

## APPENDIX P

### **WASTE PACKAGE: CORROSION OF TITANIUM GRADE 7 (RESPONSE TO CLST 6.01)**

### **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 P

### **WASTE PACKAGE—CORROSION OF TITANIUM GRADE 7 (RESPONSE TO CLST 6.01)**

This appendix provides a response to Key Technical Issue (KTI) agreement Container Life and Source Term (CLST) 6.01. This KTI agreement relates to the corrosion of Titanium Grade 7.

#### **P.1 KEY TECHNICAL ISSUE AGREEMENT**

##### **P.1.1 CLST 6.01**

Agreement CLST 6.01 was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on CLST held September 12 to 13, 2000. Subissues 1 (effects of corrosion processes on the lifetime of the containers), 2 (effects of phase instability and initial defects on the mechanical failure and lifetime of the containers), 3 (the rate at which radionuclides in spent nuclear fuel are released from the engineered barrier subsystem through the oxidation and dissolution of spent nuclear fuel), 4 (the rate at which radionuclides in high-level radioactive waste glass are released from the engineered barrier subsystem), and 6 (effects of alternate engineered barrier subsystem design features on container lifetime and radionuclide release from the engineered barrier subsystem) were discussed at the meeting (Schlueter 2000).

The wording of the agreement is as follows:

##### **CLST 6.01<sup>1</sup>**

Provide the documentation for the path forward items in the “Subissue 6: Alternative EBS design Features – Effect on Container Lifetime” presentation, slides 7 & 8. DOE stated that the documentation of the path forward items will be completed and as results become available, they will be documented in the revision of AMRs (ANL-EBS-MD-000005, Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier and the Stainless Structure Materials, and ANL-EBS-MD-000004, General Corrosion and Localized Corrosion of the Drip Shield), to be completed by LA.

##### **P.1.2 Related Key Technical Issues**

Agreement CLST 6.01 is related to CLST 6.02 and CLST 6.03 (Appendix H) and CLST 1.07 (Appendix A).

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<sup>1</sup>The path forward items referred to on slides 7 and 8 were to (1) perform more sensitive measurements of general corrosion rates by the same approach as taken for Alloy 22; (2) confirm no deleterious effects of fluoride ion and trace heavy metal ions in water on corrosion behavior of titanium with a similar approach to that taken in electrochemically based studies on Alloy 22; (3) establish damaging hydrogen levels in titanium alloys (Grade 2 vs. Grade 7 and 16 vs. Grade 5 and 24) and evaluate hydrogen charged notched tensile specimens and hydrogen pickup of galvanically coupled LTCTF specimens; (4) conduct SCC testing of titanium, similar to the approach taken for Alloy 22; and (5) confirm intergranular or internal oxidation of titanium is not applicable under Yucca Mountain thermal and environmental conditions.

## P.2 RELEVANCE TO REPOSITORY PERFORMANCE

CLST 6.01 addresses the issues related to the corrosion or corrosion-induced failure in the drip shield. Titanium and its alloys typically are extremely corrosion resistant in most natural water environments, but they are susceptible to corrosion in fluoride-containing waters and absorption of hydrogen through galvanic coupling. Therefore, fluoride effects and hydrogen induced cracking need to be evaluated to determine the impact on the drip shield function of diverting seepage water away from the waste package.

## P.3 RESPONSE

This document presents technical information and clarification for KTI agreement CLST 6.01. Agreement CLST 6.01 relates to the corrosion of drip shield materials. This document includes test results from recent experiments that relate to the effects of fluoride on the corrosion behavior of Titanium Grade 7. Other items within CLST 6.01, including issues on stress corrosion cracking, internal oxidation, hydrogen absorption, and hydrogen induced cracking, are also addressed. The main points of this technical information are summarized as follows:

- More sensitive measurements of general corrosion rates with the same approach as taken for Alloy 22 are addressed in the response to CLST 1.07 AIN-1 (Appendix A). The electrochemical experimental results for corrosion rates of Titanium Grade 7 are also included in Appendix A.
- Under repository aqueous fluoride concentrations with associated pH values, significantly enhanced corrosion of Titanium Grade 7 is not predicted. At low pH levels, calcium fluoride solubility controls the fluoride level to values below that expected in the repository and that needed to enhance Titanium Grade 7 corrosion. (At pH 4, fluoride levels in excess of 0.001 mol/L (with 4 mol/L NaCl) are necessary to enhance corrosion. Predicted repository fluoride levels at this pH level are  $3 \times 10^{-4}$  to  $10^{-5}$  mol/kg.<sup>2</sup>) At moderate pHs (6 to 8), fluoride levels are predicted to be higher. However, they remain lower than that necessary to enhance corrosion of Titanium Grade 7. At pH 8, fluoride levels in excess of 0.1 mol/kg (with 4 mol/L NaCl) are necessary to cause enhanced corrosion. Predicted repository fluoride levels at this pH level are equal to or less than  $3 \times 10^{-3}$  mol/kg.
- Fluoride ions can diminish the passivity of Titanium Grade 7 in both acidic and neutral conditions. However, no indication of fluoride increasing the localized corrosion of Titanium Grade 7 has been observed under these conditions.
- Tests were also conducted with additions of bromide ions. No significant bromide effects on corrosion of Titanium Grade 7 have been observed.

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<sup>2</sup> At these dilute concentrations, mol/L and mol/kg are approximately the same, and the units are given as they were measured.

- It is unlikely that the drip shield will fail due to hydrogen-induced cracking. Hydrogen absorption through general corrosion or galvanic coupling is not predicted to exceed the critical hydrogen limit (BSC 2003a) (see Appendix H).
- Based on the low corrosion rates measured and the estimated hydrogen pickup during the repository period (see Appendix H), hydrogen charging tests on notched titanium alloys are not believed to be needed.
- Although Titanium Grade 7 drip shields will be emplaced in the fully stress-relieved condition, subsequent rockfall-induced residual stress can potentially lead to stress corrosion cracking (SCC). Consequences of SCC due to rockfall are addressed in *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material* (BSC 2004a) and in Appendix C of this technical basis document. Analyses show that the function of the drip shields is not affected by SCC.
- It is unlikely that Titanium Grade 7 will suffer intergranular and internal oxidation attacks. The intermetallic particles are inert to corrosion, and the surface oxide film provides sufficient protection against the corrosive agents penetrating into the  $\alpha$ -phase matrix.

The project has completed an extensive review of published literature on the corrosion of Titanium Grade 7 and other titanium alloys (Hua et al. 2004) and no data have been found regarding the effects of trace heavy metal ions. This is not unexpected in view of the excellent corrosion resistance of titanium observed in a variety of environments. The general and localized corrosion resistance of titanium alloys containing palladium in a variety of environments is very high and has been well documented in literature and in project documents (Hua et al. 2004). Based on these data, the trace heavy metal ions are not expected to have any measurable effects on the corrosion of Titanium Grade 7, and no tests in waters containing trace heavy metal ions are planned. Instead, the focus of corrosion testing of titanium has been directed toward addressing the effects of the fluoride ion that is known to be deleterious to titanium alloys. Results of these tests are provided in Section P.4.

The information in this report is responsive to agreement CLST 6.01 made between the DOE and NRC. The report contains the information that DOE considers necessary for NRC review for closure of this agreement.

## P.4 BASIS FOR THE RESPONSE

### P.4.1 Effects of Fluoride and Bromide on the Corrosion of Titanium Grade 7

Titanium and its alloys demonstrate an excellent corrosion resistance due to the formation of protective passive film on their surface in both oxidizing and slightly reducing environments. Maintaining the passivity or the stability of passive film is key to preserving the corrosion resistance of titanium and its alloys. The susceptibility of titanium to corrosion in environments containing  $F^-$  is generally attributed to the formation of complexes, such as  $TiF_6^{2-}$  and  $TiF_6^{3-}$ , which are stable and soluble in electrolyte solutions.

Review of the titanium corrosion literature (Hua et al. 2004) indicates that the presence of dissolved fluoride may, under certain conditions, increase the general corrosion rate of titanium alloys including Titanium Grade 7. However, in reviewing the potential effects of fluoride on enhanced general corrosion, it is necessary to separate the studies into those using relatively freshly polished specimens and those using specimens with oxide films formed through long-term exposures or through higher temperature exposures prior to corrosion testing.

For instance, on freshly polished specimens the presence of fluoride has been found to decrease the  $E_{corr}$ , resulting in a pseudo-active/passive transition with a subsequent potential independent current region. In this region, the measured corrosion current densities were much higher than those typically observed under passive dissolution conditions.

The importance of the condition of the passive film in resisting corrosion in fluoride containing neutral solutions is well demonstrated. In corrosion tests conducted in the Long Term Corrosion Test Facility at the LLNL, excellent corrosion behavior has been observed on both uncreviced and creviced Titanium Grade 16 and Titanium Grade 7 specimens. All of these specimens have been exposed to ambient air for several months prior to placement in the test tanks. Corrosion measurements showed that fluoride concentrations of up to 1,400 ppm had no deleterious effects on general or localized corrosion (BSC 2003b). The environment containing fluoride was a multi-ionic concentrated brine with slightly alkaline pH.

In the repository, the Titanium Grade 7 drip shield will be covered with an oxide film grown relatively slowly at temperatures of about 150°C over a period of several hundred years. Such a film is expected to have a low defect density and is therefore highly resistant to breakdown (Brossia et al. 2001).

The influence of fluoride on corrosion of titanium and its alloys is strongly pH dependent. A linear relationship between pH and  $F^-$  concentration for the boundary between passive and active corrosion conditions has been developed (Nakagawa et al. 2001):

$$pH = 1.49 \log[F^-] (\text{in ppm}) + 0.422 \quad (\text{Eq. P-1})$$

According to this relationship, an active corrosion condition will not be achieved in groundwater with a neutral pH, unless  $F^-$  concentration reaches approximately 20,000 ppm. The predicted fluoride concentration in waters from dust deliquescence and in seepage waters is dependent on the brine type predicted to form (BSC 2004b, Figures 6.13-15 and 6.13-27). In a calcium chloride type brine, fluoride concentrations are predicted to be nominally  $3 \times 10^{-4}$  to  $10^{-5}$  mol/kg with pH range of 3.5 to 6.5. The fluoride concentration is low due to its solubility control by insoluble  $\text{CaF}_2$ . In a sulfate type brine, fluoride concentrations are predicted to be below  $6 \times 10^{-3}$  mol/kg with pH range 6.5 to 8. In a carbonate type brine, fluoride concentrations are predicted to be between  $10^{-2}$  and 1 mol/kg with pH range of 8.5 to 10. The fluoride concentrations are predicted to be highest in the carbonate type brine, which requires the highest fluoride concentrations in order to induce active corrosion. For the predicted repository pH and fluoride levels, the pH levels are well above those that would induce active corrosion according to Equation P-1.

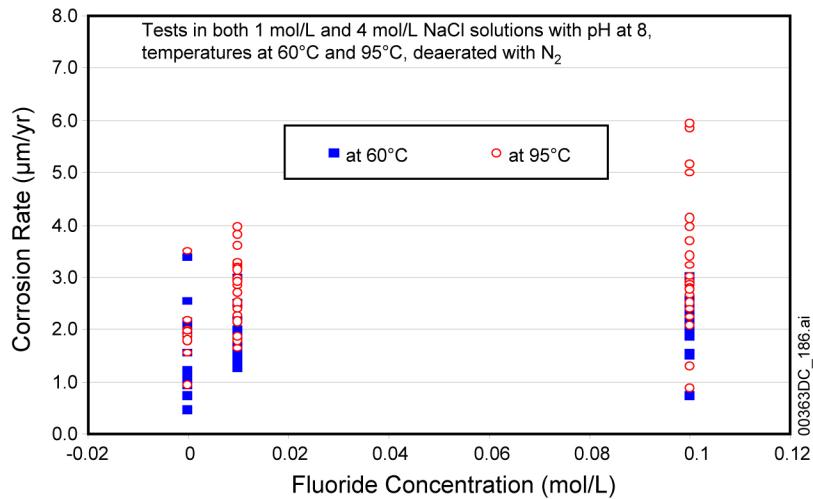
The general corrosion rate of Titanium Grade 7 was measured using linear polarization resistance measurements after Titanium Grade 7 specimens were exposed for at least 1 hour in NaCl-based solutions with various levels of NaF or NaBr content. The corrosion rate, in micrometers per year, was calculated based on the polarization resistance ( $R_p$ ) measurement results:

$$\text{Corrosion Rate, in } \mu\text{m / yr} = K_1 \cdot EW \cdot B / (R_p \cdot \rho) \quad (\text{Eq. P-2})$$

where constant  $K_1 = 3.27 \mu\text{m g}/\mu\text{A cm yr}$ ,  $EW$  is the equivalent weight of Titanium Grade 7 at 23.94,  $\rho$  is the density of Titanium Grade 7 at  $4.51 \text{ g/cm}^3$ , and  $B$  is the Stern-Gary constant. A unit of  $\text{M}\Omega\cdot\text{cm}^2$  is used for  $R_p$ . The value of constant  $B$  is calculated with the assumption of both anodic ( $\beta_a$ ) and cathodic ( $\beta_c$ ) Tafel constants at 0.12 V/decade. Therefore, in this document:

$$B = \frac{\beta_a \cdot \beta_c}{2.303 \cdot (\beta_a + \beta_c)} = \frac{0.12 \times 0.12}{2.303 \times (0.12 + 0.12)} = 0.026 \text{ (V).} \quad (\text{Eq. P-3})$$

Figure P-1 shows the corrosion rate of Titanium Grade 7 in the test solutions with a pH at 8. No significant difference in the corrosion rate was observed with or without fluoride in 1 mol/L and 4 mol/L NaCl solutions although, at 95°C, a small increase in the corrosion rate can be seen in the solution with increasing fluoride added. Figure P-1 also shows that at 95°C the corrosion rate was somewhat higher than at 60°C. Overall, no significant effects from fluoride, temperature, and chloride concentration were observed in the corrosion rate of Titanium Grade 7 at pH 8.



Source: DTN: LL040501612251.098.

Figure P-1. Short-Term Corrosion Rate of Titanium Grade 7 in NaCl Solutions with and without Fluoride Based on Linear Polarization Tests

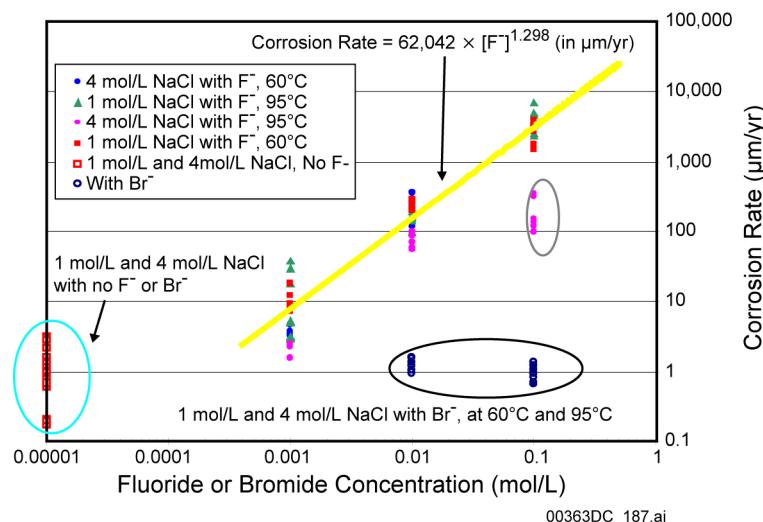
The corrosion rate of Titanium Grade 7 was increased noticeably by the presence of fluoride in acidic solutions. Figure P-2 shows that when a  $10^{-3}$  mol/L fluoride was added in pH 4 NaCl solutions, the general corrosion rate of Titanium Grade 7 was increased from 1  $\mu\text{m/yr}$  to

10  $\mu\text{m}/\text{yr}$ . An increase in the fluoride concentration increased the corrosion rate of Titanium Grade 7 significantly. However, as noted above, these fluoride levels at this pH level are not predicted under repository conditions.

Figure P-2 also shows that the presence of bromide does not affect the corrosion rate of Titanium Grade 7 in acidic NaCl solutions. The measured corrosion rate in solutions with 0.01 mol/L and 0.1 mol/L of bromide corresponds to the corrosion rate measured in NaCl-only solutions.

It should be noted that the corrosion rates derived from short-term electrochemical tests are generally not indicative of long term general corrosion rates. Under long-term exposure conditions, corrosion of Titanium Grade 7 leads to palladium enrichment on the surface, which, in turn, will lead to reduction in the general corrosion rate. For longer-term exposures in high fluorides with higher pH multi-ionic solutions, which are possible in the repository, no effects of fluorides (up to about 1,400 ppm) on the general or localized corrosion of titanium have been observed. The maximum general corrosion rate observed after a 5-year exposure in fluoride containing environment was less than 0.1  $\mu\text{m}/\text{yr}$  (BSC 2003b).

Caution should be used in applying these data to repository performance of the drip shield. The environments used in the tests are not expected in the repository, especially the ones containing high fluoride in low pH solutions where the effects of fluoride are more pronounced.



Source: DTN: LL040501612251.098.

Figure P-2. Corrosion Rate of Titanium Grade 7 in Acidic (pH 4) NaCl Solutions as a Function of Fluoride and Bromide Concentration

#### P.4.2 Effects of Fluoride and Bromide on the Polarization Behavior of Titanium Grade 7

In each Titanium Grade 7 test, an anodic polarization was performed after linear polarization resistance measurements were obtained. While fluoride did not significantly impact the general corrosion rate of Titanium Grade 7 in pH 8 solutions, fluoride was able to alter the anodic polarization behavior of Titanium Grade 7.

Although anodic polarization curves were different with the varying fluoride concentrations, the short-term corrosion rates estimated from the polarization curves were consistent with the result from polarization resistance measurements (shown in Figure P-1).

Although significant fluoride effects on the passivity of Titanium Grade 7 in NaCl solutions were observed (particularly at acidic conditions), none of the disc samples tested showed any sign of localized attack. This is likely attributed to the presence of 0.15% to 0.25% palladium in Titanium Grade 7 because the enrichment of palladium on Titanium Grade 7 surfaces limits corrosion from reaching a high rate. This is corroborated by the converging of anodic polarization curves to a current density around  $5 \times 10^{-5}$  A/cm<sup>2</sup>. A similar observation was reported by Brossia and Cragnolino (2000; 2001a; 2001b) and Brossia et al. (2001) for the polarization tests of Titanium Grade 7 in 1 mol/L NaCl, 1 mol/L NaF, and 1 mol/L NaF + 1 mol/L NaCl at 95°C. In these reports, the effects of fluoride were found to result in a pseudo active–pseudo passive transition with a subsequent potential independent region of current density considerably higher than those typically encountered during passive dissolution (as high as  $10^{-3}$  to  $10^{-1}$ , as compared to about  $10^{-6}$  A/cm<sup>2</sup>). Posttest examination of the specimens revealed that the corrosion was general in nature.

The importance of the passive film condition in resisting corrosion in fluoride-containing solutions has been reported by Brossia et al. (2001), and Lorenzo de Mele and Cortizo (2000). The latter reported that when the oxide was allowed to grow for four days, a sufficient period for the growth of a coherent oxide with a low defect concentration, the subsequent addition of fluoride in the solution had no observable effect over the subsequent two days of exposure.

#### P.4.3 Stress Corrosion Cracking of Titanium Grade 7

SCC is a fracture phenomenon caused by the combined action of tensile stress, a susceptible alloy, and a corrosive environment. Usually, only specific combinations of metallurgical and environmental conditions cause SCC. This is important because it is often possible to eliminate or reduce SCC sensitivity by modifying either the metallurgical characteristics of the metal or the makeup of the environment. Titanium Grade 7, along with Grades 1, 2, 11, and 12, are reported to be immune to SCC except in a few specific environments. These specific environments include anhydrous, methanol/halide solutions, nitrogen tetroxide (N<sub>2</sub>O<sub>4</sub>), red fuming HNO<sub>3</sub>, and liquid or solid cadmium (Schutz and Thomas 1987). Although these specific environments are not possible during the regulatory period, project-generated SCC test results indicate initiation and growth can occur in concentrated J-13 type groundwater (BSC 2004a, Figure 2A).

The sources of stress that may lead to SCC in the Titanium Grade 7 drip shield include: (1) weld-induced residual stress; (2) plastic-induced residual stress caused by seismic events; and (3) residual stress produced by rockfalls. Among those three sources of residual stress, the weld-induced residual stress will be mitigated during the postweld annealing. Residual stress from rock falls can cause SCC crack initiation in the drip shield if the stress exceeds the threshold stress for the drip shield materials. Drip shield structural response to rock falls induced by seismic events is addressed in *Drip Shield Structural Response to Rock Fall* (BSC 2004c), where the damaged area of the drip shield is calculated for each of the given rock masses. The damaged area is defined as a region of the drip shield where the calculated stress exceeds the threshold stress (BSC 2004a).

SCC initiation and growth was studied on Alloy 22 and Titanium Grade 7 under more accelerated constant load and constant stress intensity tests in pH 10.3 concentrated J-13 brines at 105°C, for up to 9,600 hours of exposure. Titanium Grade 7 did exhibit SCC at the applied stress levels of about 1.1 times the yield strength (DTN: LL021105312251.023).

SCC testing of titanium is also being performed at the Long Term Corrosion Test Facility. In the Long Term Corrosion Test Facility, U-bend specimens are exposed in several simulated concentrated groundwaters covering a range of pH values to evaluate the susceptibility of titanium alloys to both initiation and propagation of SCC. These U-bend specimens are smooth and subjected to a static residual stress type load; thus, they represent a more realistic service type experience. No SCC has been observed in Titanium Grade 7 after 2.5 years or in Titanium Grade 16 after 5 years exposure (Fix et al. 2004).

#### **P.4.4 Internal Oxidation and Intergranular Corrosion of Titanium Grade 7**

Internal oxidation is a process in which oxygen dissolves and diffuses into the alloy phase during oxidation; the less noble alloy components may react to form oxide particles within the metal. If the oxide particles are allocated primarily along the grain boundaries, the internal oxidation may lead to an intergranular attack.

For an internal oxidation event to take place in an A–B alloy (or the oxide formation of the less noble constituent within the alloy), the following prerequisites must be fulfilled (Leyens 2003):

- Oxygen has a certain solubility in metal A and alloy A–B
- B has a greater oxygen affinity than metal A
- Oxygen must have a higher diffusion rate into the alloy than the diffusion rate of constituent B towards the surface
- B must not exceed a maximum concentration leading to external oxide scale formation.

Titanium Grade 7 does not satisfy the above criteria for internal oxidation. Titanium Grade 7 is a palladium-containing  $\alpha$ -phase titanium alloy, and the formation of  $\beta$ -phase is negligible. The titanium–palladium intermetallic particles, when present, appear inert to corrosion (CRWMS M&O 2000). Most importantly, titanium has an extremely high affinity for oxygen. Thus, external oxidation will take place preferentially. With the presence of surface oxide film as a chemical and transport barrier, the likelihood of internal oxidation is greatly limited. Since the intermetallic particles in an  $\alpha$ -phase Titanium Grade 7 alloy are inert to corrosion, no weakening in the grain boundaries is predicted. Therefore, intergranular attack on Titanium Grade 7 under repository conditions is not expected.

#### **P.4.5 Hydrogen Induced Cracking of Titanium Grade 7 Drip Shield**

Titanium and its alloys are likely to take up hydrogen under a cathodic polarization condition. In a drip shield design without backfill, hydrogen generation may be caused by the galvanic coupling between the titanium drip shield surface and the ground support (i.e., rock bolts, wire

mesh, and stainless steel liners used in the drift), which may fall onto the drip shield surface. Whether the hydrogen uptake will lead to hydrogen induced cracking failure will depend on: (1) critical hydrogen content required to degrade the fracture toughness of the material; (2) the ease of absorption of this amount of hydrogen, and (3) whether the environment can polarize the metal to a potential sufficiently negative for hydrogen absorption.

The model described in *Hydrogen Induced Cracking of Drip Shield* (BSC 2003a) was developed to evaluate the hydrogen induced cracking on the drip shield. The basic premise of the model is that failure will occur once the hydrogen content exceeds a certain limit or critical value,  $H_C$ . A quantitative evaluation based on the hydrogen induced cracking model indicates that the hydrogen content in the drip shield material (Titanium Grade 7) will not exceed the critical value ( $H_c$ ) during the 10,000 years of the regulatory period. Therefore, the embrittlement of the drip shield materials is not a concern regardless of the presence of residual stress on the drip shield structures.

The quantitative evaluation includes analytical estimates indicating that there exists a large margin of safety for the drip shield against the effects of hydrogen induced cracking. As indicated in Section H.4 in Appendix H, from a conservative estimate, the hydrogen concentration in the drip shield at 10,000 years after waste package emplacement is 124  $\mu\text{g/g}$ . In comparison, the  $H_C$  value for Titanium Grade 7 is estimated to be at least 1,000  $\mu\text{g/g}$ , considering the metallurgical similarity in Titanium Grade 7 and Titanium Grade 16. This estimate is based on data reported by Ikeda and Quinn (1998), which concluded that the  $H_C$  value for Titanium Grade 16 is between 1,000 and 2,000  $\mu\text{g/g}$ . This estimate is necessary because  $H_C$  data are not available for Titanium Grade 7.

Model predictions are based on a very conservative upper bound value of 0.015 for  $f_h$ , the absorption efficiency. However, based on the available literature for the absorption of hydrogen by titanium, the value of  $f_h$  would be expected to be less than this (Tomari et al. 1999). This value was measured under very aggressive, electrochemically polarized conditions considered unachievable under repository conditions. Consequently,  $f_h$  may be assumed to have a value between 0.005 and 0.015 (BSC 2003a). Since a number of documents exist to show the hydrogen absorption rate will have decreased substantially long before the critical hydrogen concentration could be exceeded, it is reasonable to conclude that failure of the titanium drip shield by hydrogen induced cracking will not occur.

The proposed model indicates that the hydrogen concentration in the drip shield due to a galvanic couple will most likely not exceed the critical value, considering the high critical hydrogen concentration threshold and also the large volume of available titanium in the drip shield to allow the absorbed hydrogen to diffuse. Therefore, hydrogen embrittlement of the titanium drip shield is highly unlikely.

## P.5 REFERENCES

### P.5.1 Documents Cited

- Brossia, C.S.; Browning, L.; Dunn, D.S.; Moghissi, O.C.; Pensado, O.; and Yang, L. 2001. *Effect of Environment on the Corrosion of Waste Package and Drip Shield Materials*. CNWRA 2001-003. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. TIC: 252324.
- Brossia, C.S. and Cragnolino, G.A. 2000. "Effects of Environmental, Electrochemical, and Metallurgical Variables on the Passive and Localized Dissolution of Ti Grade 7." *Corrosion 2000*. Paper No. 00211. Houston, Texas: NACE. TIC: 254967.
- Brossia, C.S. and Cragnolino, G.A. 2001a. "Effects of Environmental and Metallurgical Conditions on the Passive and Localized Dissolution of Ti-0.15%Pd." *Corrosion*, 57, (9), 768-776. Houston, Texas: National Association of Corrosion Engineers. TIC: 254028.
- Brossia, C.S. and Cragnolino, G.A. 2001b. "Effect of Palladium on the Localized and Passive Dissolution of Titanium." *Proceedings of Corrosion/2001 Research Topical Symposium, Localized Corrosion*. Paper No. 01127. Houston, Texas: NACE International. TIC: 253171.
- BSC (Bechtel SAIC Company) 2003a. *Hydrogen Induced Cracking of Drip Shield*. ANL-EBS-MD-000006 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030304.0003.
- BSC 2003b. *General Corrosion and Localized Corrosion of the Drip Shield*. ANL-EBS-MD-000004 REV 01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20030626.0001.
- BSC 2004a. *Stress Corrosion Cracking of the Drip Shield, the Waste Package Outer Barrier, and the Stainless Steel Structural Material*. ANL-EBS-MD-000005 REV 01 ICN01. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040318.0010.
- BSC 2004b. *Engineered Barrier System: Physical and Chemical Environment*. ANL-EBS-MD-000033 REV 02, with errata. Las Vegas, Nevada: Bechtel SAIC Company. ACC: DOC.20040212.0004; DOC.20040426.0003.
- BSC 2004c. *Drip Shield Structural Response to Rock Fall*. 000-00C-SSE0-00300-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20040405.0019.
- CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 2000. *Review of the Expected Behavior of Alpha Titanium Alloys Under Yucca Mountain Conditions*. TDR-EBS-MD-000015 REV 00D. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20010314.0197.
- Fix, D.; Estill, J.; Wong, L.; and Rebak, R. 2004. "Susceptibility of Welded and Non-welded Titanium Alloys to Environmentally Assisted Cracking in Simulated Concentrated Ground Waters." *Corrosion 2004*. NACE International. Paper No. 04551, Houston, Texas: NACE International. TIC: 255943.

Hua, F.; Mon, K.; Pasupathi, V.; Gordon, G.; and Shoesmith, D. 2004. "Corrosion of Ti Grade 7 and Other Ti Alloys in Nuclear Waste Repository Environments—A Review." *Corrosion/2004, 59th Annual Conference & Exposition, March 28-April 1, 2004, New Orleans.* Paper No. 04689. Houston, Texas: NACE International. TIC: 255943.

Ikeda, B.M. and Quinn, M.J. 1998. *Hydrogen Assisted Cracking of Grade-16 Titanium: A Preliminary Examination of Behaviour at Room Temperature.* 06819-REP-01200-0039 R00. Toronto, Ontario, Canada: Ontario Hydro. TIC: 247312.

Leyens, C. 2003. "Oxidation and Protection of Titanium Alloys and Titanium Aluminides." Chapter 6 of *Titanium and Titanium Alloys—Fundamentals and Applications*. Edited by Leyens, C and Peters, M. Weinheim, Germany: Wiley-VCH. TIC: 256057.

Lorenzo de Mele, M.F. and Cortizo, M.C. 2000. "Electrochemical Behaviour of Titanium in Fluoride-Containing Saliva." *Journal of Applied Electrochemistry, 30,* (1), 95–100. Dordrecht, The Netherlands: Kluwer Academic Publishers. TIC: 253126.

Nakagawa, M.; Matsuya, S.; and Udo, K. 2001. "Corrosion Behavior of Pure Titanium and Titanium Alloys in Fluoride-Containing Solutions." *Dental Materials Journal, 20,* (4), 305–314. Tokyo, Japan: Japanese Society for Dental Materials and Devices. TIC: 253166.

Schlueter, J. 2000. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Container Life and Source Term (September 12–13, 2000)." Letter from J. Schlueter (NRC) to S. Brocoul (DOE/YMSCO), October 4, 2000, with enclosure. ACC: MOL.20010731.0161.

Schutz, R.W. and Thomas, D.E. 1987. "Corrosion of Titanium and Titanium Alloys." *Corrosion, 13*, 669–706 of *Metals Handbook.* 9th Edition. Metals Park, Ohio: ASM International. TIC: 209807.

Tomari, H.; Masugata, T.; Shimogori, K.; Nishimura, T.; Wada, R.; Honda, A.; and Taniguchi, N. 1999. "Hydrogen Absorption of Titanium for Nuclear Waste Container in Reducing Condition." *Zairyo-to-Kankyo, 48*, 807–814. Tokyo, Japan: Japan Society of Corrosion Engineering. TIC: 252965.

### P.5.2 Data, Listed by Data 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.

LL040501612251.098. Corrosion Behavior of Ti Grade 7. Submittal date: 05/19/04

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