925
    146.838069988104         5.19788894845765
    143.161136718560         5.39741667027817
    138.186914939792         5.59846657490171
    132.068730600921         5.79799429672223
    124.853483669171         5.99746113123062
    116.614260600029         6.19698885305114
    107.357119115931         6.39803875767468
    97.3034317741686         6.59750559218308
    86.4579672009308         6.79703331400359
    74.9011771224587         6.99656103582411
    62.6153346249622         7.19761094044765
    49.8684485871005         7.39707777495605
    36.6395278100514         7.59660549677657
    22.9045732033600         7.79765540140011
    8.95386849082134         7.99712223590850
   -5.24617308620627         8.19664995772902
   -19.6138272767991         8.39617767954954
   -34.1820271345174         8.59722758417308
   -48.6477618340314         8.79669441868148
   -63.0524260190830         8.99622214050199
   -77.3097684766058         9.19568897501039
   -91.4570747011426         9.39673887963393
   -105.197738982054         9.59626660145445
   -118.562302984862         9.79579432327496
   -131.569809516722         9.99684422789851
#    50
#   0.33333
! Stress vs. Depth      (angle =    3.14159 radians)
   -415.865139046354        0.199527721820517
   -362.417859942598        0.400577626444059
   -312.598530432091        0.600044460952455
   -265.882196480447        0.799572182772972
   -222.219909894520        0.999039017281368
   -181.208123309176         1.20008892190491
   -143.403634460936         1.39961664372543
   -108.407220280277         1.59914436554594
   -76.1508072269442         1.79861120005434
   -46.3212892555369         1.99966110467788
```

-22.2023467023383	2.19918882649840	-19.3026093727623	2.19918882649840
-20.4799961910560	2.39865566100679	5.21149806455505	2.39865566100679
-18.7509238830322	2.59970556563034	27.4730028680317	2.59970556563034
-17.0434471156446	2.79923328745085	47.2149583515208	2.79923328745085
-15.2851993904083	2.99876100927137	64.6925520590975	2.99876100927137
-13.4984627352549	3.19822784377977	79.9789546729440	3.19822784377977
-11.7033596110372	3.39927774840331	93.2536466248544	3.39927774840331
-9.91753826750540	3.59880547022383	104.388626738665	3.59880547022383
-8.17809724990545	3.79827230473222	113.567345471831	3.79827230473222
-6.53565018170979	3.99780002655274	120.872897805888	3.99780002655274
-4.93506411052133	4.19884993117628	126.414995598165	4.19884993117628
-3.38739423060864	4.39837765299680	130.187723132565	4.39837765299680
-1.90263741087899	4.59784448750519	132.316905751384	4.59784448750519
-0.489713607855721	4.79737220932571	132.881334690056	4.79737220932571
0.843266702975578	4.99842211394925	131.945057014631	4.99842211394925
2.08599916574867	5.19788894845765	129.601177488104	5.19788894845765
3.24064476099429	5.39741667027817	125.924244218561	5.39741667027817
4.30114244038550	5.59846657490171	120.950022439792	5.59846657490171
5.26208617211103	5.79799429672223	114.831838100921	5.79799429672223
6.11878500737469	5.99746113123062	107.616591169171	5.99746113123062
6.86712006405272	6.19698885305114	99.3773681000294	6.19698885305114
7.56086563277876	6.39803875767468	90.1202266159308	6.39803875767468
8.15723110901638	6.59750559218308	80.0665392741686	6.59750559218308
8.63427772410001	6.79703331400359	69.2210747009308	6.79703331400359
8.98991743474044	6.99656103582411	57.6642846224587	6.99656103582411
9.22276297694690	7.19761094044765	45.3784421249622	7.19761094044765
9.33192765043572	7.39707777495605	32.6315560871005	7.39707777495605
9.33424452065420	7.59660549677657	19.4026353100514	7.59660549677657
9.21757146964969	7.79765540140011	5.66768070336004	7.79765540140011
8.96122827751835	7.99712223590850	-8.28302400917867	7.99712223590850
8.56621605996075	8.19664995772902	-22.4830655862063	8.19664995772902
8.03430822665486	8.39617767954954	-36.8507197767991	8.39617767954954
7.36797896527553	8.59722758417308	-51.4189196345174	8.59722758417308
6.78624410098517	8.79669441868148	-65.8846543340314	8.79669441868148
6.74905975035895	8.99622214050199	-80.2893185190830	8.99622214050199
6.62815340441680	9.19568897501039	-94.5466609766058	9.19568897501039
6.43034695988661	9.39673887963393	-108.693967201143	9.39673887963393
6.16303438407325	9.59626660145445	-122.434631482054	9.59626660145445
5.83438193175135	9.79579432327496	-135.799195484862	9.79579432327496
5.45331384665473	9.99684422789851	-148.806702016722	9.99684422789851

Listing of Output Stress and Stress Intensity Factor Files (WDdata25c15to17.fil and Wddata25c18to20.fil) for (25-mm) Outer Lid Test Case

```
! Output from sccd version 1.01
! For sampled random variable z =  0.00000
! Stress vs. Depth
! argument in( 1) =      0.00000
! argument in( 2) =      1.00000
! argument in( 3) =   -356.26778
! argument in( 4) =     37.18077
! argument in( 5) =      1.43639
! argument in( 6) =     -0.06528
! argument in( 7) =      3.00000
! argument in( 8) =    322.12305
! argument in( 9) =      0.05000
! argument in(10) =     17.23689
! argument in(11) =      2.00000
! argument in(12) =     34.00000
! argument in(13) =     33.00000
#     3     2
#    50
#   0.33333
! Stress vs. Depth    (angle =    0.00000 radians)
  -341.215784707651       0.398800000000000
  -325.633364692085       0.800100000000000
  -309.739642115624        1.19890000000000
```

```
! Output from sccd version 1.01
! For sampled random variable z =  0.00000
! Stress Intensity vs. Depth
! argument in( 1) =      0.00000
! argument in( 2) =      1.00000
! argument in( 3) =   -356.26778
! argument in( 4) =     37.18077
! argument in( 5) =      1.43639
! argument in( 6) =     -0.06528
! argument in( 7) =      3.00000
! argument in( 8) =    322.12305
! argument in( 9) =      0.05000
! argument in(10) =     17.23689
! argument in(11) =      2.00000
! argument in(12) =     34.00000
! argument in(13) =     33.00000
#     3     2
#    50
#   0.33333
! KI vs. Depth        (angle =    0.00000 radians)
  -8.09691255300000       0.398800000000000
  -11.0886444800000       0.800100000000000
  -13.1274377800000        1.19890000000000
```

```
  -293.360529728595      1.60020000000000
  -276.725076327183      1.99900000000000
  -259.649895127803      2.40030000000000
  -242.372707600602      2.79910000000000
  -224.702081147980      3.20040000000000
  -206.883156194151      3.59920000000000
  -188.831551544850      3.99800000000000
  -170.457042366105      4.39930000000000
  -152.013539113604      4.79810000000000
  -133.294986374736      5.19940000000000
  -114.559581218197      5.59820000000000
  -95.5976084783162      5.99950000000000
  -76.6702981169005      6.39830000000000
  -57.6894435466940      6.79700000000000
  -38.5463100679875      7.19840000000000
  -19.5233934171268      7.59710000000000
 -0.388237329730828      7.99850000000000
   18.5767697770207      8.39720000000000
   37.6032998395972      8.79860000000000
   56.4104257774758      9.19730000000000
   75.2276811817238      9.59870000000000
   93.7769543259661      9.99740000000000
   112.165003299998      10.3962000000000
   130.475735164219      10.7975000000000
   148.456034096812      11.1963000000000
   166.306148033961      11.5976000000000
   183.778700225955      11.9964000000000
   201.067572676921      12.3977000000000
   217.932381429153      12.7965000000000
   234.559388834825      13.1978000000000
   250.716457448134      13.5966000000000
   266.483419038827      13.9954000000000
   281.930308024625      14.3967000000000
   296.839690652968      14.7955000000000
   311.373312900355      15.1968000000000
   325.325119867184      15.5956000000000
   338.844851817049      15.9969000000000
   351.739086423205      16.3957000000000
   364.068844440398      16.7945000000000
   375.880970062756      17.1958000000000
   387.003316895848      17.5946000000000
   397.550150527566      17.9959000000000
   407.365089477394      18.3947000000000
   416.546007559362      18.7960000000000
   424.953541926765      19.1948000000000
   432.667920899871      19.5961000000000
   439.568053985687      19.9949000000000
#   50
#  0.33333
! Stress vs. Depth   (angle =    1.57080 radians)
  -358.452677207651     0.398800000000000
  -342.870257192085     0.800100000000000
  -326.976534615624      1.19890000000000
  -310.597422228595      1.60020000000000
  -293.961968827183      1.99900000000000
  -276.886787627803      2.40030000000000
  -259.609600100602      2.79910000000000
  -241.938973647980      3.20040000000000
  -224.120048694151      3.59920000000000
  -206.068444044850      3.99800000000000
  -187.693934866105      4.39930000000000
  -169.250431613604      4.79810000000000
  -150.531878874736      5.19940000000000
  -131.796473718197      5.59820000000000
  -112.834500978316      5.99950000000000
  -93.9071906169005      6.39830000000000
  -74.9263360466939      6.79700000000000
  -55.7832025679875      7.19840000000000
  -36.7602859171268      7.59710000000000
  -17.6251298297308      7.99850000000000
   1.33987727702068      8.39720000000000
```

```
  -14.6239520700000      1.60020000000000
  -15.7412556300000      1.99900000000000
  -16.5649483400000      2.40030000000000
  -17.1663451100000      2.79910000000000
  -17.5702798000000      3.20040000000000
  -17.7952129600000      3.59920000000000
  -17.8596051600000      3.99800000000000
  -17.7778512400000      4.39930000000000
  -17.5614890600000      4.79810000000000
  -17.2275506700000      5.19940000000000
  -16.7851564800000      5.59820000000000
  -16.2344163700000      5.99950000000000
  -15.5815937400000      6.39830000000000
  -14.8325124700000      6.79700000000000
  -13.9923371100000      7.19840000000000
  -13.0624961600000      7.59710000000000
  -12.0377151800000      7.99850000000000
  -10.9313780700000      8.39720000000000
  -9.74728683200000      8.79860000000000
  -8.48932037700000      9.19730000000000
  -7.16114884300000      9.59870000000000
  -5.76640940000000      9.99740000000000
  -4.32730966500000      10.3962000000000
  -2.83079538300000      10.7975000000000
  -1.28043779400000      11.1963000000000
  0.320255595000000      11.5976000000000
   1.96775310200000      11.9964000000000
   3.65854282600000      12.3977000000000
   5.41509830400000      12.7965000000000
   7.21878315800000      13.1978000000000
   9.05768593000000      13.5966000000000
   10.9282573600000      13.9954000000000
   12.8269042200000      14.3967000000000
   14.7498794700000      14.7955000000000
   16.7317527100000      15.1968000000000
   18.7698867000000      15.5956000000000
   20.8228550800000      15.9969000000000
   22.8864822400000      16.3957000000000
   24.9569222200000      16.7945000000000
   27.0302191900000      17.1958000000000
   29.1346134200000      17.5946000000000
   31.3332883800000      17.9959000000000
   33.5255900500000      18.3947000000000
   35.7070131700000      18.7960000000000
   37.8729426100000      19.1948000000000
   40.0186533300000      19.5961000000000
   42.1395302100000      19.9949000000000
#   50
#  0.33333
! KI vs. Depth       (angle =    1.57080 radians)
  -7.77940628749121     0.398800000000000
  -10.6538226790538     0.800100000000000
  -12.6126682653308      1.19890000000000
  -14.0504993646222      1.60020000000000
  -15.1239898195092      1.99900000000000
  -15.9153828603987      2.40030000000000
  -16.4931969078138      2.79910000000000
  -16.8812920053652      3.20040000000000
  -17.0974048048693      3.59920000000000
  -17.1592719773584      3.99800000000000
  -17.0807238943562      4.39930000000000
  -16.8728459788606      4.79810000000000
  -16.5520023988175      5.19940000000000
  -16.1269559232988      5.59820000000000
  -15.5978121235526      5.99950000000000
  -14.9705887913014      6.39830000000000
  -14.2508814332763      6.79700000000000
  -13.4436520806810      7.19840000000000
  -12.5502732173862      7.59710000000000
  -11.5656772313323      7.99850000000000
  -10.5027231962871      8.39720000000000
```

```
   20.3664073395972      8.79860000000000
   39.1735332774758      9.19730000000000
   57.9907886817238      9.59870000000000
   76.5400618259661      9.99740000000000
   94.9281107999982      10.3962000000000
   113.238842664219      10.7975000000000
   131.219141596812      11.1963000000000
   149.069255533961      11.5976000000000
   166.541807725955      11.9964000000000
   183.830680176921      12.3977000000000
   200.695488929153      12.7965000000000
   217.322496334825      13.1978000000000
   233.479564948134      13.5966000000000
   249.246526538827      13.9954000000000
   264.693415524625      14.3967000000000
   279.602798152968      14.7955000000000
   294.136420400355      15.1968000000000
   308.088227367184      15.5956000000000
   321.607959317049      15.9969000000000
   334.502193923205      16.3957000000000
   346.831951940398      16.7945000000000
   358.644077562756      17.1958000000000
   369.766424395848      17.5946000000000
   380.313258027566      17.9959000000000
   390.128196977394      18.3947000000000
   399.309115059362      18.7960000000000
   407.716649426765      19.1948000000000
   415.431028399871      19.5961000000000
   422.331161485687      19.9949000000000
#    50
#   0.33333
! Stress vs. Depth   (angle =    3.14159 radians)
  -375.689569707651     0.398800000000000
  -360.107149692085     0.800100000000000
  -344.213427115624      1.19890000000000
  -327.834314728595      1.60020000000000
  -311.198861327183      1.99900000000000
  -294.123680127803      2.40030000000000
  -276.846492600602      2.79910000000000
  -259.175866147980      3.20040000000000
  -241.356941194151      3.59920000000000
  -223.305336544850      3.99800000000000
  -204.930827366105      4.39930000000000
  -186.487324113604      4.79810000000000
  -167.768771374736      5.19940000000000
  -149.033366218197      5.59820000000000
  -130.071393478316      5.99950000000000
  -111.144083116901      6.39830000000000
  -92.1632285466939      6.79700000000000
  -73.0200950679875      7.19840000000000
  -53.9971784171268      7.59710000000000
  -34.8620223297308      7.99850000000000
  -15.8970152229793      8.39720000000000
   3.12951483959724      8.79860000000000
   21.9366407774758      9.19730000000000
   40.7538961817238      9.59870000000000
   59.3031693259661      9.99740000000000
   77.6912182999982      10.3962000000000
   96.0019501642188      10.7975000000000
   113.982249096812      11.1963000000000
   131.832363033961      11.5976000000000
   149.304915225955      11.9964000000000
   166.593787676921      12.3977000000000
   183.458596429153      12.7965000000000
   200.085603834825      13.1978000000000
   216.242672448134      13.5966000000000
   232.009634038827      13.9954000000000
   247.456523024625      14.3967000000000
   262.365905652968      14.7955000000000
   276.899527900355      15.1968000000000
   290.851334867184      15.5956000000000
```

```
  -9.36506402539149      8.79860000000000
  -8.15642652493410      9.19730000000000
  -6.88033691487178      9.59870000000000
  -5.54028973994384      9.99740000000000
  -4.15762178428735      10.3962000000000
  -2.71979069268223      10.7975000000000
  -1.23022766519743      11.1963000000000
  0.307697331919948      11.5976000000000
   1.89059110540318      11.9964000000000
   3.51507946730819      12.3977000000000
   5.20275469418431      12.7965000000000
   6.93571120100262      13.1978000000000
   8.70250461675730      13.5966000000000
   10.4997248594721      13.9954000000000
   12.3239196032991      14.3967000000000
   14.1714887418589      14.7955000000000
   16.0756462887444      15.1968000000000
   18.0338584187100      15.5956000000000
   20.0063232340148      15.9969000000000
   21.9890288639026      16.3957000000000
   23.9782801609685      16.7945000000000
   25.9702764161681      17.1958000000000
   27.9921505067011      17.5946000000000
   30.1046082732897      17.9959000000000
   32.2109426672998      18.3947000000000
   34.3068250946231      18.7960000000000
   36.3878213995116      19.1948000000000
   38.4493918261455      19.5961000000000
   40.4871022283844      19.9949000000000
#    50
#   0.33333
! KI vs. Depth       (angle =    3.14159 radians)
  -7.46190002198242     0.398800000000000
  -10.2190008781076     0.800100000000000
  -12.0978987506616      1.19890000000000
  -13.4770466592444      1.60020000000000
  -14.5067240090184      1.99900000000000
  -15.2658173807974      2.40030000000000
  -15.8200487056275      2.79910000000000
  -16.1923042107303      3.20040000000000
  -16.3995966497387      3.59920000000000
  -16.4589387947168      3.99800000000000
  -16.3835965487123      4.39930000000000
  -16.1842028977212      4.79810000000000
  -15.8764541276350      5.19940000000000
  -15.4687553665976      5.59820000000000
  -14.9612078771051      5.99950000000000
  -14.3595838426029      6.39830000000000
  -13.6692503965527      6.79700000000000
  -12.8949670513620      7.19840000000000
  -12.0380502747723      7.59710000000000
  -11.0936392826645      7.99850000000000
  -10.0740683225743      8.39720000000000
  -8.98284121878298      8.79860000000000
  -7.82353267286819      9.19730000000000
  -6.59952498674356      9.59870000000000
  -5.31417007988769      9.99740000000000
  -3.98793390357469      10.3962000000000
  -2.60878600236445      10.7975000000000
  -1.18001753639487      11.1963000000000
  0.295139068839897      11.5976000000000
   1.81342910880635      11.9964000000000
   3.37161610861639      12.3977000000000
   4.99041108436861      12.7965000000000
   6.65263924400525      13.1978000000000
   8.34732330351461      13.5966000000000
   10.0711923589443      13.9954000000000
   11.8209349865983      14.3967000000000
   13.5930980137178      14.7955000000000
   15.4195398674887      15.1968000000000
   17.2978301374200      15.5956000000000
```

304.371066817049	15.9969000000000	19.1897913880297	15.9969000000000
317.265301423205	16.3957000000000	21.0915754878051	16.3957000000000
329.595059440398	16.7945000000000	22.9996381019371	16.7945000000000
341.407185062756	17.1958000000000	24.9103336423363	17.1958000000000
352.529531895848	17.5946000000000	26.8496875934023	17.5946000000000
363.076365527566	17.9959000000000	28.8759281665795	17.9959000000000
372.891304477394	18.3947000000000	30.8962952845995	18.3947000000000
382.072222559362	18.7960000000000	32.9066370192463	18.7960000000000
390.479756926765	19.1948000000000	34.9027001890233	19.1948000000000
398.194135899871	19.5961000000000	36.8801303222910	19.5961000000000
405.094268985687	19.9949000000000	38.8346742467688	19.9949000000000

All other test files are available for review and documented in DTN: MO0004SPASDA04.003 .

4. REFERENCES

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