APPENDIX L

WASTE PACKAGE AND DRIP SHIELD STRESS CORROSION CRACKING (RESPONSE TO TSPAI 3.03 AIN-1)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX L

WASTE PACKAGE AND DRIP SHIELD STRESS CORROSION CRACKING (RESPONSE TO TSPAI 3.03 AIN-1)

This appendix provides a response to Key Technical Issue (KTI) agreement Total System Performance Assessment and Integration (TSPAI) 3.03 additional information needed (AIN)-1. This agreement and the AIN relate to providing the technical basis for potential crack arrest and plugging of crack openings due to oxide wedging.

L.1 KEY TECHNICAL ISSUE AGREEMENT

L.1.1 TSPAI 3.03 AIN-1

Agreement TSPAI 3.03 was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on Total System Performance Assessment and Integration held August 6 through 10, 2001, in Las Vegas, Nevada (Reamer and Gil 2001).

Wording of the agreement is as follows:

TSPAI 3.03[1]

> Provide the technical basis for crack arrest and plugging of crack openings (including the impact of oxide wedging and stress redistribution) in assessing the impact of SCC of the drip shield and waste package in revised documentation (ENG1.12 and ENG1.4.1). DOE will provide the basis for crack arrest and plugging of openings (including the impact of oxide wedging and stress redistribution) in assessing the stress corrosion cracking of the drip shield and waste package in an update to the Stress Corrosion Cracking AMR (ANL-EBS-MD-000005) in accordance with the scope and schedule for existing agreement item CLST.1.12.

On July 11, 2002, the DOE submitted information to address agreement TSPAI 3.03 (Ziegler 2002). The response requested that the NRC consider the use of risk information to meet the intent of the agreement. The NRC reviewed the response and identified three additional risk program elements that are needed for the DOE to demonstrate their understanding of the risk results and make an acceptable case using risk information. This resulted in an AIN request (Schlueter 2003) for TSPAI 3.03.

[1] The content of ENG1.12 and ENG1.4.1 (Cornell 2001) is adequately represented within the text of TSPAI 3.03 AIN-1.

Wording of the AIN is as follows:

TSPAI 3.03 AIN-1

> DOE's approach to resolving Key Technical Issue agreements via risk arguments should include the following elements: 1. Enhanced consideration of the combined effects of uncertainties. 2. Transparent and traceable documentation that allows the results to be verified independently. 3. Information pertaining to the variability in the results.

Although the NRC in its review considered the presentation not supportive toward closing the agreement and issued this AIN-1, the response documented in this Appendix does not attempt to pursue the risk based arguments. Instead, the presentation focuses on addressing the technical understanding directly as described in the KTI Agreement TSPAI 3.03.

L.1.2 Related Key Technical Issue Agreements

Agreements CLST 1.12 and 1.15 are related to TSPAI 3.03 in that they discuss stress corrosion cracking (SCC) of the drip shield and waste package. Agreement CLST 1.14 is also related in that it addresses rockfall and steady-state drift degradation related dead weight effects on SCC of the drip shield and waste package. There are no other KTI agreements relevant to TSPAI 3.03.

L.2 RELEVANCE TO REPOSITORY PERFORMANCE

This agreement is related to the expected mode of aqueous transport through SCC formed in both the drip shield and waste package. Demonstration of the effect of limited crack opening area resulting from the tight nature of SCC and the tendency for oxide plugging of these tight through-wall cracks has direct impact on the performance of the repository over the regulatory period.

L.3 RESPONSE

Because the drip shields and waste packages are emplaced in the tensile residual stress-mitigated condition, the only subsequent bases for potentially generating sufficient tensile residual stresses to initiate and then propagate through-wall SCC are (1) removal by corrosion of the stress-mitigated layers or (2) seismic- or rockfall-generated mechanical damage or both that leads to through-wall residual stress gradients with outer surface tensile stresses above threshold values. The expected layer depth and resultant long-term benefits of waste package outer surface stress-mitigated layers in avoiding through-wall SCC during the regulatory period are discussed in response to CLST 1.12 in Appendix G. For the drip shield, once a threshold value for the outer surface tensile stress level is exceeded, crack propagation is assumed to go through-wall. For the waste package, once SCC initiates either on a smooth surface or at a weld flaw, it continues to propagate until the calculated crack tip stress intensity factor drops below the threshold stress intensity factor K_{ISCC}. Sources of stress considered here that can potentially drive SCC through-wall are weld residual stresses or residual stresses related to rockfall-induced mechanical damage. Rockfall and steady-state drift-collapse induced dead-weight loading effects on the drip shield and waste package SCC are discussed in response to CLST 1.14 in Appendix C. Although rockfall and steady-state drift collapse can result in local areas of drip shield SCC, they do not affect the seepage flow diversion function of the drip shield and do not result in contact or mechanical damage of the waste package by the deformed drip shield. SCC that results from seismic-induced mechanical damage and the resultant residual stress fields that occur from impacts between adjacent waste packages or between waste packages and support pallets is discussed in the seismic abstraction analysis model report (BSC 2003a).

As described in Section L.4, through-wall SCC results in very tight cracks (on the order of 100 to 200 μm crack openings) with relatively small crack opening areas, and thus water transport through these cracks in the absence of a significant pressure gradient is limited. Because of the low passive corrosion rates measured for both Titanium Grade 7 and Alloy 22 (see Section L.4), growth of passive films on the sides of propagating SCC will take greater than about 1,300 years for the crack to plug with corrosion product in the drip shield and a still greater time in the waste package. In the interim, any water flow through such tight cracks will be limited.

Because there is a decay heat-induced heat flux across both the drip shields and waste packages, the limited extent of water contacting these metal surfaces or filling any tight stress-corrosion cracks will evaporate, leaving behind calcite (and potentially other scale formers), thereby leading to crack plugging. Over time, on the order of a hundred to about a thousand years if film flow rates prevail, crack plugging will preclude ionic transport inward or radionuclide transport outward. However, total system performance assessment conservatively considers diffusive transport can occur through the stress corrosion cracks as soon as they propagate through-wall.

As described in Section L.4, the very low crack side passive corrosion rate and the high resistance of Alloy 22 to both SCC initiation and to sustained growth under the static waste package residual stress-loading conditions will preclude any deleterious oxide wedging effect on crack propagation. Any oxide-related buildup in stress intensity at a crack tip that resulted in crack extension would be quickly relieved by a small increment of crack propagation, and it would take a significant time period for new oxide buildup at the extended crack tip. Measured crack growth rates are low for Alloy 22 (greater than or equal to 2.5×10^{-10} at $30\ \mathrm{MPa \cdot m^{1/2}}$) but, in this range of K_I values, are still fast relative to the general corrosion rate. However, even if oxide wedging were to drive SCC through-wall, the small crack opening area and crack plugging from scale formation will preclude significant water ingress.

The information in this report is responsive to agreement TSPAI 3.03 made between DOE and NRC and responsive to AIN request TSPAI 3.03 AIN-1. The report contains the information that the DOE considers necessary for NRC review for closure of this agreement.

L.4 BASIS FOR THE RESPONSE

L.4.1 Stress Corrosion Cracking for the Drip Shield and Waste Package Materials

Basis for Expected Crack Plugging–The sources of stress that could potentially lead to SCC in the Titanium Grade 7 drip shield and Alloy 22 waste package outer cylindrical shell are (1) weld-induced tensile residual stress; (2) plasticity-induced tensile residual stress caused by seismic events; and (3) tensile residual stress produced by rockfall. The weld-induced tensile residual stress will be mitigated by stress relief annealing for the drip shield and by controlled quenching from the shop solution heat treatment and subsequent mechanical stress mitigation processing for the waste package final closure weld region after completion of the weld (BSC 2003b, Section 8). Consequently, following emplacement of the drip shield and waste package, the only sources of new tensile stresses that could reverse the benefits obtained by the previous stress mitigation processing are seismic- and rockfall-induced residual tensile stresses. Seismic effects are treated in the seismic abstraction analysis model report (BSC 2003a) and are not considered here. However, since rockfall can also induce regions of high sustained tensile residual stresses on the drip shield (CLST 1.14 response and BSC 2003b) an analysis is presented here on the potential consequences of these rockfall-induced stresses on SCC initiation and subsequent through-wall crack propagation leading to the potential for aqueous flow and transport through these cracks. Multiple rock falls on the same spot are ruled out because of the small probability (BSC 2003b, Section 6.3.7). However, the Project has not yet quantified this probability value. Since the drip shield is designed to preclude rockfall damage to the waste package, rockfall induced SCC will not occur on the waste package. However, once the stress mitigated layer on the outer waste package surface is removed through general corrosion, it is conservatively assumed that if the stress or in the case of surface breaking weld flaws, the flaw tip stress intensity factor exceed threshold values, SCC can potentially initiate and propagate through-wall.

Stress corrosion cracks in passive alloys, such as Titanium Grade 7 and Alloy 22, tend to be very tight (small crack opening displacement) by nature because the effective crack tip SCC growth rate is very high compared to the general corrosion rate of the unstressed sides of the crack. As the crack grows through-wall, the tensile stresses normal to the crack walls are relieved, and the resulting crack faces continue to corrode by general corrosion at very low passive corrosion rates over the full range of exposure temperatures. These corrosion rates correspond to a maximum measured value of 0.077 μm/yr for Titanium Grade 7 (based on 5-year test results) (BSC 2003b; BSC 2003c, Section 6.3.3, Table 7) and a maximum measured 5-year exposure rate of 0.023 μm/yr for Alloy 22 (BSC 2003d, p. 57).

Residual stresses resulting from rockfall on the drip shield or from general corrosion removal of stress mitigated surface layers on the waste package can cause SCC crack initiation if the resultant sustained tensile stresses exceed the threshold stress for SCC initiation, which is modeled to be 0.5 yield strength (110.4 MPa) for Titanium Grade 7 and 0.9 yield strength (257 MPa) for Alloy 22 (BSC 2003b, Section 6.2.1). Once initiated it will take about 40 years for SCC to grow through the 15 mm thick drip shield wall (BSC 2003b, Section 6.3.7) based on a measured Titanium Grade 7 static load SCC growth rate of 1.3×10^{-8} mm/s at an applied K_I of $30 \text{ MPa} \cdot \text{m}^{1/2}$ (DTN: LL021105312251.023, Figure 1-4). Because of the thicker waste package outer shell, 20 mm, and the observed lower crack growth rates for Alloy 22 of about 5×10^{-10} mm/s at an applied K_I of $30 \text{ MPa} \cdot \text{m}^{1/2}$ (BSC 2003b, Table 4.1-1), it will take about 1,270 years for the crack to grow through the waste package outer wall, assuming a similar through-wall constant K_I of $30 \text{ MPa} \cdot \text{m}^{1/2}$.

For the drip shield, once the threshold stress for SCC initiation is exceeded, through-wall SCC is conservatively assumed. For through-wall cracks in the drip shield resulting from rockfall, the calculated crack length "2c" and the crack gap (or width) "δ" are 130 mm and 157 μm, respectively (BSC 2003b, Section 6.3.7). Thus, the dense passive corrosion oxide film growing normal to each opposing crack face would need to grow until it fills the 157 μm gap. This is equivalent to about 103 μm of metal loss per crack side and results in a total per-side oxide thickness of about 182 μm based on a TiO_2 oxide-metal volume ratio of 1.76 (BSC 2003b, Section 6.3.7). At a maximum 5-year exposure passive film growth rate equivalent to 0.077 µm metal loss per year (BSC 2003c, Table 7), it will take a minimum of about 1,340 years for the crack to fill with corrosion product. For Alloy 22, the expected oxide-metal volume ratios for the likely oxides present, Cr_2O_3 and NiO (Pensado et al. 2002), are 2.02 and 1.70, respectively (ASM International 1987, p. 64, Table 2), similar to those for TiO_2. Therefore, for a comparably calculated crack opening displacement of 209µm (BSC 2001, Table 5-15) and the lower maximum measured Alloy 22 corrosion rate, 0.023 µm/yr, longer times (about 5,900 years) to fill the crack with corrosion-generated oxide can be expected. In the interim, while the crack faces are corroding passively but before the corrosion film grows to a thickness where it will completely fill the crack, there could be stagnant water "bridging" of the crack or a small amount of water transport by film flow into the crack and through the drip shield or the waste package, if also cracked. However, the small heat flux present across the drip shield and waste package wall will result in evaporation of the slowly flowing water or of the bridged water near the outer surface of the crack faces. As a result, scale deposit (e.g., for carbonate-containing waters this will be principally calcium carbonate (calcite)) will form over the crack where it intersects the surface and within the crack for the film flow case (BSC 2001, Section 3). However, for the bridged case where water transport through the crack is precluded, very little calcite precipitation will occur because the stagnant water will have limited exchanges with the outside water and evaporation is not sufficient to bring the Ca concentration beyond the calcite precipitation threshold, except at the smallest flow rates. The formation of calciferous deposits is noted in seawater environments and in heat exchangers through which natural brines are forced to flow, for example, in desalination plants (Cowan and Weintritt 1976, pp. 1 to 39 and 376 to 383). In these cases, titanium or nickel alloy surfaces are common heat sources at operating temperatures of about 100°C. Such deposits form rapidly under flowing conditions and have to be regularly removed to avoid loss of heat exchanger efficiency. In the case of concentrating pore water or J-13 water, calcite precipitation is the first stage of the concentration process. Other minerals, such as amorphous silica, will also precipitate.

A detailed set of calculations have been performed for the expected time to SCC plugging due to calcite precipitation resulting from evaporation of pore water of typical composition dripping onto a drip shield or, conservatively assuming the drip shield has failed, onto a waste package at the crack location. Calculation results are summarized in Tables L-1 and L-2 for the drip shield and waste package cases, respectively, assuming water film flow through the SCC (BSC 2001, Section 6). The minimum calculated plugging times indicated at 7,000 years result from the balance between decreasing evaporation rates as the temperature decreases with time and the retrograde temperature solubility of calcite. At the longest times, greater than or equal to 15,000 years, the heat flux has decreased to the point that no precipitation is assumed.

Table L-1. Maximum Time to Plug Drip Shield Stress Corrosion Cracks (Film Flow)

Time after Emplacement (year)	**3,000**	**5,000**	**7,000**	**10,000**	**15,000**	**20,000**
Flow Rate on Crack[a]	**Time to Plug Drip Shield SCC (year)**					
100 L/yr (0.1 m^3/yr)	711	621	369	622	no ppt	no ppt
1 m^3/yr	>609	>545	>182	>509	no ppt	no ppt
10 m^3/yr	>1492	>1133	>292	>1258	no ppt	no ppt

Source: BSC 2001, Table 6-3. (Each plugging time value is a geometric average of 3 drop sizes. Values with the > symbol represent mixed cases where only one or two drop sizes allowed plugging.)

NOTE: [a] Fracture water composition was derived with infiltration varying from 6 to 25 mm/yr. Numbers in this table assume that chemical composition of the water does not vary much with flow. no ppt = no precipitation.

Table L-2. Maximum Time to Plug Waste Package Stress Corrosion Cracks (Film Flow)

Time after Emplacement (year)	**3,000**	**5,000**	**7,000**	**10,000**	**15,000**	**20,000**
Flow Rate on Crack[a]	**Time to Plug Waste Package SCC (year)**					
100 L/yr (0.1 m^3/yr)	879	459	312	308	no ppt	no ppt
1 m^3/yr	417	282	119	233	no ppt	no ppt
10 m^3/yr	>395	>278	>98	>867	no ppt	no ppt

Source: BSC 2001, Table 6-4. (Each plugging time value is a geometric average of 3 drop sizes. Values with the > symbol represent mixed cases where only one or two drop sizes allowed plugging.)

NOTE: [a] Fracture water composition was derived with infiltration varying from 6 to 25 mm/yr. Numbers in this table assume that chemical composition of the water does not vary much with flow rate. no ppt = no precipitation.

The calculations used to derive these tables conservatively assume corrosion products generated on the crack faces and colloids, particulates, and any precipitated silica minerals do not help in plugging the crack opening and that there is a uniform water seepage advective flow in space and time. It is evident that SCC cracks are sealed in as little as a hundred years to somewhat over a thousand years when water is allowed to flow through the cracks at the expected low film-flow rate. When the cracks are bridged by water, the sealing process may take thousands of years, but no flow occurs since capillary forces hold the water. In a more realistic case of a nonuniform flow onto the drip shield, more precipitation and faster plugging will occur.

Following plugging of such a drip shield or waste package crack, any solution flow through the crack would be dominated by an efficiency factor determined by the ratio of solution runoff on the drip shield surface (or waste package) compared to through-crack flow, which, in turn, is determined by scale porosity-permeability (i.e., extent of interconnected porosity). Because of the expected high density of the evaporatively formed deposits, (porosity is typically less than 10% (BSC 2001, Section 3.13) and lack of a significant pressure gradient to drive water through the crack, the probability of solution flow through the plugged crack would approach zero.

However, for the waste package, the total system performance assessment conservatively does not take credit for oxide plugging of through-wall SCC. Instead, diffusive transport of both aqueous ionic species and radionuclide species (for both ingress and egress) through these tight cracks is currently modeled.

L.4.2 Impact of Oxide Wedging and Stress Redistribution Relative to Crack Arrest

Current Basis for Crack Arrest–Once SCC initiates on a smooth surface or at a preexisting flaw, such as a weld flaw, crack growth will continue as long as the stress intensity factor K_I at the propagating crack tip exceeds a critical threshold value defined as K_{ISCC}. Crack growth will arrest if the through-wall stress field is such that the calculated K_I value drops below K_{ISCC}. A conservative threshold stress intensity factor value can be calculated based on the fact that SCC growth is arrested because of crack blunting at the point where the crack growth rate falls to the material's general corrosion rate. The resulting relationship (BSC 2003b, Equation 20), is described as

$$K_{ISCC} = (V_{gc} / \overline{A})^{1/n} \quad \text{(Eq. L-1)}$$

where V_{gc} is the mean general corrosion rate and $\overline{A}$ and $\overline{n}$ are key parameters directly related to the respective A and n parameters in the slip dissolution–film rupture crack growth rate model (BSC 2003b, Section 6.3), with A, in turn, being a function of n. Based on this relationship, the range of threshold values used varies with the uncertainty distribution assumed for n (BSC 2003b, Table 6-6). The K_{ISCC} values range from about 3 to 29 $\text{MPa} \cdot \text{m}^{1/2}$ with a mean value of 11.4 $\text{MPa} \cdot \text{m}^{1/2}$.

Potential Oxide Wedging Effects–Because of the extremely low measured general corrosion rates for both Alloy 22 and Titanium Grade 7, the oxide thickness resulting from conversion of corrosion-related metal loss to a passive oxide layer results in a thin oxide film present on the crack faces of any propagating stress corrosion crack. As described in Section L.4.1, for Titanium Grade 7 at the maximum observed general corrosion rate of about 0.077 µm/yr it takes about 1,340 years to fill a 157-µm crack opening. For comparison, the minimum measured sustained load crack growth rate for this material is about 1.3×10^{-8} mm/s (equivalent to 410 µm/yr) and is almost 4 orders of magnitude faster than the general corrosion rate (BSC 2003b, Section 6.3.7). Thus, any oxide-related buildup in stress intensity at a crack tip that resulted in crack extension would be quickly relieved by a small increment of crack propagation, and it would take a very significant time period for new oxide buildup to refill the extended crack tip. Measured crack growth rates (BSC 2003b, Table 4.1-1) are lower for Alloy 22 (greater than about 2.5 to 5.0×10^{-10} at 30 $\text{MPa} \cdot \text{m}^{1/2}$ to 45 $\text{MPa} \cdot \text{m}^{1/2}$) but, at this range of K_I values, are still fast relative to the general corrosion rate. In considering any oxide-wedging effect on Alloy 22 crack propagation, it is important to note that the material is highly resistant to SCC initiation and subsequent propagation especially under static loading conditions representative of the waste package. To date, SCC initiation in Alloy 22 has been evaluated in a broad range of waste package-relevant and accelerated environments and has only been observed on smooth surfaces (tensile specimens) under continuous straining conditions (slow strain rate tests at a strain rate of 1.66×10^{-6} per second). For these slow strain rate tests, SCC initiation only occurred at very high plastic strain levels in one test environment (simulated concentrated water), and it required accelerated high applied electrochemical potential conditions (i.e., about 300 to 400 mV vs. Ag/AgCl as compared to a long-term open circuit potential of less than about 0 mV vs. Ag/AgCl) (BSC 2003d, Figure 6-36). Even in the case of a preexisting flaw, such as a weld flaw, it is observed experimentally (BSC 2003b, Section 6.3.4) that SCC can only be initiated at the flaw tip under cyclic, fatigue-type loading (observed in fatigue precracked compact tension specimens). However, once environmentally accelerated crack growth occurs under these cyclic loading conditions, in some cases, it can continue to propagate under sustained (noncyclic) load but only at extremely low growth rates in the range of about 2.5×10^{-10} to 5.0×10^{-10} mm/s (BSC 2003b, Table 4.1-1), even at applied stress intensity factors as high as $45\ \mathrm{MPa} \cdot \mathrm{m}^{1/2}$. Furthermore, where growth is initiated under cyclic conditions and then transitioned to constant load (or the corresponding constant stress intensity factor, K_I), the growth rate tends to reduce with continuing test time and approaches zero rate (or at most the limits of growth detection by very sensitive reversing direct current crack-monitoring techniques) (Andresen et al. 2003, Figure 12). This high degree of sustained load propagation resistance further supports the unlikelihood for oxide-wedging to significantly increase the potential for SCC propagation. Otherwise, any slow-rising load and resultant increasing K_I that would result from oxide-wedging during these compact tension specimen SCC tests would be expected to counter the observed tendency for the SCC growth rate to decrease toward zero under sustained load with exposure time.

However, even if oxide-wedging were to propagate SCC through-wall, as described earlier, the very small crack opening limits water ingress by either "bridging" or film flow and the effect of oxide-plugging further precludes significant water ingress into the waste package. Furthermore, the large range of crack growth rate uncertainty associated with the range of SCC model exponent *n* values and associated range of K_{ISCC} described earlier (BSC 2003b, Table 6-6) should readily bound any minor effect that oxide-wedging might have on increasing crack tip K_I values and thus SCC growth rates in Alloy 22.

L.5 REFERENCES

L.5.1 Documents Cited

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L.5.2 Data, Listed by Tracking Number

LL021105312251.023. Stress Corrosion Crack Growth and Initiation Measurements for C-22 and Ti-7, General Electric Global Research Center (GEGRC) 121202. Submittal date: 01/08/2003.

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