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EXPERT PANEL REPORT FOR HANFORD SITE
SINGLE-SHELL TANK INTEGRITY PROJECT

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Abstract: Two expert panel workshops were held on leak and structural integrity of single-shell tanks at the Hanford Site. The goal was to provide recommendations to Washington River Protection Solutions, LLC for implementation of an enhanced single-shell tank integrity project. The panel focused on four key elements for the tank integrity project: confirmation of tank structural integrity, assessment of the likelihood of future tank liner degradation, leak identification and prevention, and, mitigation of contaminant migration.

This report describes the issues discussed during and following the workshops, the final recommendations of the workshop panel, and the rationale for those recommendations.

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Expert Panel Report for Hanford Site
Single-Shell Tank Integrity Project

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ABSTRACT

Two expert panel workshops were held on leak and structural integrity of single-shell tanks at the Hanford Site. The goal was to provide recommendations to Washington River Protection Solutions, LLC for implementation of an enhanced single-shell tank integrity project. The panel focused on four key elements for the tank integrity project:

- Confirmation of tank structural integrity.
- Assessment of the likelihood of future tank liner degradation.
- Leak identification and prevention.
- Mitigation of contaminant migration.

The workshops were held in Richland, Washington on January 26-29, 2009 and April 29-May 1, 2009. In the first workshop, the panel received presentations outlining the history and current status of the Hanford Site’s Single-Shell Tank Farms and related projects. The panel developed issues for follow-up at the conclusion of the workshop. The second workshop focused on additional clarification of issues and development of panel recommendations.

Workshop participants included Department of Energy, academic, and industry experts in the fields of stress corrosion cracking, soils and vadose zone, electrochemistry, materials, and non-destructive evaluation.

This report describes the issues discussed during and following the workshops, the final recommendations of the workshop panel, and the rationale for those recommendations.
EXECUTIVE SUMMARY

The Single-Shell Tank Integrity Panel (the Panel) was tasked with providing Washington River Protection Solutions, LLC (WRPS) with recommendations to support the development of an enhanced Single-Shell Tank Integrity project (SSTIP).

Wastes in both the Hanford Site’s single-shell (SST) and double-shell tank (DST) systems are slated for treatment in a Waste Treatment and Immobilization Plant (WTP) that is currently under construction. Delays to the initiation of operation of the WTP will necessitate extended storage of tank wastes. These delays provide the impetus for a more robust SSTIP.

The Panel developed recommendations based on the proceedings of two workshops and the research and deliberation of the Panel and its members.

In the first workshop, the Panel considered a broad range of SST issues, including: current status, chemistry, retrieval technologies, structural integrity requirements and status, corrosion, stress corrosion cracking (SCC) and design impacts from the Savannah River Site, vadose zone characterization, leak detection, monitoring and mitigation; and non-destructive evaluation.

During this workshop, the Panel developed individual work assignments to research specific areas of interest (Martin and Terry, 2009). Based on this research and subsequent requests for additional information, the Panel held a second workshop to develop recommendations.

In developing its recommendations, the Panel agreed on three overarching values that should guide the SSTIP. First, SSTIP activities should not adversely impact final disposition of tank waste. Such disposition of SST wastes requires retrieval from the tanks and treatment in the WTP. These two activities require certain physical and chemical waste characteristics that must be integrated into decision-making for the SSTIP.

Second, SSTIP activities should be strategically focused on programmatic needs. This acknowledges the pitfalls of developing SSTIP activities that may be of interest scientifically, but offer little prospect for directly supporting the programmatic needs of safe storage, retrieval, treatment and disposal of SST wastes.

Third, SSTIP activities should protect public and worker health and safety.

The Panel has prioritized its recommendations both overall (discussed in Section 2) and within four key elements: (1) confirmation of tank structural integrity (denoted by ‘SI’), (2) assessment of the likelihood of future tank liner degradation (denoted by ‘LD’), (3) leak identification and prevention (denoted by ‘LIP’) and (4) mitigation of contaminant migration (denoted by ‘MCM’).

The recommendations are as follows, presented in their respective prioritization within each of the key elements.

Confirmation of tank structural integrity

Recommendation SI-1, Perform Modern Structural Analyses: The Panel recommends performing modern structural analyses (including seismic) on representative samples of SSTs. Such analyses are necessary to understand the structural integrity of the SSTs during a seismic event. The analysis will be useful in answering the following questions: How much rebar must remain to achieve adequate structural integrity under a major seismic event? What is the level of
confidence that at least this amount of rebar cross-sectional area exists and will remain present for the operating life of the tanks (e.g., 20 to 50 additional years)? What is the minimum required concrete strength?

**Recommendation SI-2, Perform Dome Deflection Surveys:** The Panel recommends continuation of the current dome deflection survey program. The program should be augmented to obtain dome deflection data near the haunch of the domes. The dome surveys are important as any future potential for dome collapse would be preceded by excessive downward dome deflection. The haunch data is important to determine whether dome deflections are due to downward displacement of the dome or of the footing under the sidewall.

**Recommendation SI-3, Obtain and Test Sidewall Core:** The Panel recommends obtaining and testing a vertical core from the entire depth of the sidewalls for two tanks that have leaked and had been operated at high temperatures for extended periods. Such cores will provide important data about the structural condition of concrete and rebar in the sidewalls.

**Recommendation SI-4, Perform Non-Destructive Evaluation of Concrete:** The Panel emphasizes the importance of the hierarchical aspect of this recommendation. Initially, the Panel recommends the application of two technologies: (1) visual inspection of domes to identify cracks in excess of 1/16 inch wide, rust stains on the concrete, or spalling of concrete, and (2) utilization of a ‘thumper’ truck to determine the modulus of the dome concrete. The modulus correlates with concrete strength and controls the degree of deformation that will occur under loading.

Further development and deployment of non-destructive evaluation technologies such as guided wave propagation should occur in the event initial SSTIP activities (e.g., visual inspection, modeling, vertical core results) indicate potential concrete degradation.

**Recommendation SI-5, Test Dome Concrete and Rebar ‘Plugs’:** Current plans call for the cutting of holes in the SST domes to facilitate the use of retrieval equipment. The Panel recommends the following tests on concrete and rebar ‘plugs’ removed from domes during cutting: (1) concrete compression and bend tests; and (2) rebar diameter measurement and tensile tests. These tests will provide an opportunity to obtain data on the condition of the dome concrete and rebar.

**Recommendation SI-6, Develop Engineering Mechanics Document:** The Panel recommends the development and up-to-date maintenance of a living document containing the best current understanding of engineering mechanics properties of each tank. Such a document is an important reference in understanding both the current and future structural integrity of the SSTs and will be useful in defining input information for future tank evaluations.

**Recommendation SI-7, Test Effects of Waste Exposure on Structural Integrity:** The Panel recommends measuring the physical and mechanical properties of concrete exposed for more than 28 days to simulated waste. Based on these measurements, the effects of waste/concrete/rebar reactions and temperature on the structural integrity of the tank walls should be estimated. These tests will assist in determining whether liquid waste that has leaked through the steel liner and the concrete walls could have damaged the concrete and rebar.

**Recommendation SI-8, Study the Deployment of Corrosion Potential Mapping:** The Panel recommends studying the feasibility of performing corrosion potential measurements to assess the condition of rebar in the SSTs. If potential mapping can be successfully deployed, it has the potential to detect active corrosion.
Assessment of the likelihood of future tank liner degradation

**Recommendation LD-1, Expand Leak Assessment Reports:** The Panel recommends continuing the preparation of Leak Assessment Reports for each tank farm. The Panel found the Leak Assessment Report for 241-A and 241-AX tank farms to be very helpful in understanding the status of data and information about both known and assumed leaker tanks. The discussion for each tank should include an operations summary, an operations history, an analysis of the leak location and cause, a waste loss estimate, the nature and extent of ground contamination, and a conclusion.

**Recommendation LD-2, Avoid inadvertent addition of water and chloride to SSTs:** To avoid creating conditions that could lead to liner corrosion, the Panel recommends operational procedures be implemented to prevent the inadvertent addition of water and chloride ion to the SSTs. The impact of water intrusion and unintended increases in chloride ion concentrations should be evaluated on a tank-by-tank basis.

**Recommendation LD-3, Examine “non-compliant” wastes at 25° C:** The Panel recommends selected “non-compliant” SST waste simulants be examined at 25° C. “Non-compliant” wastes are those that fail to meet specific temperature, nitrite, nitrate, and hydroxide concentration criteria. The examinations will provide information on the propensity for pitting, cracking, and corrosion at the liquid-air interface (LAI) or corrosion of the liner in the vapor space. This testing should be coordinated with the DST testing program.

**Recommendation LD-4, Develop and Deploy Guided Wave Technology:** The Panel recommends the development and deployment of guided wave, ultrasonic technology to assess the presence of macroscopic degradation of the steel liner. A design study should be undertaken to determine the optimum parameters and feasibility of an Electro-Magnetic Acoustic Transducer (EMAT) system for this application. If shown feasible, and other SSTIP activities raise concerns about liner integrity, the EMAT system should be deployed.

**Recommendation LD-5, Determine Ammonia Corrosion Control Concentration:** Ammonia in sufficient concentrations has the potential to inhibit liner corrosion. The Panel recommends laboratory testing to determine the concentration of ammonia required to control corrosion in the liquid phases of the solid and supernatant layers, at the LAI and on the exposed liner in the vapor spaces. This testing should be coordinated with the DST testing program.

**Recommendation LD-6, Assess SST Waste Compositional Variation:** The Panel recommends determining whether compositional variations in the solid layers of the SSTs deviates from general SST and DST programmatic assumptions about composition. If so, testing work may need to be performed to evaluate the propensity for stress corrosion cracking (SCC) and corrosion.

Three factors may have given rise to novel compositions in the SSTs. First, the wastes might have become layered and inhomogeneous as a consequence of waste transfer operations that mixed several waste types. Second, groundwater and rainwater might have infiltrated into waste tanks through cracks in the dome or sidewalls. Third, corrosive chloride ions have been introduced to the SSTs through operational additions of sodium hydroxide.

**Recommendation LD-7, Assess Deployment of Local Non-Destructive Evaluation Techniques:** The Panel recommends assessing the feasibility of deploying candidate local
measurement techniques (such as fluid coupled ultrasound, ultrasonic guided waves implemented using EMATs, and vibrothermography) operated as end effectors on a mechanical apparatus (such as robotic arms) deployed in the SSTs. Deploying such technologies should be based on the outcomes of other NDE recommendations (e.g. discovery of cracks via visual inspection) and a cost benefit analysis that analyzes the difficulties of employing candidate local measurement techniques.

**Recommendation LD-8, Consider Installation of Corrosion Potential Probe:** If recommended laboratory studies indicate SST chemistries aggressively foster corrosion or SCC under tank operating conditions, the Panel recommends installing a probe similar to that employed in the DSTs to measure corrosion potential. This information can be used to further assess the likelihood for corrosion or SCC.

**Recommendation LD-9, Consider Testing Tank Liner Hardness:** The feasibility and cost of removing small samples from the tank liner for hardness testing should be evaluated. If feasible and cost effective, samples should be removed from a tank that experienced high temperatures to determine if hardness increases, which could impact structural integrity, have occurred.

**Recommendation LD-10, Consider Applying Direct Current Potential Drop to SSTs:** The Panel recommends studying the feasibility of applying Direct Current Potential Drop (DCPD) to the SSTs for the purpose of locating tears in the liner. The DCPD technique is based on injecting current into a metallic component and measuring the resulting voltage (potential) at selected points. Such study could include both theoretical modeling as well as simple laboratory experiments. Once feasibility is established, a DCPD system should be developed for implementation.

This recommendation, along with consideration of local NDE techniques (Recommendation LD-8), provide a suite of techniques to assess liner degradation based on the outcome of other tests and observations, as well as the feasibility of deployment.

**Recommendation LD-11, Analyze Stress Relaxation of Tank Liners:** The Panel recommends analysis or experimental study of stress relaxation in tank liner steels to determine whether SCC is a possibility in the future.

**Leak identification and prevention**

**Recommendation LIP-1, Continue Leak Detection Monitoring and Best Management Practices and Install Enhanced SST Monitoring:** The Panel recommends continuing current Leak Detection Monitoring and Best Management Practices to monitor for leaks. Further, the Panel recommends installing enhanced monitoring based on potential leak risks at each tank farm. The 241-T Tank Farm Interim Cover Test has proved an excellent system for tracking infiltration of meteoric water. Increasing the depths and expanding the aerial extent of monitoring similar to this test will provide an excellent system for early detection and tracking of leaks.

**Recommendation LIP-2, Avoid the Addition of Water-Insoluble Absorbents to SSTs:** The Panel considered the addition of absorbents to the SSTs to further immobilize liquids. However, the Panel recommends avoiding the addition of water-insoluble solid absorbents to the SSTs as such additives do not appear effective in immobilizing water and will interfere with the future retrieval of wastes, and may adversely impact WTP operations.
**Recommendation LIP-3, Continue Use of High Resolution Resistivity:** The Panel recommends continuing utilization of High Resolution Resistivity for leak detection outside of tanks. High Resolution Resistivity can detect a 5,000 to 10,000 gallon leak by utilizing existing dry-wells to measure soil resistivity. The technique has been effectively demonstrated during recent waste retrieval activities.

**Recommendation LIP-4, Seek Engineering Methods to Increase Water Removal by Pumping From SSTs:** The Panel recommends seeking engineering solutions for the removal of additional tank liquids by pumping. While the Panel acknowledges further removal of liquids by pumping will be challenging, it is a safe and potentially efficient and cost effective method for the removal of liquids from the tanks.

**Recommendation LIP-5, Evaluate Sludge and Saltcake Liquid Leak Rates:** The Panel recommends evaluating liquid leak rate assessments of sludge and saltcake from the Savannah River Site to determine if the results are applicable to SSTs.

There is currently no evidence that liquid is leaking from the interim stabilized (retrieved) tanks that contain supernatant, sludge or saltcake. Nor is there evidence that new stress corrosion cracks have developed since the tanks were stabilized. Information as to whether liquid would leak out of sludge or saltcake through stress corrosion cracks is important when considering continued use of the SSTs.

**Recommendation LIP-6, Investigate Leak Detection Technologies for Tanks With Less Than 24 Inches of Waste:** The Panel recommends investigating and developing technologies to allow for leak detection in tanks with waste levels of less than 24 inches. Limitations of current leak detection technologies (Liquid Observation Wells and ENRAF™) do not allow for leak detection in these SSTs below 24 inches.

**Recommendation LIP-7, Evaluate Effect of Lowering SST Waste Temperature:** The Panel recommends evaluating the effect of lowering the temperature of representative waste types to determine its practical impact on drainage rates.

**Recommendation LIP-8, Assess the Feasibility of Testing for Ionic Conductivity Between Inside and Outside of SSTs:** The Panel recommends performing experiments to assess the viability of testing ionic conductivity between the inside and outside of SSTs. An ionic path between the inside and outside of SSTs could be indicative of cracks through the liner and concrete. If techniques can reliably measure such ionic conductivity, it would be useful in demonstrating whether breaches exist in SSTs.

**Recommendation LIP-9, Consider Cathodic Protection for Rebar and Exterior of Tank Liner:** The Panel recommends that cathodic protection (CP) not be deployed for use in protecting the interior of SSTs where supernatant, sludge and/or saltcake is present. The Panel further recommends that CP be considered as an option to protect the exterior of the tank liner and rebar, should evidence arise that either has corroded.

CP has the potential to suppress corrosion in the SSTs. CP has not been applied to the DSTs due to concerns that waste chemistry may lead to SCC. These issues, as well as difficulties associated with frequent replacement of electrodes, inserting electrodes into the saltcake and high CP currents have led the Panel to recommend against applying CP to the interior of the SSTs. This recommendation is tempered by the possibility of applying CP to the interior of SSTs with little or no nitrite.
Recommendation LIP-10, Evaluate Coating of Tank Liners and Installation of Polymeric Bladder: The Panel recommends evaluating both the coating of the tank liners with a material resistant to corrosion and cracking; and the deployment of a polymeric bladder to line SSTs. Many different metals, ceramics, intermetallics and polymers have the potential to be thermally sprayed onto the tank liners to reduce leakage concerns during retrieval.

Storing waste in polymeric bladders has been used successfully in the petroleum industry for the elimination of leaks in storage tanks. A bladder made of this material could line a tank if its reliability were shown to be extremely high. The Panel acknowledges that difficulties associated with introducing materials into SSTs may reduce the feasibility of implementing this recommendation.

Recommendations LIP-11, Avoid Heating and Active Ventilation Strategies for Removing Additional Water from SSTs: The Panel recommends against pursuing strategies for removing water from tanks that include active ventilation or heating. Such strategies would be expensive, heating will increase the risk of pitting corrosion and SCC, and heating could increase the risk of unacceptably vigorous exothermic reactions.

Recommendation LIP-12, Avoid Strategies to Immobilize Waste Through the Addition of Gelling Agents: As a general programmatic practice, the Panel recommends against the addition of gelling agents. Existing gelling techniques will be difficult to implement, may complicate WTP operations, and may increase the corrosivity of the waste. However, individual tank-by-tank instances may arise in which gelling a tank may be a wise option (e.g. to stop a significant tank leak or if new gelling techniques were developed).

Mitigation of Contaminant Migration

Recommendation MCM-1, Install Surface Barrier Over SST Farms: The Panel recommends design and implementation of a surface barrier to reduce recharge at the SSTs. Sources of water (leaking pipes, vaults, etc.) that could contribute to subsurface water deep percolation should also be identified and controlled. New control/barrier measures should be prioritized based on the risk associated with past and/or future releases at each tank farm.

Recommendation MCM-2, Evaluate Subsurface Leak Mitigation Technologies: A number of viable candidate subsurface leak mitigation strategies were identified in a 1994 Feasibility Study (FS). The Panel recommends evaluating leak mitigation technologies utilizing this FS as a selection guide.

- Bench scale studies on candidate technologies should be conducted.
- Demonstration in a Hanford Site field setting should be performed where appropriate.
- Currently ongoing tests, such as the injection apatite reactive zone, should be considered for application at the SST farms.
- An updated FS should be performed, using updated risk assessment methodologies and modern performance assessment technologies, with the objective of selecting a SST leak mitigation strategy and potentially a final SST Closure strategy.
- It is recognized that an updated FS and risk-based selection process may also conclude that little additional benefit can be derived from implementing a subsurface barrier in addition to implementing a surface barrier.
The Panel also prioritized its ‘top ten’ primary recommendations that form the foundation of a robust SSTIP. As is outlined in Section 2, these primary recommendations should be pursued at the initiation of the SSTIP. The primary recommendations are as follows.

Recommendation SI-1, Perform Modern Structural Analyses
Recommendation SI-2, Perform Dome Deflection Surveys
Recommendation SI-3, Obtain and Test Sidewall Core
Recommendation SI-4: Perform Non-Destructive Evaluation of Concrete
Recommendation LD-1, Expand Leak Assessment Reports
Recommendation LD-2, Avoid inadvertent addition of water and chloride to SSTs
Recommendation LIP-1, Continue Leak Detection Monitoring and Best Management Practices and Install Enhanced External SST Monitoring
Recommendation LIP-2, Avoid the Addition of Water-Insoluble Absorbents to SSTs
Recommendation LIP-3, Continue Use of High Resolution Resistivity
Recommendation MCM-1, Install Surface Barrier Over SST Farms
KEY WORDS

cathodic protection; concrete degradation; concrete mechanical properties; corrosion; corrosion chemistry; corrosion limits; corrosion potential; expert panel; guided wave; Hanford Site leak immobilization; leak integrity; leak prevention; non-destructive evaluation; seismic loading; single-shell tank; single-shell tank integrity; stress corrosion cracking; structural integrity; subsurface contaminant; surface barrier; tank chemistry; waste simulants
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LIST OF TERMS

Abbreviations and Acronyms

BMP  best management practices
CP   cathodic protection
CPP  cyclic potentiodynamic polarization
DBTT ductile to brittle transition temperature
DC   direct current
DCPD direct current potential drop
DST  double-shell tank
EIS  electrochemical impedance spectroscopy
EMAT electro-magnetic acoustic transducer
EPDM ethylene-propylene-diene monomer
ERT  electrical resistivity tomography
FS   feasibility study
FY   fiscal year
HAZ  heat affected zone
HDS  heat dissipation center
HRR  high resolution resistivity
ICM  interim corrective measure
IR   infrared
ITS  in-tank-solidification
LAI  liquid-air interface
LDM  leak detection monitoring
LOW  liquid observation well
MT   manual tape
NDE  non-destructive evaluation
ORP  Office of River Protection
PET  point electrode technique
PNNL Pacific Northwest National Laboratory
RF   radio frequency
SCE  saturated calomel electrode
SCC  stress-corrosion cracking
SCRT steel casing resistivity technique
SGE  surface geophysical exploration
SRNL Savannah River National Laboratory
SRS  Savannah River Site
SSRT slow strain rate test
SST  single-shell tank
SSTIP Single-Shell Tank Integrity Project
TBP  tri-butyl phosphate
UT   ultrasonic testing
WMA  waste management area
WRPS Washington River Protection Solutions, LLC
WTP  waste treatment and immobilization plant

Units of Measure

C    Celsius
cP   centipoise
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>F</td>
<td>Fahrenheit</td>
</tr>
<tr>
<td>ft</td>
<td>foot</td>
</tr>
<tr>
<td>g</td>
<td>gravity</td>
</tr>
<tr>
<td>gal</td>
<td>gallon</td>
</tr>
<tr>
<td>gpm</td>
<td>gallons per minute</td>
</tr>
<tr>
<td>in.</td>
<td>inch</td>
</tr>
<tr>
<td>Jc</td>
<td>fracture toughness</td>
</tr>
<tr>
<td>kHz</td>
<td>kilohertz</td>
</tr>
<tr>
<td>K</td>
<td>static fracture toughness</td>
</tr>
<tr>
<td>kJ</td>
<td>kilojoule</td>
</tr>
<tr>
<td>Ksi</td>
<td>kips per square inch</td>
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<tr>
<td>L</td>
<td>liter</td>
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<td>M</td>
<td>molar</td>
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<td>megahertz</td>
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<tr>
<td>mm</td>
<td>millimeter</td>
</tr>
<tr>
<td>MPa</td>
<td>MegaPascal</td>
</tr>
<tr>
<td>MPa-m(^{\frac{1}{2}})</td>
<td>ductile fracture toughness</td>
</tr>
<tr>
<td>mV</td>
<td>millivolt</td>
</tr>
<tr>
<td>Pascal</td>
<td>Newtons/meter(^{2})</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>psi</td>
<td>pound per square inch</td>
</tr>
<tr>
<td>S</td>
<td>second</td>
</tr>
<tr>
<td>SpG</td>
<td>specific gravity</td>
</tr>
<tr>
<td>S_y</td>
<td>yield stress</td>
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INTRODUCTION

1.1 Overview and Background

Radioactive and hazardous chemical waste is stored in 177 carbon steel tanks at the Hanford Site in southeast Washington State. 149 of the tanks are Single-Shell Tanks (SSTs) and 28 are Double-Shell Tanks (DSTs). The DSTs were constructed between 1968 and 1986.

The 149 SSTs were constructed in twelve groupings (known as ‘farms’) between 1943 and 1964. Figure 1 is a photo of an SST farm under construction. The SSTs were built with four different nominal volumes:

- Sixteen 55,000-gallon tanks, which are the 200 Series tanks in 241-B, 241-C, 241-T, and 241-U Farms.
- Sixty 530,000-gallon tanks, which are the 100 Series tanks in 241-B, 241-BX, 241-C, 241-T, and 241-U Farms.
- Forty-eight 758,000-gallon tanks, which are the 100 Series tanks in 241-BY, 241-S, 241-TX, and 241-TY Farms.
- Twenty-five 1,000,000 gallon tanks, which are the 100 Series tanks in 241-A, 241-AX and 241-SX Farms.

The SSTs received alkaline waste from multiple nuclear fuel processing operations, starting in 1944. The initial radioactive wastes were principally derived from three different chemical

Figure 1: Single-Shell Tank Farm under construction.
processing operations, each of which produced several different types of waste. The bismuth phosphate process, the REDOX process, and the PUREX process were designed to recover plutonium from irradiated reactor fuels. The bismuth phosphate wastes that were discharged to the tanks were later processed to recover uranium from the wastes by using the tributyl phosphate (TBP) process. Potassium ferrocyanide was used to scavenge cesium ion from this waste. The oldest tanks (241-B, 241-C, 241-T, and 241-U farms) were constructed to receive the wastes from bismuth phosphate plants. REDOX and PUREX wastes were stored in the 241-S, 241-A, 241-AX and 241-SX farms, which were designed to hold boiling wastes so that water could be removed from the tanks to conserve space for the retention of radioactive materials. Later operations, including the in-tank solidification (ITS) and outside-tank evaporation, were used to remove water and concentrate the wastes.

Waste additions to the SSTs ceased in 1980 and pumpable liquids have been transferred from the SSTs to the DSTs. The SSTs currently contain ten million gallons of sludge, twenty million gallons of salt cake, and one hundred thousand gallons of supernatant liquid. Sixty-seven of the SSTs are assumed to have leaked as much as one million gallons of waste to the vadose zone under the tanks.

SST wastes are slated for retrieval and treatment in a Waste Treatment Plant and Immobilization (WTP) that is currently under construction. Technical issues have delayed the schedule for initiating operations of the WTP. The delays to the WTP will necessitate extended storage in the SSTs—most of which are currently beyond their design life.

The extension of the SST’s mission has created an incentive for the tank farm contractor, Washington River Protection Solutions, LLC (WRPS) to develop an enhanced SST integrity project (SSTIP). WRPS created an expert panel on SST integrity (Panel) to provide recommendations to support the development of such a project.

The Panel developed recommendations based on the proceedings of two workshops and the research and deliberation of the Panel and its members.

In the first workshop, the Panel considered a broad range of issues, including: current status, chemistry, retrieval technologies, structural integrity requirements and status, corrosion, stress corrosion cracking (SCC) and design impacts at the Savannah River Site, vadose zone characterization, leak detection, monitoring and mitigation; and non-destructive evaluation.

At this workshop, the Panel developed individual work assignments to research specific areas of interest (Martin and Terry, 2009). Based on this research and subsequent requests for more information from WRPS, the Panel held a second workshop to develop recommendations.

In developing its recommendations, the Panel agreed on three overarching values that should guide the SSTIP. First, SSTIP activities should not adversely impact final disposition of tank waste. Such disposition of SST wastes requires retrieval from the tanks and treatment in the WTP. The waste must have certain physical and chemical characteristics for successful retrieval and treatment, and this must be considered when designing the SSTIP.

Second, SSTIP activities should be strategically focused on programmatic needs. This value acknowledges the pitfall of developing an SSTIP that includes activities that may be of interest scientifically, but offer little prospect for directly supporting programmatic needs.
Third, SSTIP activities should protect public and worker health and safety.

The Panel’s recommendations are focused on the following four key elements that form the foundation of the SSTIP:

- Confirmation of tank structural integrity;
- Assessment of the likelihood of future tank liner degradation;
- Leak identification and prevention; and,
- Mitigation of contaminant migration.

This report outlines the results of workshop discussions and Panel deliberations. It includes the rationale and prioritization of the Panel’s recommendations.

The Panel was tasked with providing recommendations to support development of a robust SSTIP—not to develop criteria allowing the reuse of SSTs for routine storage. Although this issue was clearly outside the Panel’s scope, it arose during the Panel’s deliberations several times. As a result, the Panel has included Section 7 to reflect its brief consideration of this issue.

2.0 PRIORITIZATION AND SUMMARY OF RECOMMENDATIONS

The Panel’s primary focus was to provide WRPS with recommendations supporting development of a SSTIP. Toward this goal, the Panel has prioritized its recommendations in two ways: (1) overall prioritization, and (2) prioritization within four key elements of a SSTIP.

The logic behind the Panel’s two prioritization schemes arose from the many uncertainties associated with the SSTs and the development of the SSTIP. For example, the inaccessibility of the concrete, rebar and liner of the SSTs alone raises many uncertainties. As a result, the SSTIP must remain flexible in applying different technologies and activities as the project progresses and data and information are collected.

The recommendation numbering scheme is based on the four key SSTIP elements: (1) confirmation of tank structural integrity (denoted by ‘SI’), (2) assessment of the likelihood of future tank liner degradation (denoted by ‘LD’), (3) leak identification and prevention (denoted by ‘LIP’) and (4) mitigation of contaminant migration (denoted by ‘MCM’).

2.1 Overall Prioritization of Recommendations

The Panel’s overall prioritization places each recommendation into one of two categories: (1) primary recommendations (including current tank farm activities and recommendations for new activities), and (2) secondary recommendations.

The first category is composed of primary recommendations that comprise the ‘top ten’ activities forming the foundation for the SSTIP. These activities should be pursued at the initiation of the SSTIP.

The other category is made up of secondary recommendations. While of a lower priority than the primary recommendations, the importance of the secondary recommendations should not be minimized. The Panel assumes many of these recommendations will be implemented for two
reasons. First, many of these activities consist of relatively inexpensive, simple documentation or laboratory work that could yield important information to support the SSTIP. Additionally, secondary recommendations could quickly become high priorities if indications of a problem that could impact SST integrity arise. For example, if a high priority such as visual inspection of domes identifies cracking of concrete, several secondary activities (e.g., Non-Destructive Evaluation techniques) would be necessary to further address the cracking.

2.1.1 Summary of Primary Recommendations

The primary recommendations represent the ‘top 10’ priorities that form the foundation of a SSTIP. In its review of existing information and data, the Panel found WRPS is currently performing many activities critical to a robust SSTIP. These programmatic activities are reflected in three primary recommendations (SI-2, LD-1 and LIP-1). These three recommendations acknowledge these important project building blocks, emphasize the importance of continuing them and, where necessary, recommend modifications. The other seven primary recommendations are not components of current SST programmatic activities.

The primary recommendations are as follows.

Recommendation SI-1, Perform Modern Structural Analyses
Recommendation SI-2, Perform Dome Deflection Surveys
Recommendation SI-3, Obtain and Test Sidewall Core
Recommendation SI-4: Perform Non-Destructive Evaluation of Concrete
Recommendation LD-1, Expand Leak Assessment Reports
Recommendation LD-2, Avoid inadvertent addition of water and chloride to SSTs
Recommendation LIP-1, Continue Leak Detection Monitoring and Best Management Practices and Install Enhanced External SST Monitoring
Recommendation LIP-2, Avoid the Addition of Water-Insoluble Absorbents to SSTs
Recommendation LIP-3, Continue Use of High Resolution Resistivity
Recommendation MCM-1, Install Surface Barrier Over SST Farms

2.1.2 Summary of Secondary Recommendations

The secondary recommendations are as follows.

Recommendation SI-5, Test Dome Concrete and Rebar ‘Plugs’
Recommendation SI-6, Develop Engineering Mechanics Document
Recommendation SI-7, Test Effects of Waste Exposure on Structural Integrity
Recommendation SI-8, Study the Deployment of Corrosion Potential Mapping
Recommendation LD-3, Examine “Non-Compliant” Wastes at 25°C
Recommendation LD-4, Develop and Deploy Guided Wave Technology
Recommendation LD-5, Determine Ammonia Corrosion Control Concentration
Recommendation LD-6, Assess SST Waste Compositional Variation
Recommendation LD-7, Assess Deployment of Local Non-Destructive Evaluation Techniques
Recommendation LD-8, Consider Installation of Corrosion Potential Probe
Recommendation LD-9, Consider Testing Tank Liner Hardness
Recommendation LD-10, Consider Applying Direct Current Potential Drop to SSTs
Recommendation LD-11: Analyze Stress Relaxation of Tank Liners

Recommendation LIP-4, Seek Engineering Methods to Increase Water Removal by Pumping From SSTs
Recommendation LIP-5, Evaluate Sludge and Saltcake Liquid Leak Rates
Recommendation LIP-6, Investigate Leak Detection Technologies for Tanks With Less Than 24 Inches of Waste
Recommendation LIP-7, Evaluate Effect of Lowering SST Waste Temperature
Recommendation LIP-8, Assess the Feasibility of Testing for Ionic Conductivity Between Inside and Outside of SSTs
Recommendation LIP-9, Consider Cathodic Protection for Rebar and Exterior of Tank Liner
Recommendation LIP-10, Evaluate Coating of Tank Liners and Installation of Polymeric Bladder
Recommendation MCM-2, Evaluate Subsurface Leak Mitigation Technologies
Recommendations LIP-11: Avoid Heating and Active Ventilation Strategies for Removing Additional Water from SSTs
Recommendation LIP-12: Avoid Strategies to Immobilize Waste Through the Addition of Gelling Agents

2.2 Prioritization of Recommendations Within SSTIP Key Elements

As is outlined in the Executive Summary, the Panel also prioritized its recommendations within each of the four key elements: (1) confirmation of tank structural integrity, (2) assessment of the likelihood of future tank liner degradation, (3) leak identification and prevention, and (4) mitigation of contaminant migration.

As the knowledge base from SSTIP activities evolves, it is likely the emphasis on one or more of the SSTIP’s key elements will also evolve. Moreover, variations in funding from year-to-year will also drive resource decisions for the SSTIP. The prioritization of recommendations within each key element is intended to provide WRPS relative priorities for consideration when making resource decisions as the SSTIP is initiated and as it progresses.

As the report chapters were prepared before the prioritization effort was completed, the recommendations are not presented in order of priority in their respective chapters. The recommendations within each key element are presented as follows in order of priority.

2.2.1 Prioritization of Structural Integrity (SI) Recommendations

The prioritized structural integrity related recommendations are as follows.

Recommendation SI-1, Perform Modern Structural Analyses
Recommendation SI-2, Perform Dome Deflection Surveys
Recommendation SI-3, Obtain and Test Sidewall Core
Recommendation SI-4, Perform Non-Destructive Evaluation of Concrete
Recommendation SI-5, Test Dome Concrete and Rebar ‘Plugs’
Recommendation SI-6, Develop Engineering Mechanics Document
Recommendation SI-7, Test Effects of Waste Exposure on Structural Integrity
Recommendation SI-8, Study the Deployment of Corrosion Potential Mapping

2.2.2 Prioritization of Liner Degradation (LD) Recommendations

The liner degradation recommendations, in priority order, are as follows.

Recommendation LD-1, Expand Leak Assessment Reports
Recommendation LD-2, Avoid Inadvertent Addition of Water and Chloride to SSTs
Recommendation LD-3, Examine “Non-Compliant” Wastes at 25°C
Recommendation LD-4, Develop and Deploy Guided Wave Technology
Recommendation LD-5, Determine Ammonia Corrosion Control Concentration
Recommendation LD-6, Assess SST Waste Compositional Variation
Recommendation LD-7, Assess Deployment of Local Non-Destructive Evaluation Techniques
Recommendation LD-8, Consider Installation of Corrosion Potential Probe
Recommendation LD-9, Consider Testing Tank Liner Hardness
Recommendation LD-10, Consider Applying Direct Current Potential Drop to SSTs
Recommendation LD-11: Analyze Stress Relaxation of Tank Liners

2.2.3 Prioritization of Leak Identification and Prevention (LIP) Recommendations.

The prioritized recommendations related to leak identification and prevention are the following.

Recommendation LIP-1, Continue Leak Detection Monitoring and Best Management Practices and Install Enhanced External SST Monitoring
Recommendation LIP-2, Avoid the Addition of Water-Insoluble Absorbents to SSTs
Recommendation LIP-3, Continue Use of High Resolution Resistivity
Recommendation LIP-4, Seek Engineering Methods to Increase Water Removal by Pumping From SSTs
Recommendation LIP-5, Evaluate Sludge and Saltcake Liquid Leak Rates
Recommendation LIP-6, Investigate Leak Detection Technologies for Tanks With Less Than 24 Inches of Waste
Recommendation LIP-7, Evaluate Effect of Lowering SST Waste Temperature
Recommendation LIP-8, Assess the Feasibility of Testing for Ionic Conductivity Between Inside and Outside of SSTs
Recommendation LIP-9, Consider Cathodic Protection for Rebar and Exterior of Tank Liner
Recommendation LIP-10, Evaluate Coating of Tank Liners and Installation of Polymeric Bladder
Recommendations LIP-11: Avoid Heating and Active Ventilation Strategies for Removing Additional Water from SSTs
Recommendation LIP-12: Avoid Strategies to Immobilize Waste Through the Addition of Gelling Agents

2.2.4 Prioritization of Mitigation of Contaminant Migration (MCM) Recommendations

The prioritized recommendations related to mitigation of subsurface migration are as follows.

Recommendation MCM-1, Install Surface Barrier Over SST Farms
Recommendation MCM-2, Evaluate Subsurface Leak Mitigation Technologies

3.0 CONFIRMATION OF TANK STRUCTURAL INTEGRITY

3.1 OBSERVATIONS CONCERNING THE CURRENT CONDITION OF TANKS

3.1.1 Observations Concerning Current Conditions of Concrete Domes

Surveys have been conducted on all of the SSTs approximately every two years since the early 1980s. A maximum allowable decrease in the dome elevation of 0.24 inches, relative to the baseline measurement, has been specified as the acceptable limit for SSTs.

Analytical studies summarized in Section 6.4 of Abatt (Abatt, 2002) indicate a safety factor of approximately 3.0 or larger against dome collapse for the in-situ soil overburden load. An
evaluation of the safety factor as a function of the increase in dome deflection over initial baseline measurements was conducted on Tank 241-C-106. This evaluation indicated a safety factor of approximately 2.5 for an additional downward deflection of 0.24 inch, and approximately 2.0 for an additional deflection of 0.48 inch. Thus, adequate safety margin exists if dome deflections do not increase more than 0.48 inch.

Remote visual inspection of the underside of the SST concrete domes does not indicate signs of concrete cracking, rust stains, or spalling of the concrete. One would not expect concrete cracks on the underside of the dome except possibly in the haunch area. Cracks in excess of 1/16 inch wide would indicate tensile yielding of the reinforcing steel (rebar). Cracks in excess of 1/8 inch wide are of significant structural concern. Rust stains or spalling of concrete indicate rebar corrosion.

3.1.1.1. **Recommendation SI-2: Perform Dome Deflection Surveys**

The current program of conducting dome deflection surveys on all SSTs at 24-month intervals should be continued. Additionally, it is important to assess whether deflection data can also be obtained near the haunch of the dome as well as at the center. With deflections taken only at the center, a determination of whether the deflection is due to downward displacement of the dome or due to downward displacement of the footing under the sidewall cannot be made.

This remains an important task because any future potential for dome collapse would be preceded by excessive downward dome deflection (e.g., greater than 0.5-inch).

3.1.1.2. **Recommendation SI-5: Test Dome Concrete and Rebar ‘Plugs.’**

New risers are likely to be installed in the dome of at least some of the SSTs. It would be desirable, to the extent practical, to cut the riser hole in the concrete domes in a manner such that the concrete and rebar can be removed intact. Careful visual inspection for concrete cracks, voids, rebar condition, and any signs of distress should then be performed on the “plug.” Concrete cores should be obtained from the intact removed concrete and concrete compression tests should be performed. Rebar diameters should be measured and tensile tests should be performed on rebar samples.

If intact concrete plugs are removed from the dome to install new risers, this recommended task is a high priority opportunity to improve knowledge of the dome strength.

**3.1.2 Observations Concerning Current Conditions of Concrete Walls**

Gillen (Gillen, 1982) reports the results of concrete strength tests made on a core cut vertically through the depth of the sidewall of Tank SX-115. It has been estimated that the concrete near the bottom of the sidewalls was exposed to service temperatures between 212° Fahrenheit (F) and 280° F for at least two years.

Concrete compression strength in the sidewall core tests ranged between 3825 pounds per square inch (psi) and 6960 psi with a mean value of 5550 psi. While all samples exceeded the 3000 psi design strength, a decrease in strength with depth in the sidewall was observed.

Visual examination of the cores indicated visible cracks with lengths ranging from 2 to 10 inches long, and a number of air voids up to 1 inch long. These air voids are likely indicators of poor
concrete placement during construction. No other signs of concrete degradation or chemical attack were reported.

Daniel, et al. (Daniel, et al., 1982a) reports tests on concrete and reinforcing steel under load at 180°F after exposure to waste solutions. Specimens representing wall sections of a waste storage tank were exposed to simulated waste slurry, simulated salt cake solution, and a control solution for periods varying from 3 to 36 months.

In all cases, there was not indication of attack on either the concrete or steel. Even though solutions penetrated to the reinforcement in the tests of specimens subjected to flexural loading, no evidence was found of rusting, cracking, disruption of mill scale, or loss of strength of the reinforcing steel. Petrographic examination of the concrete showed no evidence of adverse reactions between the solutions and the concrete or the steel.

Thus, preliminary indications have shown that the concrete and rebar in the tank walls remain in good condition.

3.1.2.1. Recommendation SI-3: Obtain and Test Sidewall Core

The Panel recommends obtaining and testing a vertical core from the entire depth of the sidewalls for two tanks that have leaked and had been operated at high temperatures for extended periods. This activity would be similar to the core obtained from Tank 241-SX-115.

Careful visual inspection and concrete compression strength testing should be performed on the recovered core. If any rebar steel is cut in the recovered core, this rebar should be carefully inspected, thickness measured, and tensile tested. However, care should be taken not to cut any significant fraction of hoop reinforcement (rebar) at any level.

3.2 LIKELIHOOD OF SST CATASTROPHIC COLLAPSE

The following assessment is based on the concrete conditions described in the previous section, and previously conducted analyses of the tanks summarized by Abatt (Abatt, 2002).

3.2.1 Potential for Collapse Under Non-Seismic Loading

There is no indication of significant degradation or distress of the dome or haunch regions of the tanks. Given the current state of knowledge of the tanks, collapse of the concrete dome is not a likely event under in-situ loading unless significant degradation of the concrete or rebar in the dome or haunch area was to occur in the future. Furthermore, dome collapse under in-situ loading in the future would be preceded by signs of significant distress such as:

- Excessive downward dome deflection (greater than 0.5-inch);
- Cracking of concrete (crack widths greater than 1/8-inch); and,
- Significant rust stains or spalling on concrete surfaces.

Existing analytical studies of the concrete sidewalls indicate large safety margins exist for in-situ soil loading provided the material design strengths have not seriously degraded. Furthermore, the in-situ loading is essentially axisymmetric and therefore can be resisted by the concrete alone, i.e., very little reliance on rebar strength is needed. Lastly, collapse of the sidewalls only becomes likely if a significant zone of concrete has degraded to the point that it has essentially become rubble. No indications of any such degradation exist.
Therefore, so long as dome downward deflection (since the original baseline) has not exceeded 0.5 inch, the Panel considers there to be a negligibly small probability of a sudden catastrophic collapse under non-seismic loading. This statement presupposes no substantial increase of loading on the tank dome.

3.2.2 Potential for Collapse Under Major Seismic Event

A major (significant) seismic event is characterized by peak ground acceleration in excess of 0.15 gravity (g) and a magnitude in excess of 5.5 on the Richter magnitude scale. Existing analytical studies indicate an adequate safety margin exists for such a seismic event so long as the material design strengths have not seriously degraded. Both hoop and vertical reinforcing steel is needed in the sidewalls to resist the bending stresses that occur under seismic loading. The concrete in the sidewalls must remain intact (i.e., not turned to rubble) and retain some currently unspecified minimum compression and shear strength.

Although good performance under a seismic event is likely, the Panel is not yet prepared to make any fully definitive statement concerning the structural integrity of the tanks under an unlikely major seismic event such as the $4 \times 10^{-4}$ annual frequency of exceedance ground motion being considered for other facilities at the Hanford Site. Good structural performance will depend on the condition of the rebar in the sidewalls as well as the rebar connecting the sidewalls to the basemat. Good structural performance during a major seismic event will also depend on the condition of the concrete in the lower region of the sidewalls. Although the Panel does not expect that major corrosion of this rebar or major degradation of the concrete has occurred, the actual condition of this rebar and concrete is somewhat uncertain.

Before a definitive statement can be made about the seismic structural integrity of the SSTs a modern structural analyses, including seismic loading, needs to be performed on a representative tank. This analysis needs to include the potential for loss of rebar cross-sectional area due to corrosion and potential concrete degradation from exposure to high temperature and leaking waste. The analysis will be useful in answering the following questions: How much rebar must remain to achieve adequate structural integrity under a major seismic event? What is the level of confidence that at least this amount of rebar cross-sectional area exists and will remain present for the operating life of the tanks (e.g., 20 to 50 additional years)? What is the minimum required concrete strength?

3.2.2.1. Recommendation SI-1: Perform Modern Structural Analyses

Modern structural analyses, including seismic loading, should be performed on representative samples of SSTs. Reasonable bounding estimates of material properties should be used in these analyses. A range of seismic levels (about three levels) should be considered including the $4 \times 10^{-4}$ annual frequency of exceedance ground motion level. For each seismic level considered, the amount of rebar cross-sectional area that must remain in order to achieve structural integrity of the sidewalls and connectivity to the basemat, and the minimum required concrete compressive strength should be determined. The likelihood that these minimum strength properties exist should also be assessed.

3.2.3 Recommendation SI-6: Develop Engineering Mechanics Document

The information items listed in Table 1 are needed to assess both the current and likely future structural integrity of the SSTs. This information is needed for each SST. This information should
be kept current over the remaining life of each tank in a document that can be referenced and used to define input information for future tank evaluations.

It is the Panel’s understanding that the information requested in Table 1 exists for each tank but is not generally collected into an easily available document.

**Table 1: Recommended Contents of Best Current Understanding of Engineering Mechanics Properties Document.**

### Steel Liners
- Wall thicknesses considering estimated corrosion plus estimated current corrosion rate
- Material properties and chemistry
- Estimated bulge size and shape at base of tank walls, if any, and expected cause of this bulge

### Concrete Wall and Dome
- Estimate of current material properties of concrete and rebar
- Estimate of rebar degradation resulting from tank leakage
- Estimated dome deflection, if any, and expected cause of this deflection
- Expected zones of high residual dome stress from prior loading

### Current Contents
Estimated physical characteristics of the tank contents for each stratified layer, including:

- Depth
- Specific gravity
- Bulk modulus
- Elastic Modulus
- Shear modulus
- Shear Strength if any
- Viscosity

### 3.3 NON-DESTRUCTIVE EVALUATION OF TANK CONCRETE

The elastic modulus of concrete is an important structural analysis input, controlling the degree of deformation that will occur under various loading situations. In addition, the modulus is correlated with the concrete strength. Severe decreases in modulus imply both increased deformation and decreased strength under load (stress = modulus x strain).

Elastic modulus is valuable although difficult to obtain for the SSTs. The non-destructive evaluation (NDE) of SSTs presents significant challenges because of a lack of access. Many of the techniques that are routinely used in NDE are not easily applied to SSTs because the surfaces of the concrete and steel liner are not directly accessible. Deployment of these techniques is possible, but not without significant effort to gain access. Given the cost, logistical and practical issues, a graded approach is recommended.

Ideally, the mode of degradation in a structure is understood, including both the nature and likely locations of expected defects (e.g., a fatigue crack in a region of high cyclic stress). However,
tank history and environmental uncertainties make this ideal situation unobtainable. Given these uncertainties, the exact nature and location of the expected defects is unknown. One cannot solely rely on an inspection targeted at a very local region and flaw type. Instead, one must be concerned about the existence of “unknown unknowns” and must look more broadly. This implies either an inspection with 100% coverage, which is generally impracticable in the large and inaccessible geometry of the SSTs, or a sampled inspection. The latter can only provide general confidence about the nature of the degradation processes that are underway.

All available data suggest that the integrity of the concrete tank is excellent, particularly the dome for which visual observation is possible. Not as much information is available about the sidewalls, for which there is no visual access. Structural analysis using properties considered to be “reasonable” suggest that there should be little concern under static loading. However, a possible concern could exist under seismic loads if the concrete at the bottom of the walls were “rubbelized.” The recommendation that follows is motivated by the desire to determine the most accurate concrete properties possible for use in the structural analysis.

3.3.1 Recommendation SI-4: Perform Non-Destructive Evaluation of Concrete

The Panel emphasizes the importance of the hierarchical aspect of this recommendation. The relatively simple technologies (visual inspection and utilization of a ‘thumper’ truck) should be pursued first. Additional development and deployment of technologies should occur in the event SSTIP activities (e.g., visual inspection, modeling, vertical core results) indicate potential concrete degradation. At this point, depending on the severity of the concerns, additional technologies such as guided wave propagation or the development of more localized concrete integrity measurement techniques should be pursued.

First, the Panel recommends performing a one-time remote visual inspection of the underside of the concrete domes for all SSTs. Ideally this inspection would include the entire dome, with a focus on the haunch region. If this is not feasible, the haunch regions near risers should be the focus. The inspection should identify cracks in excess of 1/16 inch wide. No such cracks should be found on the underside of the dome. If any such cracks are found, an analytical assessment of the cause of the cracks should be made.

The inspection should also look for signs of rust stains on the concrete, or spalling of concrete. These conditions are strong indicators of rebar corrosion.

This visual inspection should be repeated in the future for any SST for which dome downward movement has increased more than 0.25 inches during the prior two-year period (see Recommendation SI-2). Such an increase is an indicator of a potential problem.

Second, the Panel recommends measuring the frequencies of SST vibrations by using a commercially available ‘thumper’ truck such as that used in seismic and vibration analysis. As the truck shakes the earth, the dome response would be measured by accelerometers attached at strategic points. The modulus of the dome could be inferred from displacements and resonant frequencies. Comparing the observed data to the predictions of structural vibration models, with the modulus varied to obtain best fit, would enable this inference. It is likely that the analysis would show that the measurements are most sensitive to the modulus of the dome.

Guided wave propagation is the third technology in the hierarchy (a discussion of the general properties of guided waves is found in Section 4.3.2). Guided wave propagation should only be pursued if evidence of concrete degradation emerges from other SSTIP activities.
Guided wave energy could be propagated down the sidewalls. A ‘rubbelized’ region would produce a reflection earlier than produced by the geometrical discontinuity of the knuckle. Such a measurement would require the development of special transducers. Wavelengths significantly larger than the thickness of the wall (e.g., several feet) would likely be necessary (e.g., frequencies on the order of a few kilohertz (kHz) or lower). Special instrumentation would have to be developed for this purpose, but no fundamental barriers are anticipated in that development.

Should guided wave measurements raise concerns about the integrity of the concrete in a particular region (e.g., near the knuckle), more local measurements should be made to quantify that degradation. Carino (Carino, 2002) discusses a wide range of established candidate techniques available for SSTs. Recent research developments are discussed in Dobbmann and Wiggenhauser (Wiggenhauser, 2008). All of the techniques require local access to the wall of the tank. Should conditions dictate the need to recover such information, a small hole would have to be excavated in the soil along the outer wall of the tank to allow the access required for the instrumentation to be inserted.

3.4 ANALYSIS OF SIMULATED WASTE IMPACTS ON REBAR AND CONCRETE

3.4.1 Reactions with liquid wastes

Liquid waste that has leaked through the steel liner and the concrete walls could have damaged the concrete and rebar. Several unknowns exist concerning this potential damage: 1) the size of the crack in the liner and the associated volume of concrete in contact with the waste, 2) the effect of the waste solution on the concrete and rebar, 3) the duration the waste was in contact with the concrete, and 4) the impact of the concrete/rebar interaction with the liquid waste on the structural integrity of the tank walls. Issues related to leaks are discussed in more detail in Sections 4.1 and 4.2.

Crack sizes in the liners of known “leakers” have not been measured; therefore, it is not possible to estimate the volume of concrete exposed to liquid waste. However, a possibility exists that significant cracks resulted from “bubble” formation in the tank bottoms (discussed in Section 4.1). These large cracks would expose a significant volume of concrete to the waste in the wall-base junction area, raising a concern for the structural stability of the tanks.

There have been studies of the interaction of SST waste with concrete (RPP-10435, 2002). These studies “indicate a large range of potential concrete damage depending on the volume and temperature of the liquid waste fluids coming in contact with the concrete.” This same report (RPP-10435, 2002) stated SSTs exposed to high temperatures “could have experienced concrete strength reductions of up to 35%, depending on the temperature history of the tank.” The global damage to concrete strength caused by high temperatures is potentially far more damaging than the local damage caused by interaction of SST waste with tank walls (temperature impacts are further discussed in Section 4.2).

RPP-10435 (RPP-10435, 2002) references a 1976 study by the Portland Cement Association (SA-202, 1976). The concrete tested was made specifically for the test and matched an ASTM Type II with a calcium aluminate content of 6-8%. A total of 120 samples with dimensions of 3 x 3 x 11 ½ inches were tested. The samples were cured for 28 days before testing. Eighteen of the 120 samples contained 8 inch long No. 4 round, deformed rebar. The base solution in which the concrete bars were immersed was: 2 molar (M) sodium aluminate, 0.1 M sodium chloride, 0.2 M sodium carbonate, 0.5 M sodium sulfate, 0.1 M sodium fluoride and 0.2 M sodium phosphate. To
this base solution were added the following variable solution chemistries: 4 M, 7 M and 10 M sodium hydroxide, zero, 1M/1M and 3M/3M sodium nitrate/sodium nitrite. Tests were conducted at 50°, 100° and 150° C and examined following 1-, 2-, 3- and 6-month exposures. Tests were also conducted in Ca(OH)₂ at the same temperatures. Length change, weight change and sonic modulus were measured as a function of exposure time.

Length change was considered the most useful parameter related to concrete durability. Changes were also observed with time and temperature for each type of measurement. A failure criterion of 0.1% length change was adopted. By this criterion all samples failed within 1 month at 150° C, within 3 months at 100° C and within 6 months at 50° C except samples stored in the three 10 M sodium hydroxide, 10 M sodium hydroxide + 1M/1M and 3M/3M sodium nitrate/sodium nitrite. These latter samples were not much below the 0.1% failure limit, however. Weight change was not deemed a reliable measure of durability because crystallized salt formed during the 21-day drying period following exposure to the simulated wastes. Therefore, this weight gain offset the likely weight loss during exposure. Sonic modulus measurements showed decreases associated with cracking of concrete samples, but the trend did not follow that of length change. It appeared some crack filling occurred from salts that formed during the drying period. Cracking of the samples was characterized as minor to severe, which is consistent with the length changes observed. The samples were still intact and not reduced to rubble, nor was there evidence of rebar corrosion. Samples exposed to calcium hydroxide showed no deterioration in properties.

In summary, temperature was the dominant variable in causing a change in length. Solution chemistry was less a factor, with the exception of calcium hydroxide, which showed no effect on the concrete. Basically, all samples failed or were close to failing the length change criteria within six months at all temperatures and in all solutions.

This study can be criticized for the brevity of the 28-day concrete curing period—the samples were still “green” when exposed to the simulated waste solutions. This is further evidenced by the shrinkage observed after 1 month for samples exposed at 100° and 50° C. A second criticism is the lack of property measurements performed on the samples. The failure criterion of 0.1% length change appeared to be arbitrary. A simple compressive strength test would have been very informative.

Later studies (Daniel, Stark and Kaar, 1982a; Daniel, Stark and Kaar, 1982b; Kaar and Stark, 1981; Kaar and Stark, 1979) were performed using similar concrete reinforced with steel rebar. These samples, however, were cured 28 days in 100% RH and another 27 days before being exposed to the test solutions. The solution contacted the concrete in only a local region as defined by a tank of the solution in contact with the concrete test specimens. The test solutions were named the simulated Waste Solution and the simulated Double-Shell slurry solution. The simulated Waste Solution was 7M sodium hydroxide, 3M sodium nitrate, 3M sodium nitrite, 2M sodium aluminate, 0.1 M sodium chloride, 0.2 M sodium carbonate, 0.5 M sodium sulfate and 0.1 M sodium fluoride. The Double-Shell slurry solution was 7.3M sodium hydroxide, 6.0 M sodium nitrate, 4.5 M sodium nitrite, 4.3 M sodium aluminate, 0.7 M sodium carbonate, 0.2 M sodium sulfate and 0.3 M sodium phosphate. The samples were 9 x 12 inch cross sections, 36 inches long. In the Daniel, Kaar, Stark, 1982a study, the samples were first exposed for 13 months in simulated waste solution; followed by 12 months in the Double-Shell slurry.

Daniel, Stark and Kaar (Daniel, Stark and Kaar, 1982b) also reported on exposures up to 36 months. All tests were conducted at a temperature of 82° C. The samples were exposed to the simulated waste solutions while under either a compressive stress of 500 psi or flexure with a rebar stress of 10,000 or 20,000 psi. The flexure test samples were first flexed to produce cracks
before exposure to the test solution. The primary purpose of these tests was to ensure steel rebar was exposed to the test solution. No effects were observed on the appearance or properties of the rebar. This was demonstrated by removal of the rebar from the concrete and tensile testing. The strength of the rebar was identical to the original material after 36-month exposure. The authors state that no visual change to the concrete from exposure to these solutions was observed. No physical or mechanical tests were conducted on the concrete.

The high pH SST waste could result in sulfate-alumina (sulfate attack), alkali-silica, alkali-carbonate or calcium hydroxide leaching reactions. A sulfate-alumina reaction occurs when calcium aluminate (C₃A) in the concrete reacts with calcium sulfate. A common reaction product is Ettringite [(CaO)₆(Al₂O₃)(SO₄)₃·32H₂O]. Alkali silica reactions can produce significant expansion in concrete and cause structural problems. This is mostly seen as a reaction between the hydroxyl ions in the alkaline cement pore solution and silica within the concrete. The same holds for the alkali-carbonate reaction, which is less common than that of the alkali-silica. Alkali in the waste would also contribute to the alkali-silica reaction. The hydroxyl ion first dissolves the silica, followed by absorption of the alkali-metal ions by the dissolved silica products producing an alkali-silica gel. Cracking occurs when the alkali-silica gel absorbs water (Shah and Hookham, 1998).

In a reaction with the simulated waste, penetration of the concrete would be necessary to allow significant alkali reaction. The leaching of soluble calcium hydroxide is another possible reaction. Although this may lead to cracking, it is unlikely it would account for expansion. The lack of dimensional change for samples immersed in Ca(OH)₂ suggests the reaction that caused the dimensional change in the simulated waste could have been either Ca(OH)₂ leaching, sulfate-alumina (because of the calcium aluminate additive) or alkali-silica reaction. It is possible that all three reactions occurred. Natural sand used in the concrete would provide the silica for the alkali-silica reaction.

Portland Cement Association studies (SA-202, 1976; Daniel, Stark and Kaar, 1982a; Daniel, Stark and Kaar, 1982b; Kaar and Stark, 1981; and Kaar and Stark, 1979) showed no rebar corrosion. This is not surprising since the high pH of the concrete and waste should provide the steel an adherent and protective magnetite passive film. Rebar corrosion in roadways can be induced by the presence of Cl⁻ or CO₂. In the case of reinforced concrete roadways and bridges, CO₂ from the environment lowers the pH near the rebar such that the protective magnetite layer is not stable. The addition of Cl⁻ as deicing salt may accelerate the corrosion rate of rebar in the passive state. While Cl⁻ is possibly present in the wastes and groundwater and was present in the test solutions, its concentration is low. Also, CO₂ access to the tank walls is limited. Therefore, rebar corrosion is not considered a significant issue although concrete property reductions will result from waste and temperature exposure.

3.4.2 Effects of waste temperature

Abrams (Abrams, 1979) conducted a study into the effect of elevated temperatures on concrete. Modulus of elasticity, Poisson’s ratio, compressive strength and splitting tensile strength were measured and reported for exposure at 121°, 177° and 232° C. Concrete samples with 3,000 psi and 4,500 psi strengths were tested. A drop in the elastic modulus occurred rapidly, then slowed with time (up to 900 days with a 25% drop at 121° C and 50% drop at 232° C after 900 days.) The compressive strength did not show the same rapid drop as the elastic modulus and also showed a smaller overall decrease with a decrease of about 30% at 232° C after 900 days. The splitting tensile strength showed a similar response to the compressive strength.
3.4.3 Recommendation SI-7: Test Effects of Waste Exposure on Structural Integrity

Studies should determine the effects of simulated waste on concrete properties using samples cured longer than 28 days and measuring physical and mechanical properties of the exposed concrete. The effects of waste/concrete/rebar reactions and temperature on the structural integrity of the tank walls should then be estimated.

3.5 CORROSION POTENTIAL MEASUREMENTS OF REINFORCING STEEL IN CONCRETE OF SINGLE-SHELL TANKS

Knowledge of the condition of SST reinforcing steel is required to assess the structural integrity of the tanks. It is difficult to inspect the reinforcing steel in the tank structures using common non-destructive inspection techniques due to the poor tank access and the composite nature of reinforced concrete. Corrosion potential mapping is one candidate indirect technique for assessing the condition of the rebar and concrete in proximity to the rebar. Actively corroding reinforcing steel can result in spalling of the concrete and reduced structural integrity. Procedures for corrosion potential mapping of reinforced concrete are described in ASTM C876-91 (ASTM C876-91, 1999). This test method covers the estimation of the corrosion potential (electrical half-cell potential) of uncoated reinforcing steel in field for the purpose of determining the corrosion activity of the reinforcing steel.

The test method described in ASTM C876-91 (ASTM C876-91, 1999) is suitable for in-service evaluation and is applicable to reinforced concrete structures regardless of size or depth of concrete cover over the reinforcing steel. The results obtained cannot be used to directly estimate the structural properties of the steel or of the reinforced concrete structure. It is often necessary to use other data such as chloride contents, depth of carbonation, delamination survey findings, rate of corrosion results, and environmental exposure conditions, in addition to potential measurements, to formulate conclusions concerning corrosion activity of embedded steel and its probable effect on the service life of a structure. Nevertheless, corrosion potential measurements are a useful tool to assess whether the reinforcing steel is passive or is actively corroding.

The procedure described in the standard consists of placing a reference (half-cell) electrode on the surface of the concrete and measuring the potential of the reinforcing steel with respect to the reference electrode using a high impedance voltmeter. The impedance of the voltmeter must be sufficiently high so the potential measurement is not affected. A sponge, wetted with a conductive electrolyte, is used to provide a low resistance ionic conduction path between the reference electrode and the concrete.

Figure 2 is a schematic showing the circuitry for performing a corrosion potential measurement. Note that electrical connection to the reinforcing steel is required, but the connection does not have to be in close proximity to the location of the reading. However, a continuous electrical (electronic) path between the electrical connection and the rebar being measured must exist. This requirement is normally satisfied in a reinforced concrete structure containing uncoated reinforcing steel by the presence of multiple wire ties between the individual segments of the reinforcing steel. In the case of the waste tanks, a single connection to a riser would be sufficient, assuming that all of the risers are electrically continuous with the rebar. This could be confirmed by means of simple resistance measurements between risers.

In most cases, a concrete structure survey is performed, which consists of a series of potential measurements in a grid pattern on the surface of the structure. While there is no pre-defined minimum spacing between measurements on the surface of the concrete, the spacing should be
consistent with the structure being investigated. A spacing of about 4 feet has been found satisfactory for the evaluation of bridge decks. Generally, larger spacings increase the probability that localized corrosion areas will not be detected.

An equi-potential contour map is the most common technique for presenting the results of the potential measurements. An example is given in Figure 3. This map provides a graphical delineation of areas where corrosion activity may be occurring. In the example shown, active corrosion would be expected in the areas with the most negative potentials. In situations where the reinforcing steel is passive (not corroding), the corrosion potentials would be less negative and there would be less variation in the corrosion potentials over the surface of the concrete.

There likely will be challenges in applying this technique to the SSTs. With the possible exception of the tank dome, direct access to the concrete structure is extremely limited. Therefore, it will be necessary to place the reference electrode in the soil adjacent to the tank. This might create issues with conductivity between the reference electrode and the concrete. On
the other hand, there is a long history of monitoring the potential of underground steel structures such as tanks and pipelines. It might be necessary to perform finite element modeling to establish the area of the tank sensed, based on the soil resistivity and the distance of the reference electrode from the tank wall.

3.5.1 Recommendation SI-8: Study the Deployment of Corrosion Potential Mapping

The Panel recommends studying the feasibility of performing corrosion potential measurements to assess the condition of rebar in the SSTs. Issues that need to be addressed include the electrical continuity between the risers and the rebar mat, the area sensed by the potential measurement, and the ability of the potential measurement to detect active corrosion. A combination of resistance measurements between risers, modeling, and direct examination of a portion of the dome, following mapping, could help resolve these issues.

3.6 SUMMARY OF THE PRIORITIZATION OF STRUCTURAL INTEGRITY RECOMMENDATIONS

Following are the recommendation titles, in order of priority, for the SSTIP confirmation of tank structural integrity key element.

- Recommendation SI-1: Perform Structural Analyses
- Recommendation SI-2: Perform Dome Deflection Surveys
- Recommendation SI-3: Obtain and Test Sidewall Core
- Recommendation SI-4: Perform Non-Destructive Evaluation of Concrete
- Recommendation SI-5: Test Dome Concrete and Rebar ‘Plugs’
- Recommendation SI-7: Test Effects of Waste Exposure on Structural Integrity
- Recommendation SI-8: Study the Deployment of Corrosion Potential Mapping

4.0 ASSESS THE LIKELIHOOD OF FUTURE TANK LINER DEGRADATION

4.1 ORIGINS OF STEEL LINER FAILURES

4.1.1 Introduction

Alkaline radioactive wastes from the processing of irradiated uranium have been stored in the SSTs since 1944. The initial radioactive wastes were principally derived from three different chemical processing operations, each of which produced several different types of waste. The bismuth phosphate process, the REDOX process, and the PUREX process were designed to recover plutonium from irradiated reactor fuels. The bismuth phosphate wastes that were discharged to the tanks were later processed to recover uranium from the wastes by using the TBP process. Potassium ferrocyanide was used to scavenge cesium ion from this waste. The oldest tanks, which are in 241-B, 241-C, 241-T, and 241-U farms, were constructed to receive the wastes from bismuth phosphate plants, while the later REDOX and PUREX wastes were stored in the 241-S, 241-A, 241-AX and 241-SX farms, which were designed to hold boiling wastes so that water could be removed from the tanks to conserve space for the retention of radioactive materials. Later, other operations including in-tank solidification and outside-tank evaporation were used to remove water and concentrate the wastes.
The vadose zone under the Hanford Site has been contaminated by the leakage of waste from the SSTs during the past 60 years. At the present time, 67 SSTs are known or presumed to have leaked (Roger, 2008). Seven of these 67 (Tanks 241-A-105, 241-BX-102, 241-SX-110, 241-SX-113, 241-SX-115, 241-T-106, and 241-U-104) have each leaked more than 50,000 gallons of waste (Rifaey, 2002, Appendix D). These leaks resulted from failures of the steel liners. One objective of ongoing investigations at the Hanford Site is to determine whether the other leaks were also caused by failure of the steel liner or mishaps during waste transfer operations such as the failure of couplings or transfer lines (Johnson and Field, 2008).

The origins of the major leaks and the possible origins of some other leaks are discussed in the next sections.

4.1.2 Waste Corrosion of the Liner

Corrosion testing began early at the Hanford Site (Endow, 1952; Endow, 1954a; Endow, 1954b; Endow and Sanborn, 1954; Groves, 1953; Groves, 1954; Groves, 1958; Gruber 1957; Mallett, 1954; Parks, 1957; Pitzer, 1952; Sanborn, 1949; Sanborn, 1952; Stivers, 1957; Walker, 1958; and Ward, 1953).

The results of the early tests have been summarized by Lini (Lini, 1975) and Rifaey (Rifaey, 2002, Appendix D). In brief, the early laboratory and field work examined the corrosive properties of bismuth phosphate, metal, REDOX and PUREX wastes. The results of these tests, which are discussed by Lini and Rifaey, implied that general corrosion, pitting corrosion, or SCC were not sufficiently severe to threaten the integrity of the steel liners.

Maness (Maness, 1963 and Maness, 1974) investigated the corrosive properties of relatively concentrated solutions of sodium nitrate and ammonium nitrate. Although the outcome of the tests depended upon the properties of the metal specimens, Maness found that SCC could occur with these solutions at their boiling points. He observed that weldments were especially vulnerable to nitrate ion induced SCC. He also found that SCC occurred in 50 weight % sodium nitrate at the boiling point (Moore, 1971). In general, these two investigations demonstrated sodium nitrate solutions (over 5 M) and some waste simulants caused SCC of carbon at storage temperatures over 100° C. The same failure mode was also observed with simulated mixtures of salt cake wastes. It was recognized that significant variations in pH of the stored wastes had occurred and that SCC occurred more readily in the nitrate ion rich simulants when the pH was below 10. This testing program identified the threat of nitrate ion induced SCC when the pH was less than 10 and the temperature exceeded 100° C.

The need for additional waste storage space led to the intentional concentration of waste solutions with attendant increases in the concentrations of the non-volatile components in the liquid phases. The partial solidification of wastes resulted in the formation of liquids with high concentrations of sodium hydroxide. It was recognized that exposure of carbon steel to these very alkaline solutions may result in sodium hydroxide induced SCC. Although mixed results were obtained in the testing programs, it was concluded that concentrated sodium hydroxide solutions with compositions similar to the Hanford Site wastes could cause SCC of the steel liners at temperatures above 100° C (Payer et al., 1975 and Moore, 1975). The reality of this threat has recently been discussed by Wiersma (Wiersma, 2008) who concluded that sodium hydroxide induced SCC was responsible for the failure of certain waste tanks (Type IV) at the Savannah
River Site. These tanks contained more than 5 M sodium hydroxide at temperatures between 50° and 100° C.

Lini (Lini, 1975), who first summarized the results of the testing programs, concluded that the general corrosion rates were too small to be responsible for tank failures and the observations regarding pitting corrosion were so difficult to interpret that they were not useful for predictive purposes. However, Lini affirmed that liquids with 6 to 8 M nitrate ion at temperatures near 100° C and a stress of 50 to 100 % of the yield strength can cause SCC over relatively short time periods. He emphasized the special vulnerability of weldments to SCC.

Subsequent testing programs, which are discussed in Section 4.2, have confirmed the general findings of Lini and provided more evidence regarding the role of nitrate ion and hydroxide ion induced SCC in waste tanks.

### 4.1.3 Operations and the Origins of Major Leaks

Seven tanks (241-A-105, 241-BX-102, 241-SX-110, 241-SX-113, 241-SX-115, 241-T-106, and 241-U-104) of the 67 known or presumed leaking tanks experienced major leaks as noted in Section 4.1. The conditions under which these tanks and some related tanks were operated are discussed in this section to illustrate the conditions under which major leaks occurred.

The waste streams sent to tanks had different thermal characteristics. The bismuth phosphate, TBP and metal wastes were warmed by the decay of radioactive isotopes, but temperatures in the waste tanks that held these wastes were generally manageable. The situation was very different for REDOX and PUREX wastes. Radionuclide decay in these two wastes heated the aqueous solutions in the tanks to their boiling points in a matter of months. The 241-A, 241-AX, and 241-SX tank farms were designed to retain these boiling liquids for years. Nevertheless, two of the five tanks in 241-A farm and nine of the fifteen tanks in 241-SX farm leaked. Tanks 241-A-105, 241-SX-110, 241-SX-113, and 241-SX-115 experienced major leaks.


The Leak Assessment Report concludes that the ground contamination associated with Tanks 241-AX-102 and 241-AX-104 resulted from leaks in external Dresser couplings or nearby condensate lines rather than from a failure of the tank liners (Johnson and Field, 2008). The evidence for leakage from Tank 241-A-103 is also questionable according to their analysis.

Rogers (Rogers, 2008) indicates that Tanks 241-SX-104 and 241-SX-107 through 115 are known or presumed to have leaked. Tanks 241-SX-110, 241-SX-113, and 241-SX-115 experienced large leaks.1

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1 The as yet unpublished report regarding the 241-SX farm indicates that the soil contamination associated with Tank 241-SX-104 did not occur as a consequence of the failure of the steel liner.
Godfrey and Schmidt (Godfrey and Schmidt, 1969) provided an assessment of the status of the SX Farm. Rifaey (Rifaey, 2002, Appendix D) included this information in the assessment of tank integrity. The main features of the 1969 investigation are summarized in Table 2.

The 241-SX tanks were constructed as the first tanks designed to contain self boiling wastes. More important, the connection between the bottom plate and the side wall was made without a curved knuckle. Rather the side wall and the bottom were welded with a fillet joint at the juncture of the side wall and the bottom plate.

In contrast with the substantive commentary regarding the operation of these tanks at high temperature and the bulging of the steel liners, there is only brief commentary concerning corrosion of the liners. Rifaey (Rifaey, 2002, Appendix D) suggests hydroxide ion induced SCC was partially responsible for the failure of Tank 241-SX-113.

Rifaey (Rifaey, 2002, Appendix D) has described the leaks in Tanks 241-BX-102 and 241-T-106. Since they appear to have failed in the same manner, they are discussed together. Tank 241-BX-102 was first filled with waste in 1948. Between 1959 and 1969, radioactivity was detected in a nearby drywell. Although the origin of this radioactivity is apparently disputed, Rifaey concludes it arose from a leak in Tank 241-BX-102. In 1969, the readings in the drywell were declining, but increased when operations were initiated. The readings increased steadily and additional drywells were drilled to determine the extent of the contamination. The pattern of contamination implies

<table>
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<th>Tank (241-)</th>
<th>Preheated</th>
<th>Preheated Interval</th>
<th>Liquid Heel Used</th>
<th>First Waste Added</th>
<th>Waste Type</th>
<th>Boil with waste</th>
<th>Boil Began</th>
<th>Failure Date</th>
<th>Bulge Inspection</th>
<th>Bulge Observed</th>
<th>Present Status</th>
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<td>No</td>
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<td>No</td>
<td>Jan-61</td>
<td>1976</td>
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<td>No</td>
<td>No</td>
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<td>Nov-56</td>
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<td>Yes</td>
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<td>Yes</td>
<td>Nov-59</td>
<td>1965</td>
<td>No</td>
<td>Leaker</td>
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</table>

Note 1: Except for Present Status, the information is found in Godfrey and Schmidt (1969).

Note 2: Roger (2008) reports the present status of these tanks.
that waste was released on the southeast edge of the concrete shell near the tank footing. It was concluded the tank wall failed by pitting corrosion 22 inches above the tank bottom (Rifaey, 2002, Appendix A).

Tank 241-T-106 received first cycle decontamination waste and cladding waste (Anantatmula, Schwenk and Danielson, 1994). Rifaey concludes that Tank 241-T-106 failed in the same manner as Tank 241-BX-102 (Rifaey 2002, Appendixes A and D) on the basis of the observation that drywell readings exhibited the same pattern. However, the leak in Tank 241-T-106 was much larger, approximately 115,000 gallons of waste leaked from the tank (Rifaey, 2002, Appendix D).

Tank 241-U-104 was placed in service in 1945 when it received metal waste. Rifaey (Rifaey, 2002, Appendix A) indicates the waste in this tank boiled. This waste was removed from the tank in 1953, and inspection of the interior of the tank by periscope revealed no abnormalities (Roberts, 1961). After the removal of waste in 1956, it was discovered that the steel liner had bulged upward by approximately five feet in the center of the tank (Cluckey, 1956; Operations Managers Reports, 1956, 1958; Rifaey, 2002, Appendix A). Approximately 50% of the tank bottom was covered with liquid. Photographs of the steel bottom showed that it buckled, but did not indicate the bottom had ruptured. Additional photographs of the liner walls and concrete dome lacked sufficient resolution to determine whether corrosion had occurred. Water was added to the tank in July, 1956 to determine whether it was leaking. Initial water level measurements suggested the tank was sound. In 1961, it was discovered that approximately 45,000 gallons of water had leaked from the tank between July, 1957 and March, 1961 (Hanson, 1961; Roberts, 1961). The tank was declared a confirmed leaker in 1961.

Approximately 55 tons of diatomaceous earth was added to the tank in 1972 to absorb the remaining water (Brevick, 1996). The diatomaceous earth addition did not appear effective as radioactivity was detected in a drywell between Tanks 241-U-104 and 241-U-105 in September of 1978. The leak was attributed to Tank 241-U-104, which contained 4.25 feet of wet and dry solids. The small amount of liquid in the waste appeared in two small shallow pools approximately five feet in diameter.

4.1.4 Contributory Factors

First, the steel liners were not heat treated to relieve stresses associated with weldments and were therefore especially susceptible to SCC. This vulnerability is well documented in the corrosion literature. Another construction feature that apparently contributed to the failure of the tanks in the SX farm involved the replacement of the “radiused knuckle” region by a single, essentially perpendicular fillet welded joint between the bottom and the side wall. Rifaey (Rifaey, 2002) describes this vulnerability.

Second, although important uncertainties remain about the waste compositions delivered to the SSTs during early years of operation\(^2\), it is evident that many SST wastes could cause pitting and

\(^2\) The tanks were not sampled on a regular basis. However, one report (Sanborn, 1949) concerning wastes in Tanks 241-T-101, 241-T-102, and 241-T-103 provides insight regarding their actual compositions. Two of these tanks are presumed to have leaked. The pH of these bismuth phosphate process wastes were between 9.8 and 10.1. The temperatures varied from 35° to 80° C. The solutions contained 3M sodium ion and 0.6M nitrate ion with modestly smaller amounts of carbonate, sulfate, and phosphate ions. Little is known about the nitrite ion content, but Anderson (Anderson, 1990) implies that it was not used in the process.
cracking under the storage conditions. Plant records indicate nitrate ion wastes were stored at pH less than 10 and many of the wastes had low concentrations of nitrite ion. Indeed, Anderson (Anderson, 1990), who has formulated the chemical compositions of the principal process wastes, indicates that only cladding waste contained nitrite ion. Later operations led to the concentration of wastes and the selective increase in the concentration of the very soluble sodium hydroxide.

Third, the original waste tanks were operated at relatively high temperatures. Some tank farms were maintained at temperatures greater than 100° C for years. These operating conditions had several important consequences.

The rates of pitting, SCC and corrosion at the LAI increased with temperature.

High temperature operations also altered the physical properties of the encasements. Asphalt coating softens between 30° and 150° C. These temperatures were reached or exceeded in many tanks. Streaks and stains shown in sidewall photographs indicate asphalt has flowed down the inside of the steel liners (Rifaey, 2002, Appendix A). Some stains originate from asphalt that overflowed the top of the liners, other stains appear associated with pits or cracks.

High temperature operations concentrated the waste solutions and caused solids to precipitate on the bottom of the tanks. Superheated water entrapped in these poorly heat conducting solids produced steam that caused frequent bumping and, occasionally, vigorous explosions that expelled waste from the tanks.

Bumping was a recognized problem during the early operations of 241-S farm (Rifaey, 2002). 241-A, 241-AX and 241-SX farms were designed to contain boiling wastes. The energetic events presumably added to liner stresses. The bottom plate in at least one 241-SX tank had numerous plastically deformed ridges approximately 6 inches high and 1 to 2 feet in length (Rifaey, 2002, Appendix A). These ridges were attributed to thermal expansion of the bottom plate. Rifaey (2002, Appendix D) asserts that simple two dimensional calculations show a temperature difference of 70° C is sufficient to “create a thermally induced structural instability in a flat plate of A283, Grade C carbon steel and that tanks which received boiling waste may have been subjected to thermally induced loads sufficiently high to fail the bottoms.”

**4.1.5 Leak Origins and Paths**

Leaks described in Section 4.1.3 did not all originate in the same manner. One small leak occurred high on the side wall in Tank 241-A-105. Although its origin has not been determined, this leak apparently occurred below the surface of the supernatant layer. These circumstances are compatible with either pitting or SCC.

The major leaks in Tanks 241-BX-102 and 241-T-106 (which did not contain boiling waste) occurred on the side wall, presumably in the knuckle region of the tanks. These leaks have been attributed to corrosion at the Liquid Air Interface (LAI) in tanks that were left stagnant for years.

The major leaks that occurred in Tanks 241-A-105 and the 241-SX farm probably occurred due to mechanical ruptures. Other leaks may have originated from pitting, SCC, or weakening of the mechanical strength of steel plates by pitting or SCC. One of the explanations for failure postulates that SCC of the steel liner provided a leak path that allowed liquid to seep into spaces between the bottom of the steel liner and the concrete base. Heating vaporized this trapped liquid and led to substantial pressures, adding to the stress on the steel. Regardless of exact cause, these
ruptures created leak paths that allowed the liquids in the steel liner to contact the concrete side walls, basemats, and footings.

Serious ruptures in the steel liners were responsible for several major leaks. These ruptures occurred near the juncture of the tank bottom and the sidewall. The other major leaks occurred near the center of the bottom and at locations low on the sidewalls.

4.1.6 Correlations between waste types and leaks

Attempts have been made to correlate waste compositions with leaking tanks. Hill and Simpson (Hill and Simpson, 1994) identified 49 different waste types (for example, wastes from the REDOX or PUREX processes) and consolidated the wastes into 30 characteristic groups. They then systematically sorted the SSTs according to types of waste. In some cases, only one type of waste was sent to a tank, in other instances, two or more waste types were sent to the same tank. Anantatmula, Schwenk, and Danielson (Anantatmula, Schwenk, and Danielson, 1994), compared the waste type information provided by Hill and Simpson (Hill and Simpson, 1994) with the tank leak histories. They found a significant correlation between certain waste types and leakage. Several waste types caused leaks in all of the tanks in which they were stored and accounted for approximately 50% of leaking tanks. These waste types included REDOX waste and its variants, the waste delivered to the 241-C-200 farm known as hot semi-works waste, first and second recycle decontamination wastes from the bismuth phosphate process, and certain TBP wastes. Anantatmula, Schwenk, and Danielson (Anantatmula, Schwenk, and Danielson, 1994) found “a direct correlation between the high nitrate ion/low hydroxide ion concentration of the stored waste types and the leak status for the majority of leaking tanks.”

The waste groupings used by Hill and Simpson have subsequently been modified on the basis of improved process information histories and analytical information about the compositions of the wastes in the SSTs (Agnew, 1997; Agnew and Corbin, 1998; Place and Higley, 2007). In the course of this work, Agnew and his associates developed a methodology for estimating waste tank compositions based on process waste transfer history. In principle, the model can be used to estimate the composition of a waste tank at any desired time.

4.1.7 Conclusion

Laboratory and field work implies several factors contributed to the failure of the steel liners. First, the liners of the SSTs were not heat treated to remove stresses in the weldments and some tanks were constructed without knuckles. Second, the wastes were potentially corrosive; some wastes had high nitrate ion concentrations and low nitrite ion concentrations at pH less than 10. Subsequently, wastes with high hydroxide ion concentrations were stored in the tanks. Third, some tanks were operated at the boiling point of the waste for years. These conditions enhanced corrosion rates and led to thermal excursions that super heated water trapped beneath the solid layers causing bumping and vigorous steam eruptions. Collectively, these chemical and physical conditions caused failure of the liners by pitting, SCC and mechanical ruptures.

4.1.8 Recommendation LD-1: Expand Leak Assessment Reports

The ongoing work on the preparation of Leak Assessment Reports for each tank farm should continue. The Panel recommends, however, the discussion about each tank be expanded to include documentation and commentary on the locations and causes of the observed leaks. The discussion for each tank should include an operating summary, an operating history, an analysis
of the leak location and cause, a waste loss estimate, commentary on the nature and extent of ground contamination, and a conclusion.

4.2 ASSESSMENT OF CHEMICAL PROPENSITY FOR FUTURE LEAKS IN SINGLE-SHELL TANKS

4.2.1 Introduction

High concentrations of hydroxide ion at high temperature and high concentrations of nitrate ion can cause various forms of corrosion (SCC, pitting, LAI) of the steel liners of the SSTs. In principle, corrosion can occur on the walls above the waste surfaces, at the LAI, and in the liquids of the supernatant and solid layers. The nitrate ion corrosion hazard is mitigated in many tanks by the presence of nitrite and hydroxide ions, ammonia and low storage temperatures.

This evaluation of the future corrosion hazard of unretrieved SSTs was performed by comparing temperatures and average compositions of the liquids in the supernatant and solid layers with two related indices: the nitrite ion/nitrate ion concentration ratio and the Corrosion Chemistry Control Limits presently used for DSTs.

The composition of wastes remaining in retrieved SSTs, the novel compositions that may exist in heterogeneous solid layers, the consequences of the intrusion of water, and the possible accumulation of chloride ion are also considered.

4.2.2 Temperatures and Chemical Compositions in the Unretrieved SSTs

The current chemical compositions of many SSTs have been determined by the analysis of cores from the supernatant and solid layers. Compositions of SSTs that have not been cored have been inferred through engineering estimates based on tanks containing similar waste types, examination of historical records regarding waste transfer operations, and current temperatures of waste layers. Information compiled by Meacham (Meacham, 2008) has been used to evaluate the future corrosion threat.

The SST wastes have been cooling for many years. Twenty are stored below 30°C, six between 40°C and 50°C, eight between 50°C and 60°C, four between 60°C and 70°C and three between 70°C and 77°C.

The nitrate ion contents range from about 0.3 to 6.5 M. The concentrations of the principal corrosion inhibitors also have broad ranges. The measured and estimated concentrations of hydroxide ion range from about 0.01 M to nearly 5 M, and the nitrite ion contents range from 0.01 to approximately 3.8 M. Not surprisingly, the waste compositions in the SSTs are similar to the compositions in the DSTs.

The concentrations of nitrate, nitrite and hydroxide ions and the waste temperatures are summarized in Appendix B.

4.2.3 Previous Test Work

and ongoing investigations since 2000 (Brossia, 2008a, 2008b; Brossia, et al., 2006; Carranza, et al., 2006; Durr, 2005; Hoffman and Subramanian, 2008; Wiersma, 2008; Hoffman, et al., 2008), have examined the factors that govern rates of liner corrosion. These investigations established that corrosion rates depend upon steel properties, potential, temperature, concentrations of aggressive substances (such as nitrate ion), and inhibitors (such as nitrite and hydroxide ion).

The testing programs generally examined the influences of potential, temperature and composition on corrosion and often used Cyclic Potentiodynamic Polarization (CPP) and Slow Strain Rate Testing (SSRT) for the study of waste simulants.

The CPP test provides information regarding the corrosion potential and the propensity for the solution to cause pitting corrosion (ASTM, 2003). The specimen is first scanned in the anodic direction, then the scan direction is reversed at a pre-determined potential or current. Any hysteresis (increase in current during the backscan relative to the upward scan) provides an indication of pitting, while the size of the loop relates to the amount of pitting. If pitting occurs, the potential at which the current increases rapidly, the pitting potential, and the potential at which the current drops significantly during the backscan, the repassivation potential, are measures of susceptibility to pitting. These critical potentials can be compared to the corrosion potential.

The SSRTs define the compositional and potential regions where SCC does or does not occur (ASTM, 2006). The specimen, immersed in the test simulant, is slowly strained to failure while being maintained at a specific potential or while left at the free corrosion potential. The failure strain is noted and the fracture surface of the specimen is then examined visually and by scanning electron microscopy for evidence of SCC.

The testing programs have identified waste compositions vulnerable to pitting corrosion, corrosion at the steel-LAI, and nitrate ion promoted SCC.

4.2.4 Evaluation of Corrosion Risk in the Unretrieved SSTs

Two criteria were employed to assess the propensity for corrosion in the present compositions in the unretrieved SSTs.

First, the nitrite ion/nitrate ion concentration ratio was examined in each layer (for which compositional information was available). The results of the testing programs discussed in Sections 4.1.2 and 4.2.3 indicate that SCC does not occur in Hanford Site waste simulants at open circuit potentials when the nitrite ion to nitrate ion concentration is greater than 0.1, the pH is greater than 11, and the temperature is less than 50°C (Brossia, 2008a and 2008b).

Second, the Corrosion Control Chemistry Limits (Kirsch, 1984; HNF-SD-WM-TSR-006, 2008; Powell, 2009) established for DSTs at temperatures less than 75°C were applied to the SST wastes. These more complicated limits depend on the amount of nitrate ion in the waste. When the nitrate ion concentration is greater than 3 M, the hydroxide ion content must be greater than 0.3 M and the sum of the nitrite ion and hydroxide ion concentrations must be greater than 1.2 M. When the nitrate ion concentration is between 1.0 and 3.0 M, the hydroxide ion content must be greater than 0.1 M nitrate and the sum of the nitrite ion and hydroxide ions must be greater than 0.4 M nitrate. When the nitrate ion concentration is less than 1.0 M, the hydroxide ion content must be greater than 0.01 M and nitrite ion and hydroxide ions must be greater than 0.011 M.
Table 3: Temperatures and compositions of SST supernatant and interstitial liquids.

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<th>Tank</th>
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<th>Temp. °C</th>
<th>OH⁻ (Molar)</th>
<th>OH⁻ (pH)</th>
<th>NO₂⁻ (Molar)</th>
<th>NO₃⁻ (Molar)</th>
<th>Compliance Test (Ratio)</th>
<th>Compliance Test (DST Limits)</th>
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<td>1.00</td>
<td>14.0</td>
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<td>3.50</td>
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<td>0.42</td>
<td>2.32</td>
<td>0.18</td>
<td>Not compliant</td>
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</tbody>
</table>

Note 1: The temperatures and compositions were obtained from Meacham (2008).
Note 2: The assumed leakers are shown in gray on the left.
Note 3: Ratios that less than 0.11 and wastes that are not compositionally compliant are shown in gray on the right.
Note 4: pH is related to the hydroxide ion content by the equation: log [OH⁻(−)] = pH -14

The application of these two corrosion criteria to the SSTs reveal that 19 of the unretrieved tanks contain wastes with compositions that are not compliant with the ratio criterion, the DST Corrosion Control Chemistry Limits or both. These 19 SSTs are listed in Table 3. Generally, the hydroxide ion content is adequate, but the nitrite ion content is too low for the amount of nitrate ion in the tanks. 11 of the 19 noncompliant wastes are in tanks assumed to have leaked (Rogers, 2008).
The application of the same criteria to the former contents (Hu, 2007) of the 10 SSTs that have been retrieved implies 9 of these tanks were also noncompliant. However, most of these retrieved wastes contained very low concentrations of nitrate ion and the propensity for corrosion is not well defined by the DST criteria.

4.2.5 Other Contributory Factors

Long term storage of the wastes in the SSTs has created three other problems that deserve attention.

First, the solid layers of some SSTs have become layered and inhomogeneous as a consequence of waste transfer operations that mixed several waste types. Important variations may exist in layer compositions that are not manifest in the average compositions utilized in the analysis.

Second, groundwater might have infiltrated into waste tanks through cracks in the dome or sidewalls. Rain water might have infiltrated into tanks through risers and other dome openings. There are two related concerns. Many SSTs contain very small amounts of liquid. Therefore, the intrusion of water could adversely alter the pH of the surface layers. Also, the addition of dilute condensate solutions to the DSTs sometimes results in the formation of a separate layer with a pH between 10 and 11 that might be vulnerable to corrosion of the steel at the LAI.

Third, operations in which commercial grades of sodium hydroxide have been added to the waste tanks simultaneously introduced corrosive chloride ions into the waste tanks.

4.2.6 Future Liner Corrosion Mitigating Factors

Two natural factors will tend to mitigate the propensity for future corrosion of the unretrieved SSTs.

First, the temperatures of the wastes in the 19 SSTs containing noncompliant wastes are less than 25°C. The corrosion rates might be so slow at this temperature that neither new pits or SCC are a credible concern.

Second, ammonia, a common constituent of the SST wastes (Meacham, 2008), might inhibit corrosion at the LAI and on the steel walls in the dome spaces.

Several reports indicating the potential effectiveness of ammonia as an inhibitor of corrosion have appeared in the technical literature. This was noted in an early report from the Hanford Site (Endow, 1954a; Rifaey, 2002, Appendix F). Congdon (Congdon 1986a and 1986b) pointed out that ammonia inhibited corrosion at the LAI and in the vapor above Savannah River waste simulants. Anantatmula (Anantatmula, 1996, Anantatmula, et al., 1996, Anantatmula and Berman, 2003) reported that 100 parts per million (ppm) concentrations of ammonia suppressed vapor phase corrosion at high relative humidity with Hanford Site wastes. Subsequently, Frye, Duncan and Wyrwas (Frye, Duncan and Wyrwas, 2008) demonstrated the addition of 0.3 M ammonia to a dilute waste simulant with 0.48 M nitrate ion and 0.04 M nitrite ion prevented pitting corrosion in solution during CPP testing of another Hanford Site wastes.

4.2.7 Conclusion

There are 19 nitrate ion rich unretrieved SST wastes that presently contain nitrite ion/nitrate ion concentration ratios less than the minimum value (0.1) presumed to protect the DSTs from SCC,
or have compositions not in accord with the DST Corrosion Chemistry Control Limits. Wastes in these tanks have been out of compliance for many years. Given that the SSTs were not heat treated, an even greater propensity for SCC exists in the SSTs than in the DSTs.

Some novel compositional variations may exist because of inhomogeneous solid layers, water infiltration and the inadvertant addition of chloride ion since the last samples were analyzed.

4.2.8 Recommendation LD-2: Avoid inadvertent addition of water and chloride to SSTs

The Panel recommends operational procedures be implemented to prevent the inadvertent addition of water and chloride ion to the SSTs. It is recommended that the impact of water intrusion and the unintended increases in chloride ion concentrations be evaluated on a tank by tank basis and that operational procedures be implemented to prevent their introduction in the future.

4.2.9 Recommendation LD-3: Examine Non-Compliant Wastes at 25° C

The Panel recommends examining selected “non-compliant” SST waste simulants at 25° C to ascertain the propensity for pitting and SCC. The corrosion rates might be so slow at this temperature that examination could eliminate new pits or SCC as credible concerns. Waste simulants should also be tested to determine the propensity for causing corrosion at the LAI and on the steel walls in the vapor space. This testing work should be carefully coordinated with the DST testing program that is already underway.

4.2.10 Recommendation LD-5: Determine Ammonia Corrosion Control Concentration

The Panel recommends that laboratory tests be carried out to assess the effectiveness of ammonia as an inhibitor of corrosion in the liquid phases of the solid and supernatant layers, at the LAI and on the exposed walls in the vapor spaces. A laboratory investigation is needed to establish the relationship between the concentrations of ammonia in the vapor that are needed to control these kinds of corrosion. Again, this testing work should be carefully coordinated with the testing program that is already underway with the DSTs.

4.2.11 Recommendation LD-6: Assess SST Waste Compositional Variation

The Panel recommends determining whether the compositional variation in the solid layers of the SSTs deviates from the general SST and DST programmatic assumptions about composition. If so, testing work may need to be performed to evaluate the propensity for corrosion.

4.3 LEAK INTEGRITY OF STEEL LINERS

4.3.1 Background

Information about liner integrity is important for several reasons. Although the liner does not contribute significantly to the strength of the tank, liner integrity is essential to the prevention of leaks. Identifying the nature of the damage to the liner will contribute to understanding the material degradation mechanisms responsible for the leaks. This information could play an important role in future remediation strategies. Different actions might be taken in a tank known to have minor leaks than in one that is known to have a major tear in its liner. For tanks that are not known to have leaked, information supporting leak integrity would provide critical information in guiding their future use.
The challenges in applying NDE techniques to SST liners also apply also to the NDE of the SST concrete (see Section 3.3).

4.3.2 Guided Wave, Ultrasonic Technology to Assess the Presence of Macroscopic Degradation.

Guided waves are the basis for a form of ultrasonic inspection in which the energy is confined by the surfaces of a part. Ultrasound can propagate in the form of waves with two polarizations, longitudinal and transverse (T). If one thinks of a plate, and imagines these waves propagating at an angle with respect to the surface normal, it is obvious that the waves will be reflected each time they encounter a surface and hence will bounce back and forth down the plate. At each of these reflections, there will generally be two waves coming back, a reflected wave of the same polarization as the incident wave and a wave of the other polarization (known as the mode converted wave). In general, the superposition of these multiple reflections and mode conversions will produce a very complex and difficult to interpret wave pattern. However, for any given plate thickness, at certain combinations of frequency and angles, the multiple reflections and mode conversions form a stable pattern, characterized by a specific variation of dynamic stress and strain across the thickness of the plate that propagates without change (in the absence of attenuation) for long distances. This transverse variation is somewhat analogous to a drumhead mode of a particular shape. The electromagnetic modes of a waveguide (e.g., microwave technology) are a consequence of the same general principles. The fact that one can hear a train coming from a long way off by putting one’s ear to the rail is a mechanical example. The rail guides the vibrations created as the train’s wheels roll over the rail to the listener’s ear with very low loss. Many textbooks describe guided wave propagation, with one of the most recent written by Rose (Rose, 2004).

Guided waves are characterized by three parameters: frequency, phase velocity (rate at which phase fronts move down the plate), and group velocity (rate at which energy moves down the plate), all of which are a function of the plate thickness. Guided wave behavior is relatively simple when the wavelength (ratio of phase velocity to frequency) is larger than the plate thickness, becoming much more complex for shorter wavelength (because of the complicated nature of the interference patterns mentioned above). Accordingly, guided wave inspections are generally performed at lower frequencies than conventional ultrasonic inspections, in which generally the frequency is less than the wall thickness.

The practical advantage of guided waves is they can rapidly obtain information about large structures since the structure is scanned at the speed of sound rather than a mechanical scanning rate. However, less detailed information is obtained since the waves integrate information from the region through which they propagate. For this reason, guided waves are often used as screening tools, with other tests added if a positive indication is obtained.

Over the last decade, the interest in NDE with guided waves has grown rapidly. This is due to pipe inspection needs in chemical plants, below grade, etc. References include the plenary paper by Cawley (Cawley, 2003) and papers presented at a number of special sessions in recent conferences (Thompson and Chimenti, 2009). Commercial application of this technology is underway, but the development of codes and standards is still in its early stages.

A key design decision is the selection of the operational frequency. Several engineering trade-offs must be considered. Low frequency waves generally have a lower attenuation and hence can
propagate greater distances. However, higher frequency waves will be more directional and can obtain more information.

A particularly attractive method to implement guided wave measurements is through the use of electro-magnetic acoustic transducers (EMAT) as is shown in Figure 4 (Thompson, 1990). These devices can excite and detect guided waves without the need for a coupling medium such as fluids that are used with piezoelectric transducers, greatly facilitating measurements on the tank liner. Two strategies for implementation should be considered. In one, a pair of EMATs would be positioned diametrically opposite one another at the top of the liner. One would excite a guided mode that would propagate down one wall of the liner, around the corner, across the bottom, around the next corner and up the other wall to the receiver to identify flaws on the bottom of the tank. The presence of a significant tear to the liner would block this signal path causing a drop in the transmitted signal. In an alternative mode, a single EMAT, positioned near the top of the liner, would be operated in a pulse-echo mode. The measurement would be designed to look for reflections from tears in the liner that have a different signature from that of the reflection from the corner.

In discussions about applications to SSTs with experts in the guided wave community, three potential issues were identified, as described below. These are provided to guide feasibility discussions with potential vendors in the event that implementation is pursued.

- **How much energy will travel around the corners at the bottom of the tank as opposed to being reflected from the geometric discontinuity?** The answer will depend on the mode type, frequency and detailed geometry at the tank bottom.
- **Will the energy stay collimated and reach the bottom of the tank as a beam or will it spread out such that it travels around the tank sidewalls?** Spreading is a consequence of diffraction phenomenon controlled by the transducer aperture, W, and ultrasonic wavelength, \( \lambda \). The beam will stay collimated for a distance \( z = \frac{W^2}{4\lambda} \) from the transmitter. If the beam were required to stay collimated for a distance of 30 feet (typical of the height of side walls), and the ultrasonic guided wave phase velocity in the steel were 16,000 feet per second, the frequency, f, would then have to satisfy the relationship \( f > \frac{1.92 \times 106}{W^2} \), where W is measured in feet. Therefore, for a 1-foot aperture, one would require a frequency greater than 1.92 MHz; whereas for a 10-foot aperture, the frequency would only have to be greater than 19.2 kHz.
- **How much will a pulse be attenuated?** This is a significant unknown. Due to the microstructure, attenuation should not be a problem in a steel plate with free surfaces at low kHz frequencies. It is not clear, however, if increased attenuation will become a problem due to concrete loading the steel and water drawing energy from the guided wave in the steel. Determining how tightly the concrete is bonded to the steel would indicate whether this issue might be a problem.
4.3.2.1. Recommendation LD-4: Develop and Deploy Guided Wave Technology

The Panel recommends the development and deployment of guided wave, ultrasonic technology to assess the presence of macroscopic degradation of the steel liner. A design study should be undertaken to determine the optimum parameters of an EMAT system for this application. This should be followed by laboratory feasibility studies and implementation.

Organizations that may be helpful in the development and deployment of this technology include Guided Ultrasonics Limited (U.K.), The Welding Institute (U.K.), Southwest Research Institute, and Sonic Sensors (specializing in the use of EMATs). Peter Cawley at Imperial College (London) leads a strong academic research group specializing in the application of this technology. Guided Ultrasonics Ltd. conducts 1 to 2 day seminars on the use of guided waves. More contact information can be provided upon request.

4.3.3 Direct Current Potential Drop Test

The Direct Current Potential Drop (DCPD) technique is based on injecting current into a metallic component and measuring the resulting voltage (potential) at selected points. For example, if current is injected at one point into a flat metal plate and then extracted at a second point, a distribution of current flowing between these two points can be measured, with the greatest current density occurring along the shortest path between the points. The presence of a crack between the two probes would disrupt the current flow. The change in voltage drop between a pair of electrodes can be measured.
Similar ideas could, in principle, be applied to the tank geometry. Current could be injected on the top of one sidewall and extracted at a diametrically opposed position on the other sidewall. Current will be distributed on the path of least electrical resistance, generally the shortest distance between the two probes. Two paths of particular interest are, (1) around the circumference, a distance of \(\pi D/2\) and down one sidewall, and (2) across the bottom and up the other sidewall, a distance of \(2H+D\). \(D\) denotes the diameter of the tank and \(H\) denotes the height of the sidewall.

Tearing near the bottom of the tank would be best identified by maximizing the current passing through the bottom of the tank as opposed to that passing around the periphery. This will be easiest for shallow tanks, with the two paths being equal when \(H/D = 0.285\). Since \(H/D\) is greater than 0.285 in most tanks, a significant flow around the periphery will occur. Sufficient current might flow through the bottom to allow the detection of a major tear. The situation would be improved if the height of the tank could effectively be reduced by injecting and extracting the current lower on the sidewalls of the tank.

In detecting tears, the voltage would be received by a second set of probes, perhaps placed at 90-degree positions with respect to the injection points.

The Panel is not aware of applications of DCPD to this particular geometry, although such may have occurred. The following action is thus recommended.

**4.3.3.1. Recommendation LD-10: Consider Applying Direct Current Potential Drop to SSTs**

The Panel recommends the feasibility of applying the DCPD technique to SSTs be studied. One approach could evaluate theoretical models for the current flow in SSTs. A second approach would consist of a simple laboratory experiment. A set of small cylindrical, metal cups containing simulated tears of different length would serve as the samples. Current would be injected at one point and extracted at a diametrically opposed point. Voltage measurements could then be used to evaluate the differences in potential distributions between torn and untorn samples. This data would provide a strong indication of the feasibility of field implementation.

**4.3.4 Corrosion Potential Measurements of Liner**

The recent DST integrity project studies at ARES/DNV (Brossia, 2008a and 2008b) have found that potential is a critical parameter for determining resistance of tank steel to both SCC and pitting corrosion in waste simulants. Figure 5 shows a summary of the many SSRTs performed in different nitrate-based waste simulants at 50°C. Filled symbols represent conditions where SCC was observed and open symbols represent experiments where no SCC was observed. For simulants with nitrite/nitrate ratio >0.1, a sharp potential boundary exists near -50 millivolts (mV) versus the saturated calomel electrode (SCE), below which the tank steel is immune from SCC and above which SCC is possible. Critical potentials for pitting corrosion also exist.

At present, the aggressiveness of interstitial fluids in SST sludge and saltcake is not fully understood. While SST waste compositions do not differ significantly from DST waste compositions, or from compositions of other simulants that have been tested, some outliers might exist. Therefore, the Panel has recommended an assessment of all the SST waste compositions. Additional laboratory studies might be needed for specific chemistries that have not already been evaluated. If a similar critical potential were observed for tank liner steel in SSTs, knowledge of the tank corrosion potential would be extremely important. If the tank corrosion potential were known to be well below the critical potentials for SCC and pitting corrosion—in particular if
there were a margin of safety of more than about 100 mV—then there is a low probability of these phenomena occurring in the SST.

Probes for measuring potential, corrosion rate and cracking susceptibility have been developed and inserted into selected tanks. A probe that reliably measures the tank corrosion potential was installed in the DST 241-AN-102 in May 2008. Probes have also been installed in DSTs 241-AY-102 and 241-AY-101. The potential of 241-AN-102 has been measured to be in the vicinity of -360 mV SCE. This potential is more than 100 mV more negative than the critical potential for SCC expected for nitrate based waste (approximately -50 mV SCE) and, as a result, provides a strong indication that this tank will not exhibit pitting or SCC in the near term. Such indication of a benign condition is powerful reassurance of the tank status.

![Cracking propensity for nitrate-based solutions as a function of nitrite/nitrate ratio and test potential. Filled symbols indicate cracking, open symbols indicate no cracking (Brossia, 2008a and 2008b).](image)

**Figure 5:** Cracking propensity for nitrate-based solutions as a function of nitrite/nitrate ratio and test potential. Filled symbols indicate cracking, open symbols indicate no cracking (Brossia, 2008a and 2008b).

**4.3.4.1. Recommendation LD-8: Consider Installation of Corrosion Potential Probe**

The Panel recommends the installation of a potential probe into the sludge or saltcake layer of SSTs that have potentially aggressive interstitial liquids. This would provide critical information regarding pitting or SCC tendencies. Such action is only recommended if SST chemistries are determined, based on analysis or laboratory studies, to be aggressive to corrosion or SCC under tank operating conditions and the chemistries have not been previously addressed in the DST program. The probe could be a simplified version of those employed in the DSTs, or it might be possible to measure with a temporary “dip-stick” approach rather than a permanent probe as is being used in DSTs.

**4.3.5 NDE Screening and Characterization Techniques Capable of Assessing Local Wall Damage**

Based on the results of the guided wave, DCPD, and corrosion probe measurements (Sections 4.3.2 through 4.3.4) more detailed information about the local condition of particular liner regions might be necessary. If so, two possible alternatives should be considered: (a) using NDE probes as end effectors on a mechanical arm, and (b) inserting a remotely controlled robot to conduct inspections. In either case, wall inspections should be conducted on a sampling basis, motivated
by the same general considerations that are applied to the steel walls of the DSTs and focused on evaluating general wall thinning and weld defects.

A series of techniques should be considered, including the following: visual examination using cameras, fluid coupled ultrasound implemented in a fashion similar to that employed in the DSTs, ultrasonic guided waves implemented using EMAT (of a more localized nature than those discussed in Section 4.3.2), and vibrothermography. The motivations for the first two techniques are based on DST project experiences. The advantage of guided wave techniques is that they can rapidly provide information about defects in a large volume of material as the waves scan the material at the speed of sound. The disadvantage of guided wave techniques is the output is not as quantitative as more traditional techniques. Guided wave techniques, therefore, should be used as a screening tool to determine if further inspection is necessary. To scan more localized areas than those discussed in Section 4.3.2, higher frequencies would be required.

Vibrothermography induces a high amplitude vibration (20-40 kHz) in a local region of the structure. Surfaces of cracks will rub against one another as a result of this vibration, generating friction heat that can be detected by an infrared (IR) camera. Since Vibrothermography is an emerging technique, technical details are still being resolved. Consideration would need to be given to the ability of the IR camera to operate in the hostile environment inside the tank.

4.3.5.1. Recommendation LD-7: Assess Deployment of Local Non-Destructive Evaluation Techniques

The Panel recommends assessing the feasibility of deploying candidate local measurement techniques (such as fluid coupled ultrasound, ultrasonic guided waves implemented using EMATs, and vibrothermography) operated as end effectors on a mechanical arm. Deploying such technologies should be based on the outcomes of other NDE recommendations (e.g. discovery of cracks via visual inspection) and a cost benefit analysis that analyzes the difficulties of employing candidate local measurement techniques.

4.3.6 Low temperature fracture behavior of A285 steel and the ductile-to-brittle-transition temperature

4.3.6.1. Fracture toughness and ductile-brittle-transition temperature

SSTs were constructed from hot-rolled mild steels such as A285, A283 and A201 (RPP-11788). As with all steels, the fracture properties are temperature dependent. The fracture toughness (ductility) drops sharply with temperatures below a critical value. This ductile-to-brittle transition temperature (DBTT) is measured by Charpy or static fracture toughness tests. This temperature is reported as approximately 50°F for the Hanford tanks. As the temperature of some tanks is currently 70°F, it is important to consider the implications of activities (such as gelling the tank waste through cooling) that would further reduce tank temperatures.

Several factors favor a lower DBTT in Hanford tank liner steels. Charpy tests utilize impact loading which tends to decrease the fracture toughness and increase the DBTT relative to static tests. A shift of 100°F has been reported (Rana, 1994) between dynamic tests and static tests for carbon-manganese (C-Mn) steels. Further, the thin tank liners are loaded in plane stress conditions that increases fracture toughness relative to thicker samples or plane strain test conditions.
Above the DBTT the behavior is referred to as upper shelf fracture toughness. It has been reported that the fracture toughness (Jc) and static fracture toughness (K_Ic) for welded A285 Grade B steel is 620 inch-lb/inch^2 (110 kJ/m^2) and 143 kips per square inch (ksi) in 1/2 (157 fracture toughness (MPa-m^{1/2})), respectively (Sindelar, et al, 2000). All tests failed by ductile fracture. These are all very high fracture toughness values supporting the idea that these steels are very resistant to fracture as long as the temperature is above the DBTT.

The lower shelf toughness of tank liners is much lower than the upper shelf fracture toughness but still may be sufficient to resist fracture. Values of 30-50 ksi in 1/2 have been reported for SA 533B-1 and a Cr-Ni-Mo-V steel (Ritchie et al, 1979 and Holzman et al. 1995). If the A285 steel has similar values, cooling the tank might not raise issues. A stress equal to the yield strength, 30,000 psi, the lower shelf toughness values results in a critical flaw size of 0.3 inch. Existing stress corrosion cracks would likely be much larger than 0.3 inches. Rapid crack growth would be expected at the lower shelf temperatures if sufficient stress and stress corrosion cracks were present.

4.3.6.2. Aging effects on fracture toughness

A number of processes can embrittle steels. Most common is grain boundary segregation of species such as phosphorous, sulfur, and antimony that occur at temperatures of 500° C. These temperatures are well above those the SSTs have experienced.

Another process, strain aging, occurs in deformed materials when mobile interstitial atoms such as carbon and nitrogen migrate to dislocations and cause an increase in the yield strength and decrease in the ductility. Deformation occurs in the heat affected zone (HAZ) of welds at temperatures of approximately 25° C. The tanks were warmer than this for most of their lifetime so this embrittlement process is not likely to have occurred.

The third process, carbonitride precipitation, also results in a strength increase and ductility loss. It occurs at moderate temperatures of 200° C to 300° C. Given the lack of information, it is difficult to predict whether carbonitride precipitation has occurred in the SST A285 steel. Small steel samples would assist in determining whether hardening of the steel, and possible thermal embrittlement, has occurred.

4.3.6.3. Recommendation LD-9: Consider Testing Tank Liner Hardness

The feasibility and cost of removing small samples from the tank liner for hardness testing should be evaluated. If feasible and cost effective, samples should be removed from a tank that experienced the highest temperature to determine if hardness increases have occurred.

4.3.7 Effects of wall thinning and temperature on residual stress at welds

4.3.7.1. Stress Relaxation of residual stresses

The tank liners are compression loaded primarily from their own weight and the weight of liquids in the tanks. Tensile stresses necessary for driving SCC result primarily from residual stresses around non-stress-relieved welds and hoop stresses caused by the sludge and saltcake. Knowledge of the extent of 60 years of stress relaxation in the steel liners would help identify future risk for SCC.
Julyk (Julyk, 2002) concluded that no allowance was made for stress relaxation and stress relaxation at 300°F would be insignificant. The standard weld stress relief treatment for carbon steels is 1100°F for 1 hour. A study of steel with similar chemistry to A285 (0.2% carbon and 1% manganese) revealed the through thickness residual stresses in a 2 inch thick welded plate were substantially reduced after the steel was heated to 600°C for 2 hours over a 40-hour period (Smith and Garwood, 1992). The maximum residual stress was 600 MPa in the longitudinal direction. This was reduced to a stress of about 50 MPa. A study of stress relaxation at a temperature more relevant to Hanford Site tanks (300°F), cold worked steel with 0.8 wt% carbon was found to have relaxation between 8% and 16% of the residual stress within 72 hours at 257°F (Zeren and Zeren, 2003). This is a higher carbon steel than that in the SST so one would expect higher relaxation rates in lower carbon steel. Extended time periods are not likely to produce significantly greater relaxations as most relaxation of iron occurs within the first hours after being strained (Medrano and Gillis, 1989). An upper bound stress relief value can be obtained from stress relaxation results during tempering hardened steel (Brown, Rack, and Cohen, 1975). This upper bound value involves relaxation from dislocation movement as well as relaxation contribution from carbide formation. The results show the possibility of only 10% relaxation of residual stresses in 1 hour at 300°F. Thus, the extent of weld stress relaxation in the SST liner welds is at least 10% or 20%. This small stress relaxation would have an equally small effect on the probability of a SCC penetrating the liner since the stress intensity, $K$, is linearly related to the stress, $\sigma$, through the linear elastic stress intensity equation: 

$$K = Y \sigma (\pi a)^{1/2}$$

where $Y$ is a geometrical constant, and $a$ is the crack length. Stress intensity is the primary mechanical driving factor for SCC.

Even though the rate of stress relaxation decreases with time, a 50-year period may result in stress relaxation beyond 10-20%. Li (Li, 1967) has shown the relaxation of iron (Fe) has the following relationship: $\sigma - \sigma_1 = K (t + a) - n$ where $\sigma$ is the starting stress, $\sigma_1$ is the stress after time $t$ and $K$, $a$ and $n$ are constants. The value given for $a$ is 1 and $n$ is 0.4. Using these values stress relaxation after 50 years, relative to 1 hour, is estimated at 250 times greater. In other words, substantial relaxation could be possible given enough time. However, the relationship developed by Li was at a temperature of 70°F and the $a$ and $n$ values may change with temperature and material. The result obtained with the Li model appears unrealistic and supports the need for experimental measurements of stress relaxation in the A285 material.

### 4.3.7.2. Potential Effects of Wall Thinning

Uniform corrosion rates will produce general wall thinning at rates of approximately 0.6 mils/year in the lower (waste covered) portion of the tanks and 2 mils/yr in the upper (vapor space) portion of the tank liners (Julyk, 2002, Table 3). It is estimated that, by 2028, liner wall thickness near the bottom of the tank will be 0.2 inch and 0.120 inch near the top of the tank. The original wall thickness was 0.25 inch (Julyk, 2002, Table 3). As is discussed in the following paragraphs, such thinning could produce: (1) a change of the weld residual stresses, (2) an increase in the hoop stresses, (3) a decrease in liner break-through time for cracks, and (4) structural collapse of the tank liner.

Depending on the distribution of the weld residual stress through the tank liner thickness, general corrosion could result in a net reduction of the residual stress by removal of high stress surface material. If the stresses are uniformly distributed or concentrated at the outer diameter, this reduction would be substantially less or could even result in a stress increase. No information is available on the weld residual stress distribution through the liner wall thickness, although estimates could likely be made based on the weld geometry. No conclusion has been reached as to whether general corrosion will reduce, cause no effect, or increase the weld residual stress.
The thinner the wall thickness, the shorter the distance a stress corrosion crack must travel before breaking through the liner. However, crack velocities are sufficiently rapid in the nitrate/high pH environment that reduction in thickness will not have much impact. Given an activation energy for caustic SCC as reported by Singbeil and Tromans (Singbeil and Tromans, 1982a), a SCC velocity in Stage II is estimated at $4 \times 10^{-5}$ millimeters (mm)/s at 300°F and $3 \times 10^{-6}$ mm/s at 100°F. Breakthrough times of $1.5 \times 10^5$ seconds and $2.1 \times 10^6$ seconds result for a 0.25 inch thickness liner at 300°F and 100°F, respectively. Given the SSTs mission, a small change in wall thickness from general corrosion will have little effect on the breakthrough time of a SCC.

The self-supporting tank liner walls are aided by friction loading between the liner and the concrete. The hoop stress in the tanks from the sludge and saltcake could contribute to the friction between the liner and the concrete structure. If this frictional loading is ignored, the tank liner can be thought of as a free-standing structure. The lower portion supports the load of the upper portion. Excessive wall thinning, especially in the lower portion, could result in the collapse of the tank liner. Such a collapse would likely result in large cracks and tears in the liner and hence a significant leak rate of sludge and interstitial liquid from the tank. However, the stress in the lower portion of the tank liner is very small so excessive wall thinning would be required to result in such failure.

4.3.7.3. Recommendation LD-11: Analyze Stress Relaxation of Tank Liners

The Panel recommends further analysis or an experimental study to determine if stress relaxation in the tank liner steels could lead to future SCC.

4.4 SUMMARY OF THE PRIORITIZATION OF LINER DEGRADATION RECOMMENDATIONS

Following are the recommendation titles, in order of priority, for the SSTIP future potential for the liner degradation key element.

- Recommendation LD-1: Expand Leak Assessment Reports
- Recommendation LD-2: Avoid inadvertent addition of water and chloride to SSTs
- Recommendation LD-3: Examine Non-Compliant Wastes at 25°C
- Recommendation LD-4: Develop and Deploy Guided Wave Technology
- Recommendation LD-5: Determine Ammonia Corrosion Control Concentration
- Recommendation LD-6: Assess SST Waste Compositional Variation
- Recommendation LD-7: Assess Deployment of Local Non-Destructive Evaluation Techniques
- Recommendation LD-8: Consider Installation of Corrosion Potential Probe
- Recommendation LD-9: Consider Testing Tank Liner Hardness
- Recommendation LD-10: Consider Applying Direct Current Potential Drop to SSTs
- Recommendation LD-11: Analyze Stress Relaxation of Tank Liners
5.0 LEAK IDENTIFICATION AND PREVENTION

5.1 Leak Detection

5.1.1 Leak Detection Systems

Monitoring for leaks in the SSTs is accomplished through in-tank detection systems (Miller, 2008). In-tank systems provide the ability to determine if a leak event has occurred. The SST in-tank leak detection program operates on the assumption that liquid or semi-liquid waste levels will decrease in response to a leak, but solid levels will not. Selection of the leak detection system therefore depends in part upon the type of waste surface. In addition to level decreases, these systems also monitor for liquid intrusion into the tanks.

The ENRAF™ level gauge is the most accurate gauge used in the SSTs. It tracks level changes in tank waste by using a load cell to monitor the buoyancy of a displacer. The displacer is lowered until it encounters an upward force from a solid or liquid surface. It then tracks the position of the displacer, and reports the level of the solid or liquid surface that it has contacted. The gauge is claimed to be accurate within 0.01 inch (equivalent to approximately 27 gallons). For purposes of leak detection, the ENRAF™ gauge needs a free liquid surface below the displacer. Since nearly all of the tanks have been stabilized (i.e., free liquid and most of the interstitial liquid drained), the gauges are typically utilized for liquid intrusion monitoring.

Manual tape (MT) measurements are performed on several tanks. The system consists of a measuring tape and plummet. The tape and plummet form an electrical circuit connected to a continuity meter. The tape and plummet are manually lowered into the tank until they contact a conductive surface. In open air, the circuit remains open and the continuity meter displays no current flow. Contacting the waste surface closes the circuit, as indicated on the continuity meter. The measurement on the tape indicates the level of the waste. Since dry waste surfaces conduct electricity poorly, MTs are typically used to detect liquid intrusion.

Monitoring the level of the interstitial liquid in the SSTs is accomplished via a liquid observation well (LOW). Since 1985, 79 of the SSTs have been equipped with LOWs for the purpose of leak detection and/or intrusion monitoring (Miller, 2008). A LOW is a three-inch diameter hollow tube constructed of fiberglass, steel or TEFZEL™, which is capped at the bottom, and inserted into the solid waste to within approximately two-inches of the tank bottom (Barnes, 1995). The interior of this tube can be opened to the atmosphere via surface risers, but is isolated from the waste, thus providing a surveying environment free from direct contamination. The LOWs are surveyed using wireline-logging techniques that are common to the geophysical and petroleum industries. Thermal neutron and gross gamma ray probes are utilized to survey the waste. The resulting surveys, which are plots of depth vs. count rate, are then evaluated to determine the depth of the liquid. This system is claimed to be accurate within approximately 0.25 inches (which correlates to approximately 690 gallons in a one million gallon tank). Plots of the derived liquid interface against time are utilized to document trends and changes in liquid levels.

5.1.2 Leak Detection Monitoring Requirements and Best Management Practices

Regulatory requirements for leak detection monitoring (LDM) of SSTs are delineated in RPP-9937, Rev. 3 (Miller, 2008) and summarized in Table 4. These regulations address the technical feasibility of LDM. Best Management Practices (BMP) supplements the requirements by, where necessary. These practices are not derived from regulations, but are recommended to provide an assessment of leakage from the tanks.
Table 4: LDM and BMP requirements for SSTs based on Miller (Miller, 2008).

<table>
<thead>
<tr>
<th>Category</th>
<th># of SSTs</th>
<th>LDM and BMP requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>This category includes: (1) Tanks of suspect integrity (see Note 1) for which LDM is technically feasible, meet the interim stabilization criteria, or (2) contain liquid volumes that are not technically feasible to detect.</td>
<td>71</td>
<td>As a BMP, these tanks are monitored annually for liquid intrusion using currently available monitoring systems supplemented by visual photographic inspections on an as needed basis.</td>
</tr>
<tr>
<td>This category includes: (1) presumed sound tanks for which LDM is technically feasible, meet the interim stabilization criteria, intrusion prevention has been completed, (2) presumed sound tanks that contain liquid volumes that are not technically feasible to detect, or (3) tanks that have been retrieved.</td>
<td>72</td>
<td>As a BMP, these tanks are monitored annually for liquid intrusion and supplemented by scheduled visual photographic inspections.</td>
</tr>
<tr>
<td>This category includes tanks for which LDM is technically feasible; yet do not meet interim stabilization criteria.</td>
<td>6</td>
<td>Presumed sound tanks for which intrusion prevention has been completed require quarterly LDM or intrusion monitoring.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tanks that contain greater than 40,000 gallons of drainable interstitial liquid and do not have complete liquid intrusion prevention require weekly LDM or intrusion monitoring.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tanks in which water intrusion has been detected require weekly monitoring.</td>
</tr>
<tr>
<td>This category includes, (1) tanks for which LDM is technically feasible, the interim stabilization criteria have been met, and do not have intrusion prevention completed, (2) presumed sound tanks that do not meet the interim stabilization criteria and have completed intrusion prevention.</td>
<td>0</td>
<td>Tanks that meet interim stabilization criteria yet have not completed intrusion prevention activities would be monitored on a weekly basis using the current level monitoring systems.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presumed sound tanks that do not meet the interim stabilization criteria and have completed intrusion prevention would be monitored on a quarterly basis.</td>
</tr>
</tbody>
</table>

Note 1: A tank is of suspect integrity if it has been declared a known or assumed leaker, has a bulged liner, or stored boiling waste.

5.1.3 New or Enhanced Monitoring

The vadose zone monitoring system implemented to monitor performance of the 241-T Tank Farm Interim Cover Test (Zhang and Keller, 2006) is an excellent system for tracking infiltrating meteoric water. Expansion of this monitoring system could result in early detection and tracking of leaks. The parameters monitored by this system include: 1) soil water content, 2) soil water pressure, 3) soil temperature, and 4) calculated soil water flux. The technologies used to measure
these parameters meet most criteria for detecting the movement of pore liquids in the vadose zone, are relatively robust, have withstood peer review in the literature for the calculation of flux conditions, and are readily available from commercial sources. These technologies included: neutron moisture monitoring probe, capacitance probe, and heat-dissipation sensors. A datalogger and a meteorological station are also incorporated into the monitoring design.

Early reporting of the results of this monitoring system (Zhang et al., 2008) are promising. However, several items in the performance monitoring system for the T Tank Farm Interim Cover Test are needed to determine if the system is optimized. Evaluation of additional time series data (e.g., monitoring data from fiscal year (FY) 08, Zhang et al., 2008) will provide additional basis for evaluating longer-term operational performance. Several example items, as discussed below, illustrate the need for further consideration of specific monitoring design and installation features.

The backfill in the annulus surrounding the heat dissipation sensors (HDS) was specified as 20/40 sand. Heat dissipation sensors provide an indirect measurement of the matric potential of soil water. The sensor is generally heated for a fixed time period. Since water conducts heat much more readily than air, the rate of heat dissipation is controlled by the water content of the porous matrix. Heat dissipation sensors consist of a heater and a temperature sensor in a porous matrix material that equilibrates with the surrounding soil. The HDS are installed in very fine and wet silica flour slurry surrounded by 20/40 sand (coarse and dry); the native material also appears to be typically coarse and dry. Because of the difference in the nominal pore size distribution and moisture content between the HDS installation and the surrounding coarser sand, the potential for a capillary barrier may exist around the silica flour slurry, thus preventing equilibration of water in the porous matrix of the sensor with water in the surrounding formation native material. If a capillary barrier does exist, the HDS will remain wet (in the range of -0.2 to -0.4 bars) because moisture cannot move freely out of the slurry and dissipate into the surrounding materials, resulting in an erroneously high HDS measurement of the formation soil water content and matric potential. Soil water potentials are between 1 bar and saturation (Zhang et al., 2008), suggesting the potential for significant movement of liquids in the vadose zone. The range of soil water potential reported appears higher than anticipated for the soils commonly encountered on the Hanford Site.

It is not clear if the HDS probes (specifically the ceramic probe tips) were installed in a wet or dry condition. Equilibration of water in the ceramic probes and in the surrounding soil can result in unreliable gradient calculations as monitoring data will appear to show the soil wetting or drying. Other installations have shown significant equilibration time required for probes to match the potential of the surrounding material. This ‘equilibration’ phenomenon should be taken into account when evaluating future monitoring data.

Soil flux drain gauges (Zhang et al., 2008) did not collect drainage water. Zhang (Zhang et al., 2008) concluded that hydraulic properties of material in the drains were not adequately characterized to determine the proper height of the divergence control tube. Moisture may have been diverted around the drain gauge due to gradients induced by the instrument itself.

5.1.4 Recommendation LIP-1: Continue Leak Detection Monitoring and Best Management Practices and Enhance Monitoring Capabilities

The panel recommends continuing to maintain the current LDM and BMP approach. These practices, coupled with interim stabilization of the waste, provide a means of minimizing the potential for leakage of waste to the environment. The Panel further recommends installing enhanced monitoring based on potential leak risks at each tank farm. The 241-T Tank Farm
Interim Cover Test has proved an excellent system for tracking infiltration of meteoric water. Increasing the depths and expanding the aerial extent of monitoring similar to this test will provide an excellent system for early detection and tracking of leaks.

5.1.5 Recommendation LIP-6: Investigate Leak Detection Technologies for Tanks With Less Than 24 Inches of Waste

DOE has a leak detection plan and is in compliance with Ecology requirements for leak detection. However, for tanks with 24 inches of waste or less, the absence of LOW and a solid surface does not allow for leak detection. Currently there is no technology available for leak detection at these low waste levels. The Panel recommends investigating and developing technologies to address this deficiency.

5.1.6 Ex-tank Monitoring for Leakage During Waste Retrieval

All of the SST farms have five to eight monitoring boreholes installed around each tank. These boreholes, also referred to as dry-wells, were installed and used as part of a tank leak detection monitoring system to detect the presence of gamma-ray-emitting radionuclides in the vadose zone sediments surrounding the tanks. The boreholes are approximately 100 to 200 foot deep and are supported by a carbon steel casing. For many years, gross gamma measurements were made via the dry-wells to determine whether a tank was leaking. However, these were recently discontinued, as they are no longer considered appropriate for the task.

A new leak detection technique, High Resolution Resistivity (HRR), has been effectively demonstrated during recent waste retrieval activities. One major advantage of this technique is that it utilizes existing dry-wells. HRR uses a four-electrode system to measure the soil resistivity surrounding the tank (Schofield, 2007). Measurements are made from dry-well to dry-well, dry-well to surface, and dry-well to tank. HRR can detect a 5,000 to 10,000 gallon leak.

To use HRR effectively, baseline soil resistivity data is acquired. HRR, in conjunction with ground penetrating radar, electromagnetic induction, and differential magnetometry, were utilized to perform Surface Geophysical Exploration (SGE). These techniques identified sub-surface objects or structures that might interfere with the HRR measurements. The SGE produced sub-surface soil resistivity characterization maps. Average baseline resistivity details are contained in RPP-32477 (Schofield, 2007).

During waste retrieval for a particular tank, HRR data is collected on 15-20 minute cycles for a 48-hour period. The average slope is compared to the baseline slope threshold range for a given data pair (e.g., dry-well to tank data pair). If the slope exceeds the threshold range, a value of “1” is assigned to the data pair, while the slope is within the threshold range it is assigned a “0”. This calculation is repeated for each data pair. The 48-hour cycle is then repeated with data points older than 48 hours being replaced by the latest set of data. The “1” and “0” are used to calculate a rolling average percentage of how often each data pair exceeded baseline slope threshold ranges in 24 hours. The 24-hour rolling average percentage for all dry-well to tank data is called the Leak Potential. This value is compared to an action level setpoint and is applied only to dry-well to tank data. The action level setpoint percentage is 50%. This action level is based on several mock demonstrations of the system. A Leak Potential that exceeds the setpoint indicates a positive correlation to a physical change. Exceeding the action level triggers data evaluation to explain the cause of the data trend.
5.1.7 Recommendation LIP-3: Continue Use of High Resolution Resistivity

The Panel recommends continuing to utilize the HRR technique for ex-tank leak detection.

5.2 Assessment of Leak Rates Through Tank Liners

Water can penetrate the very tight dimensions of a stress corrosion crack as seen in nuclear reactor piping. It is not clear whether water contained in sludge or as interstitial liquid in saltcake will penetrate these tight cracks because of the forces restraining the water within the sludge.

There is currently no evidence that liquid is leaking from the interim stabilized (retrieved) tanks that contain supernatant, sludge or saltcake. Nor is there evidence that new stress corrosion cracks have developed since the tanks were stabilized. However, continued use of the SSTs requires mitigation efforts be considered to assure SST leak integrity. To determine if such mitigation technologies are necessary, the Panel investigated the issue of whether liquid would leak out of sludge or saltcake through stress corrosion cracks.

Evidence exists that SSTs have cracked in the past (see Section 4.1). Uncertainties exist as to whether the SSTs will continue to crack in the future. There is evidence that SCC will form in carbon steel at stresses of about 80% to 100% of the yield strength (Mazille and Uhlig, 1972; and Bombbara and Bernbai, 1981) in caustic solutions. Also, carbon steels have been shown to have stress intensity threshold of 10-15 MPa-m\(^{1/2}\) in caustic solutions (Singbeil and Tromans, 1972b). A stress equal to the yield strength of the carbon steel used in the tanks will cause cracking in caustic solutions with a flaw as small as 0.5 mm. This flaw could be the result of pitting or other surface defects.

Carbon steels have also been shown to experience SCC in nitrate solutions. Past SST chemistry included high concentrations of nitrate that were mitigated by additions of nitrite and hydroxide. However, it is possible that cracks formed prior to these additions.

SCC of carbon steels in nitrate solutions was studied extensively forty years ago, in part due to nuclear waste storage tank concerns (as discussed in Section 4.2). The parameters affecting the aggressiveness of nitrate solutions include, temperature, cation type, stress, and the concentration of the aggressive ions and the inhibiting chemicals steel carbon content. Somewhat unique to nitrate stress corrosion cracking is the role of the cation in the mechanism. Extensive tests on Hanford wastes have been conducted and are discussed in Section 4.2.

One evaluation that could prove useful is to determine whether the leak rate through new or future cracks is significant. Leak rates of gases through orifices are supported with experimental data and models (Worden, et al., 1962; Jones, Conn and Schafer, 1985). There have also been efforts to measure leak rates of high temperature water through cracks in nuclear piping. In these models the water is superheated to a vapor in the crack (Friedel and Westphal, 1989).

Experimental measurements and predictions of water leakage through cracks have been reported by Grebner and Hofler (Grebner and Hofler, 1992); Yano, et al., (Yano, et al., 1989); and Whitman (Whitman, 1975). Grebner and Hofler report experimentally measured and predicted leak rates ranging from 5 to 10 gallons per minute (gpm) for a water pressure of 10 MPa (1470 psi). No flaw size was given. Yano, et al., (Yano, et al., 1989) predicted leak rates of 5 to 10 gpm through a flaw of 19 x 0.25 mm and a pressure of 6.8 MPa (1000 psi). In an effort to determine leak rates from Savannah River Site waste tanks, Whitman (Whitman, 1975) performed a series of experiments using through-wall stress corrosion cracks and water under a pressure head. The cracks were formed in steel plates by nitrate SCC. For the smallest flaw of 25 x 0.15 mm of crack...
opening, Whitman measured a leak rate of less than 0.001 gpm with a pressure head of water of 37 feet.

Several forces drive liquid leak rates from sludge and saltcake. Crack pressure and capillary forces attract the liquid, capillary action in saltcake and sludge repel the liquid. An analysis performed at Savannah River National Laboratory (SRNL) (Mertz, 1999) has predicted a leak rate of 0.09 gpm for a six inch through wall crack. The fluid was assumed to have a viscosity of 5 to 10 centipoises (cP). This is a viscosity approximately 10 times greater than water. However, even this small leak rate results in the leakage of 47,304 gallons/year. Sludge has a viscosity of 20-30 cP so it is likely the leak rate will be less than 47,304 gallons/year. Mertz (Mertz, 1999) also estimated the leak rate for fluid with a viscosity similar to water leaked at 0.36 gpm or approximately 190,000 gallons/year. These results indicate unacceptable leaks could occur if leak mitigation methods are not implemented.

5.2.1 Recommendation LIP-5: Evaluate Sludge and Saltcake Liquid Leak Rates

The Panel recommends evaluating liquid leak rate assessments through sludge and saltcake from the Savannah River Site to determine if the results are applicable to the Hanford Site SSTs.

5.3 Test for ionic conductivity between the inside and outside of tanks.

It is possible that ionic pathways to the ground through liner cracks exist underneath the sludge and saltcake layers. If such a condition exists, new leaks might be generated during sluicing operations.

It might be possible to test for ionic conductivity by inserting a probe into the tank sludge layer and another outside of the tank in the ground and measuring the resistance or impedance between the two. Figures 6 and 7 show schematic illustrations of electrodes in and outside of an SST. Between these electrodes are various phases that provide resistance. To measure a resistance, a small current must be passed. Note that electrical current can be carried either by electrons in an electrical conductor such as metal or by ions in an ionic conductor such as sludge, saltcake, or soil. Current can also change between electronic and ionic conductors as the result of electrochemical reactions at the interface of an electrode and electrolyte.

It is reasonable to assume that a good electrical connection could be made between a metal probe immersed in the tank sludge or saltcake (labeled Metal 1 in Figure 6) and a resistance meter such that the resistance along that connection would be essentially zero. A resistance exists across the metal/sludge interface. In fact, an equivalent electrical circuit consisting of a parallel resistor and capacitor can represent the electrical response of many electrode/electrolyte interfaces. The resistance, called polarization resistance (Rp), is inversely proportional to the rate of the electrochemical reaction. If the metal electrode is corroding, then the polarization resistance is a measure of the corrosion rate. The capacitance is associated with the electrical double layer that sets up at this interface and is called the double layer capacitance.

Following the electrical path to the right, the ionic current would flow through the sludge or saltcake (indicated in Figure 6 as sludge for simplicity) until reaching the next barrier, the tank liner. Transport resistance through the sludge can be represented by a resistor, the value of which, $R_{\text{sludge}}$, would depend on the resistivity of the sludge and the geometry of the current flow (length and cross-sectional area). Assuming that the tank liner is intact with no ionic pathway connected with a through-crack, the current would have to convert to electronic current at the sludge/liner interface. This interface can be represented by another parallel resistor and capacitor as shown in
Figure 6. The electrochemical reaction at this interface (passive dissolution of the tank metal) would convert the ionic current back to an electronic current, which would flow through the tank metal. The resistance associated with this current, $R_{\text{liner}}$, would be essentially zero. The current would then be converted back to ionic current at the outer surface of the liner.

**Figure 6**: Schematic of a system to measure ionic pathways. Expanded image of the current path segments between a metal electrode in a tank and one in the ground including an equivalent circuit.

Figure 7: Schematic of an EIS system to measure ionic pathways.

The outer liner surface is covered with tar that acts as a sort of water-proofing. The nature of this phase in terms of its electrical and ionic resistance is not clear. However, it is certainly not a perfect water-proofing or else waste would never leak. There is some conductivity of the tar
phase, \( R_{\text{con}} \). The next phase is the concrete, which has a resistivity associated with the pore water, which reaches equilibrium with the calcium hydroxide in the cement. The conductivity of concrete, and the next phase, which is soil, depends on the amount of water available. Both concrete and soil can be quite conductive if enough water is present, which would allow passage of ionic current until reaching the interface associated with the electrode in the soil, Metal 2.

If the liner is breached by a through crack, then it is possible for part of the equivalent circuit in Figure 6 to be shorted. At a minimum the crack would short the two liner interfaces and it might also short the tar layer. If the resistance of the crack were low compared to the resistances of these interfaces and phases, then the current would flow as ionic current from the sludge to the concrete. A resistance meter operating in DC mode might sense the difference in resistance between a shorted and sound tank. One would have to use a tank thought to be sound as a control case.

Instead of using a DC resistance measurement, it might be possible to be more sensitive to such cracks using an AC measurement, which is called electrochemical impedance spectroscopy (EIS). EIS would require the use of a third electrode, a reference electrode, placed on the ground between the tank and the auxiliary or counter electrode. In brief, EIS works by applying a potential sine wave of varying frequency to an electrode and measuring the current. One can obtain the impedance as a function of the frequency. The impedance is, in general, a complex number owing to any capacitance of the equivalent circuit describing the electrochemical system. The response of a system having an ionic short through the liner would be different than that of a system having a sound liner with electrochemical interfaces on either side. This would be true if the time constants, \( R \times C \), of the polarization resistances and double layer capacitances associated with the liner interfaces were vastly different than the time constant of Metal 1 in the sludge. These different time constants would provide an EIS spectrum of very different nature than if there were an ionic path directly from the surface of Metal 1 to the soil.

As a result, the EIS response of an electrode immersed in a tank with reference and counter electrodes placed outside the tank should provide information about the existence of any through-crack in the liner. However, it would only sense cracks below the level of the sludge or saltcake. On the other hand, such a technique might be useful during retrieval operations to sense for leaks through cracks above the sludge top surface layer as liquid is sluiced into the tank. If a change in the impedance response were sensed during retrieval, operations could be shut down to prevent leakage.

EIS is a practical technique that has wide application. However, there are several unknowns and possible artifacts that would complicate the measurement. The values of the circuit elements shown in Figure 6 are unknown so that it is not clear if the resistance or impedance of a cracked liner would be different than that of a sound liner. It should be noted the area normalized resistance associated with the polarization resistance of an electrochemical interface has dimensions of \( \Omega \text{-cm}^2 \) and the resistance of the full exposed area is determined by dividing this value by the area. For a large tank, this would result in a low resistance. The stray capacitance associated with long lead wires also can create problems with this measurement.

### 5.3.1 Recommendation LIP-8: Assess the Feasibility of Testing for Ionic Conductivity between the Inside and Outside of SSTs

The Panel recommends that an assessment of the feasibility of this approach be initiated. Some laboratory-based experiments and analysis would be helpful and straightforward.
5.4 Strategies for Future Leak Prevention

5.4.1 Introduction

The prevention of future leaks in SSTs is a major objective. Wastes have been retrieved from 10 SSTs and other tanks have been interim stabilized by the removal of most of the drainable liquids. Nevertheless, the unretrieved SSTs still contain approximately 30 million gallons of radioactive waste, including more than 2.5 million gallons of drainable liquids (Roger, 2008).

The prevention of future leaks is a complex problem due to uncertainties about the conditions of the steel liners and differences in the behavior of liquids in sludge and saltcake and mixtures of sludge and saltcake. If drainable liquids remain in contact with the present steel liners, there is no assurance that future leaks can be prevented. Consequently, the strategies for future leak prevention are centered on the immobilization or removal of drainable liquids, or the introduction of new internal barriers between the wastes and steel liners.

There are major variations in the amounts of drainable liquids in the SSTs and in the properties of these liquids within the saltcake and the sludge layers of the SSTs. These variations require that liquid removal be considered on a tank-by-tank basis. Special emphasis should be given to methods that serve the interests of the community and worker health and safety, and do not compromise the future retrieval of the wastes.

5.4.2 Liquid Waste Removal

The most efficient method for removal of the drainable liquids is simply to pump them from a SST into a sound DST. Operations of this kind have been underway at the Hanford Site for many years and the interim stabilization program is virtually complete.

This program originated in the work of Handy (Handy, 1975) and was augmented by other technical contributions (Metz, 1976; Kirk, 1980; Flach, 2003a, 2003b; Strohmeier, 2007). In essence, these investigations showed the interstitial liquids drain very slowly from sludge layers, and rather rapidly from saltcake layers. The drainage rates of liquids from salt cakes are directly proportional to the height of the liquid, its density, and its viscosity. Drainage occurs until the height of the liquid column can no longer overcome the capillary forces. Estimates of this height range from approximately 0.5 to 2 feet for Hanford Site saltcake.

Engineering analyses and practical experience indicate major difficulties are encountered when pumping rates decrease to less than 0.05 gallons per minute. For example, approximately 1,000 hours were required for the drainage of approximately 100 gallons of liquid from the saltcake in Tank 25 at the Savannah River Site during the final stages of liquid removal (Strohmeier, 2007). Operational procedures, such as clearing the pumps of solid deposits, often added more water to the waste than could be removed by the continuation of the pumping operation at the limiting rates (Martin and Terry, 2009).

The present protocols permit the abandonment of pumping when the transfer rate is less than 0.05 gallons per minute (72 gallons/day). They also permit the retention of 50,000 gallons of drainable liquid within a single saltcake layer. This amount of liquid does not include the liquid retained by capillary forces, which is assumed to be 0.5 feet. As already mentioned, the SSTs now contain more than 2.5 million gallons of drainable liquids (Roger, 2008).
5.4.2.1. **Recommendation LIP-4: Seek Engineering Methods to Increase Water Removal by Pumping From SSTs**

The Panel recognizes the problems are challenging, but believes pumping is a safe and potentially efficient and cost effective method for the removal of liquids from the tanks. Consequently, the Panel recommends engineering solutions be sought for the removal of additional liquids from the tanks by pumping.

5.4.2.2. **Water Removal**

The removal of water from SSTs would decrease both the amount of liquid in the tank and the viscosity of the remaining liquid, therefore, reducing its drainability.

Water has been removed through enhanced dome ventilation and by passing air through the waste. In some circumstances, the rates of evaporation have been accelerated by heating the air, waste or both. Rates of water removal are adversely affected by the slow rates of water transport through sludge, saltcake, and surface crusts. To avoid this difficulty, air has been introduced beneath the waste surface.

The SSTs are now passively ventilated by natural variations in barometric pressure. Modeling suggests that more than 100 years are necessary to materially impact the water content of deep saltcake or sludge layer (Simmons, 1998; Meacham, et al., 1997; Sandgren, 2002). However, modeling indicates that a shallow saltcake waste (10 inches deep) would lose approximately 16 percent of its water in 10 years. In some circumstances, a 16% reduction in the water content might be sufficient to materially impact the mobility of the liquid. Generally, the removal of water by natural ventilation is too slow to accomplish the desired goal.

Water loss rates from actively ventilated tanks are much higher. The models mentioned in the previous paragraph indicate more than 1,000 gallons of water per year per tank can be removed by active ventilation.

The combination of active ventilation and heat considerably accelerate water removal. In one instance, portable air exhausters were used to remove water from the waste in Tank 241-A-104. Approximately 7,000 gallons of water were removed from the tank and photographs show the waste surface is dried and cracked (Johnson and Field, 2008).

The surface crust presumably decreased the water transport rate through the partially dried solids beneath the surface and through the surface crust. This difficulty has been circumvented by passing heated air in concentric tubes below the solid surfaces.

Steam coils and other methods have been used to heat the wastes and accelerate drying during ITS operations (Rifeay, 2002, Appendix D). For example, a heat exchanger, operated at 115º C, removed water from Tank 241-BY-101. At the end of the operation, the density of the residual liquid was about 1.6 g/mL and the viscosity was 21 cP at 33º C (Brevick, 1996; Dunn, 1986).

Other methods considered for accelerating water removal include microwave heating (Brevick, 1996; White, 1990; Berry, 1990) and wiped film evaporation techniques (Brevick, 1996; DP82-157-2, 1982). Additional rate enhancements could be achieved by the use of drying agents.

The Panel concludes implementation of a water removal strategy would require expensive active ventilation and heating. Heating will increase the risk of pitting corrosion and SCC. In addition,
two concerns central to the interests of community and worker health and safety arise. First, heating increases the rates of decomposition of organic compounds and the attendant risk of unacceptably vigorous exothermic reactions (Meacham, et al., 1997; Sandgren, 2002). Second, heating accelerates the formation and release of hydrogen, inorganic and organic compounds (Mahoney, et al., 1999; Stock, 2001; Stock and Huckaby, 2004). On balance, the Panel does not regard accelerated water removal as an attractive approach for future leak prevention.

5.4.2.2.1. Recommendations LIP-11: Avoid Heating and Active Ventilation Strategies for Removing Additional Water from SSTs

The Panel recommends against pursuing strategies from removing water from tanks that include active ventilation or heating.

5.4.3 Liquid Waste Immobilization

The attempts to immobilize waste by the addition of solid absorbents have not been encouraging. Large amounts of diatomaceous earth (27 to 95 tons) were added to six SSTs in 1972 (241-BX-102, 241-SX-113, 241-TX-116, 241-TX-117, 241-TY-106, and 241-U-104) and Portland cement was added to another SST (241-BY-105). None of these operations were judged successful (Brevick, 1996). The diatomaceous earth clumped during addition and did not spread evenly over the surface. The cement powder initially spread across the liquid surface, but did not mix sufficiently to provide the desired protective barrier (Brevick, 1996). Attempts to remove residual liquid from this tank were unsuccessful because the main underground transfer line was blocked by cement. Even more discouraging, Tank 241-U-104 continued to leak after the addition of 55 tons of diatomaceous earth (Rifaey, 2002).

5.4.3.1. Recommendation LIP-2: Avoid the Addition of Water-Insoluble Absorbents to SSTs

The Panel recommends the addition of water-insoluble solid absorbents be avoided. Such additions do not appear to be especially effective for immobilizing water, will interfere with the future retrieval of wastes, and may adversely impact WTP operations.

5.4.3.2. Addition of Gel Agents

Immobilizing liquids by adding organic and inorganic thickening agents has been considered previously. Organic compounds including starch, acrylates, methacrylates, carboxymethylcellulose, and polymers grafted to starch are effective because they are naturally slow moving molecules that restrict motion within the liquid phase by interconnecting the aqueous network via numerous hydrogen bonds and other dipolar interactions. Advantages include the maturity of such techniques and the ability to reverse the process by dilution. The disadvantages of the approach include problems associated with mixing gelling reagents with interstitial liquids dispersed through heterogeneous solid layers, relatively high material costs and increased radiolytic and chemical production of hydrogen during storage in SSTs and in future operations of the WTP (Meacham, 2008).

At least two inorganic gelling agents have been identified. One tactic involves adding silica gels that immobilize the drainable liquid, but can be subsequently pumped as liquids. The second involves the use of carbon dioxide to gel aluminum-rich waste through pH adjustment. It has been
reported that, “large quantities of complex aluminum hydroxide gel are produced by passing carbon dioxide through simulated waste solutions equivalent to those found in Tank 241-SY-101” (Alexander, et al., 2006). These gels restrict interstitial liquid mobility by converting saltcake into sludge. Gel formation can be reversed by the adjustment of the pH (Alexander, et al., 2006).

The use of silica gels is also a mature technology, with similar problems associated with dispersal of organic gelling agents in the heterogeneous solids. In addition, it would be necessary to demonstrate that silica gels are compatible with WTP operations. Gelling aluminum rich wastes by adding carbon dioxide is a promising technology. However, two important complications exist. First, the addition of carbon dioxide will likely increase the corrosivity of the waste. Second, the sodium hydroxide used to reconstitute the liquid will adversely impact future operations.

5.4.3.2.1. Recommendation LIP-12: Avoid Strategies to Immobilize Waste Through the Addition of Gelling Agents

As a general programmatic practice, the Panel recommends against the addition of gelling agents. Existing gelling techniques will be difficult to implement, may complicate WTP operations, and may increase the corrosivity of the waste. However, individual tank-by-tank instances may arise in which gelling a tank may be a wise option (e.g. to stop a significant tank leak or if new gelling techniques were developed).

5.4.3.3. Cooling

Cooling the waste would presumably increase the viscosity and reduce the mobility of the interstitial liquid. The temperature required to render the liquids sufficiently immobile does not appear to have been investigated. However, Poloski (Poloski, et al., 2007) formulated an empirical expression for the description of the viscosities of Hanford Site wastes based on densities and temperatures. The expression implies the effect of temperature would be significant. To illustrate, the measured viscosities of two different wastes with densities of approximately 1.5 g/mL are 22 cP (25°C) and 27 cP (29°C). The Poloski formulation implies the viscosities at 18°C (the natural ground temperature at the Hanford Site) would be approximately 29 and 35 cP, respectively. For comparison, the viscosities of ethylene glycol (antifreeze) and glycerol are about 22 and 1,400 cP, respectively, at ambient temperature.

The influence of temperature on viscosity is sufficiently large to suggest that cooling, which would also reduce the mobility of the liquids in complex solid matrices in other ways, would materially slow the drainage of liquids from sludge and saltcake wastes. Lowering the temperature has the added advantage of reducing the general corrosion rate and the likelihood of pitting and SCC. However, carbon steels exhibit a ductile to brittle transition with decreasing temperature and the impact of this transition on tank integrity would need to be assessed.

5.4.3.3.1. Recommendation LIP-7: Evaluate Effect of Lowering SST Waste Temperature

The Panel recommends the effect of lowering the temperature on the drainability of representative waste types be determined during other investigations of drainability (Recommendation LIP-5).
5.4.4 Internal Barriers on Steel Liner

Tank inspections at the Savannah River Site imply numerous small cracks in the steel liners have been sealed by water evaporation and the waste solidification in the cracks (Martin and Terry, 2009 and Martin, 2009). Such findings suggest that the cracks may be sealed by the addition of silicates, sugars, and clays. Technology of this kind has been considered previously (Bamberger, et al., 2001). This approach suffers from the same disadvantages that have been discussed previously for other additives.

An alternative approach involves introducing a synthetic bladder into the tank and transfer of waste into the bladder. This technique has been used successfully in the petroleum industry for the elimination of leaks in storage tanks. The polymer Ethylene-Propylene-Diene Monomer (EPDM) is known to be rather resistant to alkaline waste and simulants. A bladder made of this material could line a complete tank if its reliability were shown to be extremely high.

5.4.4.1. Coating of liner interior with barrier layer

Given the potential for cracks in the liner above the current waste level, concerns of additional leaks during sluicing retrieval exist. Sluicing might raise the liquid level to a crack, resulting in leakage. It would be advantageous to identify a method to seal the tank liner inner wall sufficiently to allow safe retrieval by sluicing.

Thermal spray technology was invented in 1910 and has been applied widely since the 1980’s (Davis, 2004). Thermal spray technologies accelerate fine dispersions of particles or molten droplets and impact a surface to form conformal and adherent layers. Each particle or droplet forms a flattened “splat.” Many different metals, ceramics, intermetallics and polymers can be thermal sprayed. Typical applications improve wear resistance, corrosion resistance, thermal resistance, or electrical properties. If the inner liner surfaces could be covered with a protective coating prior to retrieval, then leakage concerns would be assuaged.

There are several issues relevant to the application of thermal sprayed layers onto SST liners. A thermal spray deposit typically contains 1-2% porosity and a connecting pathway could allow leakage over time. However, for low pressures and short time periods, even porous coatings might resist leakage. A related technology, cold spraying, can deposit 100% dense coatings. Titanium is a corrosion resistant metal utilized in cold spray applications.

Thermal spray is performed over a distance of inches, not feet. To create an adherent deposit layer, surface layers should be removed by grit blasting before thermal spraying. It is possible to grit blast and simultaneously collect the residue with a vacuum system. It would be necessary to remove hazardous gases such as hydrogen during any such operation.

Another potential application for coating the liner would be the reuse of known sound SSTs. Such tanks might be used to hold low temperature, in-spec waste with low aggressiveness. The first step would be to use NDE methods to assure liner integrity. Leak integrity would be enhanced by coating the liner surface with a material resistant to corrosion and SCC.

5.4.4.1.1. Recommendation LIP-10: Evaluate Coating of Tank Liners and Installation of Polymeric Bladder

The Panel recommends evaluating both the coating of the tank liners with a material resistant to corrosion and SCC; and the deployment of a polymeric bladder to line SSTs. The Panel
acknowledges that difficulties associated with introducing materials into SSTs may reduce the feasibility of implementing this recommendation.

5.4.5 Evaluation of the use of cathodic protection of the SST liners

There is considerable evidence that the SST liners have leaked due to SCC in non-stress relieved welds. It is conceivable that the stresses at the cracks have relaxed during the last 50 years and it is also possible that the sludge and salt cake will not cause SCC. However, a conservative conclusion is that the conditions of the tank are still sufficient to cause SCC (an estimate of stress relaxation is provided in Section 4.3.7.1). Also, since the chemistry of the sludge and salt cake are known, it can be estimated whether the conditions exist to cause SCC.

Cathodic protection (CP) is widely applied to suppress corrosion of thousands of miles of underground pipelines, offshore structures, and steel reinforcing bar in concrete, bridges and water storage tanks. CP requires a source of direct current, an auxiliary electrode (anode) located at some distance from the protected structure and a conducting medium between the two. The applied voltage is based on the resistance of the ionic medium and the current density required to protect the component. CP works on the principle of protecting a structure from corrosion by the impressed current driving the electrochemical potential of the protected part to lower values. The dissolution rate decreases exponentially with decreasing potential, so the corrosion rate can be greatly decreased by CP. Singbeil and Tromans (Singbeil and Tromans, 1982) have concluded that caustic SCC of carbon steels is an anodic dissolution driven cracking process. Therefore, it is reasonable to expect that suppression of anodic dissolution in the SST tank liners would greatly reduce the potential for SCC. Also, SCC can initiate from pits. Pitting is also an anodic dissolution corrosion process that is suppressed by CP.

The feasibility of applying CP to DSTs was conducted and reported by E.L. Moore (Moore, 1977). It was concluded that such a system would not be necessary because nitrite was added to the liquid waste and CP could cause corrosion based on a study conducted at Battelle Columbus Laboratories (Payer, 1977). The corrosion study suggested the tanks were adequately protected from SCC when nitrite was added to the high pH, nitrate-containing waste. However, there was also evidence that SCC could occur at potentials below the active SCC potentials. This conclusion was based on the presence of a small anodic peak in the potential-current curve at potentials below the primary anodic corrosion peak for iron in these environments. Therefore, CP was deemed not necessary and potentially harmful to the integrity of DSTs.

Most of the SSTs also have nitrite present in the supernatant and solid layer (see Sections 4.1 and 4.2). Therefore, these tanks likely have conditions similar to those which led to the decision to not employ CP for the DSTs. However, several of the non-retrieved SSTs have little or no nitrite and should be examined regarding their potential for SCC.

Another reason that a CP system could be harmful is based on the results of Singbeil and Tromans (Singbeil and Tromans, 1982) who found intergranular SCC in caustic solutions in the active-passive electrochemical potential range but transgranular SCC in caustic solutions at the open circuit potential. Driving the potential lower with a CP system could activate the transgranular SCC form of caustic SCC.

Several practical considerations raise issues for the application of CP in the SSTs: (1) frequent replacement of the reference and anode electrodes, (2) difficulty of penetrating the saltcake with these electrodes, and (3) high CP currents as a result of the large, unprotected surface area of the tanks.
Use of CP for the protection of the exterior of the tank and/or the rebar is a viable option. Waste from overfilled tanks or leaks have contacted the external surface of the tank liner and rebar. Whether this caused corrosion or is continuing to cause corrosion is unknown. The high pH waste should not have caused much corrosion to either the outside diameter of the liner or the rebar. Also, it is possible that ground water has seeped through the concrete and caused corrosion of the rebar and outside diameter of the tank liner.

5.4.5.1. Recommendation LIP-9: Consider Cathodic Protection for Rebar and Exterior of Tank Liner

The Panel recommends that CP not be deployed for use in protecting the interior of SST tanks where supernatant, sludge and/or saltcake is present. The Panel further recommends that CP be considered as an option to protect the exterior of the tank liner and rebar, should evidence arise that either has corroded.

5.5 SUMMARY OF THE PRIORITIZATION OF LEAK IDENTIFICATION AND PREVENTION RECOMMENDATIONS

Following are the recommendation titles, in order of priority, for the SSTIP leak identification and prevention.

- Recommendation LIP-1: Continue Leak Detection Monitoring and Best Management Practices and Enhance Monitoring Capabilities
- Recommendation LIP-2: Avoid the Addition of Water-Insoluble Absorbents to SSTs
- Recommendation LIP-3: Continue Utilization of High Resolution Resistivity
- Recommendation LIP-4: Seek Engineering Methods to Increase Water Removal From SSTs
- Recommendation LIP-5: Evaluate Sludge and Saltcake Liquid Leak Rates
- Recommendation LIP-6: Investigate Leak Detection Technologies for Tanks With Less Than 24 Inches of Waste
- Recommendation LIP-7: Evaluate Effect of Lowering SST Waste Temperature
- Recommendation LIP-8: Assess the Feasibility of Testing for Ionic Conductivity between the Inside and Outside of SSTs
- Recommendation LIP-9: Consider Cathodic Protection for Rebar and Exterior of Tank Liner
- Recommendation LIP-10: Evaluate Coating of Tank Liners and Installation of Polymeric Bladder
- Recommendations LIP-11: Avoid Heating and Active Ventilation Strategies for Removing Additional Water from SSTs
- Recommendation LIP-12: Avoid Strategies to Immobilize Waste Through the Addition of Gelling Agents

6.0 MITIGATION OF CONTAMINANT MIGRATION

6.1 Introduction: Natural and Man-made Recharge: A Driving Force

Groundwater recharge is a hydrologic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose zone and is often expressed as a flux to the water table surface. Recharge occurs both naturally (e.g., as the result of rainfall) and
anthropologically (e.g., by "artificial groundwater recharge" either intentional or accidental as with pipe leaks), where rainwater and or other sources of water are routed to the subsurface.

SST leak information contains many uncertainties (Zhang and Keller, 2006). Leak dates, leak volumes, leak detection limits (i.e., the minimum size leak that can be detected) and the spatial distribution of wells required to detect leaks in areas deemed at highest risk all contribute to these uncertainties. Historical water migration into the subsurface has been associated with precipitation and leaks from water lines, pumps, sumps, unlined ditches and trenches, surface spills, and run-on from offsite locations.

Though annual precipitation at the site averages less than 180 mm/year, recharge of meteoric precipitation can be significant and is enhanced by the lack of vegetation in the SST farms and the presence of erosion-armoring gravel that constitutes a barrier to evaporation. Gee, et al. (Gee, et al., 2007) reports that recharge averaging more than 60 mm/year has been measured for over 25 years at the Hanford Site. Recharge reported by Gee et al. for bare gravel-covered surfaces, such as exists at the SSTs, ranges from 50 to 100 mm/year. The effective recharge at the SSTs is locally enhanced and concentrated in the subsurface when downward percolating water is diverted by the sloping, low-permeability concrete domes of the SSTs (Khaleel et al., 2007). This mechanism is analogous to the concentration of rainwater dripping off the roof eave of a residence.

6.2 Past SST Leak Detection Methods

SST leak detection has been accomplished using several methods. Inventory systems using tank soundings and remote camera inspections are limited by access difficulties and potentially permeability-limiting salt cake and sludges in the tank interior. Near-tank systems are also used to detect the leaked material in the soil very close to the tanks. These methods have been evaluated using external sensor arrays deployed at a mock-tank that detected changes in the near-surface electrical field related to increased moisture content (Barnett et al., 2003). Also, historic and newer dry wells (approximately 800 wells) extending deeper in the vadose zone have been monitored for gamma radiation.

Performance evaluation testing was performed for two types of Electrical Resistivity Tomography (ERT): Point-Electrode Technique (ERT-PET) and Long-Electrode Technique (ERT-LET). A second method, High-Resolution-Resistivity Steel Casing Resistivity Technique (HRR-SCRT) was also tested (Barnett et al., 2003). Both methods were reported successful in identifying leaks (nine out of 13 leaks were detected) and reasonably estimating the volume of the leak (ERT-LET could not estimate leak volumes; ERT-PET overestimated the leak volumes by a factor of two). Success was dependent on the exceptional performance of the geophysical monitoring equipment and the data acquisition system.

Historically, monitoring of the dry wells has identified the general location of leaked materials within the vadose zone. The monitoring data indicate contaminant movement due to infiltration of meteoric water through relatively high-permeability soil materials surrounding the tanks.

6.3 Surface Barriers to Mitigate Future Leachate Migration

6.3.1 Surface Barrier Effectiveness

The application of interim surface barriers has been successful at reducing infiltration at waste facilities, and is a standard practice at many municipal landfill facilities. Khaleel, et al. (Khaleel,
et al., 2007) modeled a “no-surface barrier” scenario that calculated recharge of 100 mm/year infiltration with no surface barrier. For an interim surface barrier scenario, the model estimated recharge at 0.5 mm/year.

Knepp (Knepp, 2002) conducted a preliminary evaluation of Interim Corrective Measures (ICMs) that have been evaluated as they relate to the waste management area (WMA) S-SX. Knepp (Knepp, 2002) stated that, “ICMs are response actions having the objective of reducing contaminant migration to groundwater to acceptable regulatory levels and which require a balancing of risk, benefits, and costs.” The study compared the performance of a surface barrier to a near-surface barrier and to an overhead structure. The only surface barrier evaluated was a 6 cm (2.5 inch) layer of asphalt cement pavement. The near-surface barrier consisted of an impervious, buried geo-fabric (geomembrane liner or geosynthetic clay) system over the entire WMA S-SX to direct surface water to the outer boundaries of the WMA. For both the surface and near-surface barriers, a run-off collection system consisting of ditches and pipes would be required to route collected surface water to existing drainage routes. The overhead structure consisted of an enclosed shelter covering the majority of the surface water control area of the WMA. An asphalt apron would be constructed around the perimeter of the structure to capture surface water and route that water to a run-off collection system.

The ICMs were evaluated using a relative scoring system for the following criteria: safety, regulatory compliance, life cycle cost analysis, tank integrity, future retrieval and processing, schedule, proven technology, maintainability, operability, constructability, decontamination, decommissioning, and disposal. Based on this, implementation of a surface barrier ranked highest among the three. The cost estimate presented to implement the surface barrier in the 241-S and 241-SX tank farm WMAs was $3,373,000 and $3,892,000, respectively.

An interim barrier of spray-on polyurea was applied in 2008 as part of a demonstration project (Badden, 2008) It would be useful to have a little more information. Monitoring instrumentation was installed both under and outside of the interim demonstration barrier. Modeling estimates (Khaleel et al., 2007) and baseline data indicate in the absence of a surface barrier, surface infiltration may further distribute contamination within the vadose zone and continue to impact groundwater in the area.

Data from the FY 2007 monitoring report shows that monitoring instrumentation is working as intended; however, only the sensors outside of the interim cover footprint were gathering data. It is assumed that the sensors beneath the interim cover have been collecting data since the application of the cover in 2008. Review of FY 2008 monitoring data will provide insight as to whether the instrumentation beneath the cover is working properly.

The interim surface barrier demonstration instrumentation was designed to detect and quantify surface infiltration. The instrumentation associated with the demonstration project is limited. The recommended expansion of the surface barrier system should be accompanied by design and expansion of the monitoring system. Despite a lack of current data, the modeling results presented by Khaleel et al. (Khaleel et al., 2007) indicate a significant reduction in recharge.

Surface barriers have proven effective at reducing infiltration. Surface barriers are the most common form of landfill remediation because they are both effective and less expensive than other technologies (FRTR, 2009). The FRTR (2009) states, “The most effective single-layer caps are composed of concrete or bituminous asphalt. It is used to form a surface barrier between landfill and the environment. An asphalt concrete cap would reduce leaching through the landfill into an adjacent aquifer.”
6.3.2 Subsurface Techniques to Mitigate Future Leachate Migration

Treat et al. (Treat et al., 1995) published a report that evaluated the feasibility of 13 subsurface barriers deemed viable for application to the SSTs. Additional concepts were discussed but considered less viable. Eleven of the thirteen techniques were standoff in character, meaning the options were to be installed some distance in the subsurface from several tanks or a tank farm. Two of the techniques were characterized as close-coupled, or designed-to-be-installed in contact with individual tanks. The information was subjective and required testing to determine their respective suitability.

The viable options that Treat et al. (Treat et al., 1995) evaluated, along with salient caveats for each concept, are summarized below.

6.3.2.1. Standoff Options

6.3.2.1.1. Chemical Jet Grout Encapsulation using Cementitious Grouts

Chemical jet grout encapsulation isolates waste systems by using high-pressure jet grouting to form columns of grouted soil via directionally-drilled wells. Portland cements, bentonite clays, or more exotic grouts are used. Concerns raised included producing contaminated soils during drilling and installing complete and uniform barrier without extensive overlapping of barrier sections.

6.3.2.1.2. Ice Encapsulation using Freeze Walls

Two freezing methods were considered: (1) slow-rate freezing or closed-loop systems and (2) fast-freezing or open-loop systems (e.g., liquid nitrogen). Directional drill holes with steel casings are used to emplace the desired freezing line. An open system could quickly freeze the soil and then couple with a closed-loop system to maintain the freeze wall barrier. Concerns include whether the system would create sufficiently low permeability within the highly transmissive Hanford Site soils or whether it would be necessary to inject supplemental water. This action could have the undesirable side effect of mobilizing soluble contaminants. Installation could potentially create some stresses on the SSTs due to the expansion of the soil during the freezing process. As an active subsurface barrier concept, freeze walls would likely require a refrigeration plant to maintain the barrier.

6.3.2.1.3. Jet Grout Curtains using Cementitious Grout

Jet-grouted curtains are similar to grout encapsulation except that both vertical and horizontal well drilling, rather than directionally drilled wells, would be used for injection. Concerns similar to those associated with other grouting scenarios were also noted for this methodology. Emplacement of the horizontal component of this solution was deemed problematic.

6.3.2.1.4. Permeation Chemical Grouting using Cementitious Grouts

Permeation chemical grouts would be injected at lower pressures than jet grouts. Both vertical and horizontal barriers would be formed. Horizontal drilling would be utilized for the placement of a horizontal permeated grout barrier beneath a tank farm. This technology raises seismic concerns as joints between grouted zones could separate under tension. Variation in soil texture
and porosity (e.g., silt lenses, clastic dikes, and other soil heterogeneities) will likely prevent uniform permeation of chemicals which may result in ungrouted soil volumes.

6.3.2.1.5. Wax Emulsion Permeation Grouting using Grouts with Thermoviscous Fluids

Wax has a high-melting point and is composed of C-24 to C-32 esters of long-chained acids and alcohols. In this concept, an emulsion of wax, water and a surfactant is injected in the target soil zone. The wax particles move through the soil pores with the fluid. Once inside the soil matrix, the wax particles aggregate and move through void spaces until they bridge an opening and become fixed. Bridging these openings between pores reduces the permeability of the soil. Concerns are the wax may destabilize in the presence of SST leachates with a high pH (> 12.0) and the wax, like other petroleum products, is susceptible to bacterial biodegradation over time.

6.3.2.1.6. Silicate Permeation Grouting using Colloidal Silica, Sodium Silicates

Sodium silicate grout consists of four components: water, an acidic liquid consisting of glyoxal and additives, an alkaline liquid consisting of silicon dioxide and sodium oxide, and an aqueous suspension of non-agglomerated silica particles in an alkaline medium. Colloidal silica, a colloidal suspension with gelling properties, was also considered. When the pH decreases to less than 10, the colloid would polymerize or gel, form a cross-linked network, and reduce soil permeability. As with other grouting methods, predicting the movement of injected grout is difficult due to the anisotropy and heterogeneity of most Hanford Site soils.

6.3.2.1.6.1 Polymer Permeation Grouting using Grouts with Polymer Grouts, Polyacrilates

Polymer permeation grouting employs an injected liquid monomer or resin that is converted to a polymer to form a concrete-like monolithic barrier. Polymer-forming chemicals could be injected into the ground using the same methods for emplacing cement slurry walls. Polymer grout is expensive compared to standard grouts. Some polymer grouts (e.g., furfuryl alcohol) are chemically incompatible with Hanford Site soils.

6.3.2.1.6.2 Formed-In-Place Horizontal Grout Barriers using Rubberized Cements, Clays and Grouts

Horizontal grout barriers could be constructed in-situ in a basin configuration without excavation. A proprietary technology would generate a concrete barrier slab of uniform thickness (0.3 m) between guide wires placed by horizontal drilling methods. Demonstration projects had not been completed at the time of the Treat et al. (Treat et al., 1995) report. As a result, the feasibility of the technology had not been completely demonstrated. Any formation of concrete cold joints may render the barrier prone to leakage over time.

6.3.2.1.7. Radio Frequency Desiccating Subsurface Barriers using Electrodes

A radiofrequency (RF) heating process was considered for the formation of an active desiccating barrier underneath SSTs. RF energy applied to electrodes would heat a 2 to 3 m (7 to 10 ft) thick soil layer to temperatures above 100° C moisture creating a dry barrier. Concerns were that horizontal holes must be drilled to relatively low tolerances to achieve the 1 to 2 m (3.3 to 6.6 ft) spacing required for the RF electrodes. As with the Circulating Air Barrier (CAB), the absence of a physical barrier would complicate recovery of leaked waste (particularly sudden, large volume events).
6.3.2.1.8. Sheet Metal Piling Subsurface Barriers using Sheet Metal w/Grout

Interlocking metal sheet piling in a vertical configuration forms sheet metal piling subsurface barriers. This barrier is coupled with a horizontal barrier to form a complete barrier envelope. Injecting grout where the sheets are joined seals sheets. Concerns are that the approach has typically been limited to vertical sheet piling installations. The technology is not usually applicable to soils containing boulders or large cobbles such as may exist at the Hanford Site.

6.3.2.2. Close-Coupled Options

Close-coupled options, as described below, are designed to be installed in contact with individual SSTs.

6.3.2.2.1. Close-coupled Injected Chemical Barriers using Low-cost Filler and Polymer

This close-coupled subsurface barrier option adapts the concepts of jet and permeation grouting in angled boreholes using directional drilling methods. Injectate chemicals include Portland cement, polymer formers, and aggregating emulsions. The chemical grout would be formed against the sides and bottom of an individual SST. In one version, the close-coupled barrier walls are installed directly against the tank walls using vertical boreholes. The horizontal members of the barrier are installed in two layers using horizontal boreholes. Close-coupled barriers may induce physical stresses on the tank, depending on the emplacement method used. Close-coupled injected chemical barriers are relatively unproven and have undergone little testing. The area between many of the tanks is restricted (nominally 25 feet).

6.3.2.2.2. Induced Liquefaction Barriers using Sheet Metal with Polymer

This close-coupled subsurface barrier option combines sheet metal piling to create a vertical barrier with caisson-drilled horizontal jet grouting. One to three caissons (or a coffered trench) would first be excavated using a 5 to 7 m (15 to 20 foot) diameter clamshell. An overlapping horizontal jet grout curtain would be installed via horizontal wells through the caisson(s) or coffered trenches. Finally, vertical injection wells would be installed between the SST and sheet metal piling/jet grout curtain to inject grout, polymers, or other barrier-forming material, encapsulating the SST. Concerns are that sheet metal pilings may be subject to corrosion without CP. Boulders and large cobbles may cause the sheet metal edges to deflect. The horizontal component of this barrier had not been demonstrated at the time of the study. Potentially contaminated soils could be brought to the surface during the excavation of caissons or trenches.

6.3.3 Leverage Past Work and Recent Technological Developments

Since the Treat et al., (Treat et al., 1995) report was written, advancements have been made in environmental remediation technologies. The knowledge base has increased substantially for nearly all of the remediation technologies considered in 1994. In addition, new remedial technologies have been identified.

6.3.3.1. New Potential SST Leak Mitigation Technology: Injected Apatite Reactive Zone

As an example of recent advances in subsurface remediation, an in-situ remediation technology, has been recently identified that utilizes the placement of apatite \([\text{Ca}_{10}(\text{PO}_4)_6(\text{X})_2]\), where X is a monovalent anion such as \(\text{OH}^-, \text{Cl}^- \text{or F}^-\). Apatite is very resistant to biodegradation, highly stable and remains unaltered for thousands of years. As described by Moore (US Patent No. 6,592,294
B1; July 15, 2003), the proprietary placement process is based on injecting a solution of calcium citrate and sodium phosphate into soil. As the citrate is biodegraded, calcium is gradually released and reacts with the phosphate to form insoluble calcium phosphates that transform into apatite. Apatite is a strong sorbent for radionuclides and heavy metals. Apatite strongly sorbs uranium, plutonium, strontium, lead and other contaminants (Seaman, et al., 2003).

Because citrate forms strong complexes with calcium, it prevents the calcium from immediately reacting with the phosphate before it can be injected into the soil. However once injected, citrate is easily metabolized by microorganisms. As the citrate is biodegraded, calcium is gradually released and reacts with phosphate to form insoluble calcium phosphates. At pH between 7 to 9, and in the presence of fluoride, conditions are favorable for apatite formation.

Hydroxyapatite and apatitic compounds have been demonstrated to irreversibly sorb a variety of constituents including actinides, strontium, and lead. Technetium is also sorbed when a second material is added that reduces the technetium before capture by the apatite (Sandia National Laboratory, undated). Tests conducted in a laboratory setting indicate that, in highly oxidizing conditions, technetium does not desorb from apatite (Sandia National Laboratory, 2001a). The technology appears to have promise for SST application and proposals have been written for demonstration of the technology in bench-scale and field-testing environments (Sandia National Laboratory, 2001b).

In 2008-2009, a series of presentations reported on testing to determine the appropriate rate of Ca-citrate-PO$_4$ solution injection with the objective of achieving relatively uniform spatial distribution of apatite, and to determine the optimum injection rate to balance Sr-90 adsorption with Sr-90 migration to the aquifer. Effective delivery of the solution to both low- and high-permeability zones involves a slow injection until the low permeability material is nearly saturated, followed by a high injection rate resulting in the wetting of nearby high-permeability zones (Szecsody et al., 2008).

A field study, comprised of three injection tests, was conducted in which 300,000 gallons of solution was injected into a total of 16 wells screened across the Hanford and Ringold Formations. The peak Sr-90 concentration in down-gradient monitoring wells increased 8.3 times at a relatively high stoichiometric ratio of calcium to phosphate and citrate. Subsequent injection tests were conducted with lower calcium and citrate concentrations that reduced Sr-90 in the monitoring wells (Thompson et al., 2009).

6.3.3.2. Potential SST Leak Mitigation Technology: Electrokinetic Remediation

Electrokinetic remediation is a process in which a low-voltage direct-current (DC) is applied across a volume of contaminated soil between electrodes in the soil. Under the influence of a DC field, contaminants can be moved toward an electrode and then recovered. Electrokinetics has been applied to move contaminants to a target zone for extraction. Electrokinetics was eliminated in a previous Hanford Site technology screening study (WMP-27397, 2005) to support remediation of technetium-99 in the deep vadose zone. It is not effective in dry soils and would be difficult to implement in the deep vadose zone. Key problems include uncertainty of consequences induced by concentrating contaminants and water in a small area of the vadose zone, limited zone of influence for the electrodes, and limited applicability in low moisture content soils (USDOE, 2008). Due to these challenges, electrokinetics was not included for treatability testing in the Fluor Hanford Inc. study (WMP-27397, 2005).
6.3.3.3. Potential SST Leak Mitigation Technology: Circulating Air Barrier (CAB)

As previously discussed, the CAB system is a desiccant-type barrier designed to prevent the movement of liquid contaminants toward groundwater. It employs air circulation and a processing system to lower the soil water saturation in a subsurface zone. The concept of CAB was evaluated in a study (USDOE, 1993) of barrier systems that could be installed beneath and around the tank farms with a minimum of excavation. The CAB can be installed using either vertical or horizontal wells to establish a pattern of air injection and extraction wells. The moving air vaporizes water and carries the water vapor to an extraction well. Over time, circulation of the air reduces the water saturation in the swept interval, and continues to remove, by evaporation, liquids that move into the zone. In the event of a leak, the CAB system desiccation zone provides a monitoring point for early leak detection. The desiccation zone also provides a means to withdraw volatile contaminants by vapor extraction or to mitigate aqueous chemical migration by reduction of the saturation level. Identified advantages of the CAB system include non-physical confinement, active monitoring and leak detection, commercially available equipment, a monitored zone for emergency response, and high potential for integration with other remediation technologies. However, the concept needs to be demonstrated to develop data needed for scale-up and regulatory acceptance. Field pilot testing of the CAB system is underway at the Hanford Site, although published results are not currently available.

6.3.3.4. Performance Assessment Monitoring of Subsurface Barriers

SST subsurface leak mitigation strategies will require performance assessment and monitoring programs to demonstrate effectiveness in relation to remedial action objectives. Significant advancements have been made in the areas of subsurface monitoring, remote data acquisition, and data handling and interpretation. The technological capability exists to cost-effectively: place sensors, conduct real time and automatic remote data acquisition, handle and manipulate large datasets, and quickly provide data interpretations (e.g., leak location, leak volume, pore liquid travel velocity).

6.3.3.5. SST Leak Mitigation Combined with SST Closure Strategy

The optimum leachate mitigation strategy should support the objective of final tank closure. For example, Knepp (Knepp, 2002) accounted for life cycle cost analysis, tank integrity, and future retrieval and processing in his evaluation of ICMs.

6.3.3.6. Risk Assessment

Risk assessment methodologies have also advanced since the Treat et al., (Treat et al., 1995) report. SST leak mitigation strategies should be evaluated based on modern risk evaluation methodologies. In the past 15 years, toxicological data that underlies risk calculations has expanded and improved. Exposure information has improved through data collection. The methodologies upon which cancer risk evaluation is based have also improved. These new advancements in the science of risk assessment should be addressed in a modern risk evaluation to provide the risk reduction estimates associated with SST leak mitigation.

6.3.3.7. Limited Benefit of Subsurface Barriers

Treat et al., (Treat et al., 1995) found that capping the tank farm with a surface barrier capable of limiting recharge to 0.05 cm/year (0.02 in/year) may result in acceptable risks for some tanks if collapse of the tank domes could be prevented. Treat, et al., (Treat et al., 1995) also concluded the
use of subsurface barrier concepts would not result in significant additional risk reduction. Except for the clean-closure application, the cost-effectiveness of subsurface barrier technologies is essentially equal and relatively low. The cost-effectiveness of the subsurface barriers, calculated by the method most favorable to subsurface barriers, is about 0.0001 times that of surface barriers, and 0.01 times that of the set of baseline technologies.

### 6.3.4 Recommendation MCM-1: Install Surface Barrier Over SST Farms

Recommendations for future interim measures (Badden, 2008) related to minimizing surface infiltration are valid and should be accomplished as soon as possible, specifically constructing, maintaining, or upgrading run-off and storm water control structures and constructing interim barriers at other tank farm areas. Design and implementation of a surface barrier to reduce recharge at the SSTs is recommended. Sources of water that could contribute to subsurface water deep percolation should be identified and controlled. New control/barrier measures should be prioritized based on risk associated with past and/or future releases. In a recently published study, Maann (Maann, 2009) presents criteria for prioritizing future SST interim barriers and for evaluating barrier performance. This study should be used as the initial basis for implementing interim surface barriers.

### 6.3.5 Recommendation MCM-2: Evaluate Subsurface Leak Mitigation Technologies

A number of viable candidate subsurface leak mitigation strategies have been identified in the past. Since the last published Feasibility Study (FS) in 1994, new viable remedial technologies have been identified and developed, and older technologies have matured and improved. Using the previously conducted FS as a selection guide, a program to evaluate the viable leak mitigation technologies should be initiated. This program should consist of bench scale studies (where possible), followed by demonstration in a Hanford Site field setting where appropriate. In some cases, these tests have already been initiated. The above-mentioned injection apatite reactive zone and CAB technologies are examples that have already been implemented. Concurrently, an updated FS should be performed, using updated risk assessment methodologies and modern performance assessment technologies. It is recognized that an updated FS and risk-based selection process may also conclude, as before in the Treat et al., (Treat et al., 1995) study, that only little additional benefit can be derived from implementing a subsurface barrier in addition to implementing a surface barrier.

### 6.4 SUMMARY OF THE PRIORITIZATION MITIGATION OF CONTAMINANT MIGRATION RECOMMENDATIONS

Following are the recommendation titles, in order of priority, for the mitigation of contaminant migration key element.

- Recommendation MCM-1: Install Surface Barrier Over SST Farms
- Recommendation MCM-2: Evaluate Subsurface Leak Mitigation Technologies

### 7.0 REUSE OF SSTS

The Panel was tasked with providing recommendations to support development of a robust SSTIP—not developing criteria allowing the reuse of SSTs for routine storage.
Although this issue was clearly outside the Panel’s scope, it arose during the Panel’s deliberations several times. As a result, the Panel has included this section to reflect its deliberations on this issue.

Generally, the Panel discussed the difficulty of executing activities necessary to demonstrate that an SST was sufficiently sound to be reused. Some initial thoughts on this issue include:

- SST inspection and hydrostatic testing would be necessary. This report outlines many of the difficulties that currently face inspection efforts (e.g. waste characteristics, lack of SST access, and geometry of SSTs). If the inspection goal were SST reuse, the requirements would likely be quite stringent and, as a result, increase the difficulty of inspection.

- SSTs with compositions not in compliance with the Kirsch (See Section 4.2.4) criterion or those that have a nitrite to nitrate ion concentration ratio less than 0.1 should be excluded from consideration for reuse. Most of these tanks fail the compliance test because they have insufficient nitrite ion or low pH.

- SSTs that have boiled waste for long intervals should be excluded.

- SSTs that have contained waste type compositions known to have a high propensity for leaking should be excluded.

- SSTs that contain benign waste types could be considered for reuse.

- SSTs that maintained stagnant waste levels for long periods should be excluded as LAI corrosion would be a concern.

The Panel acknowledges the topic of SST reuse is politically sensitive. Given this, and the technical difficulty of demonstrating whether SSTs are sound, much time and effort would be necessary to develop a process by which a decision to reuse SSTs could be made.
8.0 REFERENCES


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APPENDIX A

SHORT BIOGRAPHIES FOR SINGLE-SHELL TANK INTEGRITY PANEL

MICHAEL T. TERRY, P.E., PANEL CHAIR
CONSULTANT
Perot Systems Government Services

Mr. Terry is currently providing independent consulting services to clients such as the US Department of Energy and the US Nuclear Regulatory Commission. He earned a Masters Degree in Mechanical Engineering from Washington University and a BS in Mathematics from the University of New Mexico. He has extensive experience in nuclear and process safety; engineering, design, and construction of nuclear and non-nuclear facilities and processes; program and project design and implementation; management systems and organizational development; professional facilitation; and project management and administration.

Recently, Mr. Terry has been assisting the Double-Shell Tank Integrity Project (DSTIP) at CH2M HILL, Hanford Group, Inc. (CH2M HILL). His primary responsibilities include chairing an Expert Panel on tank waste chemistry optimization, oversight of the implementation of the recommendations from the original panel report as chair to an expert panel oversight committee, and providing technical and programmatic guidance on matters related to the DSTIP. He has also chaired and facilitated a workshop with another expert panel assembled to investigate vapor space corrosion in the Hanford double-shell tanks. In addition to these activities for the CH2M HILL, Mr. Terry facilitated a High-Level Liquid Waste Tank Integrity Workshop for the Savannah River National Laboratory, with participation similar to the Hanford double-shell tank integrity workshops.

TODD MARTIN, PANEL CO-CHAIR
CONSULTANT

Todd has worked on Department of Energy Environmental Management issues for nearly 20 years. Todd received his Masters in Environmental Sciences from Bard College and Bachelor of Science in Biology from Whitworth College. Consulting with DOE, contractors, states, and public interest organizations Todd has worked to forge consensus in DOE communities to ensure cleanup protects the health and safety of the public, workers and the environment and is technically sound, publicly accountable and fiscally responsible. Todd is currently leading the river corridor clean up standards working group for DOE-RL.

JOHN A. BEAVERS, PH.D.
CHIEF TECHNOLOGY OFFICER
CC Technologies, A DNV Company

Dr. Beavers is Chief Technology Officer of CC Technologies, a corrosion engineering and research company. Currently, he serves on the Expert Panel Oversight Committee for Chemistry Optimization for Double-Shell Tanks at Hanford. He has directed and contributed to numerous research programs on corrosion performance of structural materials. These programs have included failure analyses, critical literature reviews, and laboratory and field evaluations of metallic and non-metallic materials. Dr. Beavers has utilized state-of-the-art electrochemical, surface analytical, and mechanical techniques for evaluation of materials performance for different forms of corrosion.
Electrochemical techniques used include potentiodynamic polarization, polarization resistance, electrochemical impedance spectroscopy, electrochemical noise, and galvanic current measurements. Surface analytical techniques used include Auger electron spectroscopy, x-ray photoelectron spectroscopy, energy dispersive x-ray spectroscopy, scanning electron microscopy, transmission electron microscopy, electron microprobe, and x-ray diffraction. Mechanical techniques used include elastic and plastic fracture mechanics and dynamic mechanical loading techniques such as slow strain rate and low cycle fatigue.

**STEPHEN J. CULLEN, PHD.**
CONSULTANT
D.B Stephens and Associates

Dr. Cullen is a Principal Hydrogeologist with more than 30 years of experience. Areas of expertise include vadose zone and groundwater flow and transport modeling, hydrocarbon and halocarbon site investigations, contaminant source identification, hazardous and solid waste landfill investigations and monitoring systems, metals and radionuclide investigations, land disposal of biosolids and sewage effluent, land treatment facilities, intrinsic bioremediation as well as active approaches to soil and groundwater remediation. Dr. Cullen has provided expert opinions and testimony for resolution of a wide range of groundwater and vadose zone characterization, monitoring, and remediation problems. Dr. Cullen was co-author of the Handbook of Vadose Zone Characterization and Monitoring published in 1995 by Lewis Publishers.

**GERALD FRANKEL, PHD.**
PROFESSOR and DIRECTOR
Fontana Corrosion Center at The Ohio State University

Dr. Frankel’s primary interests are in the fields of corrosion and electrochemistry. He has focused on localized corrosion, passivation, coatings, inhibition, corrosion of electronic and magnetic materials, X-ray absorption studies of electrochemically-formed films using synchrotron radiation, behavior of anodes used in electrodeposition applications, and electrodeposition of magnetic materials. Presently, he serves on the Expert Panel Oversight Committee for Chemistry Optimization for Double-Shell Tanks at Hanford. The current activities in Dr. Frankel’s group are focused largely on localized corrosion, and primarily on the corrosion and protection of Al and Al alloys. His group is using a number of approaches to study pitting, intergranular corrosion and exfoliation corrosion of Al alloys related to aging aircraft. His group has initiated novel uses of Atomic Force Microscopy-based techniques in the study of corrosion, including Scanning Kelvin Probe Force Microscopy and Atomic Force Microscopy scratching. The mechanism by which chromates inhibit the corrosion of Al alloys has been studied in earlier projects.

Currently his group is studying the inhibition mechanisms of various chromate replacements. Corrosion of welds has been another focus of Dr. Frankel’s work. A Cr-free consumable for the welding of stainless steel is currently under development with the goal of minimizing the production of Cr-containing weld fumes. In another study, the susceptibility of oxide dispersion strengthened Ni-based superalloys to hydrogen embrittlement is under study. Dr. Frankel is the author of over 150 publications, primarily in the field of corrosion.
RUSSELL H. JONES, PHD.
CONSULTANT
GT Engineering

Dr. Russell H. Jones has 38 years of experience in materials development, evaluation, and characterization. Dr. Jones has extensive experience in the fields of stress corrosion cracking, radiation effects on materials, corrosion, and high-temperature composites. His work in stress corrosion cracking includes evaluation of the effects of hydrogen, aqueous, high-temperature, and nuclear environments on crack growth behavior of iron, nickel, aluminum, and magnesium alloys, and ceramics and ceramic composites. Dr. Jones was one of the original members of the Expert Panel for Chemistry Optimization for Double-Shell Tanks at Hanford.

Dr. Jones’ nuclear experience includes development of materials for advanced nuclear reactors and irradiation assisted stress corrosion cracking for light water reactors. Specific corrosion experience includes evaluation of the effects of interface, grain boundary, and surface chemistry on corrosion of materials including Yucca Mountain waste container materials. Dr. Jones has been instrumental in the development of SiCf/SiC composites for advanced nuclear reactor applications including high-temperature properties, corrosion and radiation stability. Dr. Jones has expertise in fracture toughness testing of metal and ceramic materials.

ROBERT P. KENNEDY, PHD.
STRUCTURAL MECHANICS
RPK Structural Mechanics

Dr. Kennedy has over 30 years of experience in static and dynamic analysis: design of special purpose civil- and mechanical-type structures particularly for the nuclear, petroleum, and defense industries: design of structures to resist extreme loadings including seismic, missile impact, extreme wind, impulsive loads, and nuclear environmental effects; and development of computerized structural analysis methods.

Dr Kennedy has more than 30 years of experience in the seismic design and evaluation of liquid storage tanks. He has co-author or was the prime contributor to

• BNL 52361, Seismic Design and Evaluation Guideline for the Department of Energy High-Level Waste Storage Tanks and Appurtenances

Dr. Kennedy chaired the ASCE committee that wrote ASCE Standard 4, Seismic Analysis of Safety-Related Nuclear Structures.

LEON STOCK, PHD.
CHEMIST
Independent Consultant
Professor Emeritus, Department of Chemistry, University of Chicago

Professor Stock has written approximately 210 articles and authored or co-authored numerous papers related to Hanford Site waste. His recent work at the Hanford Site has centered on the rates of hydrogen generation in the tanks and in the Waste Treatment and Immobilization Plant and on the occurrence and chemistry of organic compounds within the waste tanks. Currently, he
serves on the Expert Panel Oversight Committee for Chemistry Optimization for Double-Shell Tanks at Hanford.

KARTHIK SUBRAMANIAN
FELLOW TECHNICAL ADVISER
High Level Waste Integration
URS Washington Division

Karthik Subramanian has experience and expertise in basic and applied research, specifically in materials processing and consequent performance. His relevant expertise includes mechanical and environmental testing, hydrogen isotope effects on polymers and structural metals, and aqueous corrosion of structural materials. Karthik’s research experience at the Savannah River National Laboratory (SRNL) focused on (1) structural integrity programs for high level waste tanks, including design and implementation of corrosion control; and (2) life-cycle engineering for tritium reservoirs, involving the development of structure, property, performance models for long-term hydrogen/tritium/helium effects on structural materials. Karthik’s current focus is on integrating the activities related to high level waste for the URS Washington Division including structural integrity programs and multi-faceted technology development and operational programs.

BRUCE THOMPSON, PHD.
PROFESSOR AND DIRECTOR
Center for Nondestructive Evaluation, Ames Laboratory

Bruce Thompson is the Director of the Center for Nondestructive Evaluation, Director of the Ames Laboratory Applied NDE Program, and a Distinguished Professor in the Department of Materials Science and Engineering and in the Department of Aerospace Engineering and Engineering Mechanics. He received his B.A. in Physics from Rice University (1964), his M.S. in Physics from Stanford University (1965) and his Ph.D. in Applied Physics from Stanford University (1971). From 1970 to 1980 he served as a member of the technical staff and Group leader of Ultrasonic Applications at the Rockwell International Center before coming to Iowa State University.

Thompson's research interests fall in the area of ultrasonic nondestructive evaluation. Specialties include the analysis and development of noncontact sensors, in particular electromagnetic acoustic transducers, modeling the effects of measurement geometry on ultrasonic inspection, studying the uses of ultrasound to characterize a variety of microstructural and material properties such as stress, texture, porosity, grain size, and anisotropy and partially contacting interfaces, and uses of physics-based simulation tools to assist in the determination of probability of detection.

Thompson is the author of 6 major invited review articles in the field of nondestructive evaluation, over 90 articles in archival journals and over 323 papers in edited conference proceedings. He has been awarded 24 U.S. patents and presently serves as the Editor-in-Chief of the Journal of Nondestructive Evaluation. Dr. Thompson was one of the authors of Guidelines for Development of Structural Integrity Programs for DOE High-Level Waste Storage Tanks (BNL-52527).
BRUCE J. WIERSMA, PHD.
FELLOW ENGINEER
Savannah River National Laboratory

Dr. Wiersma has 17 years of experience in the corrosion and structural integrity disciplines at the Savannah River Site. His primary responsibilities have been associated with the structural integrity of high-level waste tanks. He has developed experimental programs to evaluate the corrosion performance of materials utilized on the Savannah River Site, and he led the team that developed the in-service inspection program for the high-level waste tanks. Currently, he serves on the Expert Panel Oversight Committee for Chemistry Optimization for Double-Shell Tanks at Hanford.
# APPENDIX B

## TEMPERATURES AND COMPOSITIONS OF SUPERNATANT AND INTERSTITIAL LIQUIDS OF UNRETRIEVED SSTs

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Note 1: The temperatures and compositions were obtained from Meacham (2008).

Note 2: The known and presumed leakers are shown in gray in the Tank column on the left.

Note 3: pH is related to the hydroxide ion content by the equation: \( \log [\text{OH}^-] = \text{pH} - 14 \)