Hanford Double-Shell Tank Thermal and Seismic Project - Increased Liquid Level Analysis for 241-AP Tank Farms

TC Mackey

Richland, WA 99352
U.S. Department of Energy Contract DE-AC27-99RL14047

EDT/ECN:	EDT 822360	UC:	
Cost Center:		Charge Code:	
B&R Code:		Total Pages:	263

Key Words: Double-Shell Tank, Tank, Integrity Project, Thermal, Seismic, TPA, M-48-14

Abstract: The overall scope of the project is to complete an up-to-date comprehensive analysis of record of the DST System at Hanford. The "Double-Shell Tank (DST) Integrity Project - DST Thermal and Seismic Project" is in support of Tri-Party Agreement Milestone M-48-14.

TRADEMARK DISCLAIMER. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

Printed in the United States of America. To obtain copies of this document, contact: Document Control Services, P.O. Box 950, Mailstop H6-08, Richland WA 99352, Phone (509) 372-2420; Fax (509) 376-4989.

DATE:
STA: 4
HANFORD RELEASE
ID: 2
FEB 16 2007

JE Bratton 2/16/07
Release Approval Date

Release Stamp

Approved For Public Release

SUBCONTRACTOR CALCULATION REVIEW CHECKLIST

Subject: Hanford Double-Shell Tank Thermal and Seismic Project – Increased Liquid Level Analysis for 241-AP Tank Farms

The subject document has been reviewed by the undersigned.
The reviewer reviewed and verified the following items as applicable.

Documents Reviewed: RPP-RPT-32237 Rev. 0

Analysis Performed By: M. Rinker et.al.

- Design Input
- Basic Assumptions
- Approach/Design Methodology
- Consistency with item or document supported by the calculation
- Conclusion/Results Interpretation
- Impact on existing requirements
- _____

TC Mackey T. C. Mackey 2/1/07
Reviewer (Print/Sign) Date

C. DeFigh-Price C. DeFigh-Price 2/1/2007
Organizational Manager (Print/Sign) Date

PNNL-16372
RPP-RPT-32237, Rev. 0 Limited Distribution

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Hanford Double-Shell Tank Thermal and Seismic Project – Increased Liquid Level Analysis for 241-AP Tank Farms

J. E. Deibler
K. I. Johnson
S. P. Pilli
N. K. Karri
M. W. Rinker
F. G. Abatt*
B. G. Carpenter*

January 2007

Prepared for
CH2M HILL Hanford Group, Inc.
in Support of the
Double-Shell Tank Integrity Program

Sponsored by the U.S. Department of Energy
under Contract DE-AC05-76RL01830

*M&D Professional Services, Richland, WA

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights**. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

This document was printed on recycled paper.

PNNL-16372
RPP-RPT-32237, Rev. 0
Limited Distribution

Hanford Double-Shell Tank Thermal and Seismic Project – Increased Liquid Level Analysis for 241-AP Tank Farms

J. E. Deibler
K. I. Johnson
S. P. Pilli
N. K. Karri
M. W. Rinker
F. G. Abatt*
B. G. Carpenter*

January 2007

Prepared for
CH2M HILL Hanford Group, Inc.
in Support of the Double-Shell Tank Integrity Program

Pacific Northwest National Laboratory
Richland, WA 99352

*M&D Professional Services, Richland, WA

Executive Summary

This report summarizes the results of the Double-Shell Tank Increased Liquid Level Analysis. This combined analysis provides a thorough, defensible, and documented analysis that will become a part of the overall analysis of record for the proposed liquid level increase in the Hanford 241-AP Double-Shell Tank (DST) Farms.

The bases of the analytical work presented in this report are two ANSYS® finite element models that were modified from the previous DST structural integrity analyses to represent the AP tanks operating with 460 inches of liquid waste, at a temperature of 210°F and a specific gravity of 1.83. The Thermal and Operating Loads Analysis (TOLA) model includes the effects of temperature on material properties, creep, concrete cracking, and various waste and annulus pressure-loading conditions. The seismic model considers the interaction of the tanks with the surrounding soil, including a range of soil properties, and the effects of the waste contents during a seismic event.

The structural evaluations completed with the AP tank models do not reveal any structural deficiencies with the integrity of the DSTs under these increased waste level operating conditions. The analyses represent 60 years of use, which extends well beyond the current date to 2046. Bounding material properties were also selected to provide the most severe combinations.

The reinforced concrete structure was evaluated as specified by the American Concrete Institute (ACI) code requirements for nuclear safety-related structures (ACI-349). The demand was demonstrated to be lower than the capacity at all locations.

The primary tank was evaluated using the American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code, Section III, Division 1, Service Level D capacities for combined seismic plus non-seismic loading as prescribed in Day et al. (1995) and Bandyopadhyay et al. (1995). Using factored inelastic seismic demands per the International Building Code (IBC), it was demonstrated that the general primary membrane stress intensity in the primary tank remained well below the material yield stress for combined seismic and non-seismic loading. Similarly, the combined non-seismic and factored inelastic seismic demands for local membrane, plus bending as well as local membrane, plus bending, plus thermal loading, remained well below the capacities defined by the code. Potential concerns regarding the Service Level D criterion allowing gross deformation that would require the removal of components from service were shown to be unfounded, because the primary general membrane stress is below yield, thus precluding gross plastic deformation. Therefore, the primary tank is acceptable according to the established criteria.

The concrete and steel structures are demonstrated to meet the requirements of the IBC 2003. While the IBC does not explicitly address underground tanks, provision is made within the code to satisfy its requirements by demonstrating compliance with the requirements of the ACI code for concrete structures. Similarly, the IBC references the ASCE code for steel structures, which in turn requires compliance with the ASME B&PV code. Consequently, by demonstrating compliance with the ACI and ASME codes, the Hanford double-shell tanks are shown to satisfy the requirements of the IBC.

®ANSYS is a registered trademark of ANSYS, Inc., Canonsburg, Pennsylvania.

The primary tank buckling evaluation demonstrated that the current limit on the maximum vacuum level of 12 inches water gauge is acceptable given the current lack of corrosion in the tanks and the expectation that the maximum waste temperature will not exceed 210°F. For this analysis, the occurrence of maximum tank vacuum was classified as a service level C, emergency load condition. This limit is predicated on maintaining the minimum allowable waste level at 12 inches to preclude bottom uplift from occurring.

The potential for stress corrosion cracking (SCC) of the primary tank, particularly the lower knuckle, was assessed. Based on the recent analysis, current testing, and the historical operational record dating back to 1971, it can be concluded that SCC is unlikely if the present operating requirements are maintained.

The concrete-backed steel liner was evaluated to ASME Section III, Division 2 requirements. The liner strain was determined to be below allowable levels for all load cases.

Attachment of the steel liner to the concrete walls is through the use of J-bolts, which were also evaluated to ASME Section III, Division 2 requirements. In all cases, the J-bolts were shown to have adequate margin.

Contents

Executive Summary iii
Acronyms xiii
Units xiv
1.0 Introduction 1.1
1.1 Purpose of the DST Increased Liquid Waste Level Analysis 1.1
1.2 Impact of Analysis 1.2
1.3 Analysis Methodology 1.2
1.4 Double-Shell Tank Design 1.3
1.4.1 Thermal Characteristics 1.4
1.4.2 Ventilation System 1.4
1.4.3 Primary Tank 1.4
1.4.4 Secondary Liner 1.4
1.4.5 Concrete Shell 1.4
1.4.6 Insulating Concrete 1.5
1.5 Organization of the Increased Liquid Level Analysis Report 1.5
2.0 TOLA Model 2.1
2.1 Introduction 2.1
2.2 241-AY Finite Element Model 2.1
2.2.1 241-AY Tank Model Geometry 2.1
2.2.2 241-AP Tank Model Modifications 2.2
2.2.3 ANSYS® Model Construction 2.2
2.2.4 Real Constants 2.8
2.3 Material Properties 2.11
2.3.1 Structural Concrete 2.12
2.3.2 Insulating Concrete 2.14
2.3.3 Structural Steel 2.14
2.3.4 Reinforcing Steel 2.15
2.3.5 Soils 2.15
2.3.6 Coefficients of Friction at Material Interfaces 2.18
2.4 Loads 2.19
2.4.1 Thermal Loads 2.19
2.4.2 Mechanical Loads 2.30
2.4.3 ACI Load Factors 2.31
2.4.4 Load Step Procedure 2.32
3.0 Seismic Model 3.1
3.1 Introduction 3.1
3.2 Finite Element Model 3.1
3.2.1 Model Description 3.1
3.2.2 Concrete Model 3.3
3.2.3 Primary Tank 3.9

3.2.4 Insulating Concrete 3.13
3.2.5 J-Bolts 3.13
3.2.6 Secondary Liner 3.16
3.2.7 Waste 3.16
3.2.8 Primary Tank/Concrete Dome Interface 3.18
3.2.9 Primary Tank/Insulating Concrete Interface 3.19
3.2.10 Insulating Concrete/Secondary Liner Interface 3.19
3.2.11 Soil/Concrete Tank Interface 3.19
3.2.12 Excavated/Native Soil Interface 3.20
3.2.13 Waste/Primary Tank Interface 3.21
3.2.14 Concrete Wall/Footing Interface 3.22
3.2.15 Surface Loads 3.22
3.3 Soil Model 3.23
3.3.1 Soil Properties 3.23
3.3.2 Excavated Soil 3.25
3.3.3 Native Soil 3.27
3.4 Boundary Conditions 3.28
3.4.1 Soil Boundary Conditions 3.28
3.4.2 Tank Boundary Conditions 3.30
3.5 Seismic Input 3.32
3.6 Load Cases 3.35
3.6.1 Acceptance Criteria for Response Spectra 3.35
3.6.2 Modification to ANSYS® Base Time Histories 3.37
3.6.3 ANSYS® Base Acceleration Time Histories 3.38
3.7 Model Excitation 3.42
4.0 Model Reconciliation 4.1
5.0 Structural Acceptance Criteria 5.1
5.1 Introduction 5.1
5.2 Design and Construction Specifications for 241-AP Tanks 5.1
5.3 Applicable Codes 5.2
5.3.1 Design Codes of Record for the DSTs 5.2
5.3.2 Steel Design Codes of Record 5.2
5.3.3 Concrete Design Codes of Record 5.2
5.3.4 Contemporary Codes for Structural Evaluation of the DSTs 5.2
6.0 Analysis Results 6.1
6.1 ACI Structural Concrete Evaluation 6.1
6.1.1 Best Estimate Soil – Best Estimate Concrete 6.2
6.1.2 Upper Bound Soil – Best Estimate Concrete 6.8
6.1.3 Lower Bound Soil – Best Estimate Concrete 6.8
6.1.4 Best Estimate Soil – Fully Cracked Concrete 6.8
6.2 ASME Primary Tank Evaluation 6.18
6.2.1 Primary Tank Results 6.18
6.2.2 Evaluation Criteria Discussion 6.19

6.2.3 ANSYS® Seismic Sloshing Concerns 6.20
6.2.4 Best Estimate Soil – Best Estimate Concrete 6.20
6.2.5 Upper Bound Soil – Best Estimate Concrete 6.20
6.2.6 Lower Bound Soil – Best Estimate Concrete 6.20
6.2.7 Best Estimate Soil – Fully Cracked Concrete 6.20
6.3 Primary Tank Stress Corrosion Cracking Evaluation 6.31
6.3.1 Analytical Evaluation 6.31
6.3.2 DST Operating Experience 6.33
6.3.3 Seismic Considerations 6.34
6.4 Primary Tank Buckling Evaluation 6.35
6.4.1 Evaluation Method 6.35
6.4.2 Evaluation Criteria 6.39
6.4.3 Buckling Results 6.40
6.5 ASME Concrete-Backed Steel Evaluation 6.41
6.5.1 Best Estimate Soil – Best Estimate Concrete 6.41
6.5.2 Upper Bound Soil – Best Estimate Concrete 6.41
6.5.3 Lower Bound Soil – Best Estimate Concrete 6.41
6.5.4 Best Estimate Soil – Fully Cracked Concrete 6.42
6.6 J-Bolt Evaluation 6.54
7.0 Conclusions and Recommendations 7.1
7.1 Reinforced Concrete 7.1
7.2 Primary Tank 7.1
7.3 Stress Corrosion Cracking 7.1
7.4 Primary Tank Buckling 7.1
7.5 Concrete-Backed Liner 7.2
7.6 J-Bolts 7.2
8.0 References 8.1
Appendix A – Software Acceptance A.1
Appendix B – ANSYS® Model Files B.1

Figures

1-1 Cross Section of a Typical Double-Shell Tank 1.3
1-2 Typical Double-Shell Tank Configuration 1.3
2-1 Comparison of 241-AP and TOLA Models 2.2
2-2 Finite Element Mesh of Full Model 2.3
2-3 Close-up Showing Finite Element Mesh of Tank 2.3
2-4 Close-up Showing Mesh of Haunch 2.4
2-5 Close-up Showing Mesh of Tank Base 2.4
2-6 Concrete Elastic Modulus 2.12
2-7 Concrete Strength Used for Finite Element Analysis 2.13
2-8 Structural Steel Elastic Modulus 2.14
2-9 Structural Steel Coefficient of Thermal Expansion 2.15
2-10 Steel Reinforcing Bar Stress-Strain Curves 2.16
2-11 Soil Configuration Adjacent to DSTs 2.17
2-12 Distribution of Soil Properties in the DST Finite Element Model 2.17
2-13 Undisturbed Soil Elastic Modulus and Poisson's Ratio 2.18
2-14 Backfill Soil Elastic Modulus 2.18
2-15 Temperature Distribution at Step 2 in the Design Basis Transient 2.21
2-16 Temperature Distribution at Step 3 in the Design Basis Transient 2.22
2-17 Temperature Distribution at Step 4 in the Design Basis Transient 2.23
2-18 Temperature Distribution at Step 5 in the Design Basis Transient 2.24
2-19 Temperature Distribution at Step 6 in the Design Basis Transient 2.25
2-20 Steady-State Temperature Distribution at Steps 7 and 8 in the Design Basis Transient 2.26
2-21 Temperature Distribution at Step 9 in the Design Basis Transient 2.27
2-22 Temperature Distribution at Step 10 in the Design Basis Transient 2.28
2-23 Temperature Distribution at Step 11 in the Design Basis Transient 2.29
2-24 Temperature Distribution at Step 12 in the Design Basis Transient 2.30
2-25 Analysis Flow Plan 2.32
3-1 AY Primary Tank Dimensions 3.2
3-2 Composite Tank Model Detail 3.2
3-3 Concrete Tank Profile, Including Shell Thickness 3.9
3-4 Concrete Tank Model Detail 3.9
3-5 Primary/Concrete Tank Node Geometry 3.10
3-6 Primary Tank Model Detail 3.12
3-7 Primary Tank Model Detail – Knuckle Region 3.12
3-8 Insulating Concrete Model Detail 3.13
3-9 J-Bolt Geometry Detail 3.14
3-10 J-Bolt Model Detail 3.15
3-11 Spring Elements – J-Bolts to Primary Tank 3.15
3-12 Secondary Liner Model Detail 3.16
3-13 Waste Model Detail 3.17
3-14 Waste Model Detail, Interface with Tank Dome 3.18
3-15 Contact Elements – Primary Tank to Concrete Dome 3.18
3-16 Contact Elements – Insulating Concrete Top and Bottom 3.19
3-17 Contact Elements – Soil to Concrete Tank 3.20

3-18 Spring Elements – Concrete Footing to Soil 3.20
3-19 Contact Elements – Near Soil to Far Soil 3.21
3-20 Contact Elements – Waste to Primary Tank 3.21
3-21 Contact Elements – Concrete Wall to Footing 3.22
3-22 Mass Elements – Soil Surface 3.22
3-23 Excavated Soil Model Detail 3.26
3-24 Excavated Soil – Softened Soil Zones 3.26
3-25 Model Detail 3.27
3-26 Far-Field Soil Model Detail 3.27
3-27 Link Elements – Edges of Soil Model 3.28
3-28 Boundary Conditions – Soil Base 3.29
3-29 Boundary Conditions – Typical Soil Layer 3.29
3-30 Boundary Conditions – Slaved Boundary Conditions 3.30
3-31 Boundary Conditions – Symmetry Plane 3.30
3-32 Boundary Conditions – Concrete Tank 3.31
3-33 Boundary Conditions – Primary Tank 3.31
3-34 Boundary Conditions – Secondary Liner 3.32
3-35 Comparison of Horizontal Surface Spectra at 5% Spectral Damping 3.33
3-36 Comparison of Vertical Surface Spectra at 5% Spectral Damping 3.33
3-37 Horizontal and Vertical Surface Acceleration Time History 3.34
3-38 Horizontal and Vertical Surface Displacement Time History 3.34
3-39 Ratio of the ANSYS® Tank Foundation Level Spectra to the SHAKE Surface Spectrum for Horizontal Excitation 3.36
3-40 Envelope of the Ratio of the ANSYS® Tank Foundation-Level Spectra to the SHAKE Surface Spectrum for Vertical Excitation 3.36
3-41 Ratio of the ANSYS® Tank Foundation Level Spectra to the SHAKE Surface Spectrum for Modified Horizontal Excitation 3.37
3-42 Envelope of the Ratio of the Tank Foundation Level Spectra to the Surface Spectra for Modified Vertical Excitation 3.38
3-43 Horizontal and Vertical Base Acceleration Time History, −266 feet, Lower Bound Soil 3.39
3-44 Horizontal and Vertical Base Displacement Time History, −266 feet, Lower Bound Soil 3.39
3-45 Horizontal and Vertical Base Acceleration Time History, −266 feet, Best Estimate Soil 3.40
3-46 Horizontal and Vertical Base Displacement Time History, −266 feet, Best Estimate Soil 3.40
3-47 Horizontal and Vertical Base Acceleration Time History, −266 feet, Upper Bound Soil 3.41
3-48 Horizontal and Vertical Base Displacement Time History, −266 feet, Upper Bound Soil 3.41
6-1 Reinforced Concrete Sections – Dome and Haunch Area 6.2
6-2 Reinforced Concrete Sections – Wall 6.3
6-3 Reinforced Concrete Sections – Slab 6.3
6-4 BES – BEC, Load Combination 1 ..... 6.4
6-5 BES – BEC, Load Combination 4, Meridional 6.4
6-6 BES – BEC, Load Combination 4, Circumferential 6.5
6-7 BES – BEC, Load Combination 4, Shear 6.5
6-8 BES – BEC, Load Combination 4, In-Plane Shear 6.6
6-9 BES – BEC, Load Combination 9, Meridional 6.6
6-10 BES – BEC, Load Combination 9, Circumferential 6.7
6-11 BES – BEC, Load Combination 9, Shear 6.7

6-12 UBS – BEC, Load Combination 1 ..... 6.8
6-13 UBS – BEC, Load Combination 4, Meridional 6.9
6-14 UBS – BEC, Load Combination 4, Circumferential 6.9
6-15 UBS – BEC, Load Combination 4, Shear 6.10
6-16 UBS – BEC, Load Combination 4, In-Plane Shear 6.10
6-17 UBS – BEC, Load Combination 9', Meridional 6.11
6-18 UBS – BEC, Load Combination 9', Circumferential 6.11
6-19 UBS – BEC, Load Combination 9', Shear 6.12
6-20 LBS – BEC, Load Combination 1 ..... 6.12
6-21 LBS – BEC, Load Combination 4, Meridional 6.13
6-22 LBS – BEC, Load Combination 4, Circumferential 6.13
6-23 LBS – BEC, Load Combination 4, Shear 6.14
6-24 LBS – BEC, Load Combination 4, In-Plane Shear 6.14
6-25 LBS – BEC, Load Combination 9', Meridional 6.15
6-26 LBS – BEC, Load Combination 9', Circumferential 6.15
6-27 LBS – BEC, Load Combination 9', Shear 6.16
6-28 BES – FCC, Load Combination 4, Meridional 6.16
6-29 BES – FCC, Load Combination 4, Circumferential 6.17
6-30 BES – FCC, Load Combination 4, Shear 6.17
6-31 LBS – FCC, Load Combination 4, In-Plane Shear 6.18
6-32 Relative Magnitude of TOLA and Seismic Primary Membrane Stress Intensity 6.21
6-33 BES – BEC Primary Membrane Stress Intensity 6.21
6-34 BES – BEC Primary Membrane + Bending Stress Intensity 6.22
6-35 BES – BEC Primary Membrane + Bending Stress Intensity 6.22
6-36 BES – BEC Primary + Secondary Stress Intensity Range 6.23
6-37 BES – BEC Primary + Secondary Stress Intensity Range 6.23
6-38 UBS – BEC Primary Membrane Stress Intensity 6.24
6-39 UBS – BEC Primary Membrane + Bending Stress Intensity 6.24
6-40 UBS – BEC Primary Membrane + Bending Stress Intensity 6.25
6-41 UBS – BEC Primary + Secondary Stress Intensity Range 6.25
6-42 UBS – BEC Primary + Secondary Stress Intensity Range 6.26
6-43 LBS – BEC Primary Membrane Stress Intensity 6.26
6-44 LBS – BEC Primary Membrane + Bending Stress Intensity 6.27
6-45 LBS – BEC Primary Membrane + Bending Stress Intensity 6.27
6-46 LBS – BEC Primary + Secondary Stress Intensity Range 6.28
6-47 LBS – BEC Primary + Secondary Stress Intensity Range 6.28
6-48 BES – FCC Primary Membrane Stress Intensity 6.29
6-49 BES – FCC Primary Membrane + Bending Stress Intensity 6.29
6-50 BES – FCC Primary Membrane + Bending Stress Intensity 6.30
6-51 BES – FCC Primary + Secondary Stress Intensity Range 6.30
6-52 BES – FCC Primary + Secondary Stress Intensity Range 6.31
6-53 Comparison of TOLA and AN-107 Lower Knuckle Principal Stress 6.32
6-54 Effect of Applied Bending Stress on Calculated Stress Intensity Factor for the Lower Knuckle of Tank AN-107 ..... 6.33
6-55 Buckling Model 6.36
6-56 Buckling Model Loads 6.36

6-57 Buckling Load Deflection Curve 6.37
6-58 Model Displaced Shape at Vacuum Limit 6.38
6-59 BES – BEC, Principal Membrane Strain – Tension 6.42
6-60 BES – BEC, Principal Membrane Strain – Compression 6.42
6-61 BES – BEC, Principal Membrane + Bending Strain Outer Surface – Tension 6.43
6-62 BES – BEC, Principal Membrane + Bending Strain Outer Surface – Compression 6.43
6-63 BES – BEC, Principal Membrane + Bending Strain Inner Surface – Tension 6.44
6-64 BES – BEC, Principal Membrane + Bending Strain Inner Surface – Compression 6.44
6-65 UBS – BEC, Principal Membrane Strain – Tension 6.45
6-66 UBS – BEC, Principal Membrane Strain – Compression 6.45
6-67 UBS – BEC, Principal Membrane + Bending Strain Outer Surface – Tension 6.46
6-68 UBS – BEC, Principal Membrane + Bending Strain Outer Surface – Compression 6.46
6-69 UBS – BEC, Principal Membrane + Bending Strain Inner Surface – Tension 6.47
6-70 UBS – BEC, Principal Membrane + Bending Strain Inner Surface – Compression 6.47
6-71 LBS – BEC, Principal Membrane Strain – Tension 6.48
6-72 LBS – BEC, Principal Membrane Strain – Compression 6.48
6-73 LBS – BEC, Principal Membrane + Bending Strain Outer Surface – Tension 6.49
6-74 LBS – BEC, Principal Membrane + Bending Strain Outer Surface – Compression 6.49
6-75 LBS – BEC, Principal Membrane + Bending Strain Inner Surface – Tension 6.50
6-76 LBS – BEC, Principal Membrane + Bending Strain Inner Surface – Compression 6.50
6-77 BES – FCC, Principal Membrane Strain – Tension 6.51
6-78 BES – FCC, Principal Membrane Strain – Compression 6.51
6-79 BES – FCC, Principal Membrane + Bending Strain Outer Surface – Tension 6.52
6-80 BES – FCC, Principal Membrane + Bending Strain Outer Surface – Compression 6.52
6-81 BES – FCC, Principal Membrane + Bending Strain Inner Surface – Tension 6.53
6-82 BES – FCC, Principal Membrane + Bending Strain Inner Surface – Compression 6.53
6-83 BES – BEC, J-bolt Displacement Evaluation 6.54
6-84 BES – BEC, J-bolt Force Evaluation 6.55
6-85 UBS – BEC, J-bolt Displacement Evaluation 6.55
6-86 UBS – BEC, J-bolt Force Evaluation 6.56
6-87 LBS – BEC, J-bolt Displacement Evaluation 6.56
6-88 LBS – BEC, J-bolt Force Evaluation 6.57
6-89 BES – FCC, J-bolt Displacement Evaluation 6.57
6-90 BES – FCC, J-bolt Force Evaluation 6.58

Tables

1-1 DST 241-AP Required Load Conditions for Analysis 1.2
2-1 Double-Shell Tank 241-AY Design Drawings 2.1
2-2 Foundation Concrete Rebar Volume Ratios 2.9
2-3 Wall Concrete Rebar Volume Ratios 2.9
2-4 Dome Concrete Rebar Volume Ratios 2.10
2-5 Haunch Concrete Rebar Volume Ratios 2.10
2-6 J-bolt Spacing Calculations 2.11
2-7 Coefficients for the ANSYS® Creep Law 2.13
2-8 Structural Properties for the Insulating Concrete 2.14
2-9 Coefficients of Friction 2.19
2-10 Temperature States that Define the Design Basis Annual Thermal Cycle for the ANSYS® Structural Model 2.20
2-11 DST 241-AP Load Conditions for Analysis 2.31
3-1 ANSYS Model Input File Description 3.3
3-2 Concrete Tank Centerline Coordinates 3.4
3-3 Best Estimate Concrete Properites, 250°F 3.6
3-4 Fully Cracked Concrete Properites 3.7
3-5 Primary Tank Dome Coordination Calculation 3.11
3-6 J-Bolt Stiffness/Area Calculation 3.14
3-7 Best Estimate Native Soil Iterated Soil Properties 3.23
3-8 Best Estimate Excavated Soil Iterated Soil Properties 3.24
3-9 Upper Bound Native Soil Iterated Soil Properties 3.24
3-10 Upper Bound Excavated Soil Iterated Soil Properties 3.24
3-11 Lower Bound Native Soil Iterated Soil Properties 3.25
3-12 Lower Bound Excavated Soil Iterated Soil Properties 3.25
4-1 Element Correlation for ACI Evaluation 4.2
4-2 Element Correlation for Primary Tank Evaluation 4.3
4-3 Element Correlation for Concrete-Backed Liner Evaluation 4.4
4-4 Element Correlation for J-bolt Evaluation 4.4
5-1 Summary of the S_m Allowables that were Specified for Each of the DST Designs 5.3
5-2 Summary of Hanford Double-Shell Tank Structural Concrete Design Basis 5.4
5-3 Summary Table of the Local and Global Significance of Failure of the Various DST Components 5.6
5-4 Stress Intensity Classification 5.6
6-1 Comparison of TOLA and AN-107 Analyses 6.32
6-2 Primary Tank Buckling Evaluation 6.40
6-3 Summary of Primary Tank Buckling Evaluation 6.41
6-4 J-bolt Allowable Loads 6.59

Acronyms

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials Standards
AWS	American Welding Society
BEC	Best Estimate Concrete
BES	Best Estimate Soil
B&PV	Boiler and Pressure Vessel
COF	coefficient of friction
CTE	coefficient of thermal expansion
DOE	U.S. Department of Energy
DSA	Documented Safety Analysis
DST	Double-Shell Tank
FCC	Fully Cracked Concrete
FE	finite element
IBC	International Building Code
K_{ISCC}	Threshold stress intensity factor
LBS	Lower Bound Soil
MCE	maximum considered earthquake
ν	Poisson's ratio
NUREG	U.S. Nuclear Regulatory Commission Regulation
PC	Performance Category
PNNL	Pacific Northwest National Laboratory
PSHA	probabilistic seismic hazard analysis
PWHT	post weld heat treatment
SCC	stress corrosion cracking
SpG	specific gravity
SRS	Savannah River Site
TOLA	Thermal and Operating Loads Analysis
UBS	Upper Bound Soil
USGS	U. S. Geological Survey
w.g.	water gauge
WTP	Waste Treatment Plant

Units

°F	degree Fahrenheit
ft	foot/feet
g	gravitational acceleration
in.	inch
kip	1000 pounds
ksf	1000 pounds per square foot
ksi	1000 pounds per square inch
ksi in.$^{1/2}$	1000 pounds per square inch square root inch
lb	pound
mil	1/1000 inch
psi	pounds per square inch
yr	year

1.0 Introduction

As provided in the CH2M HILL Hanford Group, Inc. (CH2M HILL) statement of work to the Pacific Northwest National Laboratory (PNNL) entitled *Double-Shell Tank (DST) Integrity Project – DST Thermal and Seismic Analyses, Revision 2*, the overall scope of this project is to complete an analysis of record of the DST system at Hanford. The analysis was conducted to provide analytical documentation of the DST system's structural integrity and to support programmatic decisions toward the continued operations of these tanks during waste cleanup operations at the Hanford Site. This work will establish a defensible basis for operating specifications for continued use of the DSTs as well as provide an estimate of the remaining useful lives of the tanks.

The overall scope of the project is defined by activities that were completed over a 4-year period. The primary activities are:

- Thermal and Operating Loads Analysis (TOLA)
- Evaluation of Alternative Liquid Waste Levels in the DSTs
- Seismic Analysis
- Minimum Allowable Wall Thickness Analysis
- Buckling Analysis

Reports have been published documenting the Thermal and Operating Loads (TOLA) Analysis (Rinker et al. 2004), the Seismic Analysis (Rinker et al. 2006c), the Buckling Analysis (Johnson et al. 2006), and the Combined Thermal and Operating Loads with Seismic Analysis (Rinker et al. 2006d). This report documents the evaluation of the proposed increased liquid level in the 241-AP Tank Farms.

1.1 Purpose of the DST Increased Liquid Waste Level Analysis

Ensuring adequate waste storage volume is critical to the success of the U.S. Department of Energy's (DOE's) mission to retrieve, treat and dispose of the radioactive waste in the Hanford Tank Farms. Increasing the waste volume stored in the existing DSTs is an attractive option to the construction of new tanks. The purpose of the DST Increased Liquid Level Analysis is to demonstrate the structural integrity of the DSTs under the loading imposed by an increase in the liquid waste level above the current design limits. Review of tank design and operating parameters limited the DSTs under consideration for an increase in waste level to the 241-AP tanks.

The previous analyses (TOLA, Seismic, Buckling, and Combined) developed and analyzed a tank model for a set of bounding thermal and operating load cases and bounding geometry (AY). These nonlinear time-dependent analyses calculated the effects of heating the tank to the maximum operating temperature, long-term operation at elevated temperatures, and operating temperature cycles. These analyses also accounted for the degradation of modulus of elasticity, compressive strength, etc., in the concrete with extended exposure to elevated temperatures. The results predict time-dependent creep, cracking, stresses, strains, and deformations for the entire structure.

The seismic analysis considers the interaction of the tank with the surrounding soil and the effects of the primary tank contents. The DST and the surrounding soil are modeled as a system of finite elements.

The depth and width of the soil incorporated into the analysis model are sufficient to obtain appropriately accurate analytical results. The analysis includes the soil-structure interaction (SSI) model represented by several (nonlinear) contact surfaces in the tank structure. The contained waste was modeled explicitly in order to capture the fluid-structure interaction behavior between the waste and the primary tank. Detailed analyses of the increased interaction between the contained waste and the curved dome area of the primary tank resulting from the increased liquid waste level are described in the Increased Liquid Level Seismic report (Rinker et al. 2007).

The previous analyses addressed bounding load cases and geometry and do not consider conditions that would apply to specific tanks. The objective of this work was to perform an analysis for the AP tanks, which are the only tanks being considered for the increase waste level. The previously developed models were used with only minor modifications to represent the AP tanks. The load conditions for this analysis are summarized in Table 1-1. The work is documented (including analysis input files) in such a manner to expedite potential future sensitivity calculation and other tank-specific calculations as required by future needs.

Table 1-1. DST 241-AP Required Load Conditions for Analysis

Design Load	Value	Notes
Design Life	> 50 years	A 60-year design life is used
Maximum Corrosion Rate	1 mil/yr	A total corrosion allowance of 0.060 inch is applied to the specified nominal thicknesses
Soil Cover	8.5 ft @ 125 lb/ft^3	Relative to dome apex
Hydrostatic	460 inches @ 1.83 SpG	Current tank contents are below 1.5 SpG
Pressure	–12 in. water gauge (w.g.)	Primary Tank
	–20 in. w.g.	Annulus
Pressure	40 lb/ft^2	Uniform
	200,000 lb	Concentrated
Live Load	210°F	Maximum bulk temperature of waste

1.2 Impact of Analysis

The primary impact of the Increased Liquid Level analysis is to allow for increased waste storage volume in the double-shell tanks. Raising the level in 241-AP Tank Farm by approximately 40 inches will increase the storage volume in each tank by roughly 100,000 gallons. The impacts of the additional storage volume on Hanford Site operations are the responsibility of DOE and the Tank Farm Contractor.

1.3 Analysis Methodology

The analysis was conducted with two separate and distinct ANSYS finite element models. The normal thermal and operating loads are considered in the TOLA model, which is described in detail by Rinker et al. (2004). The seismic loads are considered in the seismic model, which is described in detail by Rinker et al. (2006c). Results from the separate TOLA and seismic analyses are combined as necessary in various Excel spreadsheets for the appropriate code evaluation. The Combined Summary report (Rinker et al. 2006d) outlines the method of combining results. Details for each model are given in Chapters 2 and 3 of this report. The combined results are presented in Chapter 6.

1.4 Double-Shell Tank Design

Figure 1-1 is a simplified diagram of a typical DST structure, showing an inner primary tank and an outer secondary tank covered by a reinforced-concrete shell. The primary and secondary tanks are made of carbon steel plate varying from 3/8 to 15/16 inch thick. The top of the concrete dome is 15 inches thick and it becomes thicker toward the wall. The walls are 18 inches thick. The entire tank structure is buried at a depth of 6 to 8 feet, measured from the top of the tank dome (Han 1996). Figure 1-2 shows the configuration in 3-dimensional cross section.

The 241-AP Tank Farm was constructed over a period of about 4 years (from 1983 to 1986), with a design life of 50 years. These tanks have been in service for approximately 21 years.

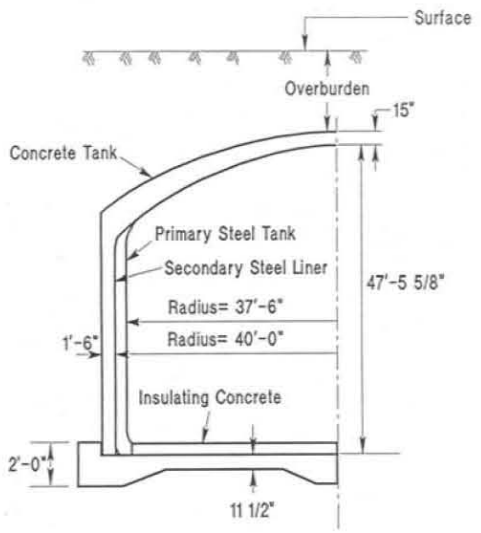


Figure 1-1. Cross Section of a Typical Double-Shell Tank

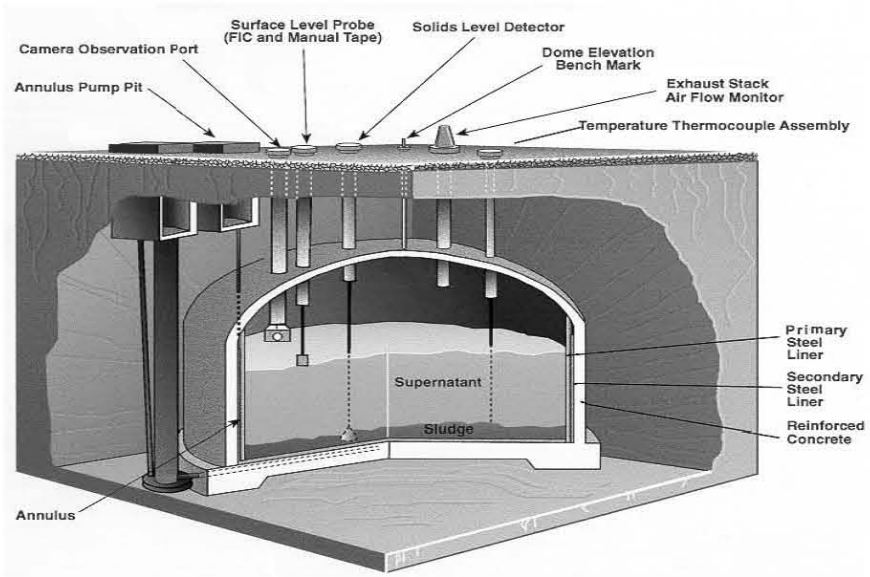


Figure 1-2. Typical Double-Shell Tank Configuration

1.4.1 Thermal Characteristics

The bounding analyses reported in the Combined TOLA and Seismic Analysis (Rinker et al. 2006d) used the design thermal load from 422 inches of 350°F waste. That report describes the historical review of actual operating temperatures for all the DSTs. While that review did not indicate any waste temperatures in the AP tanks approaching the design limit of 210°F, a maximum waste temperature of 210°F was assumed for each thermal cycle for the Increased Liquid Level analysis. The ANSYS thermal model described in the Buckling report (Johnson et al. 2006) was used to develop the thermal profiles for use in the thermal cycle.

1.4.2 Ventilation System

The annulus ventilation systems for the DSTs are designed to perform three functions: 1) provide primary tank leak detection through continuous radiation monitoring of the annulus exhaust air, 2) limit temperature build-up in the secondary tank concrete, and 3) remove heat and moisture from the annulus space. The primary tank ventilation systems perform similar functions: 1) limit flammable gas accumulation, 2) limit temperature build-up in the primary tank and secondary tank concrete, 3) maintain a vacuum on the primary tank, and 4) remove heat and moisture from the primary tank in order to minimize vapor space corrosion (Duncan 2003).

1.4.3 Primary Tank

The 75-foot-diameter primary steel tank provides containment for the stored waste. The primary tank varies in thickness from a minimum of 3/8 inch in the dome to a maximum of 1 inch at the bottom center of the tank. The primary tank is constructed from a series of formed segmented plates welded in a staggered arrangement. All butt welds on the primary tank received 100% radiographic examination during construction. The tanks were also post-weld heat treated to stress relieve the welds. The primary tank resists the hydrostatic and hydrodynamic waste loads and the internal pressure.

1.4.4 Secondary Liner

The secondary steel tank, or liner, lies beneath the insulating concrete and is built directly on top of the concrete foundation. The secondary tanks are about 5 feet larger in diameter than the primary tanks, resulting in a 2.5-foot-wide annular space between the primary and secondary tanks. The secondary liner is joined to the primary tank dome at the upper haunch area, and the two tanks are enclosed in a reinforced concrete shell. The secondary liner provides a second confinement barrier for potential primary tank leaks, thus preventing uncontrolled releases of waste to the environment.

1.4.5 Concrete Shell

On the outside of the secondary tank is a reinforced concrete shell. The exterior concrete shell comprises a foundation, walls, and a dome that completely enclose the secondary tank and primary tank dome. The structural concrete foundations are about 88 feet in diameter and are designed to distribute all weight loads to the ground below. The structural foundation contains drain lines and leak-detection wells to collect any leakage from the secondary liner. The top of the concrete foundation also contains slots to drain any liquid that might leak from the secondary tank.

The concrete shell wall is constructed of steel-reinforced concrete. The shells are about 83 feet in outside diameter and about 18 inches thick and rest on steel slide plates supported by the tank foundation. The concrete shells were poured directly against the secondary liner (i.e., the secondary liner was used as a casting form for the concrete shell). The dome is 15 inches thick and is constructed of steel-reinforced concrete.

Steel riser pipes penetrate the concrete dome and the top of the primary and secondary tanks. The risers provide access to the primary tank and the annulus space for waste transfer operations, equipment installation, and monitoring. The risers are located in covered pits or are located at grade at specific locations above the pits.

1.4.6 Insulating Concrete

The primary tank rests on an 8-inch-thick insulating concrete support pad, located between the primary and secondary tank floors. The concrete pad includes air distribution and drain slots in a radial pattern, which are designed to maintain a uniform tank bottom temperature, to provide a means of heat removal and leak detection, and to help eliminate pockets of water condensation. To provide supplemental cooling, air can be routed through the drain slots via the annulus ventilation system. The drain slots allow any leakage from the primary tank to drain into the annular space, where leak-detection instrumentation is installed.

1.5 Organization of the Increased Liquid Level Analysis Report

The organization and content of this report are described briefly as follows:

- Chapter 1 – Introduction: Provides the background and overall purpose of the Double-Shell Tank Thermal and Seismic Analysis. The scope of the Increased Liquid Level analyses is described. Basic DST information is also included in this chapter.
- Chapter 2 – TOLA Model: Describes the ANSYS® finite element model used for the thermal and operating loads analyses. Summarizes the material properties, loads and load case combinations.
- Chapter 3 – Seismic Model: Describes the ANSYS® finite element model used for the seismic analyses. Summarizes the material properties, boundary conditions and acceleration time-histories.
- Chapter 4 – Model Reconciliation: Discusses the differences between the TOLA and seismic models and the methods for combining results.
- Chapter 5 – Structural Acceptance Criteria: Describes the code-based acceptance criteria used to evaluate the combined results.
- Chapter 6 – Analysis Results: Provides a summary of the increased liquid level results. The ACI concrete evaluation for each run is presented, followed by the ASME primary tank evaluation. The stress-corrosion cracking criteria for the primary tank are considered next, followed by buckling analyses of the primary tank. Finally, the ASME evaluation of J-bolts and the secondary liner are assessed.
- Chapter 7 – Conclusions and Recommendations: Summarizes the increased liquid level analysis with conclusions regarding DST structural integrity based on the evaluations conducted.
- Appendix A – ANSYS Validation and Verification for TOLA analysis.
- Appendix B – ANSYS Model Files: Documents the TOLA model input and post-processing files.

2.0 TOLA Model

2.1 Introduction

This chapter describes the ANSYS® finite element (FE) model, material properties, and loads used for the double-shell tank (DST) Increased Liquid Level analysis. Complete documentation of the model is found in the TOLA report (Rinker et al. 2004). The current report contains summaries of the model, material properties and loads. The TOLA report should be referenced for complete model description and background information.

The TOLA analysis was conducted on a model of the 241-AY tank, which was selected as the bounding DST geometry. However, only the 241-AP tanks are being considered for the increase in waste liquid level. It is recognized that significant differences (as summarized in Table 2.4 of the TOLA report) exist between the AP tanks and the TOLA model. These include higher strength structural steel, higher strength concrete, higher strength reinforcing steel, increased thickness foundation, and increased amounts of reinforcing steel. The only modifications to the TOLA model used for the increase liquid level analysis to accommodate the differences in the AP tank design were to the primary tank wall thickness. The use of the TOLA model with the lower strength and thinner materials ensures an additional conservatism to the analysis.

2.2 241-AY Finite Element Model

This section describes the geometry and construction of the ANSYS® finite element model. A comprehensive description of the FE model is found in the TOLA report (Rinker et al. 2004). The TOLA report should be referenced for complete model description and background information. As noted above, these sections describe the TOLA model of the 241-AY tank.

2.2.1 241-AY Tank Model Geometry

The TOLA report provided the rationale for choosing the 241-AY tank as the basis for the bounding model for the DST analyses. The geometry for this tank was taken from the design drawings listed in Table 2-1. A limited number of construction drawings, relating primarily to the steel tank construction, also were referred to for confirmation of dimensions.

It was helpful to review the other tank drawings, particularly 241-SY, because of its similarity to the 241-AY tank. In addition, the newer tank drawings, such as 241-AP, provided valuable insight to the reinforcing steel details.

Table 2-1. Double-Shell Tank 241-AY Design Drawings

Drawing #	Title
H-2-64306	Tank foundation plan
H-2-64307	Structural insulating concrete plan and details
H-2-64310	Concrete tank section and details
H-2-64311	Concrete dome reinforcement plan and details
H-2-64449	Tank elevation and details

2.2.2 241-AP Tank Model Modifications

As noted above, modifications to the TOLA model were limited to changes to the primary tank wall thickness. Figure 2-1 illustrates the differences in the wall thickness between the TOLA model and the AP modifications. The difference in waste depth is also depicted in this figure.

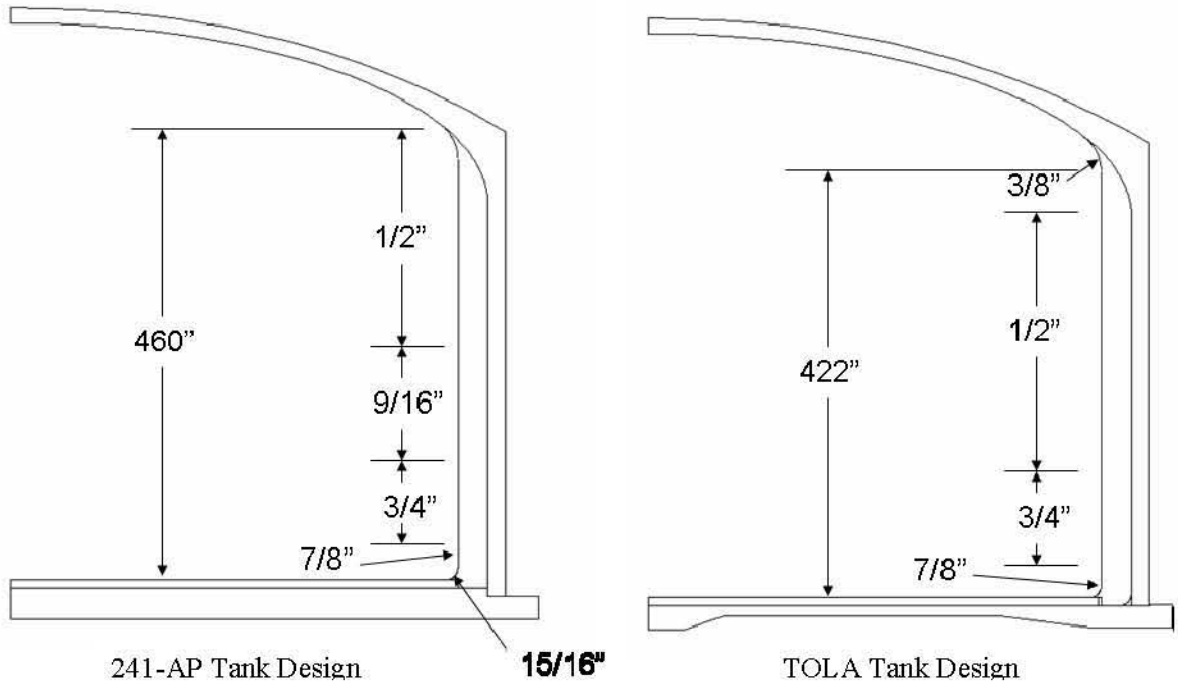


Figure 2-1. Comparison of 241-AP and TOLA Models

2.2.3 ANSYS® Model Construction

ANSYS® Version 7.0 was used for the TOLA analyses. The FE model was developed using ANSYS® APDL macros that build the geometry in 2-D and sweep the cross section about the tank central axis. The macros are listed in Appendix B and also are available electronically. A 2.9-degree section of the tank was modeled with symmetry boundary conditions. This gives an element length of 24 inches in the circumferential direction at the concrete tank inside diameter, which is equal to the J-bolt spacing. Figures 2-2 through 2-5 show various aspects of the model.

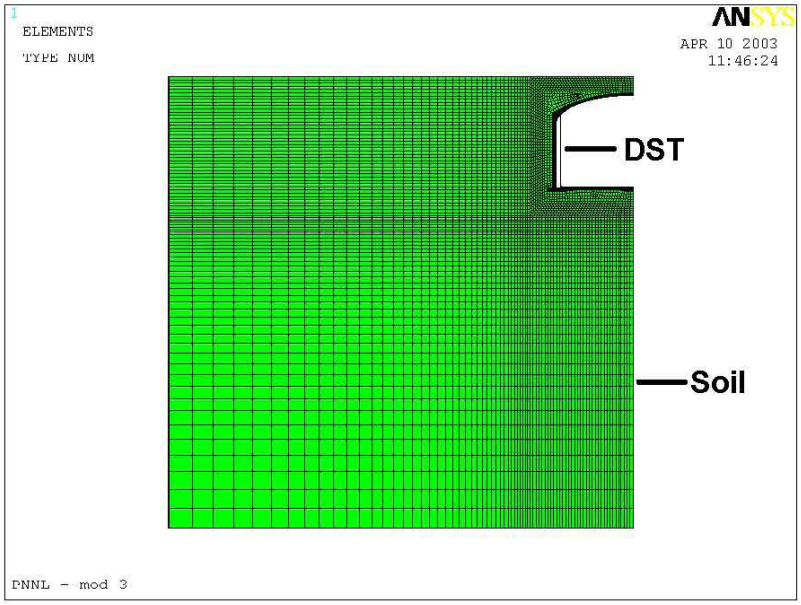


Figure 2-2. Finite Element Mesh of Full Model

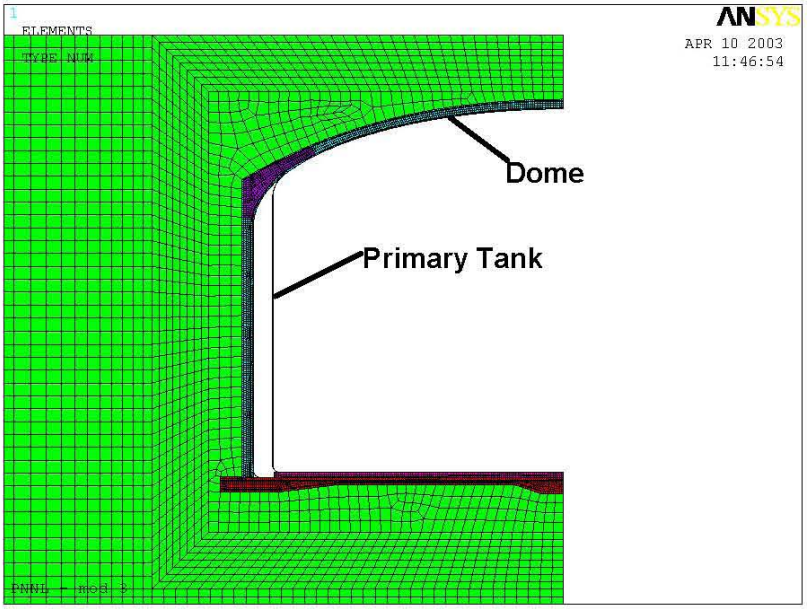


Figure 2-3. Close-up Showing Finite Element Mesh of Tank

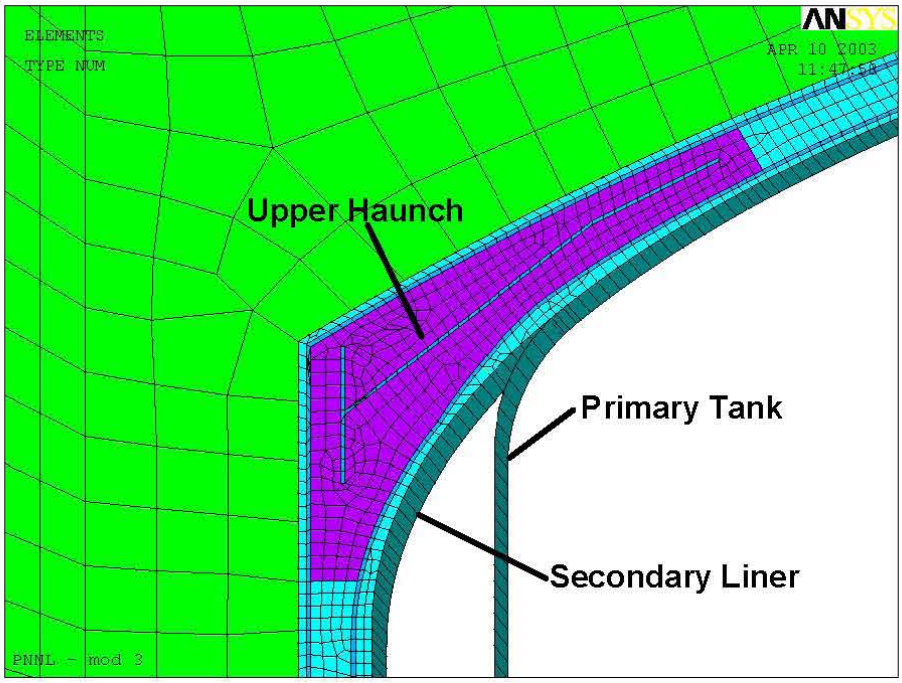


Figure 2-4. Close-up Showing Mesh of Haunch

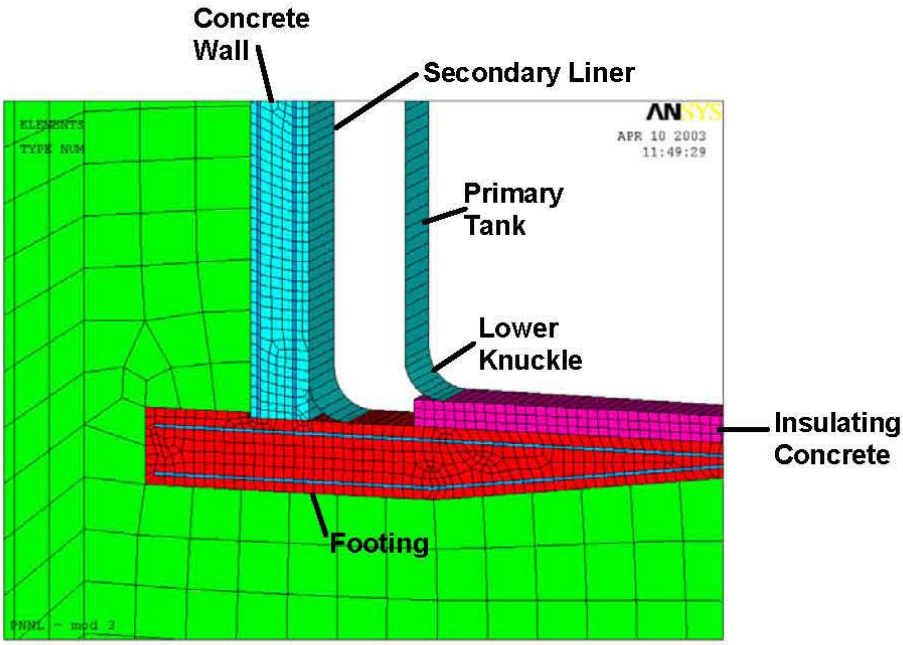


Figure 2-5. Close-up Showing Mesh of Tank Base

The model was constructed with a nominal soil overburden of 8.3 feet. The subgrade undisturbed soil depth is specified at 168 feet below the foundation. The lateral soil dimension is 240 feet and includes a "stair step" boundary to distinguish between undisturbed soil and compacted backfill.

SOLID65 elements are used to represent the reinforced concrete regions. The tank liners, insulating concrete confinement ring, liner construction stiffeners, and the anchors use SHELL181 elements with full integration. The J-bolts and studs use BEAM4 elements. Nonlinear contacts between various surfaces use the TARGET170 and CONTACT173 elements. SOLID45 elements are used to explicitly represent the soil.

The reinforced concrete is divided into regions that have different steel reinforcement ratios, where it is assumed that the thickness of each rebar layer is 1 inch. The rebar capabilities of the SOLID65 concrete elements were used to represent the reinforcing steel. For regions with nonzero reinforcement ratios, the element attributes include an element coordinate system and two rotation angles that identify the rebar orientation. The element x-axis is parallel to the radial direction, the y-axis is parallel to the circumferential direction, and the z-axis is parallel to the vertical direction. The dome uses the z-axis for the vertical/radial direction. The haunch region uses a spherical coordinate system to define the local x-direction (radially outward from the global origin at the bottom/center of the primary tank) to represent the diagonal ties. Note that the directions used for the rebar's three volume ratios specified as real constants are not in the element coordinate system x-, y-, or z-directions (ESYS), but rather the element x-direction for x, rotation angle theta for y, and rotation angle phi for z. See the ANSYS® Elements Manual and Theory Manual for SOLID65 for more detail.

The ANSYS® concrete material model has no provision for representing the post-cracking tension stiffening behavior of reinforced concrete. The stiffness of an element becomes zero immediately upon cracking. As a consequence, achieving convergence proved nearly impossible during the large-scale cracking that occurs in the model during a thermal cycle. Previous DST analytical reports describe similar difficulties and relate the use of "glue elements" to stabilize the solution. For this analysis, a set of SOLID45 elements was superimposed over the SOLID65 concrete elements to provide numerical stability to the model. These elements were assigned a low modulus (approximately 0.5% of the nominal concrete modulus). The use of these augmented stiffness elements greatly facilitated the model convergence and was demonstrated to have no significant impact on the resulting forces, moments, stress, or strain.

The program flow for the model, including a brief description of each macro, is as follows:

SET_SLICE.MAC

- **PNNLA.MAC** – basic tank parameters and 2-D geometry, no soil geometry. Geometry divided to accommodate rebar, J-bolts, and construction stiffeners later. Many area components created.
  - **SET_PARMS** – sets model parameters that may change (e.g., loads, material properties, overburden depth)
- **PNNLA2.MAC** – element attribute (real, type, mat, esys) assignments (not values) to geometry (not soil)
  - **SET_RX.MAC** – selects areas within a range of x
  - **SET_REAL.MAC** – assigns real constant attribute to each area
  - **SET_RY.MAC** – selects areas within a range of y
  - **SET_REAL.MAC** – assigns real constant attribute to each area

  - **SET_REAL.MAC** – assigns real constant attribute to each area
- **PNNLA3.MAC** – identify as components: J-bolt lines (line_bolt), stiffener lines (line_stiff), anchor lines (line_anch in haunch), primary tank lines (line_prim), secondary liner lines (line_secon), bottom anchor lines (line_botanch)
- **PNNLA4.MAC** – 2-D soil geometry, 2-D mesh of soil and the other 2-D solids, rotate to create 3-D geometry/mesh for slice model (no 3-D shell elements), note that soil geometry/mesh is later redefined in set_soil.mac
  - **MESH_SIZE.MAC** – sets default element size for rebar and soil elements, sets sweep angle, and sets number of divisions per quadrant
- **PNNLA5.MAC** – merges nodes/keypoints at slab/rebar and tank/rebar; couples all soil nodes to corresponding structural nodes and top of slab to bottom of wall and top of slab to bottom of insulating concrete (note that all coupling is later deleted)
- **PNNLA6.MAC** – generates J-bolts, studs, wall base plate, confining ring below secondary liner, confining ring for insulating concrete, wall, and dome stiffeners
- **PNNLA7.MAC** – generates primary tank geometry and mesh, defines values for all tank real constants, couples vertical displacements at liner bottom
- **PNNLA8.MAC** – generates secondary liner geometry and mesh, couples vertical displacements at liner bottom, couples shell horizontal displacements to sidewall, couples shell vertical displacements to dome, merges secondary liner nodes with slab top nodes
- **PNNLA9.MAC** – merges liner to J-bolts/studs/anchor nodes, applies constraints
  - **SET_MATERIALS.MAC** – sets all material properties
  - **SET_OPTIONS.MAC** – includes/excludes certain nonlinear material models (e.g., nonlinear concrete, creep, nonlinear steel liner, nonlinear rebar, nonlinear soil)
  - **SET_SOIL.MAC** – creates soil geometry and mesh; couples to concrete
- Delete all coupled sets
- **SET_AREAS_SLICE.MAC** – defines area components for contact definition
- Add steel plate below wall (on slab)
- Add nonlinear contact with appropriate friction coefficients per Section 3.6.2 between soil/concrete, secondary liner/concrete wall, primary tank/dome, primary tank/insulating concrete, slab top/insulating concrete, and wall/slab
- Merge insulating concrete bottom/secondary liner nodes, liner/concrete nodes at centerline
- **SET_ESYS_3D.MAC** – defines all rebar elements real, modifies secondary liner elements above 357.5 inch to be 3/8 inch thick
- **APPLY_LOADS_SLICE.MAC** – reverses area normal of radiused section of secondary liner, applies parametric loads
  - **MESH_SIZE.MAC** – sets default element size for rebar and soil elements, sets sweep angle, and sets number of divisions per quadrant

- Apply axisymmetric boundary conditions
- Copy J-bolts, etc. for slice model; divide J-bolt/bottom anchors by 2 for slice model
- Couple nodes at primary/secondary liner intersection
- Define soil layers including elevation and material properties
  - **SET_SLAYER.MAC** – applies soil material properties to a layer
- **SET_BACKFILL.MAC** – defines backfill region and sets linear and nonlinear material properties
- Define augmented stiffness elements
- Merge duplicate contact elements/nodes
- Apply gravity, waste depth, surface loads, annulus and primary tank pressures
- **SET_SLICEB.INP** runs the thermal cycling for years 1 through 5
- **Extended13yr.INP** runs the thermal cycling and creep for years 6 through 18
- **TwoYrCycle.INP** runs the thermal cycling for years 19 and 20
- **TwoYrCycleWith460wh.INP** increases the waste level to 460 inches and runs the thermal cycling for year 21 and 22
- **Extended36yr.INP** runs the thermal cycling and creep for years 23 through 58
- **TwoYrCycTo60Yr.INP** runs the thermal cycling for year 59 and 60
- **SET_SLICED6.INP** runs ACI load combination 4
- **SET_SLICEH.INP** runs the thermal cycle for load combination 9

The ANSYS® concrete material model is used for the SOLID65 elements. This model allows for cracking and crushing, as well as variable shear transfer for open/closed cracks. In addition, the implicit creep material model for concrete was used. ANSYS® allows for the concrete cracking/crushing material model and creep material model to be used simultaneously.

The soil elements use the Drucker-Prager constitutive model, which has an internal friction angle, cohesion, and a dilatancy angle as material properties (see Section 2.3.5). A small positive value of cohesion is used to represent the Hanford cohesionless soils, and the dilatancy angle is assumed to be equal to the friction angle (this parameter induces volume changes as a function of element shear stress).

The soil region surrounding the concrete tank and foundation is coupled to the concrete using nonlinear surface-to-surface contact elements, where the sliding friction coefficient is as specified in Section 2.3.6.

The tank liners are coupled to the structural and nonstructural concrete in a similar manner, i.e., with nonlinear contact elements. A friction coefficient is used for these surfaces as well, as specified in Section 2.3.6. These include contact between the following surfaces:

- secondary liner and tank
- primary tank and dome
- bottom of primary tank and top of insulating concrete

- top of slab and bottom of insulating concrete
- bottom of secondary liner and top of slab
- bottom of tank wall and top of slab.

2.2.4 Real Constants

ANSYS® uses real constants to define element properties for certain element types, e.g., thickness for shell elements. The thicknesses of the different regions of the steel liners are defined in **SET_PARMS.MAC** and assigned in **PNNLA7.MAC**. The thickness of the primary tank that is in contact with the waste was given a 0.001 inch/year corrosion allowance for the desired 60-year design life, for a total reduction of 0.060 inch at the beginning of the analysis. Real constants for the wall and dome stiffeners are defined in **PNNLA6.MAC**.

2.2.4.1 Reinforcing Steel

The concrete reinforcing steel is modeled by using the rebar capabilities of the ANSYS® SOLID65 element. Elements of 1-inch thickness were defined in the appropriate locations in the dome, haunch, wall, and foundation. The real constants for the rebar elements include the following for each of three possible rebar directions:

- the rebar material ID
- steel volume ratio
- two angles used to orient the rebar directions relative to the element coordinate system.

Tables 2-2 through 2-5 show the calculations for the steel volume ratios required for the concrete rebar elements. The geometry of the rebar, including the locations of transition between rebar volumes, is defined in **PNNLA.MAC**. Real constants are initially assigned by location in **PNNLA2.MAC**. The volume ratios and rebar orientation are defined in **SET_ESYS_3D.MAC**.

2.2.4.2 J-bolts

The tank design drawings listed in Table 2-1 specify a J-bolt spacing of 2 feet by 2 feet. The 3-D finite element model was constructed as a 2.9-degree wedge, which gives the correct 24-inch spacing at the concrete wall (480 feet). The J-bolts at smaller radii were modified as shown in Table 2-6 to preserve the correct area. The J-bolts are straight and extend through the interior rebar layer.

Table 2-2. Foundation Concrete Rebar Volume Ratios

Description:	Slab Bottom								
Elevation (in.)	**Radius (in.)**	**Bar Size**	***Meridional* Spacing[a]**	**# Bars[a]**	**Volume Ratio**	**Bar Size**	***Hoop* Spacing**	**Volume Ratio**	**Real Constant**
NA	75	5	12	NA	0.0256	5	12	0.0256	101
	115	5	NA	48	0.0258	5	12	0.0256	102
	202	5	NA	95	0.0316	5	12	0.0256	103
	350	5	NA	189	0.0360	5	12	0.0256	104
	369	5	NA	240	0.0326	5	12	0.0256	105
	435	5	NA	240	0.0293	5	12	0.0256	106
	444	5	NA	240	0.0267	6	8	0.0552	107
	528	7	NA	512	0.1016	6	8	0.0552	108
Description:	**Slab Top**								
Elevation (in.)	**Radius (in.)**	**Bar Size**	***Meridional* Spacing**	**# Bars**	**Volume Ratio**	**Bar Size**	***Hoop* Spacing**	**Volume Ratio**	**Real Constant**
NA	75	5	12	NA	0.0256	5	12	0.0256	111
	115	5	NA	45	0.0242	5	12	0.0256	112
	202	5	NA	99	0.0330	5	12	0.0256	113
	350	5	NA	198	0.0377	5	12	0.0256	114
	369	5	NA	198	0.0269	5	12	0.0256	115
	435	5	NA	256	0.0313	5	12	0.0256	116
	444	5	NA	256	0.0284	6	8	0.0552	117
	528	5	NA	256	0.0259	6	8	0.0552	118

(a) The drawings used to obtain this information specify rebar by spacing or # bars; therefore, where a measurement for Meridional spacing is given, information for # bars is not recorded, and vice versa.
NA = not applicable.

Table 2-3. Wall Concrete Rebar Volume Ratios

Description:	Wall								
Elevation (in.)	**Radius (in.)**	**Bar Size**	***Meridional* Spacing[a]**	**# Bars[a]**	**Volume Ratio**	**Bar Size**	***Hoop* Spacing**	**Volume Ratio**	**Real Constant**
147	75	6	12	NA	0.0368	8	8	0.0982	201/206
204	115	6	9	NA	0.0491	8	8	0.0982	202/207
303	202	6	9	NA	0.0491	8	12	0.0654	203/208
339.5	350	8	12	NA	0.0654	8	12	0.0654	204/209
381.5	369	8	12	NA	0.0654	8	12	0.0654	205/210

(a) The drawings used to obtain this information specify rebar by spacing or # bars; therefore, where a measurement for Meridional spacing is given, information for # bars is not recorded, and vice versa.
NA = not applicable.

Table 2-4. Dome Concrete Rebar Volume Ratios

Description: Elevation (in.)	Dome Radius (in.)	Bar Size	*Meridional* Spacing[a]	# Bars[a]	Volume Ratio	Bar Size	*Hoop* Spacing	Volume Ratio	Real Constant
NA	120	6	NA	51	0.0453	6	12	0.0368	301
	183	6	NA	101	0.0490	6	12	0.0368	302
	270	6	NA	202	0.0651	6	12	0.0368	303
	304.5	6	NA	202	0.0496	8	6	0.1309	304
	314	8	NA	346	0.1399	8	6	0.1309	305
	354	8	NA	346	0.1300	9	6	0.1657	306
	368.9	8	NA	346	0.1197	9	4	0.2485	307
	391	8	NA	346	0.1139	9	4	0.2485	308

(a) The drawings used to obtain this information specify rebar by spacing or # bars; therefore, where a measurement for Meridional spacing is given, information for # bars is not recorded, and vice versa.
NA = not applicable.

Table 2-5. Haunch Concrete Rebar Volume Ratios

Elevation (in.)	Haunch External Radius (in.)	Bar Size	*Meridional* Spacing[a]	# Bars[a]	Volume Ratio	Bar Size	*Hoop* Spacing	Volume Ratio	Real Constant
NA	450	8	NA	519	0.1534	9	4.5	0.2209	401
NA	496	8	NA	519	0.1375	9	4.5	0.2209	402
NA	496	8	4	NA					
408	NA	6	6	NA	0.2700	8	6	0.1309	404
452	NA	8	6	NA	0.1309	9	4	0.2485	403
Elevation (in.)	**Internal Radius (in.)**	**Bar Size**	***Meridional* Spacing[a]**	**# Bars[a]**	**Volume Ratio**	**Bar Size**	***Hoop* Spacing**	**Volume Ratio**	**Real Constant**
NA	480	8	NA	519	0.1489	9	4.5	0.2209	406
408	NA	8	6	NA	0.1309	8	6	0.1309	405
Elevation (in.)	**Middle Radius (in.)**	**Bar Size**	***Meridional* Spacing[a]**	**# Bars[a]**	**Volume Ratio**	**Bar Size**	***Hoop* Spacing**	**Volume Ratio**	**Real Constant**
NA	486.5	6	NA	163	0.0261	9	4.5	0.2209	502
435	487	6	NA	163	0.0235	9	8	0.1243	500
451	NA	4	18	NA	0.0109	9	8	0.1243	501
	Ties	**Bar Size**	***Meridional* Spacing**	**Hoop Space**	**Volume Ratio**				
NA		4	16	18	0.0007	NA	NA	NA	NA

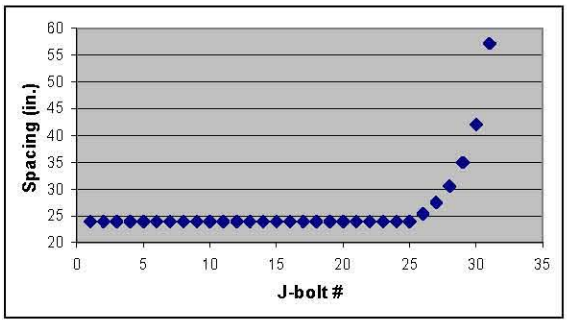
(a) The drawings used to obtain this information specify rebar by spacing or # bars; therefore, where a measurement for Meridional spacing is given, information for # bars is not recorded, and vice versa.
NA = not applicable.

Table 2-6. J-Bolt Spacing Calculations

DST-AY
J-bolt Spacing

	r (in.)	h (in.)
Reference Location:	431.69	460.19
Spacing (in.):	24.00	

J- Bolt Number	Radial Position (in.)	Vertical Position (in.)	Angle (deg)	Spacing (in.)	
1	479	19	90	24.00	At radial positions where R > 319 in., the chord length
2	479	43	90	24.00	between J-bolts is the reference spacing. Where
3	479	67	90	24.00	R < 319 in., the chord length is increased to preserve
4	479	91	90	24.00	the contributary area (4 ft^2). The contributary area is
5	479	115	90	24.00	calculated as $A = (r_2^2-r_1^2)*\Delta\theta/2$. If r_2^2 is known and
6	479	139	90	24.00	$\Delta\theta$ is assumed fixed, then r_1^2 can be evaluated.
7	479	163	90	24.00	
8	479	187	90	24.00	The linear vertical angle is approximated by eye from H-2-64449.
9	479	211	90	24.00	
10	479	235	90	24.00	
11	479	259	90	24.00	
12	479	283	90	24.00	
13	479	307	90	24.00	
14	479	331	90	24.00	
15	479	355	90	24.00	
16	479	379	75	24.00	
17	473	402	65	24.00	
18	462	424	55	24.00	
19	449	443	45	24.00	
20	432	460	40	24.00	(Liner Intersection)
21	412	474	35	24.00	
22	391	486	30	24.00	
23	369	496	25	24.00	
24	347	504	20	24.00	
25	324	511	15	24.00	
26	299	515	10	25.32	
27	272	518	9	27.52	
28	241	522	8	30.51	
29	206	525	7	34.86	
30	165	527	6	41.98	
31	107	529	5	57.22	



2.3 Material Properties

This section summarizes the material properties used in the TOLA finite element model. A comprehensive description of the structural and thermal properties is found in the TOLA report (Rinker et al. 2004). The TOLA report should be referenced for complete material property description and background information. The lower concrete and steel strengths of the TOLA analysis were

maintained in the Increased Liquid Level finite element model. The higher strength of the A537 steel used in the AP tanks was used for the allowable stress evaluation of the primary steel tank.

2.3.1 Structural Concrete

This section summarizes the structural properties of reinforced concrete that were used in the finite element analysis. The concrete properties listed here represent Hanford batch concrete with a 3 ksi specified minimum compressive strength, as specified for the 241-AY tank design. The properties are summarized in the figures and tables in this section.

The concrete elastic modulus was prescribed to be temperature-dependent, as shown in Figure 2-6. The concrete compressive and tensile strengths are shown in Figure 2-7. These are the mean strengths as described in the TOLA report (Rinker et al. 2004). These values are used in the ANSYS® cracking algorithm employed with the SOLID65 concrete elements. The crushing capabilities of the SOLID65 elements were not used. The ACI code evaluation (see Section 6.1 of Chapter 6) used the lower bound compressive strengths of 4.5 ksi specified minimum strength concrete to determine the load and moment capacities of the reinforced concrete tank structure. Thus, the analysis conservatively used the mean strength properties to determine the demand and the lower bound properties to establish the concrete section capacity. The TOLA report (Rinker et al. 2004) describes the basis for the concrete strength degradation as a function of temperature.

The coefficient of thermal expansion (CTE) of concrete was taken to be 0.37 x 10^{-6} in./in./°F. Poisson's ratio was specified to be 0.15.

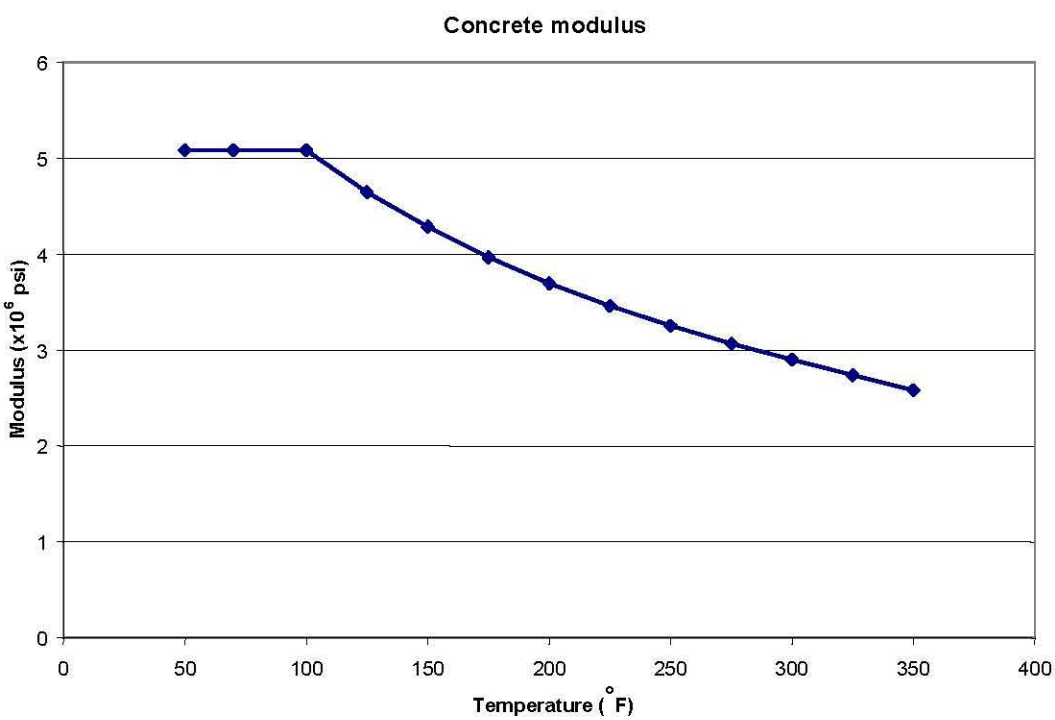


Figure 2-6. Concrete Elastic Modulus

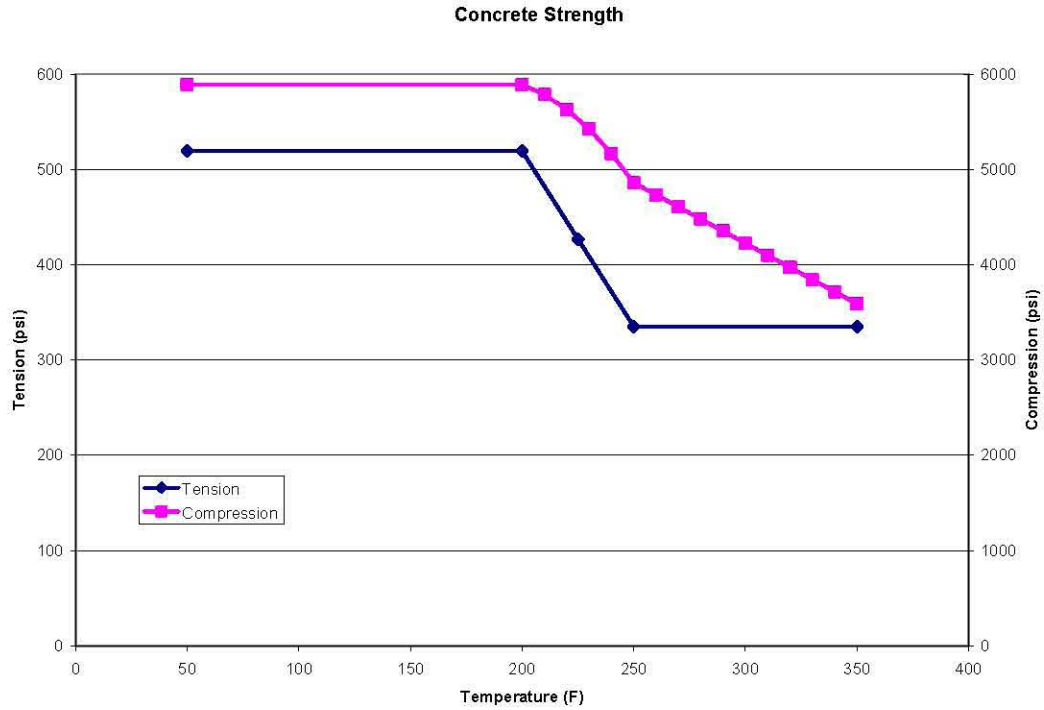


Figure 2-7. Concrete Strength Used for Finite Element Analysis

Previous DST analyses have identified concrete creep as being an important material parameter. The TOLA report (Rinker et al. 2004) describes the procedure and data used for defining the concrete creep material model. The time-hardening creep algorithm in ANSYS® is defined as

$$\dot{\varepsilon}_{cr} = C_1 \sigma^{C_2} t^{C_3} e^{-C_4/T} \tag{1.1}$$

The coefficients used for the ANSYS® time-hardening implicit creep law are given in Table 2-7. The creep law parameters are provided to ANSYS® via the TBDATA command found in **SET_PARMS.MAC**.

Table 2-7. Coefficients for the ANSYS® Creep Law

Coefficient	Value
C1	0.2545×10^{-6}
C2	1
C3	–0.838
C4	320

2.3.1.1 Degraded Concrete Properties

It was necessary to develop a method to prevent the concrete modulus and strength from "recovering" during subsequent thermal cycles after the initial degradation due to elevated temperature. This was accomplished by redefining the concrete material properties in their degraded condition at the end of the first year at 210°F. Because the degradation is temperature-dependent, this definition required segregating the concrete elements into groups of 10-degree increments based on their maximum

temperature (steady-state). A modified set of concrete properties in the degraded condition was defined. At the conclusion of the first year of creep, the properties of each 10-degree group of concrete elements were changed using the ANSYS® mpch command to redefine these elements with the degraded properties.

2.3.2 Insulating Concrete

A linear elastic material model was prescribed for the insulating concrete. Table 2-8 lists the structural properties that were used. The compressive strength was not used in the finite element analysis, but was employed in the evaluation of the insulating concrete stress level.

Table 2-8. Structural Properties for the Insulating Concrete

Material Property	Units	Value – Tank AY
Compressive Strength	psi	200
Elastic Modulus	psi	165,000
Poisson's Ratio		0.15
Density	lbf/ft^3	50
Coefficient of Thermal Expansion	in./in.–°F	3.7

2.3.3 Structural Steel

The elastic modulus of the primary tank and the secondary liner structural steels was defined to be temperature-dependent, as shown in Figure 2-8. An elastoplastic material model was defined with a yield of 36,000 psi and a tangent modulus of 1% the nominal elastic modulus. The density of steel was taken as 490 lb/ft^3. Poisson's ratio was taken as 0.30. The steel CTE was defined to be temperature-dependent, as shown in Figure 2-9.

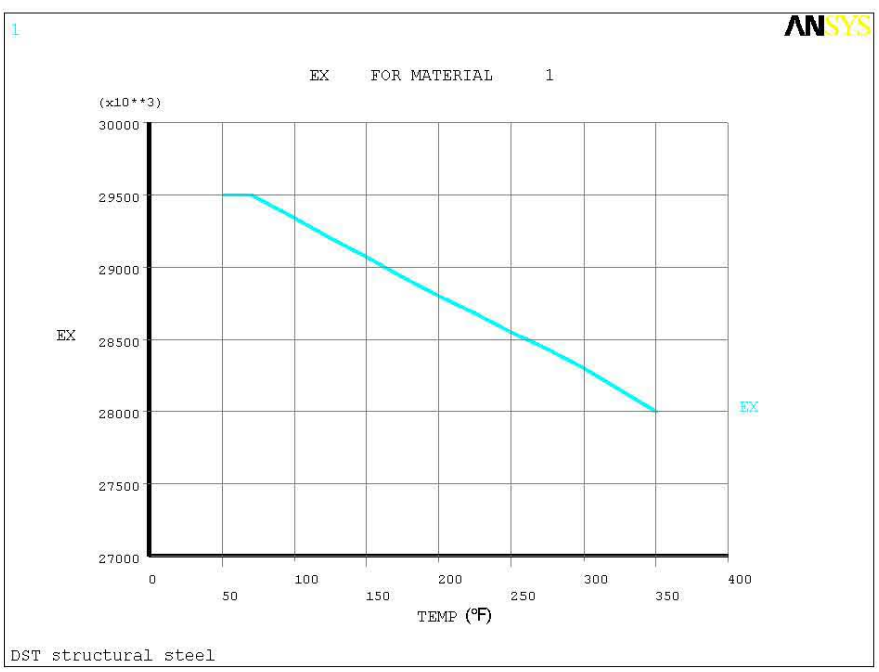


Figure 2-8. Structural Steel Elastic Modulus

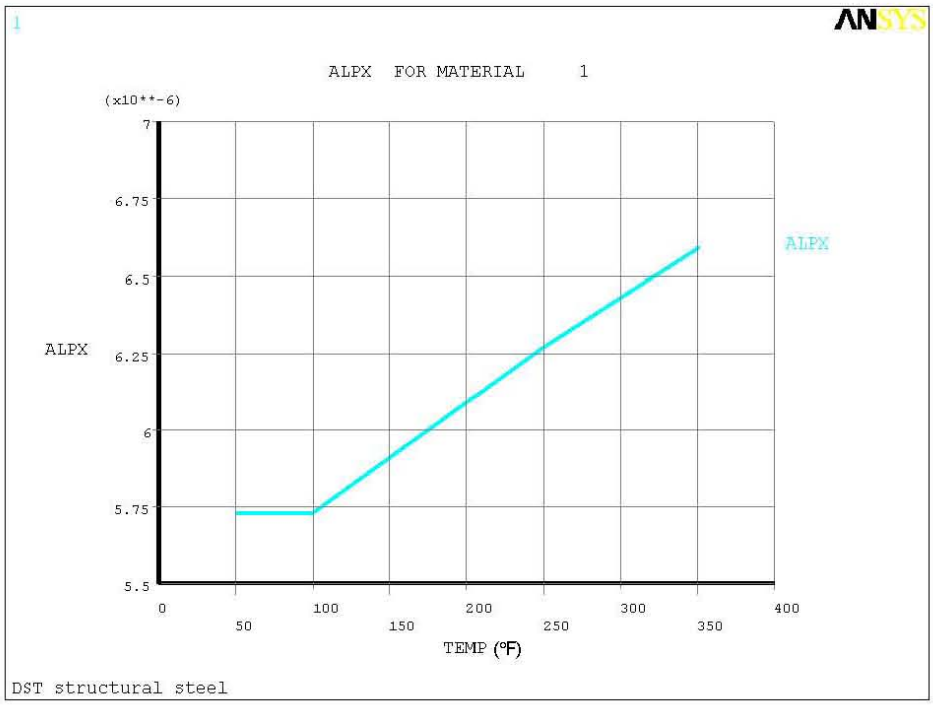


Figure 2-9. Structural Steel Coefficient of Thermal Expansion

2.3.4 Reinforcing Steel

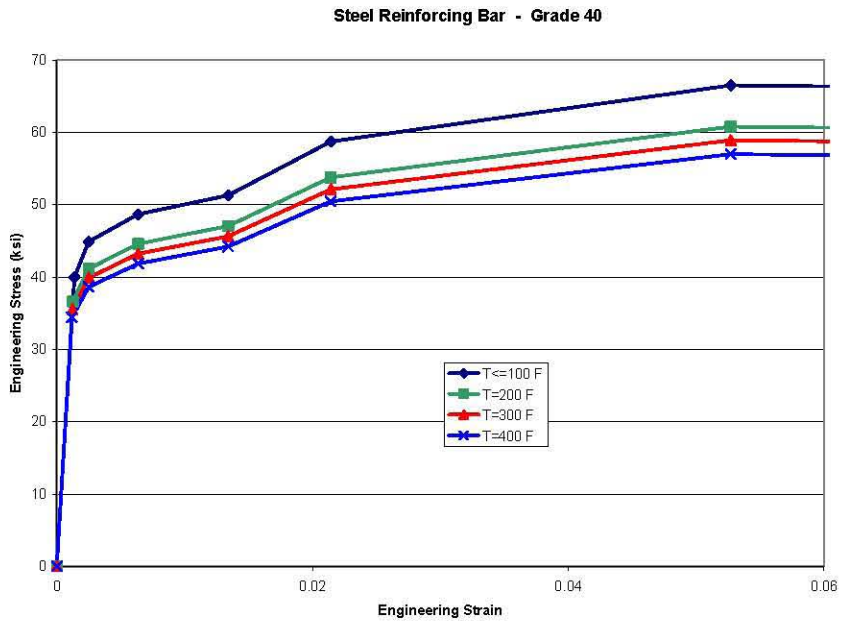
Two grades of reinforcing steel were used in the construction of the 241-AY DST. Rebar with 40,000 psi yield strength was used in the slab, and steel with 60,000 psi yield strength was used in the wall and dome. The nonlinear stress-strain curves shown in Figure 2-10 for both grades of rebar were implemented in the ANSYS® model. The density was specified to be 490 lb/ft^3. Poisson's ratio was taken as 0.3 and the mean CTE was specified as 6 x 10^{-6} in./in.-°F.

2.3.5 Soils

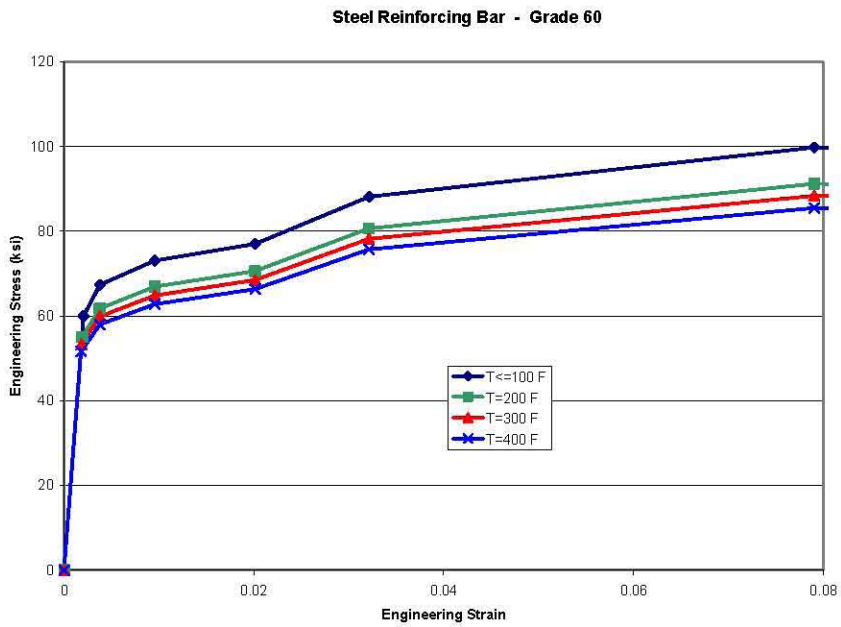
Distinction was made between the undisturbed soil and the compacted backfill, as shown Figure 2-11. The DST foundation is supported by the undisturbed native soil. The backfill applies radial pressure and axial frictional force to the tank walls and a dead load to the dome. The FE soil properties were distributed accordingly, as depicted in Figure 2-12.

The soil dimensions are:

Soil depth below foundation:	168 feet
Overburden depth:	8.3 feet
Radial extent (from center of tank):	240 feet
Excavation slope:	Stair-stepped approximation with 1.5:1 slope



(a)



(b)

Figure 2-10. Steel Reinforcing Bar Stress-Strain Curves: a) Grade 40 rebar (slab), b) Grade 60 rebar (wall and dome)

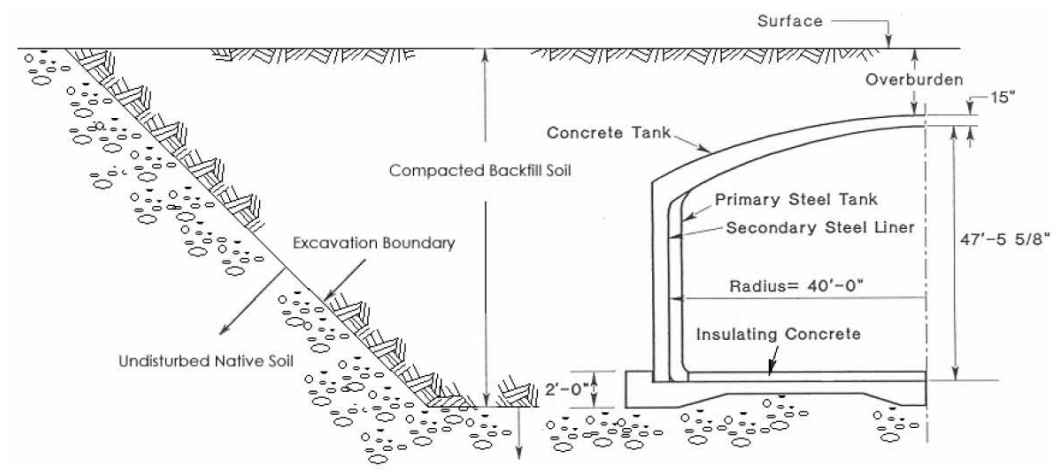


Figure 2-11. Soil Configuration Adjacent to DSTs

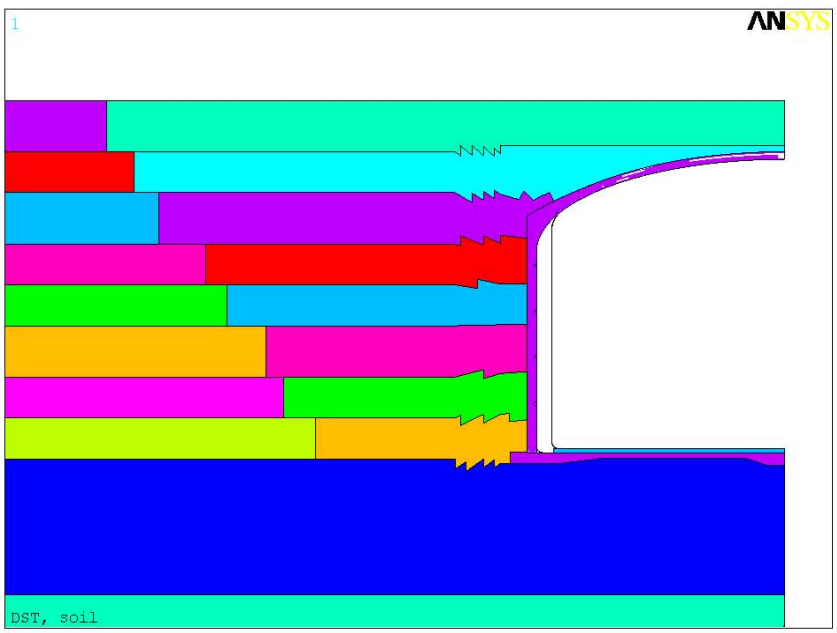


Figure 2-12. Distribution of Soil Properties in the DST Finite Element Model

The soil constitutive model used for the DST analysis was the ANSYS® Drucker-Prager elastoplastic model. The elastic response is determined by the elastic modulus (E) and the Poisson's ratio (υ). The elastic modulus and Poisson's ratio must be assigned according to the soil depth because the Drucker-Prager model does not adjust the stiffness for confining pressure. The undisturbed soil elastic modulus and Poisson's ratio are shown in Figure 2-13. The compacted backfill soil modulus is shown in Figure 2-14. The backfill Poisson's ratio was constant at 0.27.

The Drucker-Prager plasticity parameters were defined to be constant with soil depth and temperature. The values used are: cohesion = 1.0 psi, friction angle = 35°, and dilatancy angle = 8°. The undisturbed soil density was 110 lb/ft^3 and the compacted backfill density was 125 lb/ft^3. A detailed discussion is presented in the TOLA report (Rinker et al. 2004).

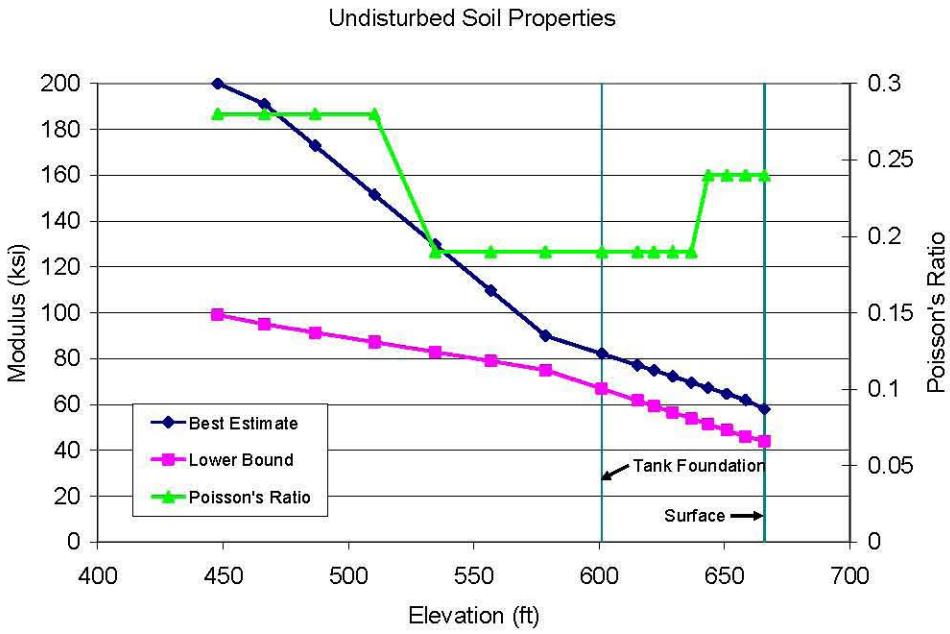


Figure 2-13. Undisturbed Soil Elastic Modulus and Poisson's Ratio

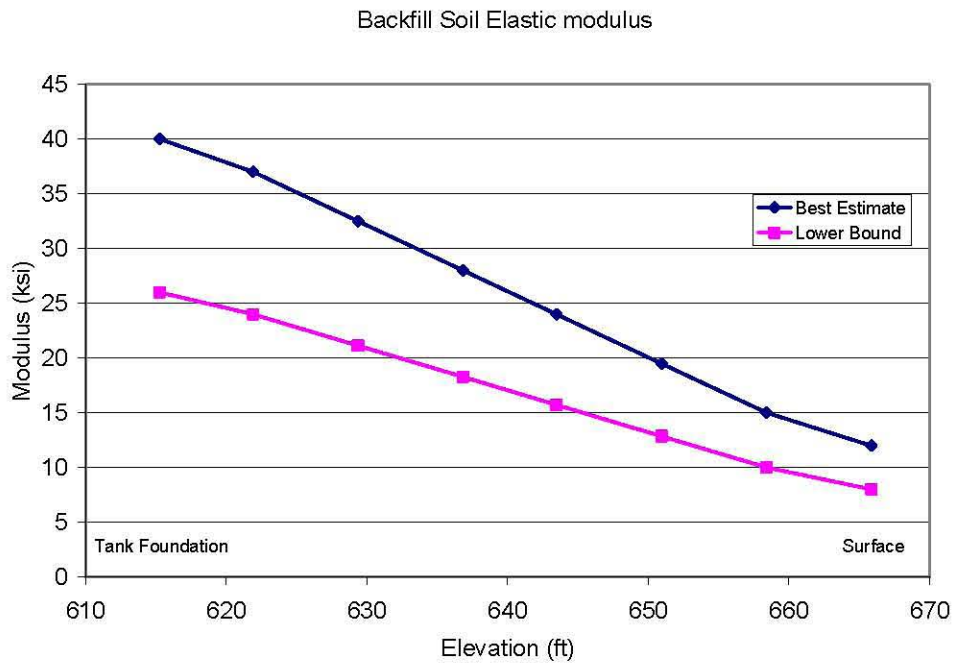


Figure 2-14. Backfill Soil Elastic Modulus

2.3.6 Coefficients of Friction at Material Interfaces

The DST finite element model includes several contact interfaces where friction forces must be accounted for. Table 2-9 summarizes the coefficients of friction (COF) that are used in the DST model. The basis for these values is given in Rinker et al. (2004).

Table 2-9. Coefficients of Friction

Material Interface Description		Coefficient of Friction
Soil-to-Concrete:	Dome	0.3
	Side Walls	0.05
	Base Mat	0.6
Concrete-to-Steel (concrete cast against steel)		0.4
Concrete-to-Steel (insulating concrete-to-primary tank)		0.3
Steel-to-Steel (graphite-lubricated)		0.2

2.4 Loads

This section describes the loads used in the thermal and operating load analysis. A comprehensive description of the load and boundary conditions is found in the TOLA report (Rinker et al. 2004). The TOLA report should be referenced for complete load description and background information.

The load parameters are defined in **SET_PARMS.MAC** and are applied in **APPLY_LOADS_SLICE.MAC**. The loading sequence is defined in **SET_SLICE.MAC** and subsequent input files.

2.4.1 Thermal Loads

The temperature distributions described in the TOLA report (Rinker et al. 2004) were applied as thermal loads. The temperature profiles represented a yearly thermal cycle that includes the design basis heat-up transient, a steady-state dwell time at the maximum design waste temperature, followed by the design basis temperature cool-down transient. Table 2-10 presents the time and waste temperatures that define the cycle. Multiple temperature distributions were solved during the waste heating and cooling segments of the transient to ensure that the maximum effect of the transient temperature gradients was captured in the structural evaluations of the concrete and steel sections. It was also conservatively assumed that the steady-state temperature distribution corresponding to a maximum waste temperature of 210°F was achieved at the end of the high-temperature segment of the transient. This approach ensures that the maximum concrete temperatures and the maximum thermal degradation in the concrete strength and stiffness are considered. At the low waste temperature of 50°F it was also assumed that the transient ended with the tank and surrounding soil returning to the uniform 50°F initial temperature. The mechanical analyses assume 50°F as the initial stress-free temperature for the soil, steel, and concrete.

The DST model temperatures are used in the analysis for including the effects of concrete thermal degradation, temperature-dependent steel properties, and differential thermal expansion between the steel and the concrete. The different temperature fields corresponding to the mechanical solution (steps 2 through 12 in Table 2-10) are shown in Figures 2-15 through 2-24. (Note that solution steps 7 and 8 are the same temperature state and only plotted once.) Data files for the temperature distributions are prohibitively large for inclusion in this report as appendixes but are available on the electronic media version of this report.

Table 2-10. Temperature States that Define the Design Basis Annual Thermal Cycle for the ANSYS® Structural Model

Step No.	Comment	Days	Waste Temp., °F	Plot Label
1	Initial Temperature = 50°F uniform	0	50	
2	Fast heat to 125°F (@ 10°F/hour)	0.3	125	h1
3	First step to 210°F (@ 20°F/day)	2.4	167.5	h2
4	Second step to 210°F	4.6	210	h3
5	Intermediate step toward Steady-State	23	210	h4
6	Steady-State @ 210°F	38	210	Ss
7	Hold – Steady-State @ 210°F	350	210	Hold
8	Material Property Change	351	210	
9	First step to 125°F cool-down (@ 20°F/day)	353	167.5	c1
10	Second step to 125°F	355	125	c2
11	Fast cool-down to 50°F (@ 10°F/day)	355.6	50	c3
12	Tank cool-down transient to 50°F	356.6	50	c4
13	Uniform 50°F	365	50	

The service life of the 241-AP Tank Farm is 50 years. For the purpose of this analysis, a life of 60 years was selected. This value was chosen based on the number of years already in service and the anticipated continuing waste storage. While the historical data suggest a three-year full-temperature cycle, an annual cycle was conservatively specified for the thermal loading. However, the completion of an analysis with 60 thermal cycles proved problematic with the model convergence issues. Review of the preliminary results demonstrated little change in the concrete cracking, concrete force and moments and tank stress beyond the first several cycles. In addition, the creep rate decreases over time (see the TOLA report Chapter 3). Accordingly, analyses consisted of one thermal cycle per year of 422 inches of waste for 5 years followed by 13 years of creep at elevated temperature followed by two annual thermal cycles. The waste level was then increased to 460 inches. Two annual thermal cycles were conducted at this waste level followed by 36 years of creep at elevated temperature, concluding with two final thermal cycles, as described in Section 2.4.4.

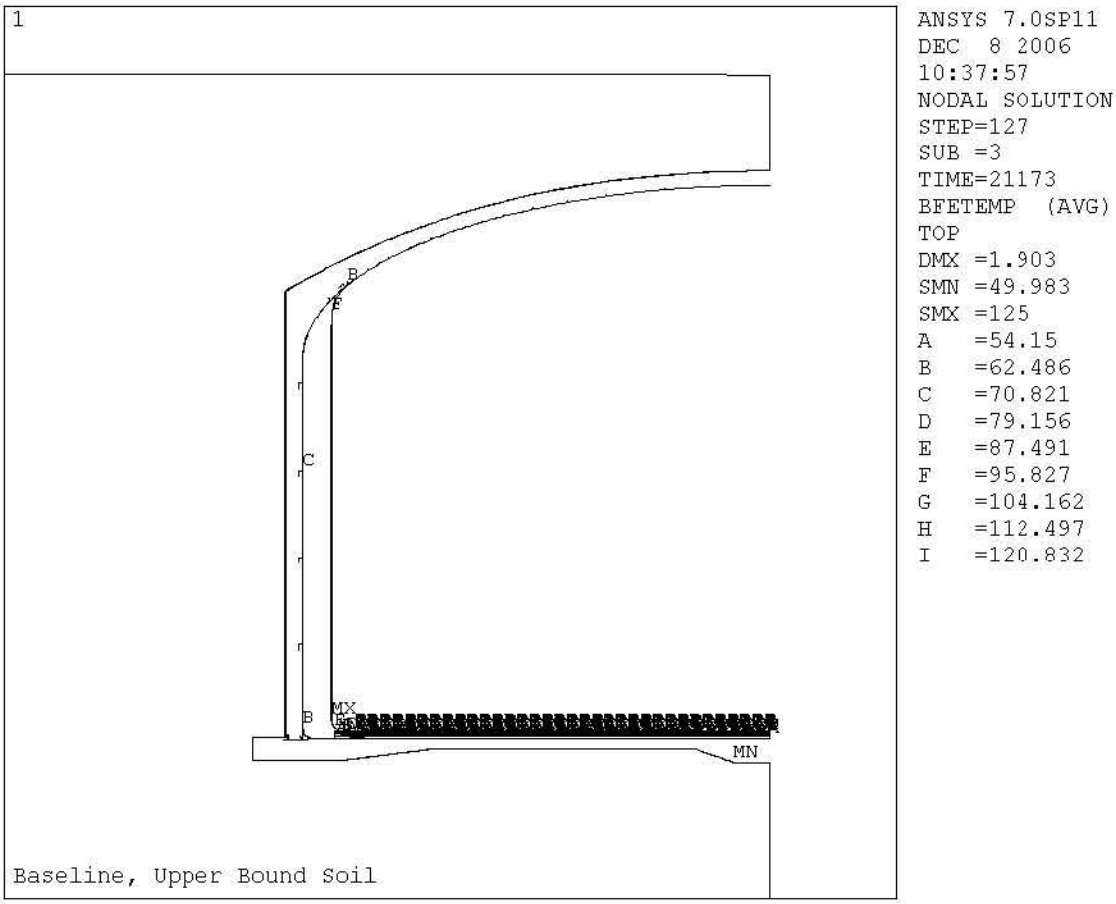


Figure 2-15. Temperature (°F) Distribution at Step 2 (Table 2-10) in the Design Basis Transient (waste temperature = 125°F)

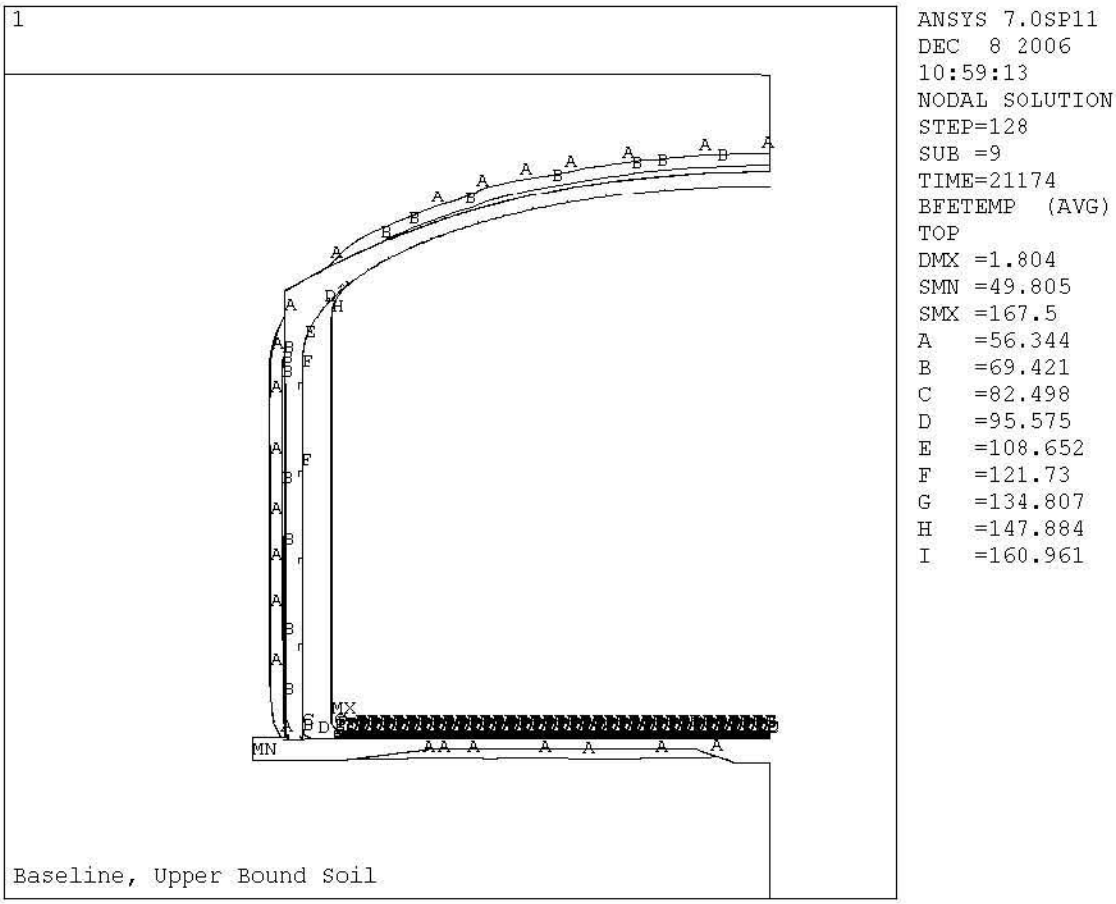


Figure 2-16. Temperature (°F) Distribution at Step 3 (Table 2-10) in the Design Basis Transient (waste temperature = 167.5°F)

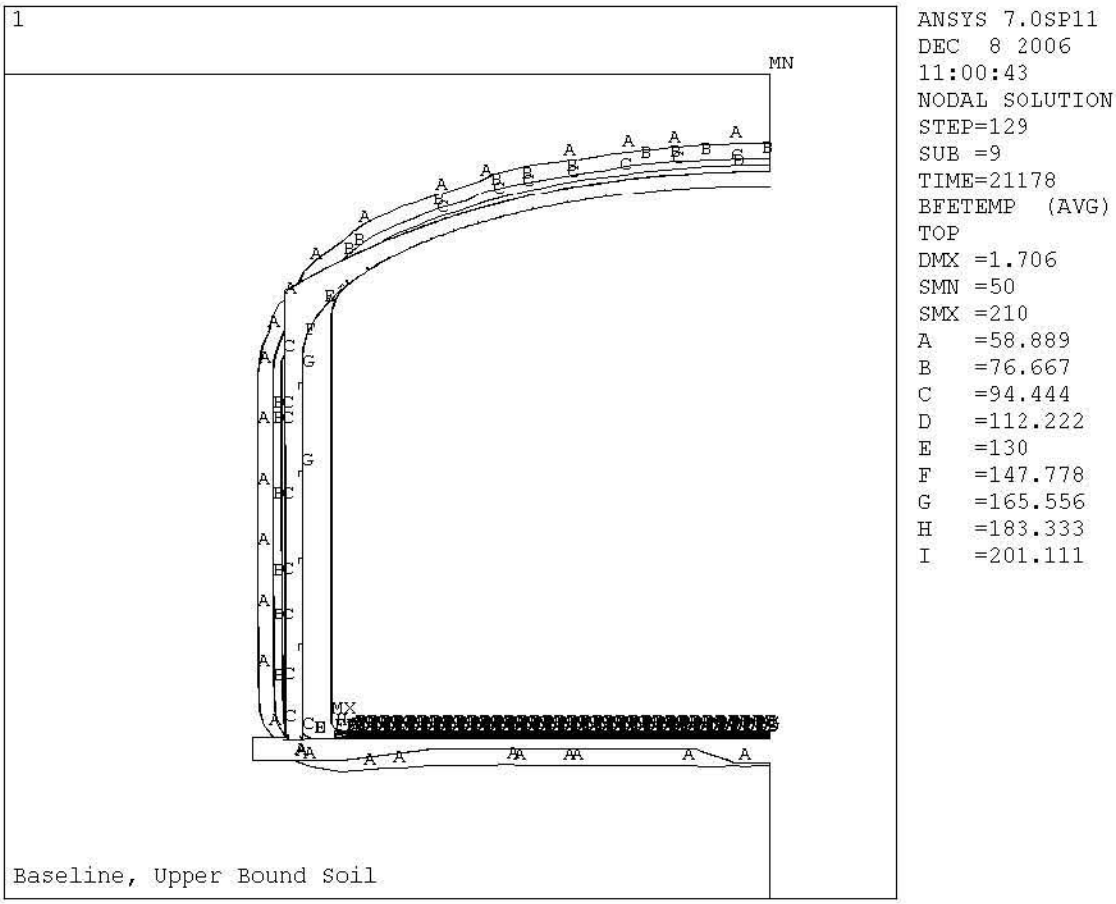


Figure 2-17. Temperature (°F) Distribution at Step 4 (Table 2-10) in the Design Basis Transient (waste temperature = 210°F)

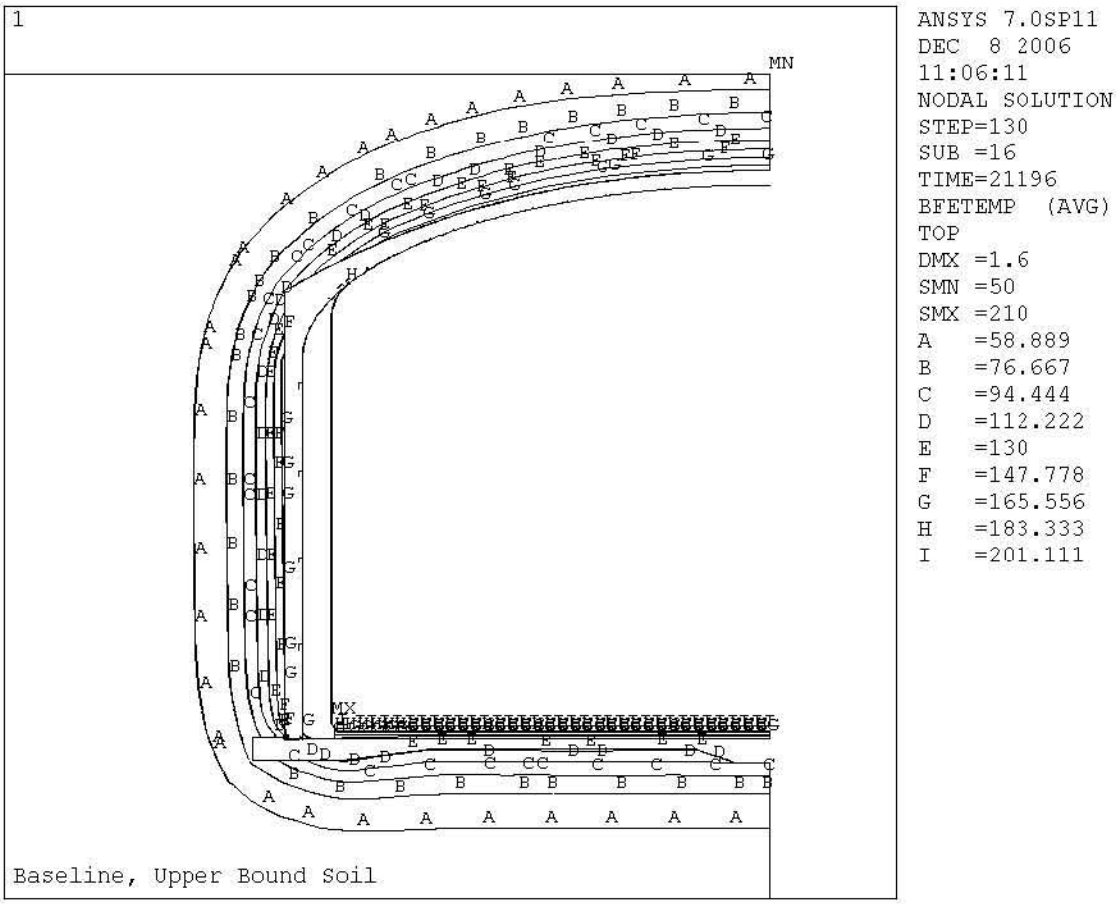


Figure 2-18. Temperature (°F) Distribution at Step 5 (Table 2-10) in the Design Basis Transient (waste temperature = 210°F)

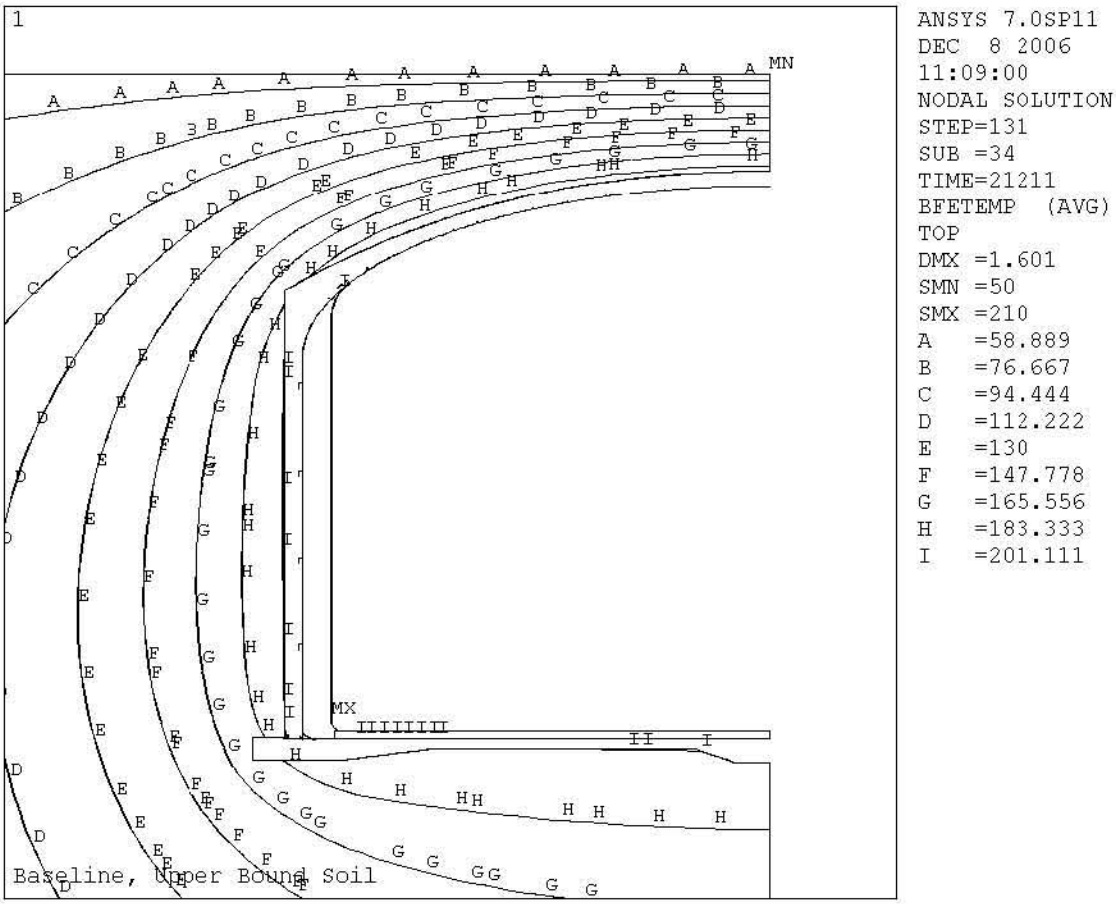


Figure 2-19. Temperature (°F) Distribution at Step 6 (Table 2-10) in the Design Basis Transient (waste temperature = 210°F)

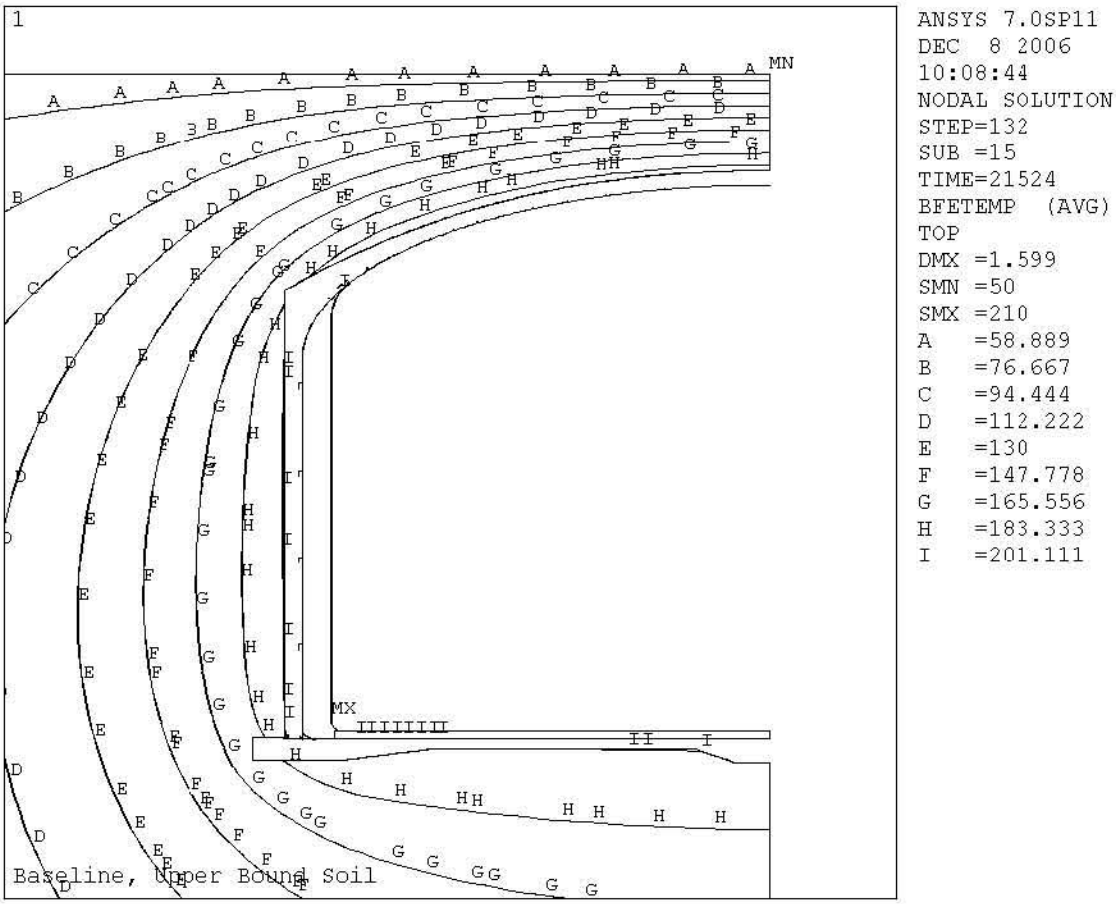


Figure 2-20. Steady-State Temperature (°F) Distribution at Steps 7 and 8 (Table 2-10) in the Design Basis Transient (waste temperature = 210°F)

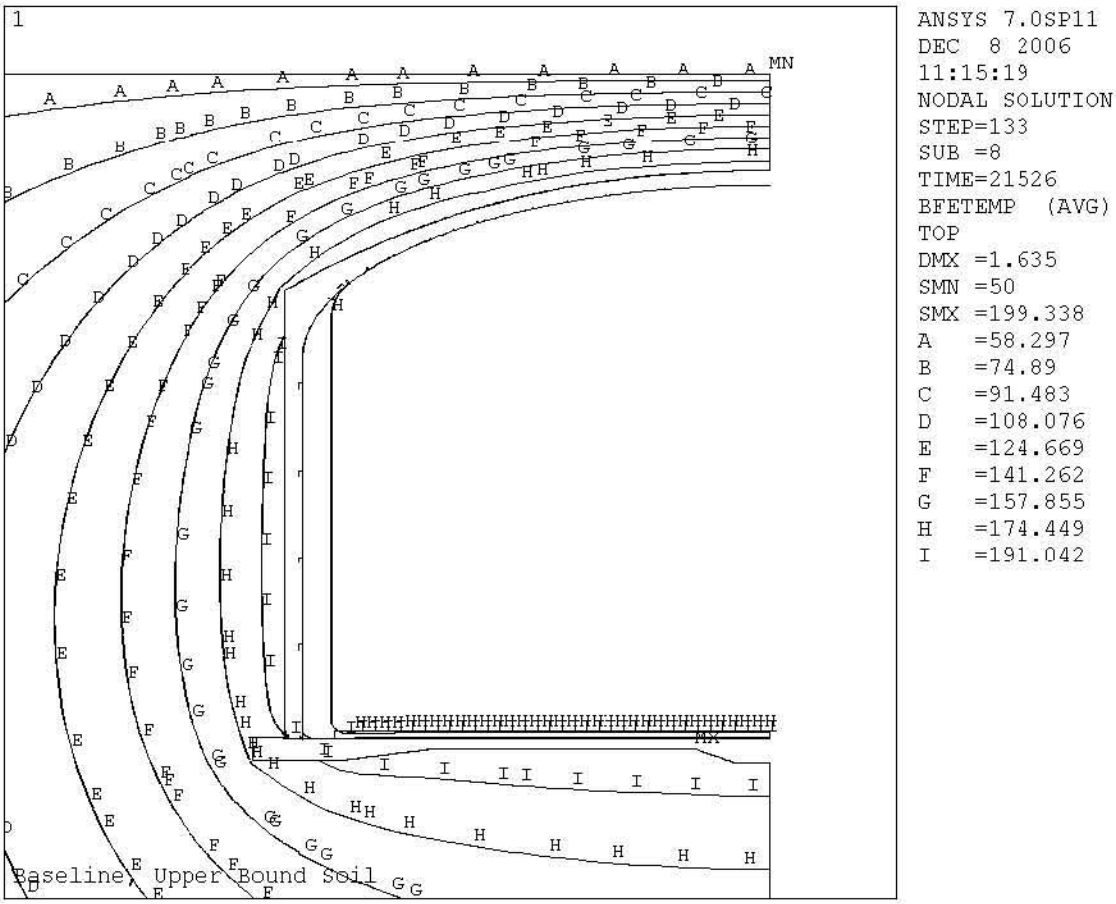


Figure 2-21. Temperature (°F) Distribution at Step 9 (Table 2-10) in the Design Basis Transient (waste temperature = 167.5°F)

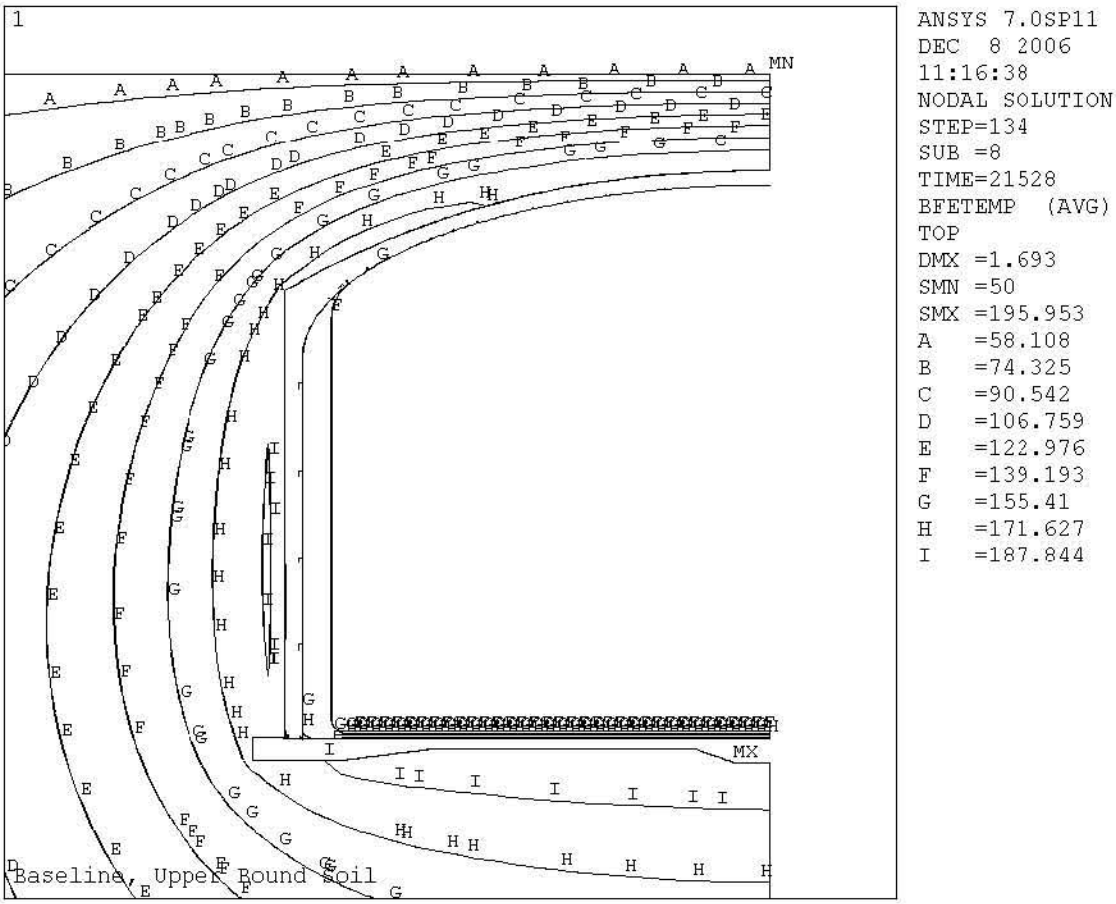


Figure 2-22. Temperature (°F) Distribution at Step 10 (Table 2-10) in the Design Basis Transient (waste temperature = 125°F)

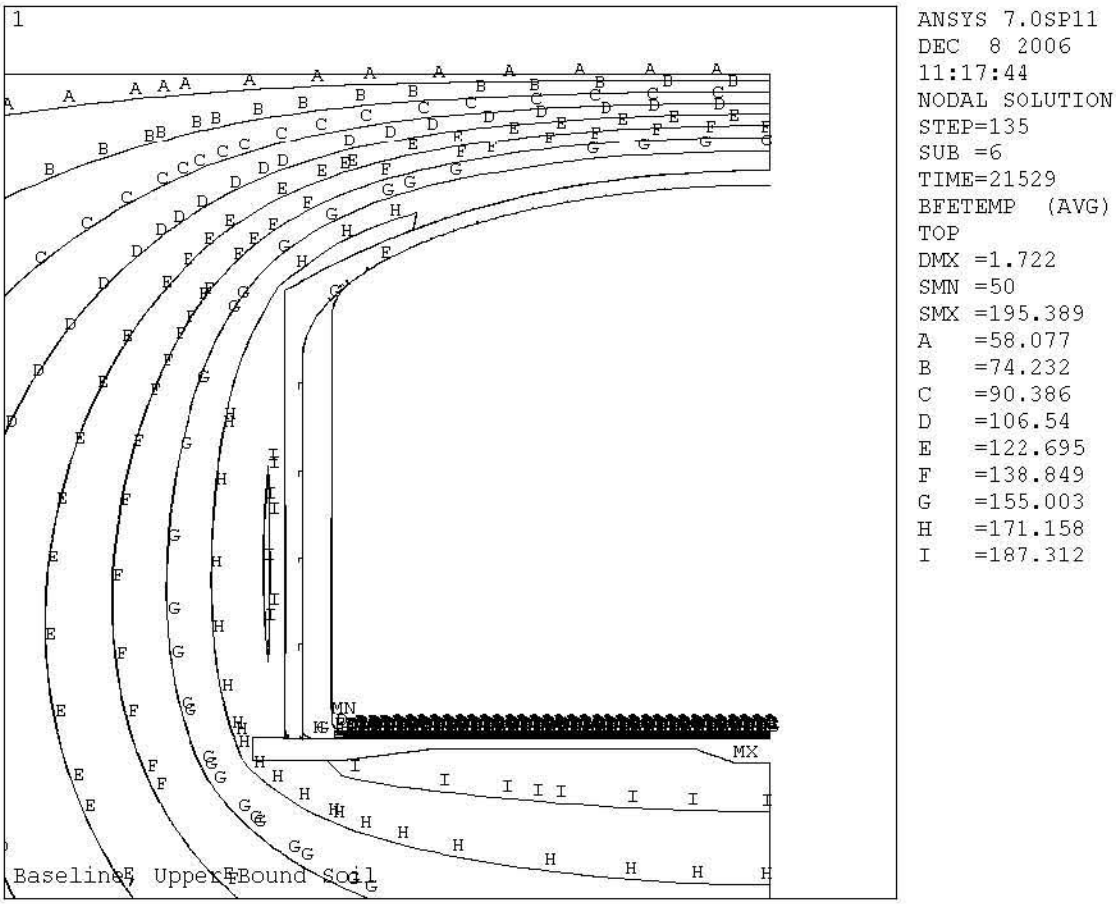


Figure 2-23. Temperature (°F) Distribution at Step 11 (Table 2-10) in the Design Basis Transient (waste temperature = 50°F)

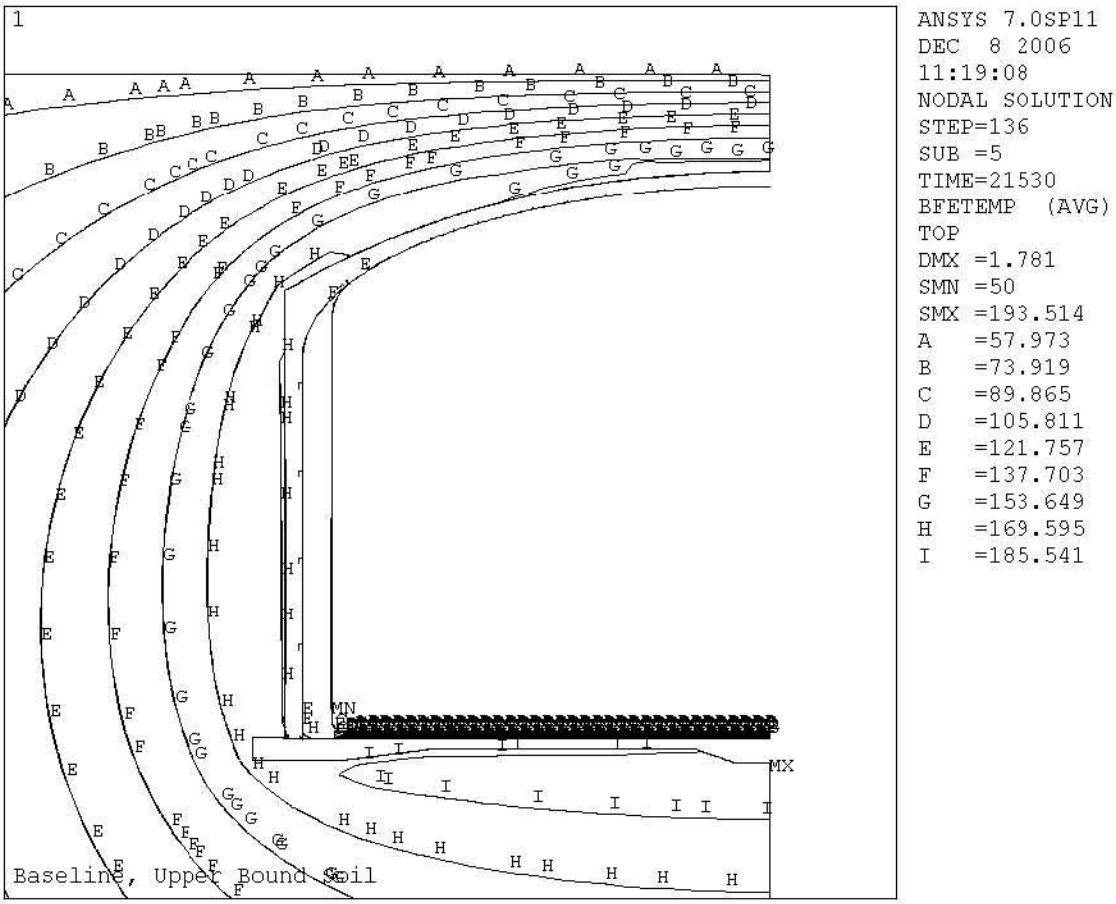


Figure 2-24. Temperature (°F) Distribution at Step 12 (Table 2-10) in the Design Basis Transient (waste temperature = 50°F)

2.4.2 Mechanical Loads

Table 2-11 lists the non-seismic loading conditions that are specified in the statement of work for this project. The list contains both structural and thermal operating loads that are both static and transient in nature. The concentrated live load was increased at the end of the nominal 60-year analysis.

Table 2-11. DST 241-AP Load Conditions for Analysis

Design Load	Value	Notes
Design Life	> 50 years	A 60-year design life is used.
Maximum Corrosion Rate	1 mil/yr	A total corrosion allowance of 0.060 inch is applied to the specified nominal thicknesses.
Soil Cover	8.3 ft @ 125 lb/ft^3	Relative to dome apex.
Hydrostatic	460 inches @ 1.83 SpG	Current tank contents are below 1.5 SpG
Pressure	−12 in. water gauge (w.g.) ≤ $P_{primary}$ ≤ +60 in. w.g.	Primary Tank
	−20 in. w.g. ≤ $P_{annulus}$ ≤ +60 in. w.g.	Annulus
	−12 in. w.g. ≤ $P_{primary}$ −$P_{annulus}$	Differential
Live Load	40 lb/ft^2	Uniform
	200,000 lb. nominal	Concentrated
Thermal	210°F	Maximum bulk temperature of waste
	20°F/day	Waste maximum heatup/cooldown rate
	1/yr	Cyclic rate

2.4.3 ACI Load Factors

The load factors required by ACI 349 were achieved by directly applying them to the relevant load in a separate load step. The load factors to be applied in this analysis are a subset of the possible combinations specified in ACI 349-90, Section 9.2 (ACI 1992). The subset is defined by WHC-SD-WM-DGS-003 (Day et al. 1995). The normal operating and thermal loads specified for analysis are:

U = Demand Load (comprised of combinations of the following):
D = Dead Load (tank + overburden + concentrated dead load + piping and equipment)
L = Live Loads
L1 = uniform live load
L2 = concentrated live load
F = Hydrostatic waste pressure
V = Vapor pressure loading (annulus and vapor space)
H = Lateral soil pressure
T = Thermal load (internal forces and moments caused by temperature distribution within the concrete). Normal (T_o) and abnormal ($T_{abnormal}$) cases are specified. As described in Chapter 4, the abnormal temperature cases are bounded by the design thermal transient that is applied in the thermal and operating loads analysis.
R_o = Piping and equipment reactions[(a)]

The credible but improbable extreme environmental load is:

E_{ss} = Safe Shutdown Earthquake (SSE) effects – Design Basis Earthquake effects

WHC-SD-WM-DGS-003 does not distinguish L1 from L2, or V from F. Those items are combined into L and F. We chose to maintain a distinction and combine them algebraically as a matter of form.

(a) R_o is not considered in this analysis.

The applicable ACI load combinations reduce to:

Load Combination 1: $U = 1.4(D + F + V) + 1.7(H + L1 + L2)$
Load Combination 4: $U = D + F + V + H + L1 + L2 + T + E_{ss}$
Load Combination 9: $U = 1.05D + 1.05(F + V) + 1.3(L1 + L2 + H) + 1.05T_o$

Load combination 9 is, in terms of load factors, intermediate between load combination 1 and load combination 4. Instead of applying load combination 9, we conservatively applied load combination 1 then added the thermal loads with the temperatures increased by 5% as discrete load steps; that is, load combination 9: $U = 1.4 (D+F+V) + 1.7 (H+L1+L2) + 1.05 T$.

2.4.4 Load Step Procedure

Figure 2-25 shows the flow plan used to model the 61 years of thermal cycles. The analysis is divided into several distinct analyses to facilitate a restart in the event of convergence difficulties. The time spans from years 5 to 18 and from years 22 to 58 are single thermal cycles held at the steady-state temperature for nominally 13 and 53 years, respectively. These are followed by two thermal cycles to capture any effect the long-term creep may have had on the cracking of the concrete and subsequent load distribution. The waste level was increased from 422 inches to 460 inches following year 20. The ASME and ACI load combinations 1 and 4 evaluations are carried out at the end of or during year 60. An additional thermal cycle (year 61) is completed with the temperatures increased by 5% to provide a conservative evaluation of ACI load combination 9.

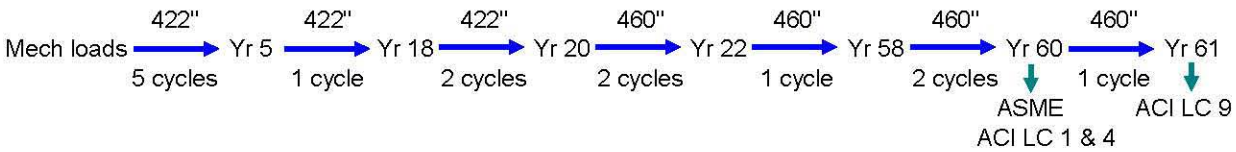


Figure 2-25. Analysis Flow Plan

3.0 Seismic Model

3.1 Introduction

This chapter describes the ANSYS® finite element (FE) model, material properties, and loads used for the double-shell tank (DST) seismic analysis. Complete documentation of the seismic model supporting the proposed liquid level increase in the AP Tank Farms may be found in the Seismic Analysis report (Rinker et al. 2007). The current report contains summaries of the model, material properties, and loads. The Seismic Analysis report should be referenced for complete model description and background information.

3.2 Finite Element Model

The model used for the evaluation of the AP tank configuration and increased liquid level is based on the model developed for the AY tank and a liquid level of 422 inches (Rinker et al. 2006c). Key differences in the increased liquid level and the AY model are as follows:

- AP tank geometry used (geometry and wall thicknesses)
- Waste level increased to 460 inches
- Waste specific gravity increased to 1.83
- Selected contact element normal stiffnesses softened to reduce "chatter"
- Number of contact areas used for waste/primary tank interface increased

For completeness, a detailed description of the model development is provided below.

3.2.1 Model Description

A model of a Hanford double-shell tank was created and analyzed using version 8.1 of the general purpose finite element program ANSYS®. A half-symmetry model of the DST, including the concrete tank, primary tank, secondary liner, J-bolts, waste, and surrounding soil, was developed to evaluate the seismic loading on the DST.

The tank model geometry was based on the AP tank configuration shown in Hanford Drawing H-2-90534. The primary tank has a 450-inch radius and the height of the vertical wall is 422.3 inches. The nominal dome apex is 561.5 inches above the bottom of the tank. The models were run using waste depths of 460 inches. An excerpt from Drawing H-2-90534 is shown as Figure 3-1. Figure 3-2 shows the complete model. Details for each part of the model are discussed in the following sections.

The detailed ANSYS model was developed based on coordinates used in the TOLA model. A series of input files were used to break the model creation into manageable parts. The files used and a short description are provided in Table 3-1. Files that are common to all load cases are provided in Appendix E of the Increased Liquid Level Seismic report (Rinker et al. 2007). Files that are unique to a specific load case are provided in the appendix of that report for each load case

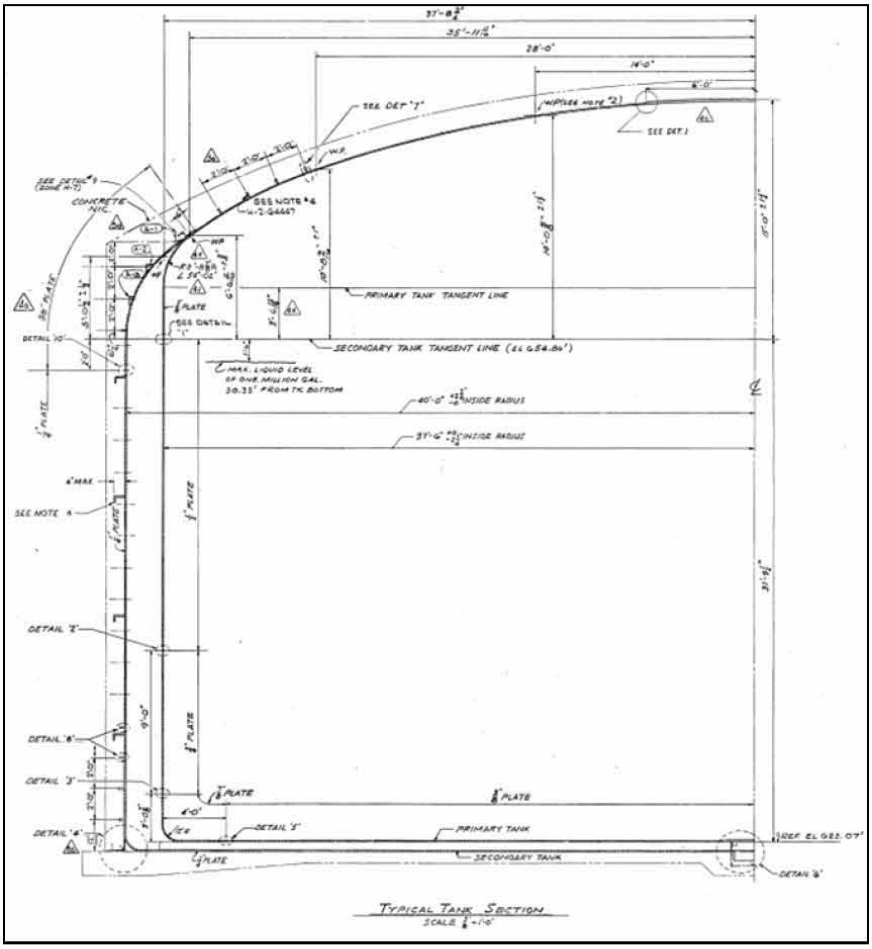


Figure 3-1. AY Primary Tank Dimensions

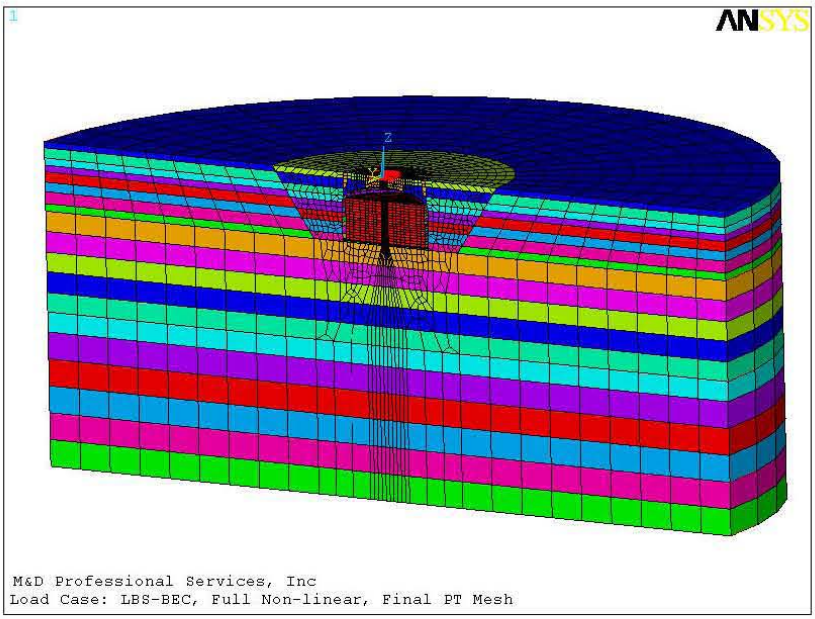


Figure 3-2. Composite Tank Model Detail

Table 3-1. ANSYS Model Input File Description

File Name	Description
Run-Tank.txt	Calls each input for development of model.
Tank-Coordinates-AY.txt	Defines key geometry and model parameters. Concrete geometry set to match PNNL section cut locations.
Tank-Props-###.txt	Defines concrete material and real properties for model. Uses properties based on best estimate or fully cracked conditions. Each tank layer can be assigned unique properties.
Tank-Mesh1.txt	Creates concrete tank mesh. Foundation and wall are separate entities.
Primary-Props-AY.txt	Defines primary tank material and real properties.
Primary.txt	Creates primary tank mesh. Primary tank is not connected to concrete tank.
Insulate.txt	Creates insulating concrete mesh. Uses existing geometry from concrete and primary tanks, but is not connected.
Waste-Solid-AY.txt	Creates model of waste. Uses Solid45 elements with low shear modulus. Uses primary tank geometry.
Interface1.txt	Creates interface connections or contacts between pieces of model.
Interface-gap1.txt	Creates interface connections or contacts between pieces of model.
Bolts-friction.txt	Creates elements for J-bolts and contact surface between the primary tank and concrete tank in the dome.
Liner.txt	Creates elements for Secondary Liner.
Near-Soil-1.txt	Creates soil model for excavated region around tank. Merges coincident nodes with concrete tank.
Soil-Props-###-Geo.txt	Defines all soil geometry and material properties. Excavated region and native soil have different material properties. Unique files are used for each soil condition (UB, BE, LB).
Far-Soil.txt	Creates far-field/native soil to a radius of 320 ft and depth of 266 ft. Merges coincident nodes with near soil and concrete tank. Places large mass at bottom of model for excitation force.
Fix-Soil.txt	Creates the contact interface between the excavated soil and native soil portions of the model.
Slave.txt	Creates slaved boundary conditions around exterior of model.
Boundary.txt	Creates boundary conditions for symmetry. Does not set boundary conditions for solution phase.
Live_Load.txt	Applies surface concentrated load over center of dome.
Outer-Spar.txt	Creates spar elements at edge of soil model to control shear behavior.
### Unique files are used for each concrete and soil condition – best estimate, lower bound, upper bound soils, and fully cracked concrete.	

All components of the model are based on 9-degree slices over the half model, for a total of twenty slices. The model description will address the tank components first, then the surrounding soil.

3.2.2 Concrete Model

The first component developed in the model is the concrete tank shell and footing. Thirty-three sections are used between the dome and center of the floor for each 9-degree slice. In the detailed TOLA slice model, seventy sections were identified and used for extracting forces and moments. Using the profile coordinates for these seventy sections, a subset of 33 sections was developed for the profile of the ANSYS® seismic model (see Figure 3-3). Based on the need to allow for connecting other portions of the full model, some coordinates were adjusted relative to the TOLA slice model.

The geometry of the concrete tank is based on a combination of data from drawings and TOLA slice model. The basic geometry is based on drawings H-2-90439 and H-2-90442. Nodal locations were selected to correspond reasonably well to the TOLA model. This placement was done to simplify load combinations. Table 3-2 provides a listing comparison of nodal coordinates for the ANSYS® seismic model and TOLA slice model.

Input file "Tank-Coordinates-AY.txt" is used to read coordinate data for the concrete tank.

Table 3-2. Concrete Tank Centerline Coordinates

		Coordinates			ANSYS		
	Section	**R (inch)**	**H (inch)**	**T (Inch)**	**X**	**Z**	**Set #**
		0	568.6	15	0	568.8	1
Dome	1	30.2	568.6	15			
				15	45	568	2
Dome	2	61.4	567.5	15			
Dome	3	90.4	565.8	15	90.4	565.8	3
Dome	4	120.72	563.21	15	120.72	563.21	4
Dome	5	152.9	559.7	15	152.9	559.7	5
Dome	6	184.14	555.34	15			
Dome	7	211.4	550.7	15	211.4	550.7	6
Dome	8	239.1	545.2	15	239.1	545.2	7
Dome	9	271.85	537.45	15			
Dome	10	306.63	527.68	15	306.63	527.68	8
Dome	11	316.22	524.68	15			
Dome	12	335.6	518.2	15	335.6	518.2	9
Dome	13	356.7	510.37	15			
Dome	14	371.86	504.24	15			
Dome	15	393.7	494.5	15	393.7	494.5	10
Dome	16	404.5	489.3	18.92			
Haunch	17	415.2	483.7	20.31			
Haunch	18	428.7	476.2	22.58	428.7	476.2	11
Haunch	19	441.8	468.2	25.56			
Haunch	20	454.5	459.5	29.46			
Haunch	21	469.9	447.4	36.36	469.9	447.4	12
Haunch	22	483.8	423.18	29.71			
Haunch	23	486.9	407.1	22.52	486.9	407.1	13
Haunch	24	488.47	393.5	19.07			
Wall	25	489	382.1	18	489	382.1	14
Wall	26	489	360.8	18			
Wall	27	489	345.6	18			
Wall	28	489	335	18	489	335	15
Wall	29	489	321	18			
Wall	30	489	306	18			
Wall	31	489	300	18			
Wall	32	489	281	18	489	281	16
Wall	33	489	260.5	18			
Wall	34	489	236	18	489	236.5	17
Wall	35	489	210.5	18			
Wall	36	489	201	18			
Wall	37	489	186.8	18	489	186.8	18
Wall	38	489	171	18			

Table 3-2. (contd)

		Coordinates			ANSYS		
	Section	**R (inch)**	**H (inch)**	**T (Inch)**	**X**	**Z**	**Set #**
Wall	39	489	150.5	18			
Wall	40	489	145.5	18	489	145.5	19
Wall	41	489	120.5	18			
Wall	42	489	100.5	18			
Wall	43	489	80	18			
Wall	44	489	60	18	489	70.0	20
Wall	45	489	39.9	18			
Wall	46	489	21	18	489	20	21
Wall	47	489	–4.5	18			
					489	–4.0	22
					531	–4.0	23
Slab	48	517	–18.4	23.5			
Slab	49	508.5	–18.4	23.5			
Slab	50	503	–18.4	23.5			
Slab	51	496.8	–19.1	23.5			
Slab	52	493	–19.1	23.5			
Slab	53	489	–19.1	22	489	–4.0	24
Slab	54	485.1	–19.1	22			
Slab	55	481	–19.1	22			
Slab	56	477	–19.1	22			
Slab	57	471	–19.1	22			
Slab	58	465	–19.1	22			
Slab	59	440	–19.1	19.38	438	–4.0	25
Slab	60	421.4	–17.9	17.05			
Slab	61	390	–15.9	13.12			
					410	–4.0	26
Slab	62	358	–13.9	9.13	358	–4.0	27
Slab	63	338	–13.4	8			
Slab	64	277.7	–13.4	8	277.7	–4.0	28
Slab	65	218.5	–13.4	8	218.5	–4.0	29
Slab	66	180	–13.4	8	180	–4.0	30
Slab	67	129.9	–13.4	8	129.9	–4.0	31
Slab	68	95.7	–13.4	8	95.7	–4.0	32
Slab	69	54	–17.1	15.43			
					36	–4.0	33
Slab	70	20	–20.1	21.5			
					0	–4.0	34
Note: The concrete tank wall is 8 inches short due to modeling error.							

Element stiffnesses are also based on the TOLA slice model for best estimate concrete conditions for a maximum temperature of 250°F. Common properties for all concrete sections are provided below.

$\nu = 0.18$
Damping – 7%

Input file "Tank-Props-BEC-250.txt" defines the concrete tank material properties and real constants (thickness) for the best estimate concrete. Input file "Tank-Props-BEC-Crack.txt" defines the concrete tank material properties and real constants (thickness) for the fully cracked concrete. Table 3-3 provides a complete listing of section properties based on the TOLA model. Table 3-4 provides concrete section properties assuming all sections are cracked.

Table 3-3. Best Estimate Concrete Properites, 250°F

Cracked	Eshl	Shell Thickness t-shl		Shell Density, Rho-shl		M&D Section		PNNL Section
Y/N	(psi)	(ksf)	(in.)	(ft)	(lb/in.^{3})	(lbf/ft^3)	No.	No.
N	4.502E+06	648,297	15.35	1.28	0.08484	147		1
N	4.352E+06	626,754	15.18	1.26	0.08578	148	1	2
N	4.306E+06	620,114	15.12	1.26	0.08609	149	2	3
N	4.282E+06	616,594	15.09	1.26	0.08627	149	3	4
N	4.262E+06	613,774	15.15	1.26	0.08595	149		5
N	4.243E+06	610,922	15.13	1.26	0.08609	149	4	6
N	4.315E+06	621,305	15.21	1.27	0.08559	148	5	7
N	4.295E+06	618,475	15.19	1.27	0.08572	148		8
N	4.216E+06	607,093	15.17	1.26	0.08583	148	6	9
N	4.201E+06	604,939	15.15	1.26	0.08594	148		10
N	4.439E+06	639,237	15.39	1.28	0.08463	146	7	11
N	4.425E+06	637,265	15.34	1.28	0.08487	147		12
N	4.405E+06	634,338	15.32	1.28	0.08497	147	8	13
N	4.392E+06	632,441	15.31	1.28	0.08504	147		14
N	4.316E+06	621,503	15.30	1.28	0.08510	147		15
N	4.406E+06	634,531	19.32	1.61	0.08499	147		16
N	4.366E+06	628,756	20.73	1.73	0.08505	147	9	17
N	4.323E+06	622,528	22.99	1.92	0.08527	147		18
Y	1.655E+06	238,350	26.72	2.23	0.08302	143		19
Y	1.345E+06	193,677	26.78	2.23	0.09548	165	10	20
N	4.000E+06	575,959	37.86	3.15	0.08337	144	11	21
N	3.960E+06	570,283	30.93	2.58	0.08339	144		22
Y	1.264E+06	182,025	21.60	1.80	0.09052	156		23
Y	1.409E+06	202,953	18.00	1.50	0.09197	159	12	24
Y	1.120E+06	161,221	15.28	1.27	0.10227	177		25
Y	1.093E+06	157,426	15.36	1.28	0.10170	176	13	26
Y	1.076E+06	155,010	15.42	1.28	0.10133	175		27
Y	1.068E+06	153,784	14.00	1.17	0.11163	193		28
Y	1.068E+06	153,784	14.00	1.17	0.11163	193		29
Y	1.068E+06	153,784	14.00	1.17	0.11163	193	14	30
Y	9.490E+05	136,651	13.53	1.13	0.11552	200		31
Y	9.490E+05	136,651	13.53	1.13	0.11552	200		32
Y	9.490E+05	136,651	13.53	1.13	0.11552	200	15	33
Y	9.490E+05	136,651	13.53	1.13	0.11552	200		34
Y	9.490E+05	136,651	13.53	1.13	0.11552	200	16	35
Y	9.490E+05	136,651	13.53	1.13	0.11552	200		36
Y	9.490E+05	136,651	13.53	1.13	0.11552	200		37
N	9.589E+05	138,084	14.89	1.24	0.10496	181	17	38
N	3.467E+06	499,310	18.08	1.51	0.08644	149		39
Y	3.435E+06	494,646	18.06	1.50	0.08652	150		40
Y	8.568E+05	123,378	12.89	1.07	0.12123	209	18	41
Y	8.568E+05	123,378	12.89	1.07	0.12123	209		42
Y	8.655E+05	124,633	14.21	1.18	0.10997	190	19	43
Y	8.655E+05	124,633	14.21	1.18	0.10997	190		44
Y	8.568E+05	123,378	12.89	1.07	0.12123	209		45
Y	8.638E+05	124,388	12.86	1.07	0.12149	210	20	46
Y	8.871E+05	127,746	14.12	1.18	0.11067	191		47
N	3.810E+06	548,683	23.64	1.97	0.09606	166	21	48
N	3.764E+06	542,010	23.65	1.97	0.09604	166		49
Y	1.038E+06	149,405	20.05	1.67	0.10680	185		50
Y	1.054E+06	151,733	20.06	1.67	0.10674	184		51
Y	1.075E+06	154,870	20.12	1.68	0.10643	184	22	52
Y	7.157E+05	103,055	14.04	1.17	0.13627	235		53

Table 3-3. (contd)

Cracked	Eshl	Shell Thickness t-shl		Shell Density, Rho-shl		M&D Section		PNNL Section
Y/N	(psi)	(ksf)	(in.)	(ft)	(lb/in.^{3})	(lbf/ft^3)	No.	No.
N	3.571E+06	514,287	17.19	1.43	0.09959	172	23	54
N	3.570E+06	514,043	13.20	1.10	0.10383	179		55
Y	1.140E+06	164,113	6.14	0.51	0.16690	288	24	56
N	3.632E+06	522,946	7.94	0.66	0.11656	201	25	57
Y	1.349E+06	194,254	4.96	0.41	0.18649	322	26	58
Y	1.387E+06	199,783	7.02	0.58	0.16289	281	27	59
Y	1.129E+06	162,553	6.61	0.55	0.17280	299	28	60
Y	1.393E+06	200,531	5.01	0.42	0.22800	394	29	61
Y	1.163E+06	167,538	4.81	0.40	0.23765	411	30	62
Y	8.719E+05	125,560	12.28	1.02	0.14557	252		63

Table 3-4. Fully Cracked Concrete Properites

Is Section Cracked?	Eshl		Shell Thickness t-shl		Shell Density, Rho-shl		M&D Section	PNNL Section
	(psi)	(ksf)	(in.)	(ft)	(lb/in.^{3})	(lbf/ft^3)	No.	No.
Y	1.435E+06	206,708	14.64	1.22	0.08893	154		1
Y	1.084E+06	156,131	13.21	1.10	0.09854	170	1	2
Y	9.438E+05	135,907	12.40	1.03	0.10504	182	2	3
Y	8.552E+05	123,148	11.78	0.98	0.11053	191	3	4
Y	9.951E+05	143,289	12.81	1.07	0.10168	176		5
Y	9.318E+05	134,181	12.41	1.03	0.10491	181	4	6
Y	1.141E+06	164,239	13.58	1.13	0.09590	166	5	7
Y	1.089E+06	156,781	13.32	1.11	0.09774	169		8
Y	1.029E+06	148,115	13.08	1.09	0.09951	172	6	9
Y	9.768E+05	140,657	12.53	1.04	0.10391	180		10
Y	1.512E+06	217,769	14.64	1.22	0.08897	154	7	11
Y	1.482E+06	213,340	14.39	1.20	0.09048	156		12
Y	1.443E+06	207,751	14.28	1.19	0.09119	158	8	13
Y	1.417E+06	204,062	14.20	1.18	0.09168	158		14
Y	1.371E+06	197,485	14.12	1.18	0.09219	159		15
Y	1.544E+06	222,339	18.42	1.53	0.08916	154		16
Y	1.474E+06	212,206	19.67	1.64	0.08962	155	9	17
Y	1.394E+06	200,772	21.66	1.81	0.09047	156		18
Y	1.531E+06	220,469	27.13	2.26	0.08177	141		19
Y	1.240E+06	178,532	27.37	2.28	0.09343	161	10	20
Y	1.046E+06	150,644	34.88	2.91	0.09050	156	11	21
Y	1.270E+06	182,924	32.31	2.69	0.07982	138		22
Y	1.163E+06	167,483	22.03	1.84	0.08873	153		23
Y	1.302E+06	187,438	18.31	1.53	0.09041	156	12	24
Y	1.028E+06	147,988	15.59	1.30	0.10025	173		25
Y	1.004E+06	144,559	15.67	1.31	0.09972	172	13	26
Y	9.887E+05	142,377	15.72	1.31	0.09937	172		27
Y	9.808E+05	141,234	14.29	1.19	0.10936	189		28
Y	9.808E+05	141,234	14.29	1.19	0.10936	189		29
Y	9.808E+05	141,234	14.29	1.19	0.10936	189	14	30
Y	8.690E+05	125,131	13.83	1.15	0.11297	195		31
Y	8.690E+05	125,131	13.83	1.15	0.11297	195		32
Y	8.690E+05	125,131	13.83	1.15	0.11297	195	15	33

Table 3-4. (contd)

Is Section Cracked?	Eshl		Shell Thickness t-shl		Shell Density, Rho-shl		M&D Section	PNNL Section
	(psi)	(ksf)	(in.)	(ft)	(lb/in.^{3})	(lbf/ft^3)	No.	No.
Y	8.690E+05	125,131	13.83	1.15	0.11297	195		34
Y	8.690E+05	125,131	13.83	1.15	0.11297	195	16	35
Y	8.690E+05	125,131	13.83	1.15	0.11297	195		36
Y	8.690E+05	125,131	13.83	1.15	0.11297	195		37
Y	8.782E+05	126,463	15.21	1.27	0.10273	178	17	38
Y	8.690E+05	125,131	13.83	1.15	0.11297	195		39
Y	7.828E+05	112,717	13.20	1.10	0.11839	205		40
Y	7.828E+05	112,717	13.20	1.10	0.11839	205	18	41
Y	7.828E+05	112,717	13.20	1.10	0.11839	205		42
Y	7.908E+05	113,881	14.54	1.21	0.10747	186	19	43
Y	7.908E+05	113,881	14.54	1.21	0.10747	186		44
Y	7.828E+05	112,717	13.20	1.10	0.11839	205		45
Y	7.891E+05	113,629	13.17	1.10	0.11864	205	20	46
Y	8.104E+05	116,693	14.45	1.20	0.10813	187		47
Y	9.322E+05	134,235	21.54	1.79	0.10546	182	21	48
Y	9.324E+05	134,263	21.66	1.80	0.10488	181		49
Y	9.504E+05	136,857	20.46	1.71	0.10463	181		50
Y	9.659E+05	139,096	20.46	1.71	0.10465	181		51
Y	9.861E+05	141,998	20.52	1.71	0.10436	180	22	52
Y	6.510E+05	93,743	14.43	1.20	0.13263	229		53
Y	7.229E+05	104,097	14.13	1.18	0.12109	209	24	54
Y	8.420E+05	121,245	11.21	0.93	0.12227	211		55
Y	1.048E+06	150,866	6.25	0.52	0.16372	283	24	56
Y	1.147E+06	165,097	4.93	0.41	0.18777	324	25	57
Y	1.246E+06	179,441	5.05	0.42	0.18346	317	26	58
Y	1.283E+06	184,804	7.11	0.59	0.16072	278	27	59
Y	1.038E+06	149,438	6.73	0.56	0.16977	293	28	60
Y	1.288E+06	185,420	5.09	0.42	0.22441	388	29	61
Y	1.070E+06	154,101	4.90	0.41	0.23326	403	30	62
Y	7.964E+05	114,687	12.57	1.05	0.14218	246		63

Input file "Tank-Mesh1.txt" develops the concrete tank model. Element type SHELL143 is used for the concrete tank to be able to extract through-wall shear forces.

Figures 3-3 and 3-4 show the profile and full concrete tank model, respectively.

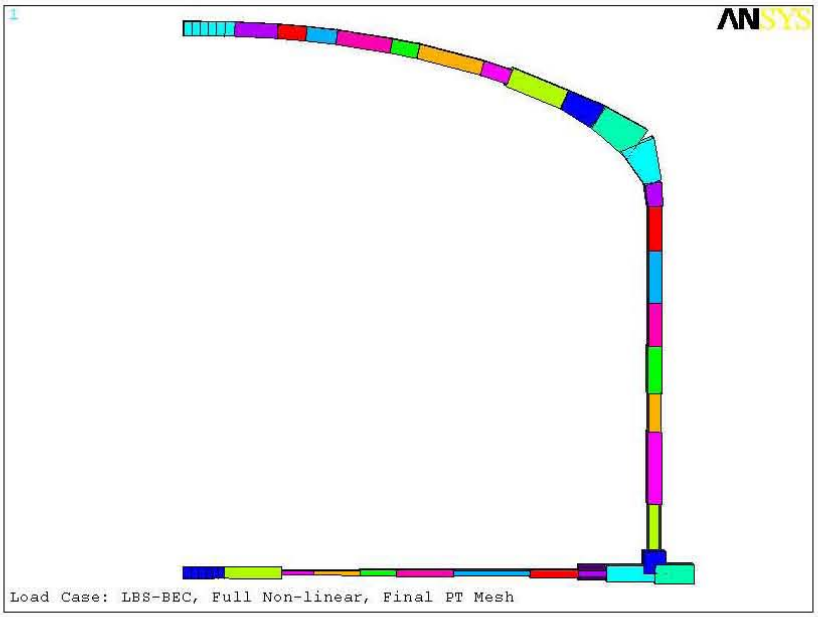


Figure 3-3. Concrete Tank Profile, Including Shell Thickness

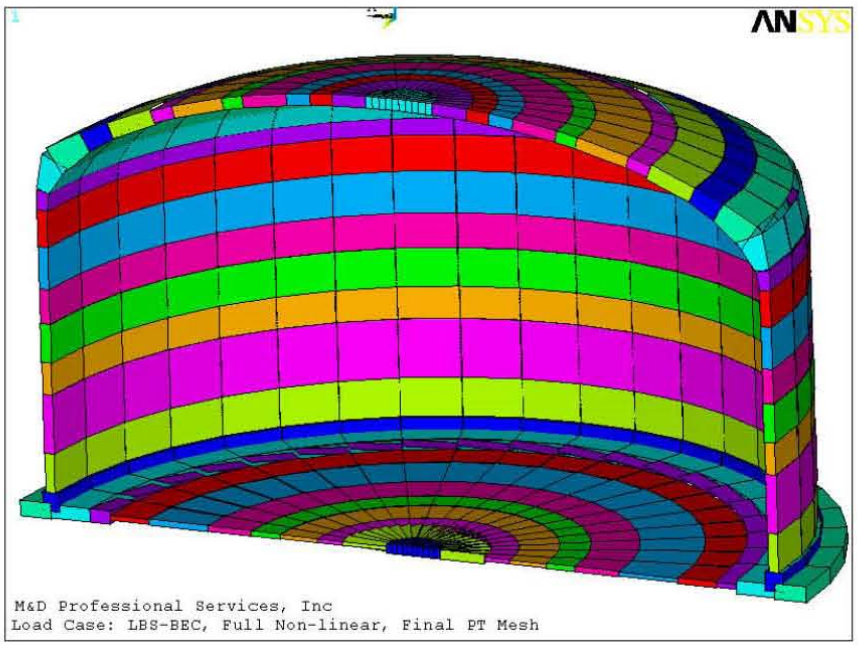


Figure 3-4. Concrete Tank Model Detail

3.2.3 Primary Tank

The geometry of the primary tank is based on drawing H-2-90534. To ensure that the J-bolt elements are perpendicular to the primary tank, the primary tank dome coordinates were calculated based on the location of the corresponding concrete tank coordinate, taking into account the concrete shell thickness, and normal to the primary tank (see Figure 3-5). The concrete shell thickness used is based on the nominal concrete thickness.

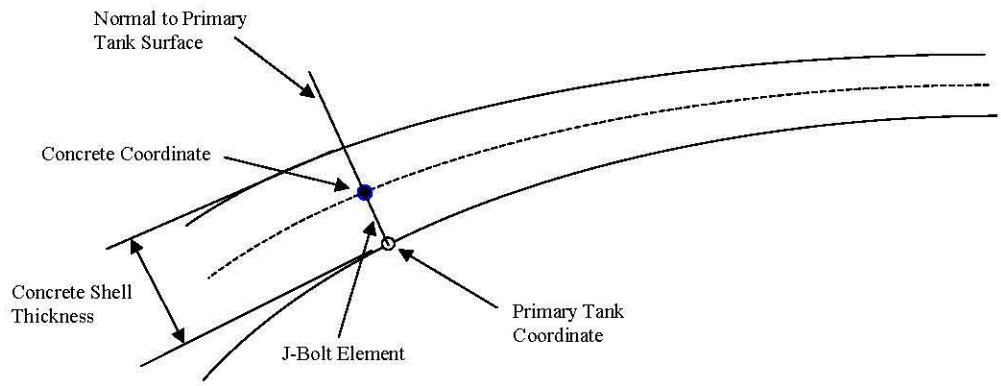


Figure 3-5. Primary/Concrete Tank Node Geometry

The location of the primary tank nodes were iteratively determined a follows:

Select a value for x (radial distance from center of the tank).

Calculate the respective location for y' based on the defined shape of the primary tank. The primary tank is an ellipse with a major axis of 80 feet and minor axis of 30 feet. The equation for location of y' is as follows:

$$y' = a\sqrt{1-\frac{x^2}{b^2}} - a, \; where \tag{3.1}$$

$$a = Minor\ Radius = 180\ in.$$

$$b = Major\ Radius = 480\ in.$$

$$x = Test\ Location\ for\ x$$

$$For\ x = 61.0398,\ y' = 180\sqrt{1-\frac{61.0398^2}{480^2}} - 180 = -1.46 \tag{3.2}$$

The slope of the ellipse can be calculated by taking the derivative of the equation for y'.

$$\frac{d}{dx}\left(a\sqrt{1-\frac{x^2}{b^2}}\right) = -\frac{x\frac{a}{b}}{\sqrt{b^2-x^2}} \tag{3.3}$$

For x = 61.0398, the slope of the ellipse is –0.048. The corresponding angle is the arctangent of the slope, or in this case, –0.048. The length of line connecting the centerline of the concrete to the primary tank is half the thickness of the tank at that point. Therefore, to check the accuracy of the assumed x location of the primary tank, back-calculate the location of the concrete coordinates. If the back-calculated concrete location is the same as the known location, the x location of the primary tank must be correct, otherwise, reselect x until it is correct. The primary tank dome coordinate calculations are summarized in Table 3-5.

Following the example, for concrete location of (60.4), the x location of the primary tank is 61.0398. y' was determined to be –1.46. Adjusting this to value for the vertical location of the center of the ellipse, add 561.45 (elevation of the primary tank at the apex). For this case, y=559.99. The check is as follows:

$$X_{conc} = X_{primary} + \frac{t}{2}\sin(\theta), \text{ where } \theta \text{ is the angle of the slope from horizontal} \tag{3.4}$$

$$X_{conc} = 61.0398 + \frac{15}{2}\sin(0.048) = 61.39966 \approx 61.4 \tag{3.5}$$

$$Y_{conc} = Y_{primary} + \frac{t}{2}\cos(\theta) = 559.99 + \frac{15}{2}\cos(0.048) = 567.48136 \approx 567.5 \tag{3.6}$$

Table 3-5. Primary Tank Dome Coordination Calculation

Concrete				Primary Tank							
X	**y**	**T**	**Error**	**x**	**y**	**y'**	**Slope**	**Angle (rad)**	**Angle (Deg)**	**Y Offset**	**X Offset**
0	**568.95**	15	0%	**0**	561.45	0.00	0.000	0.000	0.000	7.500	0.000
30.2	568.6	15	0%	30.0238	561.10	–0.35	–0.024	–0.023	–1.346	7.498	–0.176
45	568.2	15	0%	44.7369	560.67	–0.78	–0.035	–0.035	–2.010	7.495	–0.263
61.4	567.5	15	0%	61.0398	559.99	–1.46	–0.048	–0.048	–2.753	7.491	–0.360
120.72	563.21	15	0%	119.9972	555.73	–5.72	–0.097	–0.097	–5.530	7.465	–0.723
152.9	559.7	15	0%	151.9685	552.19	–9.26	–0.125	–0.125	–7.134	7.442	–0.931
211.4	550.7	15	0%	210.0535	543.30	–18.15	–0.183	–0.181	–10.343	7.378	–1.347
239.1	545.2	15	0%	237.5336	537.86	–23.59	–0.214	–0.210	–12.055	7.335	–1.566
306.63	527.68	15	0%	304.4248	520.62	–40.83	–0.308	–0.298	–17.099	7.169	–2.205
335.6	518.2	15	0%	333.0513	511.07	–50.38	–0.361	–0.347	–19.866	7.054	–2.549
393.7	494.5	15	0%	390.2214	486.27	–75.18	–0.524	–0.482	–27.633	6.645	–3.479
428.7	476.2	22.58	0%	422.2643	467.04	–94.41	–0.694	–0.607	–34.752	9.276	–6.436
				432	459.91	–101.54	–0.774	–0.659	–37.750	0.000	0.000
				440	453.39	–108.06	–0.860	–0.710	–40.700	0.000	0.000
A	180										
B	480										

Element thicknesses are based on the drawing H-2-90534 but reduced by 0.06 inches for the corrosion allowance (see Section 2.2.4). General steel properties are used and are as follows:

Elastic Modulus (E) = 4,176,000 kip/ft^2
Poisson's Ratio (ν) = 0.30
Mass Density (ρ) = 0.001522 kip-sec^2/ft^4 = (0.490 kip/ft^3)/(32.2 ft/sec^2)
Damping = 2%

Tank coordinates are developed in the model from input file "Tank-Coordinates-AY.txt." Tank element properties are from input file "Primary-Props-AY." The tank mesh is generated using "Primary.txt" and uses SHELL143 elements.

Figure 3-6 shows the full primary tank model, and Figure 3-7 shows the detail in the knuckle region at the bottom of the tank.

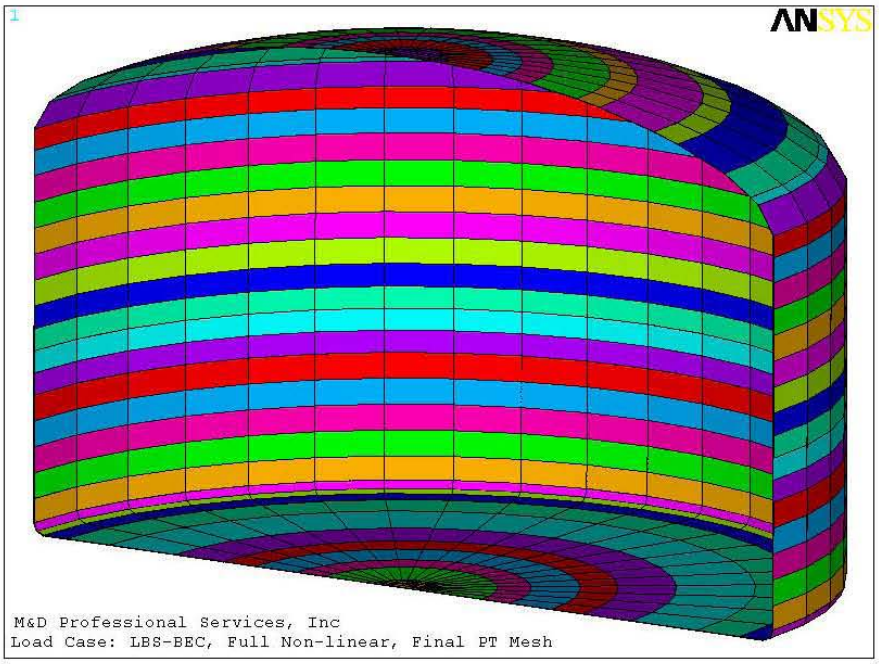


Figure 3-6. Primary Tank Model Detail

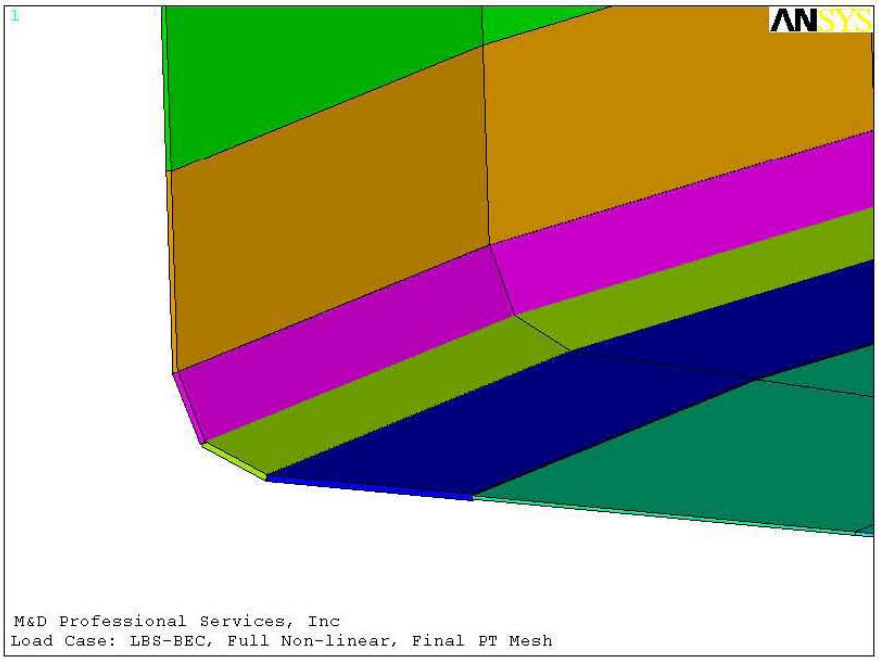


Figure 3-7. Primary Tank Model Detail – Knuckle Region

3.2.4 Insulating Concrete

The insulating concrete uses the geometry defined for the concrete and primary tanks and fills in the open volume with solid element (SOLID45). Concrete properties are taken as follows Rinker et al. (2004).

Elastic Modulus (E) = 23,760 kip/ft^2
Poisson's Ratio (ν) = 0.15
Mass Density (ρ) = 0.00155 kip-sec^2/ft^4 = (0.050 kip/ft^3)/(32.2 ft/sec^2)
Damping = 7%

Material properties for the insulating concrete are in the file "Tank-Props-BEC-250.txt." The element mesh is generated using "Insulate.txt." Figure 3-8 shows the insulating concrete elements.

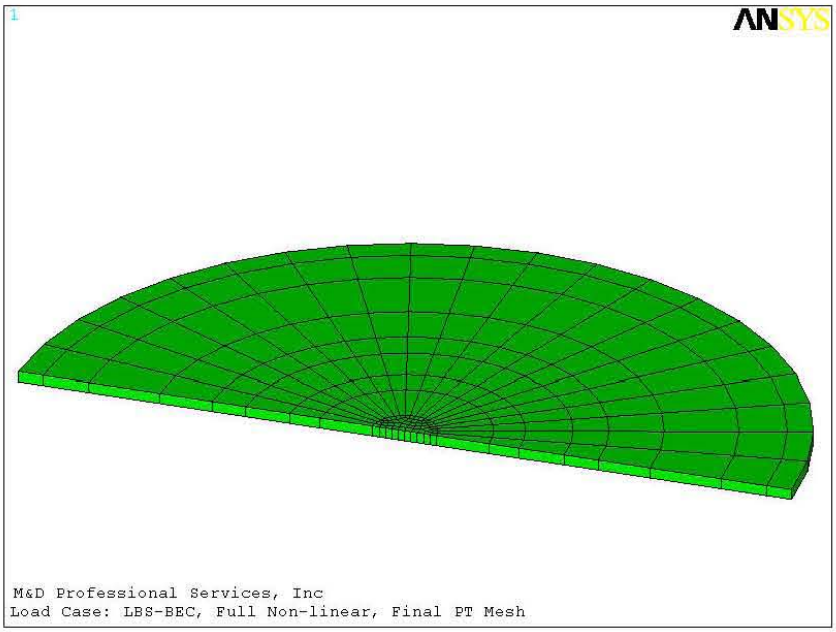


Figure 3-8. Insulating Concrete Model Detail

3.2.5 J-Bolts

The physical orientation of the J-bolts connecting the primary tank to the concrete tank is shown in Figure 3-9. The J-bolts are modeled using beam elements (BEAM44) and spring elements (COMBIN14). The stiffness properties are calculated to provide an axial stiffness equal to the total stiffness related to the J-bolts in the attributed area. Based on drawing H-2-90534 the J-bolts are spaced on an average of 2 feet in each direction. Therefore, the stiffness of the bolts in the model is based on the number of 4-ft^2 areas associated with the element. The BEAM44 elements are modeled as essentially rigid, and three orthogonal springs included providing an appropriate stiffness.

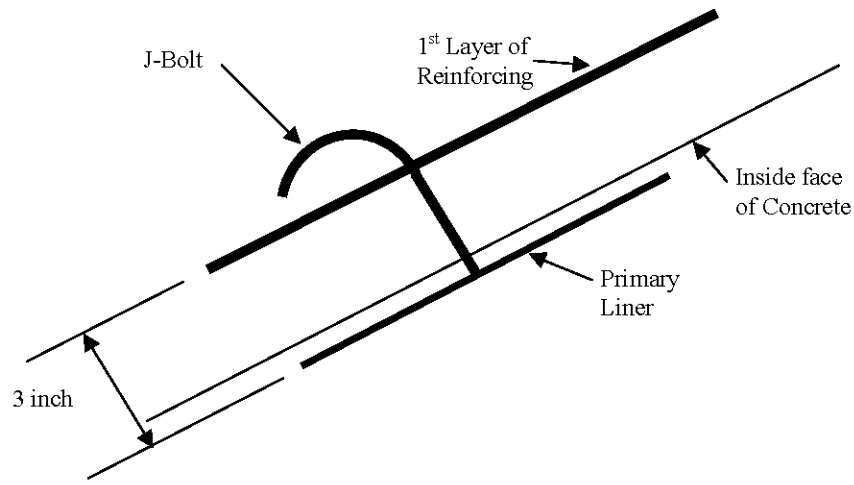


Figure 3-9. J-Bolt Geometry Detail

The stiffness of a single J-bolt was initially based on the physical dimension for the installation. The bolt is 1/2 inch in diameter and is hooked around the first layer of reinforcing steel, which has a 3-inch cover. Therefore, the stiffness is as follows:

$$k = \frac{EA}{L} \tag{3.7}$$

$$E = 29{,}000{,}000\, psi$$

$$A = \frac{\pi d^2}{4} = \frac{\pi\left(\frac{1}{2}\right)^2}{4} = 0.196\ in.^2 \tag{3.8}$$

$$L = 3\ in.$$

$$k = \frac{(29{,}000{,}000)(0.196)}{3} = 1.895E6\ lbf\ /\ in. = 22{,}736\ kip/ft \tag{3.9}$$

The required area is calculated based on the number of bolts to be represented and the thickness of the concrete at the bolt location. The J-bolt stiffness calculations are summarized in Table 3-6.

Table 3-6. J-Bolt Stiffness/Area Calculation

Ring No.	1	2	3	4	5	6	7	8	9	10	11
x	0.00	44.72	89.87	120.00	151.97	210.05	237.53	304.42	333.05	390.22	422.26
y	561.45	560.77	558.37	555.83	552.29	543.40	537.96	520.72	511.17	486.37	467.14
Apex ΔY	0.00	0.68	3.08	5.62	9.16	18.05	23.49	40.73	50.28	75.08	94.31
Delta Y	0.00	0.68	2.40	2.53	3.54	8.89	5.43	17.25	9.55	24.80	19.23
x'	0.00	44.72	89.92	120.13	152.24	210.83	238.69	307.14	336.83	397.38	432.67
x"	0.00	44.72	89.93	120.17	152.34	211.10	239.11	308.19	338.37	400.69	438.06
Horizontal Midpoint	22.36	67.33	105.05	136.26	181.72	225.11	273.65	323.28	369.53	419.37	443.88
Ring Area	785.52	6335.32	10214.81	11827.27	22708.34	27726.13	38033.10	46534.03	50329.54	61766.66	41420.22
Number of Bolts in Ring	1.36	11.00	17.73	20.53	39.42	48.14	66.03	80.79	87.38	107.23	71.91
Bolts per element (20 Sections)	1.36	0.55	0.89	1.03	1.97	2.41	3.30	4.04	4.37	5.36	3.60

After testing the model using gravity loads, it was determined that the stiffness calculated above did not provide a good match to the TOLA slice model for the same loading. Therefore, the stiffness of the bolts was "tuned" to provide similar results to the TOLA slice model. The J-bolt model is developed using input file "Bolt-Friction.txt." See Figure 3-10 for the distribution of J-bolts. Figure 3-11 shows the locations of spring elements connecting the end of each J-bolt to the primary tank.

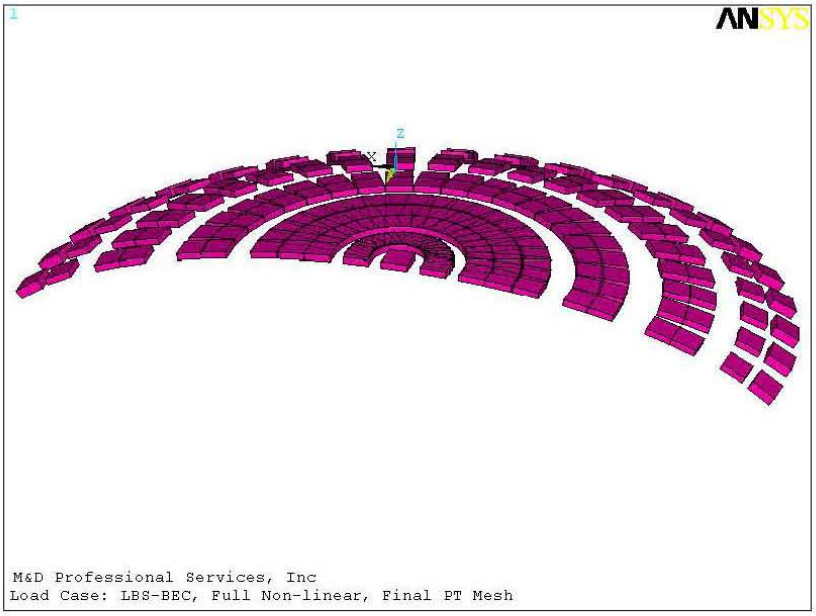


Figure 3-10. J-Bolt Model Detail

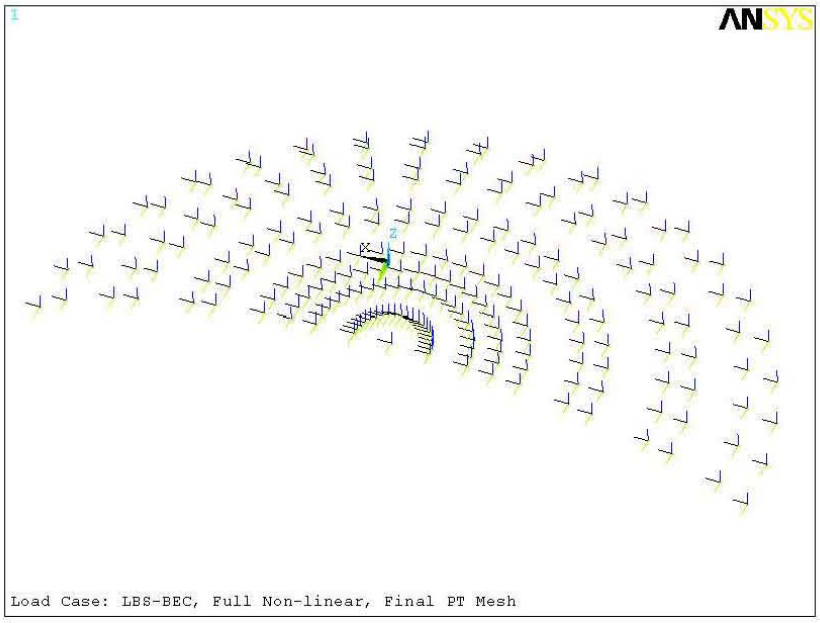


Figure 3-11. Spring Elements – J-Bolts to Primary Tank

3.2.6 Secondary Liner

The secondary liner is modeled using SHELL143 elements and its geometry is taken from H-2-90534. The steel thickness is 0.375 inch in the floor transitioning to 0.5625 inch in the knuckle and 0.5 inch in the lower wall. The model stops after the 1st full wall element coincident with the liner. The secondary liner is shown in Figure 3-12.

Input file "Liner.txt" develops the model for the liner using the geometry defined for the concrete tank in "Tank-Coordinates.txt." The following material properties are used for the steel liner.

Elastic Modulus (E) = 4,176,000 kip/ft^2
Poisson's Ratio (ν) = 0.30
Mass Density (ρ) = 0.001522 kip-sec^2/ft^4 = (0.490 kip/ft^3)/(32.2 ft/sec^2)
Damping = 2%

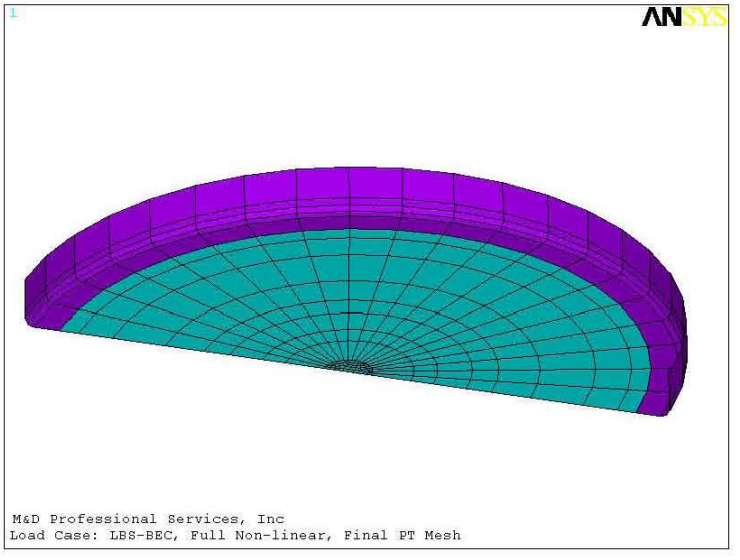


Figure 3-12. Secondary Liner Model Detail

3.2.7 Waste

The waste is modeled using solid elements (SOLID45) with material properties defined to emulate a liquid. The waste elements are meshed such that there are no common nodes with the primary tank; however, those on the exterior (at the primary tank) are coincident with the primary tank nodes. Contact elements are used for the interface between the waste and the primary tank. The material properties are as follows:

Elastic Modulus (E) = 25.92 kip/ft^2
Poisson's Ratio (ν) = 0.4999
Mass Density (ρ) = 0.003294 kip-sec^2/ft^4 = (1.7*0.0624 kip/ft^3)/(32.2 ft/sec^2)
Damping = 0
Shear Modulus (G) = 0.216 kip/ft^2

The elastic modulus E was calculated based on the Bulk Modulus of water (~300,000 psi). Using a value of ν close to 0.5 (0.49999), the value of E can be calculated.

$$B = E/[3(1-2\nu)] \text{ or} \tag{3.10}$$

$$E = B[3(1-2\nu)] = 300{,}000[3(1-2(0.49999))] = 18\text{lb/in}^2 = 2.592\text{kip/ft}^2 \tag{3.11}$$

The shear modulus G can then be calculated based on E and ν, G=E/[2(1+ν)]. For the values shown above, this gives a value for G of 0.864 kip/ft^2. However, because a fluid cannot carry shear, a smaller value is used. The value was selected such that the solution remains mathematically stable.

Figure 3-13 shows the waste elements.

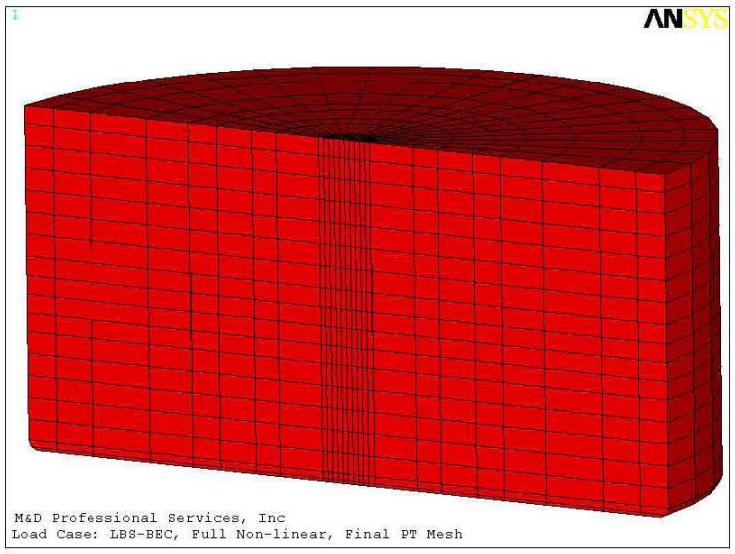


Figure 3-13. Waste Model Detail

Two benchmarking studies were performed to assess the fluid-structure interaction behavior of the primary tank and contained waste under seismic excitation. In the study documented in Rinker et al. (2006b), the fluid-structure interaction was simulated in ANSYS®. In the study documented in Rinker and Abatt (2006), the fluid-structure interaction was simulated using MSC.Dytran® (Dytran). The studies showed that the modeling approach used in ANSYS® adequately predicts the total hydrodynamic reaction force and pressure distribution both vertically and circumferentially, but that the model was deficient in predicting the convective response of the waste.

The fundamental difference between the current increased liquid level analysis and the earlier analysis at the baseline liquid level of 422 inches (Rinker et al. 2006c) is increased interaction between the contained waste and the curved dome area of the primary tank (see Figure 4.14). Thus, the stresses induced by the interaction of the liquid and the dome are of particular concern. The results from the Dytran sub-model analysis are compared to the results of a similar ANSYS® sub-model of a primary tank, as well as to the results from the global ANSYS® models in the Increased Liquid Level Seismic report (Rinker et al. 2007).

® Dytran is a registered trademark of MSC Software Corporation. Santa Ana, California.

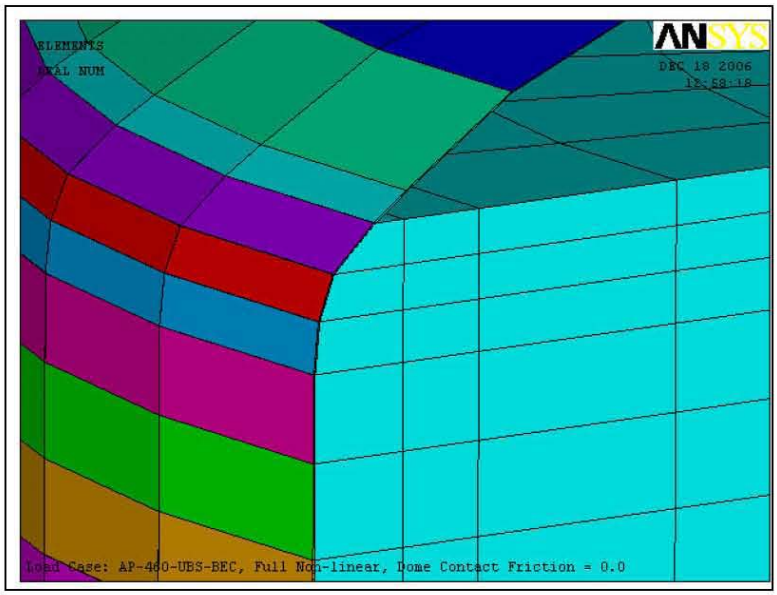


Figure 3-14. Waste Model Detail, Interface with Tank Dome

3.2.8 Primary Tank/Concrete Dome Interface

A combination of TARGE170 and CONTA173 elements are used to model the interface between the top of the primary tank and the inside face of the concrete dome. Key-Option controls are used to place the interface location at the inside face of the concrete (or bottom of the concrete shell element). A coefficient of friction of 0.01 was used for the contact surface. The low friction value results in the J-bolts being the primary load path for shear between the primary tank and the dome. A small value is used instead of zero to improve model solution stability.

The contact surface is developed using input file "bolt-friction.txt." Figure 3-15 shows the contact and target elements comprising the dome contact surface.

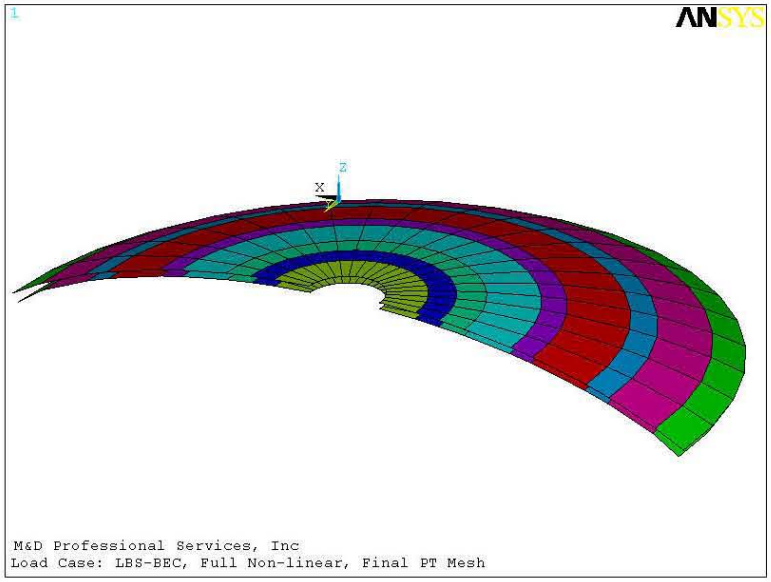


Figure 3-15. Contact Elements – Primary Tank to Concrete Dome

3.2.9 Primary Tank/Insulating Concrete Interface

A combination of TARGE170 and CONTA173 elements are used to model the interface between the bottom of the primary tank and the top of the insulating concrete. The contact and target surfaces are modeled as coincident (i.e., no offsets are included for shell thicknesses). A coefficient of friction of 0.4 was used for the contact surface. The contact surface is developed using input file "interface1.txt." Figure 3-16 shows the contact elements (top layer of elements).

3.2.10 Insulating Concrete/Secondary Liner Interface

A combination of TARGE170 and CONTA173 elements are used to model the interface between the bottom of the primary tank and the top of the insulating concrete. The contact and target surfaces are modeled as coincident (i.e., no offsets are included for shell thicknesses). A coefficient of friction of 0.4 was used for the contact surface. The contact surface is developed using input file "interface1.txt." Figure 3-16 shows the contact elements (bottom layer of elements).

3.2.11 Soil/Concrete Tank Interface

A combination of TARGE170 and CONTA173 elements are used to model the interface between the soil and the concrete tank, and for the interface plane between the native and excavated soils. A coefficient of friction of 0.2 was used for the contact surface between the soil and the concrete tank during the gravity loading solution phase (static case) to realistically simulate the distribution of geostatic loads. The friction coefficient was then increased to 0.6 for the transient portion of the solution to simulated the dynamic frictional response at this interface. Rinker et al. (2006c) describes the soil friction model in complete detail. See Figure 3-17 for the contact surface model.

For the interface between the bottom of the footing and the native soil, COMBIN14 (spring) elements were used. Arbitrary high stiffness values were applied to these springs because the flexibility at the interface is already included in the material properties for the concrete and soil. See Figure 3-18 for the location of the interface springs.

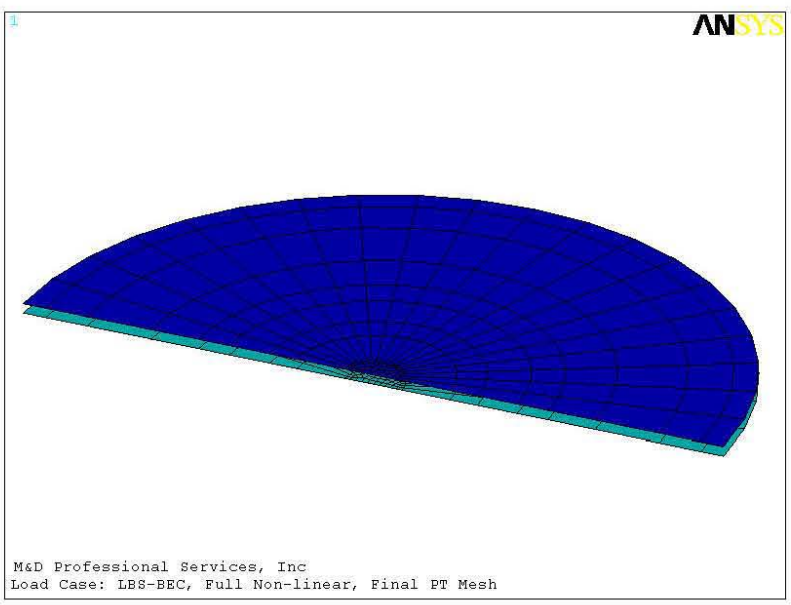


Figure 3-16. Contact Elements – Insulating Concrete Top and Bottom

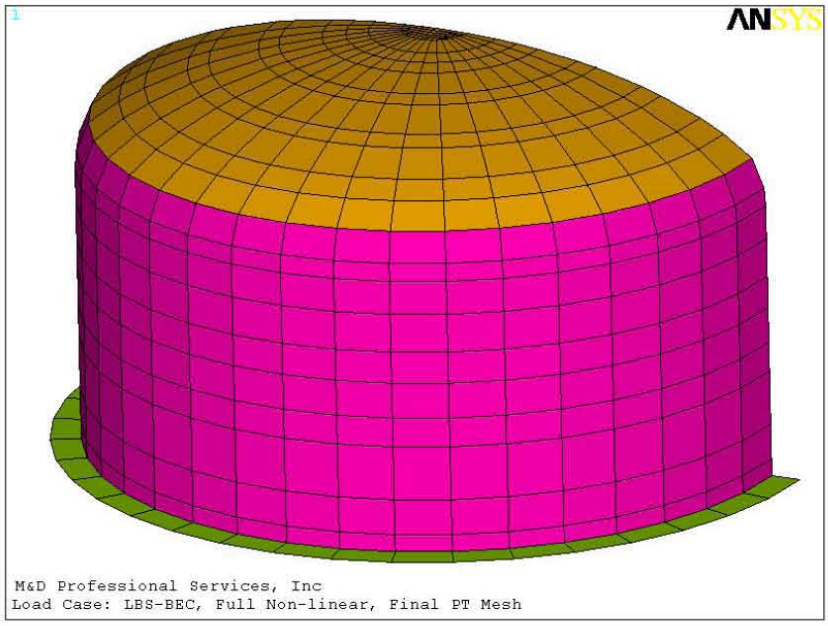


Figure 3-17. Contact Elements – Soil to Concrete Tank

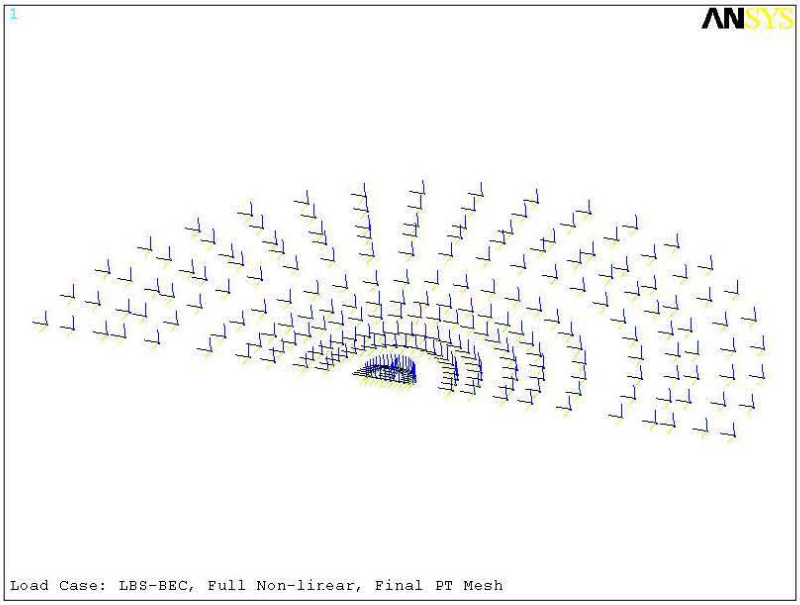


Figure 3-18. Spring Elements – Concrete Footing to Soil

3.2.12 Excavated/Native Soil Interface

A combination of TARGE170 and CONTA173 elements are used to model the interface between the native and excavated soils. An initial coefficient of friction of 0.3 is used for the gravity (static) analysis. The coefficient of friction is changed to 0.7 for the transient analysis. This surface is included to improve the initial conditions for the transient analysis by allowing an initial displacement between the native and excavated soil but located far enough away that is does not have a significant effect on the tank behavior. Figure 3-19 shows the contact elements constituting the soil interface.

This surface is developed using the input file "fix-soil.txt"

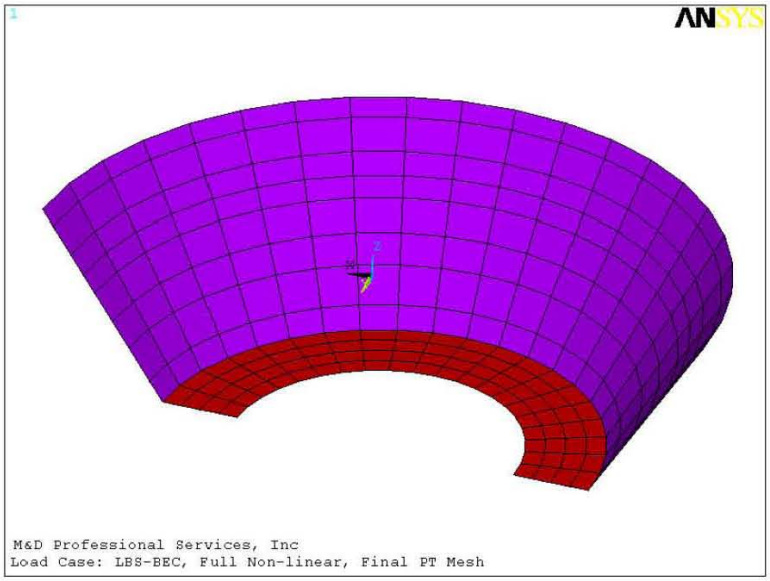


Figure 3-19. Contact Elements – Near Soil to Far Soil

3.2.13 Waste/Primary Tank Interface

A combination of TARGE170 and CONTA173 elements are used to model the interface between waste and primary tank. No friction is included for this surface. A high stiffness was defined for this contact to obtain the correct hydrostatic pressure on the tank. The high stiffness of the contact was needed because the waste model was very soft. Excessive displacements occur without modifying the contact stiffness. The contact surface is divided into multiple zones to enhance the performance of the contacts. This approach captures more realistic waste pressures in areas of higher curvature (dome and knuckle regions). The contact surface is developed using input file "Waste-Soild-AY.txt." The interface between the waste and primary tank is shown in Figure 3-20.

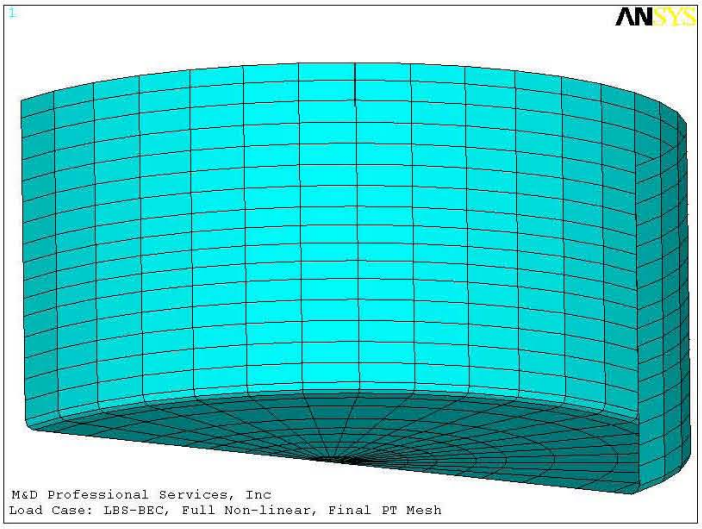


Figure 3-20. Contact Elements – Waste to Primary Tank

3.2.14 Concrete Wall/Footing Interface

The contact at the bottom of the wall was modeled using CONTA178 elements. A friction coefficient of 0.2 was used for this contact to reflect the steel on steel interface. Use of contact elements for this interface will be used to determine if displacement can occur during a seismic event. The contact elements allow only normal and shear forces (no moments) to be transferred to the footing. The contact between the bottom of the wall and the footing is shown in Figure 3-21.

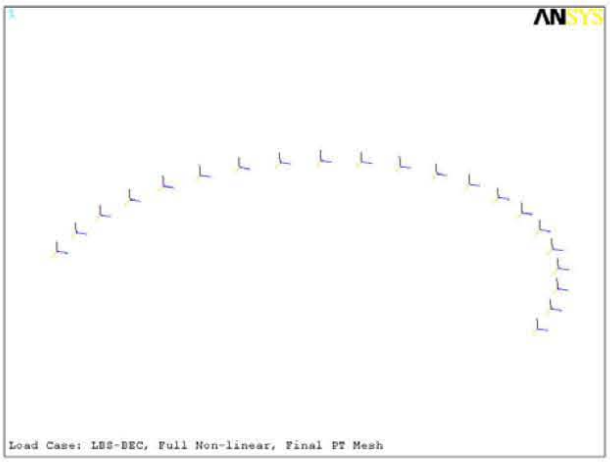


Figure 3-21. Contact Elements – Concrete Wall to Footing

3.2.15 Surface Loads

MASS21 elements were added to the soil surface over the center of the dome to create a "live load" over the tank dome. The mass provides an equivalent weight of 200,000 lbf. Mass elements were used in lieu of forces to capture the dynamic participation of equipment that creates this load. Figure 3-22 illustrates the placement of the mass elements.

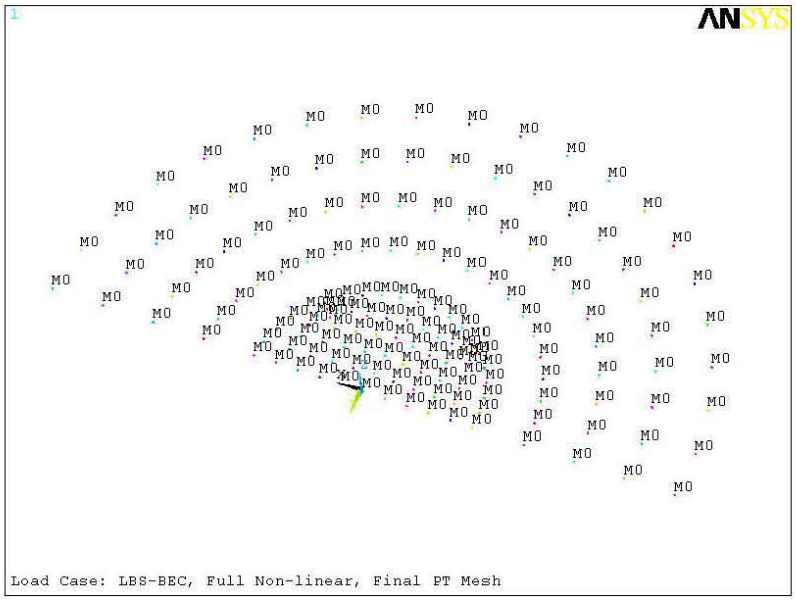


Figure 3-22. Mass Elements – Soil Surface

3.3 Soil Model

This section describes the geometry and construction of the ANSYS® finite element model of the soil surrounding the DST. A comprehensive description of the FE model is found in the Seismic Analysis report (Rinker et al. 2006c). The Seismic Analysis report should be referenced for complete model description and background information.

3.3.1 Soil Properties

The soil surrounding the tank is modeled in two groups, the excavated soil and the far-field soil. The excavated soil fills the volume outside the concrete tank and is bounded by the slope matching the soil removed during construction. The far-field soil is comprised of all other soil out to a radius of 320 feet and a depth of 266 feet. Both regions are modeled using SOLID45 elements.

Two SHAKE analyses were performed for each soil condition to obtain soil properties for the layering used in the model (Rinker et al. 2006a). One run used the native soil properties and is used for the far-field soil material properties. The second run used material properties associated with structural backfill and the results are used for the material properties in the excavated soil region.

Soil properties used for the model are listed in Tables 3-7 through 3-12.

Table 3-7. Best Estimate Native Soil Iterated Soil Properties

Layer Depth	Damping	G	Poisson's Ratio	E	Density	Material Property No.
2.5	0.017	6622.3	0.24	16,423	110	901
9.2	0.025	6241.7	0.24	15,479	110	902
16.4	0.034	5839.1	0.24	14,481	110	903
22.1	0.028	5930.4	0.24	14,707	110	904
29	0.032	5724.9	0.19	13,625	110	905
37.2	0.033	6494.2	0.19	15,456	110	906
44.7	0.033	7366.4	0.19	17,532	110	907
52.9	0.025	8811.9	0.19	20,972	110	908
65.5	0.026	9851.5	0.19	23,447	110	909
82	0.027	9721.9	0.19	23,138	110	910
98.8	0.029	9560.1	0.19	22,753	110	911
115.5	0.033	9272.5	0.19	22,069	110	912
132	0.025	10831.8	0.19	25,780	110	913
148.3	0.027	10644	0.19	25,333	110	914
167.5	0.022	13867.4	0.28	35,501	120	915
189.5	0.021	15416	0.28	39,465	120	916
211.5	0.023	15064.3	0.28	38,565	120	917
233.5	0.025	14732.5	0.28	37,715	120	918
255.5	0.024	16209.2	0.28	41,496	120	919

Table 3-8. Best Estimate Excavated Soil Iterated Soil Properties

Layer Depth	Damping	G	Poisson's Ratio	E	Density	Material Property No.
2.5	0.019	3920.4	0.27	9,958	125	801
9.2	0.035	3463.4	0.27	8,797	125	802
16.4	0.048	3088.5	0.27	7,845	125	803
22.1	0.039	3231.8	0.27	8,209	125	804
29	0.048	3005.6	0.27	7,634	125	805
37.2	0.055	2829.8	0.27	7,188	125	806
44.7	0.059	2729.6	0.27	6,933	125	807
52.9	0.045	3018.4	0.27	7,667	125	808

Table 3-9. Upper Bound Native Soil Iterated Soil Properties

Layer Depth	Damping	G	Poisson's Ratio	E	Density	Material Property No.
2.5	0.016	10004.3	0.24	24,811	110	901
9.2	0.022	9607.3	0.24	23,826	110	902
16.4	0.027	9268.4	0.24	22,986	110	903
22.1	0.022	9383.3	0.24	23,271	110	904
29	0.026	9068.8	0.19	21,584	110	905
37.2	0.027	10289.2	0.19	24,488	110	906
44.7	0.028	11649.1	0.19	27,725	110	907
52.9	0.022	13709.7	0.19	32,629	110	908
65.5	0.022	15284.2	0.19	36,376	110	909
82	0.024	15035.4	0.19	35,784	110	910
98.8	0.025	14863.1	0.19	35,374	110	911
115.5	0.026	14746.3	0.19	35,096	110	912
132	0.02	16982.4	0.19	40,418	110	913
148.3	0.021	16838.8	0.19	40,076	110	914
167.5	0.019	21821.5	0.28	55,863	120	915
189.5	0.019	23910.6	0.28	61,211	120	916
211.5	0.02	23673.5	0.28	60,604	120	917
233.5	0.02	23525	0.28	60,224	120	918
255.5	0.019	25917.8	0.28	66,350	120	919

Table 3-10. Upper Bound Excavated Soil Iterated Soil Properties

Layer Depth	Damping	G	Poisson's Ratio	E	Density	Material Property No.
2.5	0.017	5956.9	0.27	15,131	125	801
9.2	0.027	5554.3	0.27	14,108	125	802
16.4	0.039	5041.9	0.27	12,806	125	803
22.1	0.031	5191.5	0.27	13,186	125	804
29	0.035	5005.7	0.27	12,714	125	805
37.2	0.042	4747.8	0.27	12,059	125	806
44.7	0.047	4551.9	0.27	11,562	125	807
52.9	0.037	4864.9	0.27	12,357	125	808

Table 3-11. Lower Bound Native Soil Iterated Soil Properties

Layer Depth	Damping	G	Poisson's Ratio	E	Density	Material Property No.
2.5	0.018	4382.9	0.24	10,870	110	901
9.2	0.03	4004	0.24	9,930	110	902
16.4	0.043	3590.3	0.24	8,904	110	903
22.1	0.034	3739.6	0.24	9,274	110	904
29	0.04	3551.3	0.19	8,452	110	905
37.2	0.042	4004.4	0.19	9,530	110	906
44.7	0.042	4561.5	0.19	10,856	110	907
52.9	0.03	5629.7	0.19	13,399	110	908
65.5	0.03	6331	0.19	15,068	110	909
82	0.035	6066.4	0.19	14,438	110	910
98.8	0.039	5831.4	0.19	13,879	110	911
115.5	0.043	5633.7	0.19	13,408	110	912
132	0.032	6786.7	0.19	16,152	110	913
148.3	0.032	6763.3	0.19	16,097	110	914
167.5	0.028	8619.5	0.28	22,066	120	915
189.5	0.028	9445.3	0.28	24,180	120	916
211.5	0.029	9314.8	0.28	23,846	120	917
233.5	0.029	9320.7	0.28	23,861	120	918
255.5	0.026	10588.1	0.28	27,106	120	919
279	0.014	29929.7	0.3	77,817	125	920
304	0.014	29856.3	0.3	77,626	125	921
329	0.015	29714.3	0.3	77,257	125	922
354	0.015	29602.2	0.3	76,966	125	923

Table 3-12. Lower Bound Excavated Soil Iterated Soil Properties

Layer Depth	Damping	G	Poisson's Ratio	E	Density	Material Property No.
2.5	0.023	2547.2	0.27	6,470	125	801
9.2	0.044	2126.7	0.27	5,402	125	802
16.4	0.066	1782.2	0.27	4,527	125	803
22.1	0.053	1910.9	0.27	4,854	125	804
29	0.061	1777	0.27	4,514	125	805
37.2	0.067	1689.3	0.27	4,291	125	806
44.7	0.07	1628.4	0.27	4,136	125	807
52.9	0.056	1815.9	0.27	4,612	125	808

3.3.2 Excavated Soil

The excavated soil portion of the soil is developed using the input file "Near-Soil-1.txt." Figures 3-23 through 3-25 show the detail of the excavated region of soil. Two zones in the soil above the dome are softened to break the potential arching that can occur in the soil model. This arching effect can occur because linear elastic properties are used for soil, which means that the soil as modeled can carry tension. The development of the softened regions of the soil over the tank dome is discussed in detail in the Seismic Analysis report (Rinker et al. 2006c).

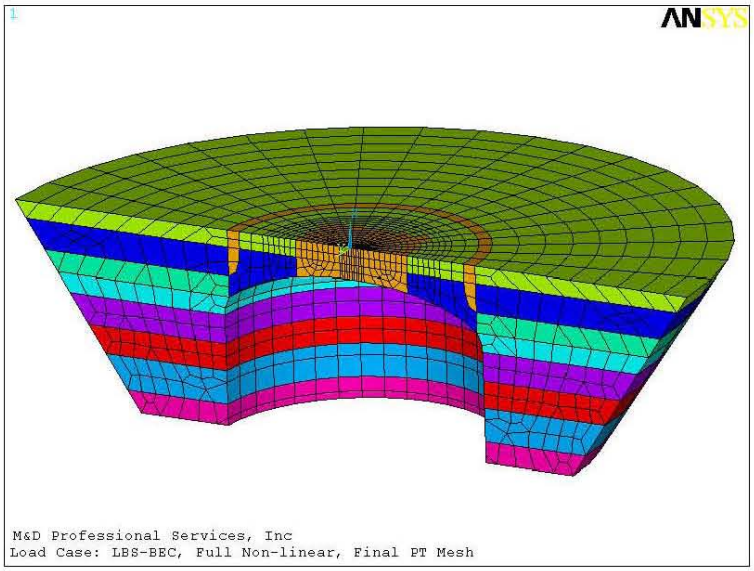


Figure 3-23. Excavated Soil Model Detail

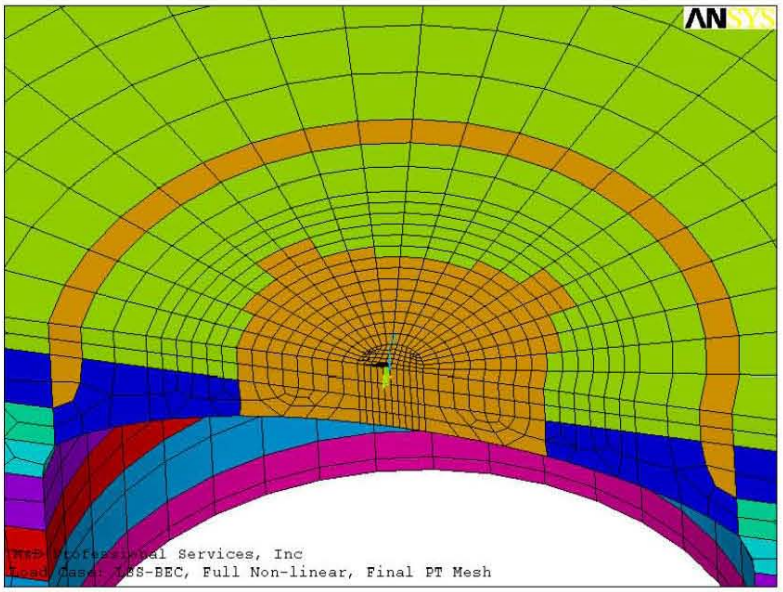


Figure 3-24. Excavated Soil – Softened Soil Zones

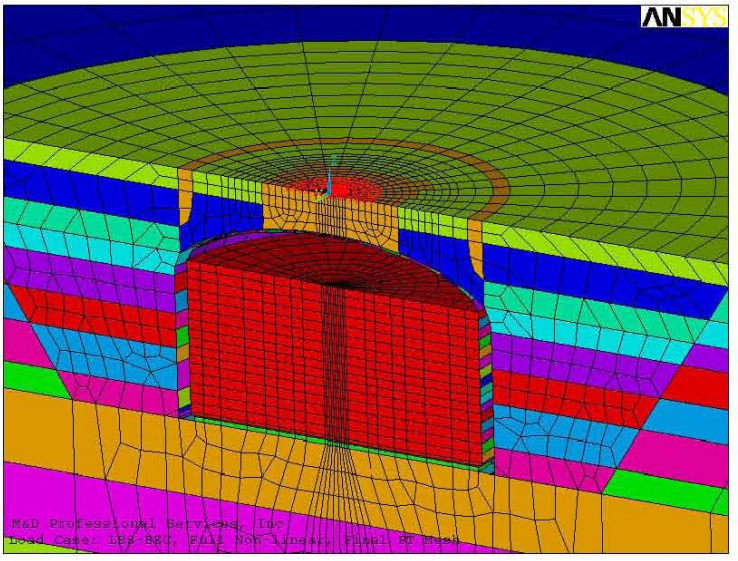


Figure 3-25. Model Detail

3.3.3 Native Soil

The native soil region of the model is developed using input file "Far-Soil.txt." SOLID45 elements are used and the material properties are discussed above. Figure 3-26 shows the native soil portion of the model.

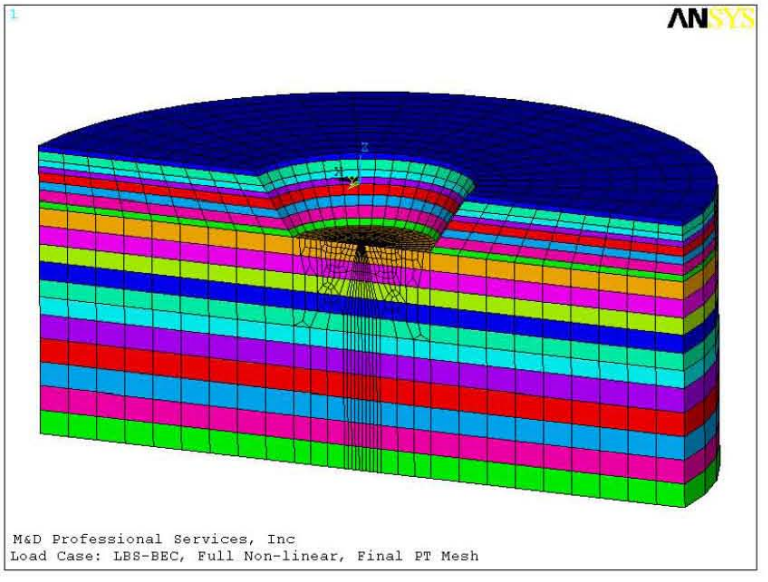


Figure 3-26. Far-Field Soil Model Detail

LINK8 elements are used to connect the native soil slaved nodes on each layer to the symmetry plane. These are required because the slaved node of a couple cannot have a boundary condition applied to it. Therefore, to maintain the desired soil behavior, the link elements effectively complete the coupling of the outside soil node at each layer. Figure 3-27 shows the locations of the link elements. Input file "Outer-Spar.txt" develops these elements.

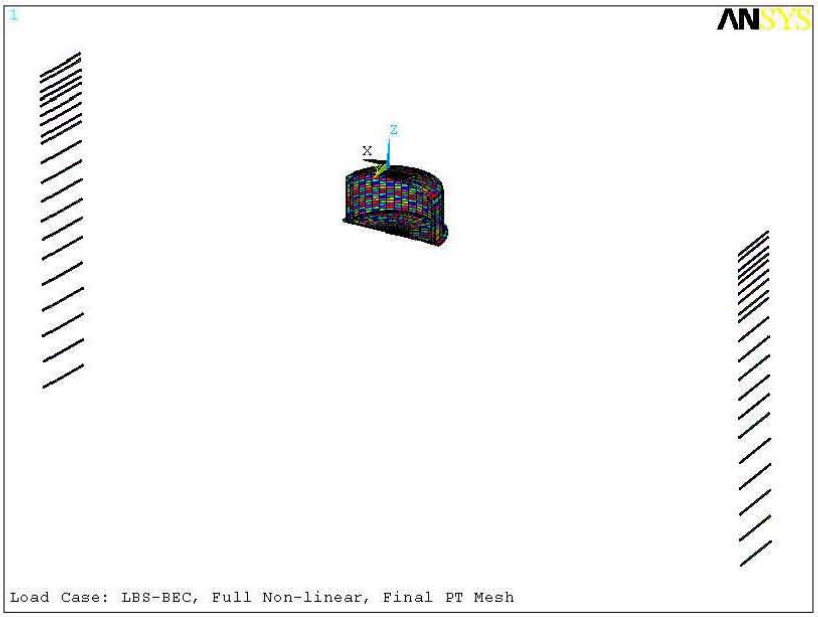


Figure 3-27. Link Elements – Edges of Soil Model

3.4 Boundary Conditions

This section describes the boundary conditions applied to the ANSYS® seismic finite element model. A comprehensive description of the FE model is found in the Seismic Analysis report (Rinker et al. 2006c). The Seismic Analysis report should be referenced for complete model description and background information.

3.4.1 Soil Boundary Conditions

All nodes on the outside edge (radius = 320 feet) have been "slaved" to a single node at each layer. Couples are used in each of the three translations to force the soil to behave essentially as a shear beam. This approach is used to create the appropriate conditions for vertical and horizontal waves to pass through the model (see Figures 3-29 and 3-30). The effectiveness of this approach is documented in Rinker et al. (2006a). All nodes on the bottom of the model (−266 feet) are coupled together to create a rigid foundation (see Figure 3-28). The symmetry plane for the soil has all nodes fixed for Y translation, see Figure 3-31.

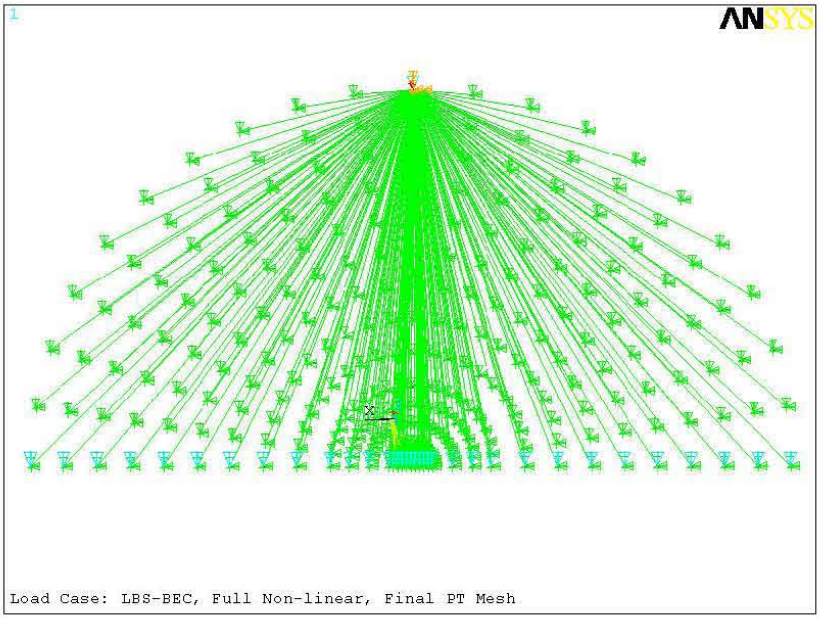


Figure 3-28. Boundary Conditions – Soil Base

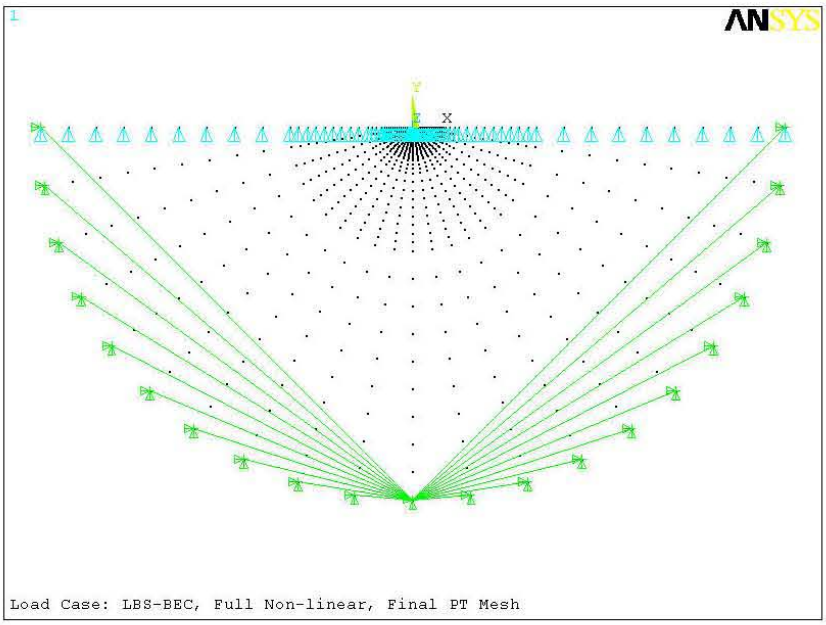


Figure 3-29. Boundary Conditions – Typical Soil Layer

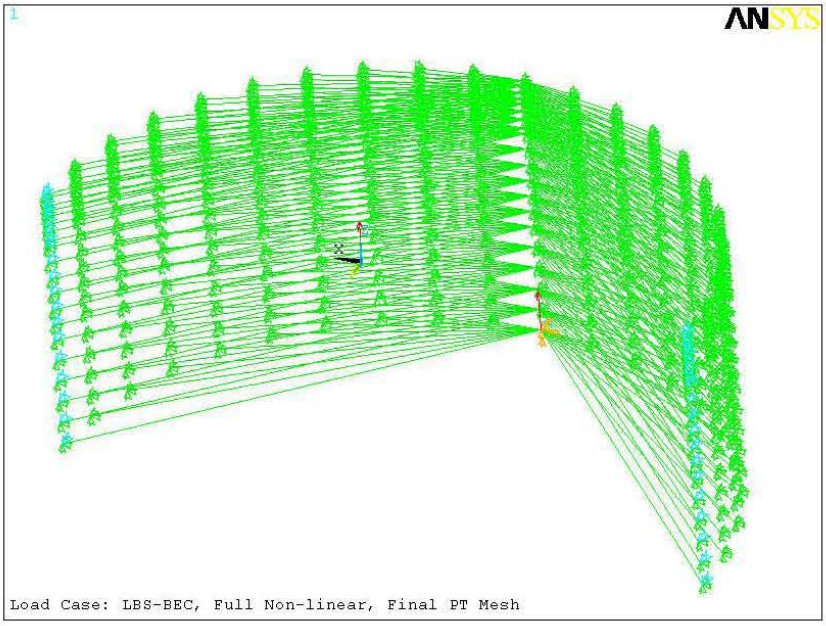


Figure 3-30. Boundary Conditions – Slaved Boundary Conditions

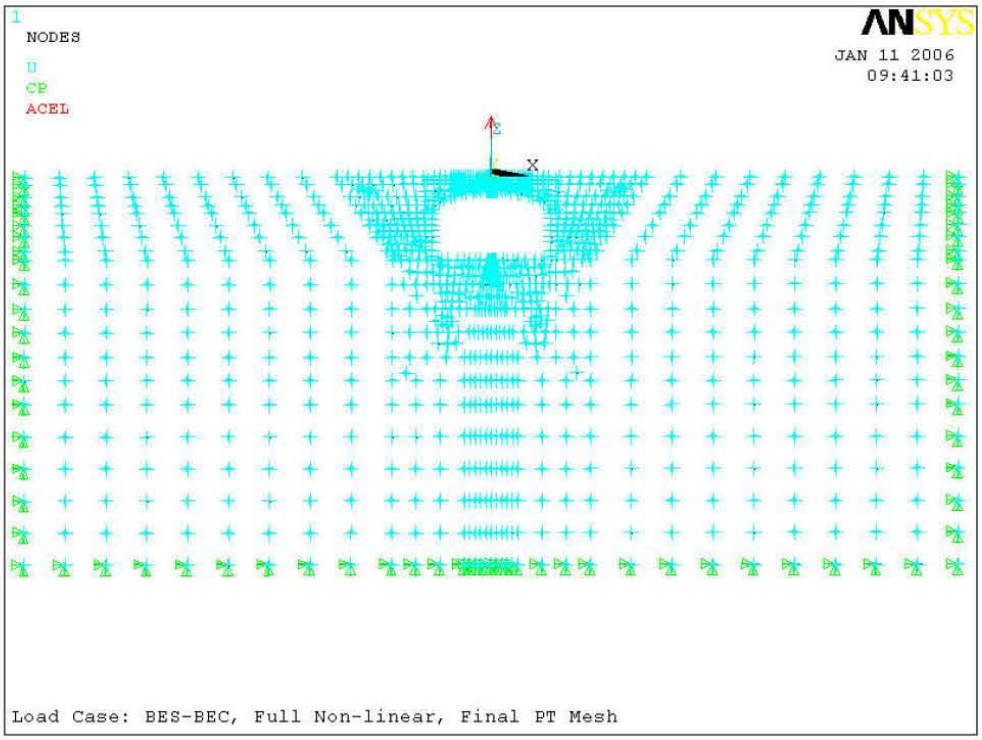


Figure 3-31. Boundary Conditions – Symmetry Plane

3.4.2 Tank Boundary Conditions

The tank model has all nodes on the symmetry plane fixed to the Y translation, X rotation, and Z rotation (see Figures 3-32 and 3-33). Couples have been used between some components to ensure that

compatible displacements occur. Where no common nodes exist between the concrete tank and secondary liner, couples are used to control the deformation of the secondary liner where it is in contact with the concrete tank. This ensures that the secondary liner does not "pass through" the concrete on the footing and on the walls (see Figure 3-34).

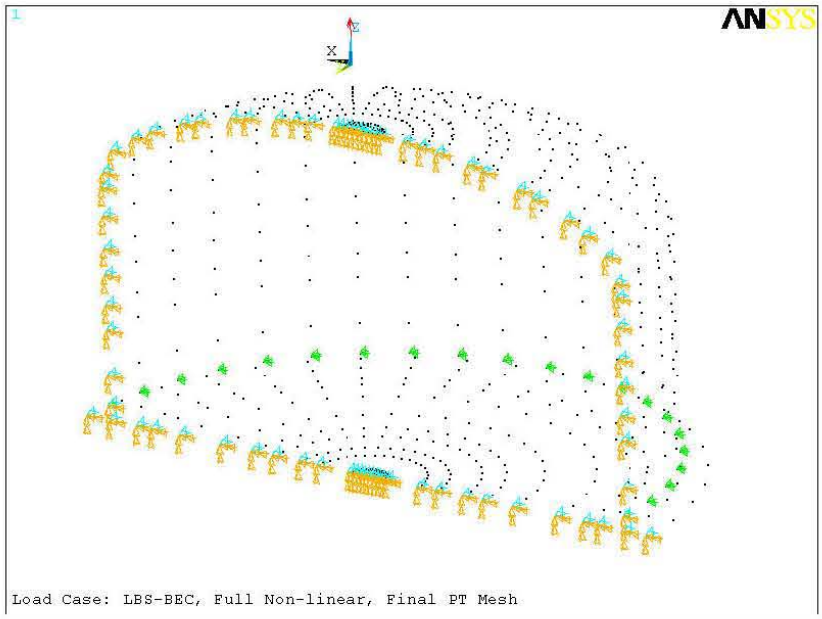


Figure 3-32. Boundary Conditions – Concrete Tank

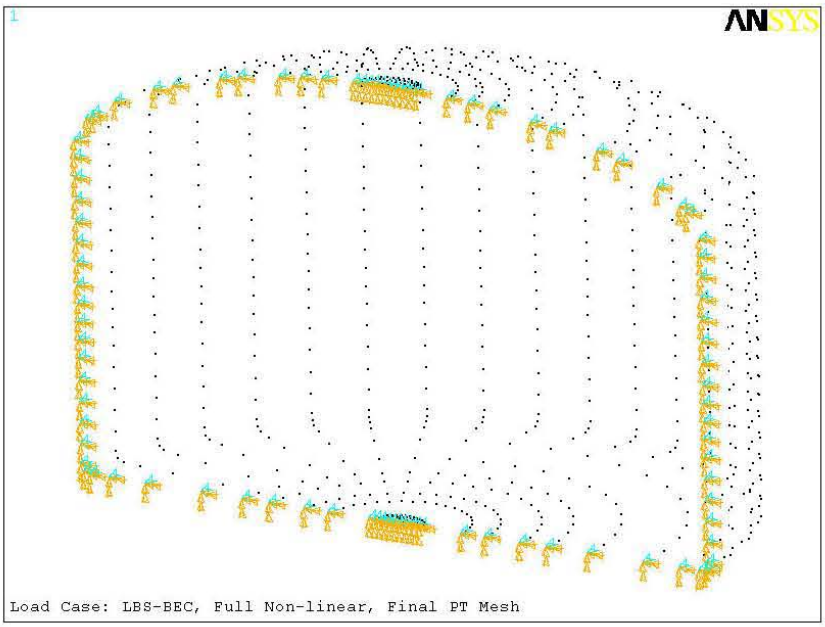


Figure 3-33. Boundary Conditions – Primary Tank

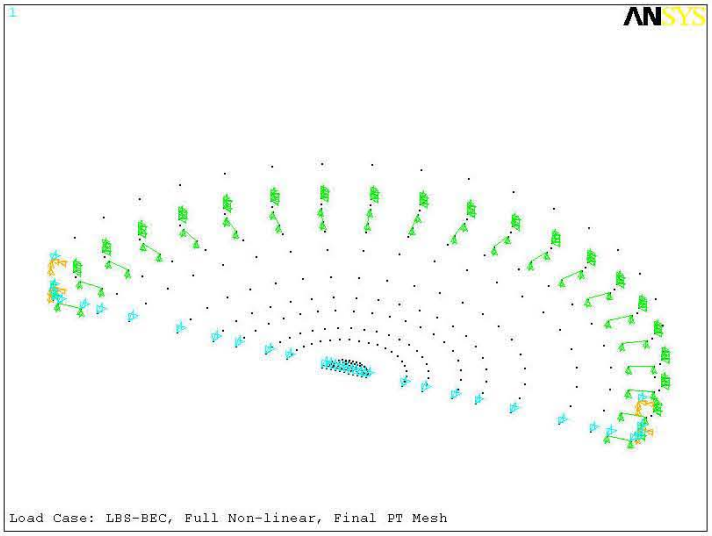


Figure 3-34. Boundary Conditions – Secondary Liner

3.5 Seismic Input

The seismic analysis of the DSTs requires appropriate acceleration time-history records representing the required seismic excitation. Time-history records must be available for both the horizontal and vertical directions. Typically, the required seismic input is specified in terms of design spectra. If time-histories are required, such time histories are often synthesized numerically subject to certain requirements related to the proper representation of the design spectra (ASCE 1998, NUREG-0800). The time-history records used in this analysis of the DSTs were existing time-histories that were used on the Hanford Waste Treatment Project (WTP). The justification for the use of existing time-histories is presented below.

The Hanford Tank Farms Documented Safety Analysis, or DSA (RPP-13033), designates the DSTs as Performance Category 2 (PC-2) structures. DOE-STD-1020-2002, Section 2, states that the ground motions for PC-2 shall be developed following IBC 2000, in which the surface response spectra are specified to be 2/3 of the Maximum Considered Earthquake (MCE) ground motions. The MCE ground motions are defined as the ground motions with a mean annual frequency of exceedance of 4×10^{-4} (2% probability of exceedance in 50 years). The MCE motions may be defined based on either the USGS National Hazard Mapping results, adjusted for the appropriate site classification, or from a site-specific Probabilistic Seismic Hazard Analysis (PSHA). If the MCE response spectrum is to be defined from a site-specific PSHA, it cannot be less than 80% of the spectrum defined from the USGS National Hazard Mapping results. The PC-2 ground motions used in the DST analysis are based on a site-specific PSHA. The detailed development of the PC-2 spectra for the DST Farms is documented in Rinker and Youngs (2006).

Acceleration time-histories for two horizontal components and one vertical component of seismic motion were synthesized for the seismic design and evaluation of the Hanford Site WTP (BNFL 2000). The horizontal design spectrum for the WTP is anchored at 0.257*g* (peak ground acceleration (PGA), and the vertical design spectrum is anchored at 0.175*g* PGA. The time histories generated to match the WTP design spectra were previously used by M&D Professional Services in the preliminary soil-structure interaction analysis of the WTP high-level waste and pretreatment facilities, and were readily available (M&D 2001a and 2001b).

The Hanford Double-Shell Tank Farms horizontal design spectrum for 5% spectral damping is shown in Figure 3-35. Also shown in the figure are the horizontal control motion spectra for the WTP project. All reference or control motions are defined at the soil surface. Similar plots for the vertical direction are shown in Figure 3-36.

The relationships between the design spectra and the control motion response spectra show that it is acceptable to use the acceleration time-histories from the WTP for the analysis of the DSTs.

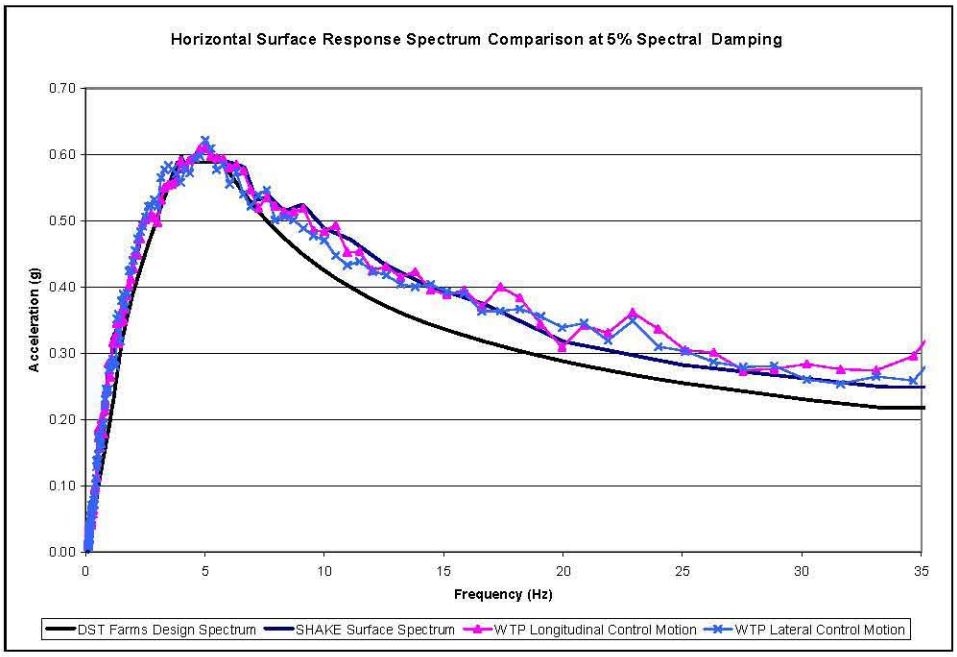


Figure 3-35. Comparison of Horizontal Surface Spectra at 5% Spectral Damping

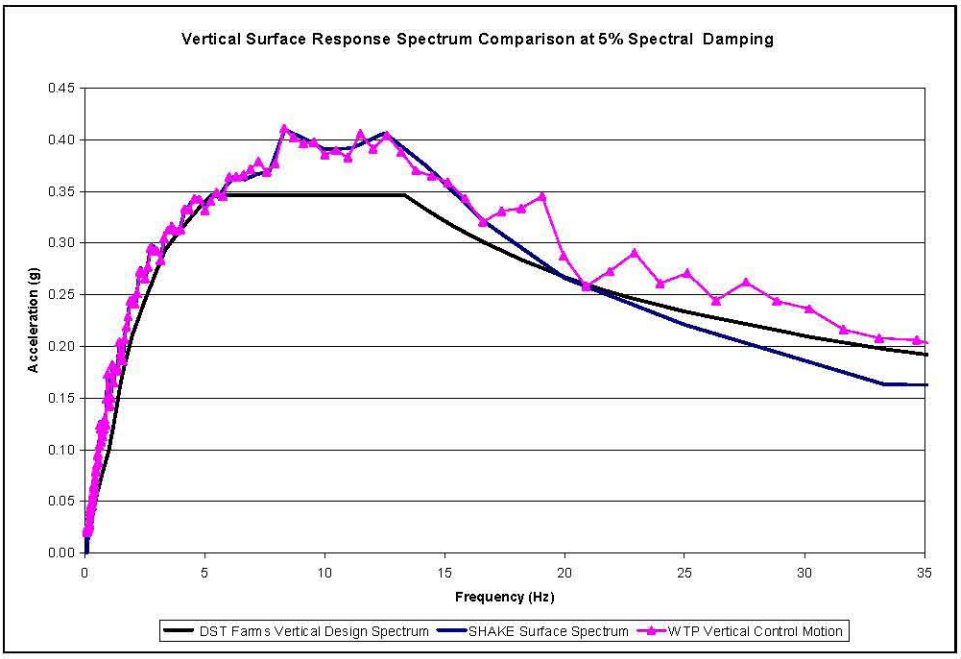


Figure 3-36. Comparison of Vertical Surface Spectra at 5% Spectral Damping

Acceleration and displacement time histories for horizontal and vertical input are shown in Figures 3-37 and 3-38, respectively.

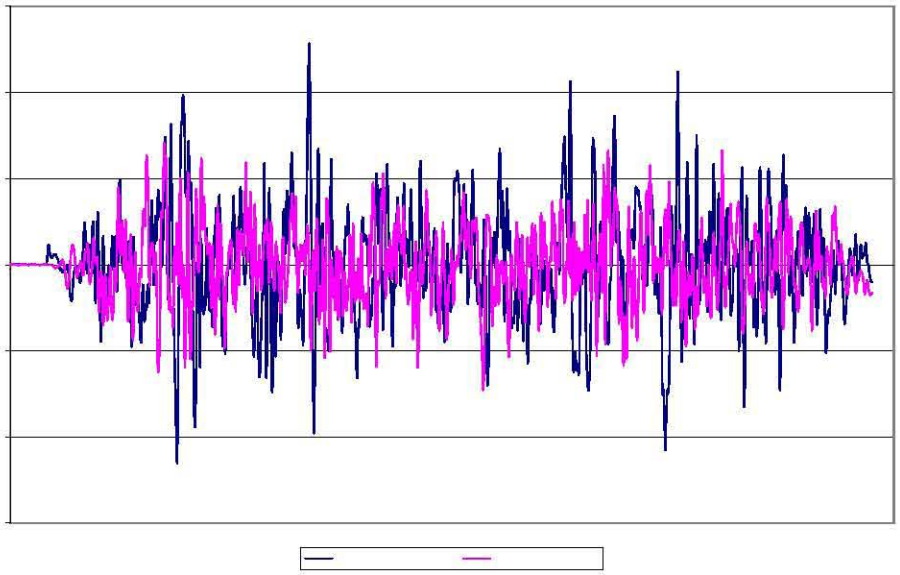


Figure 3-37. Horizontal and Vertical Surface Acceleration Time History

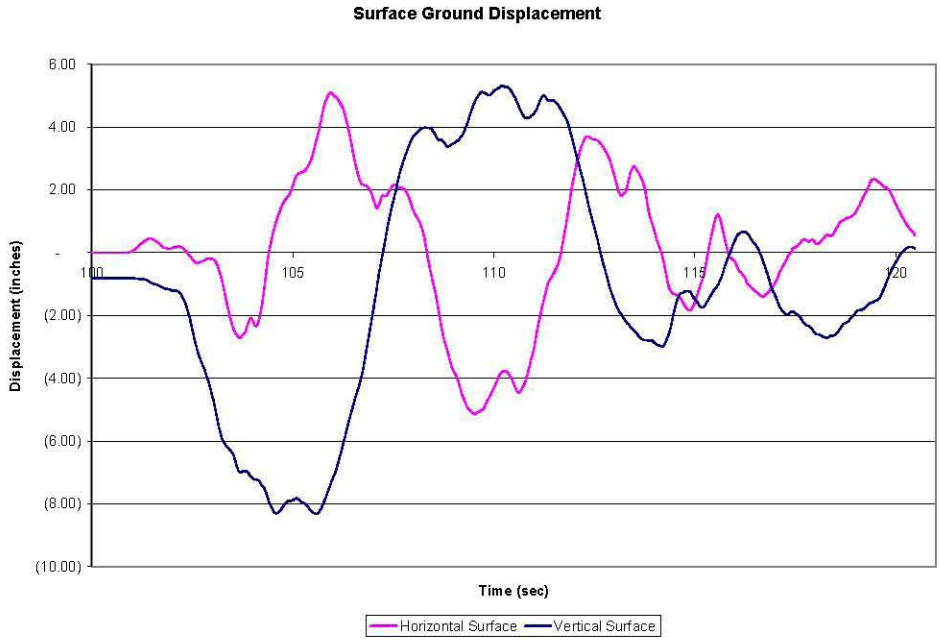


Figure 3-38. Horizontal and Vertical Surface Displacement Time History

3.6 Load Cases

Four separate load cases have been considered in this analysis. These cases are:

- Lower Bound Soil, Best Estimate Concrete (LBS-BEC) Properties
- Best Estimate Soil, Best Estimate Concrete (BES-BEC) Properties
- Upper Bound Soil, Best Estimate Concrete (UBS-BEC) Properties
- Best Estimate Soil, Fully Cracked Concrete (BES-FCC) Properties

These four cases are intended to cover the most significant areas of uncertainty for response of the DSTs to seismic loading. The three variations in soil properties address the variability and uncertainty in soil properties. The fully cracked concrete case covers the additional uncertainty of expected concrete condition.

Each load case consists of two analyses. First a gravity case is analyzed. Results from the gravity-only case will be used to determine the seismic-only results from the non-linear transient analysis. The second analysis for each case is a non-linear time-history analysis. Two input motions (horizontal and vertical) have been defined as acceleration time histories consisting of 2048 time steps. Acceleration time histories were developed for each of the three soil conditions at the −266-foot level.

3.6.1 Acceptance Criteria for Response Spectra

The following acceptance or screening criteria were applied to the tank foundation-level response spectra generated by the ANSYS® column model:

1. The envelope of the best estimate, lower bound, and upper bound response spectra at the tank foundation level (−57.6 feet) should be at least 60% of the surface control motion. This criterion applies to both horizontal and vertical motion.

2. The envelope of the best estimate, lower bound, and upper bound ANSYS® and Dytran response spectra at the tank foundation level (−57.6 feet) should be at least 90% of the SHAKE response spectrum.

3. The envelope of the best estimate, lower bound, and upper bound ANSYS® and Dytran response spectra at the tank foundation level (−57 feet) should be greater than or equal to the SHAKE response spectrum over any ±15% bandwidth.

The above criteria should be met for both horizontal and vertical spectra. Additional criteria were evaluated for these input motions and response spectra. The additional criteria are discussed in Rinker et al. (2006a). The first condition is intended to minimize the dip that can occur in deconvolved response spectra at moderate depth at the frequency of the overlying soil column. Such a dip appears in the foundation level SHAKE spectrum shown in Figure 3-38 as well as in other plots.

The tests of the first criterion are shown graphically for both horizontal and vertical input, as shown in Figures 3-39 and 3-40, respectively. The results indicate that the first condition is not met at all frequencies. Modifications to ensure that the condition is met are discussed in Section 3.6.2.

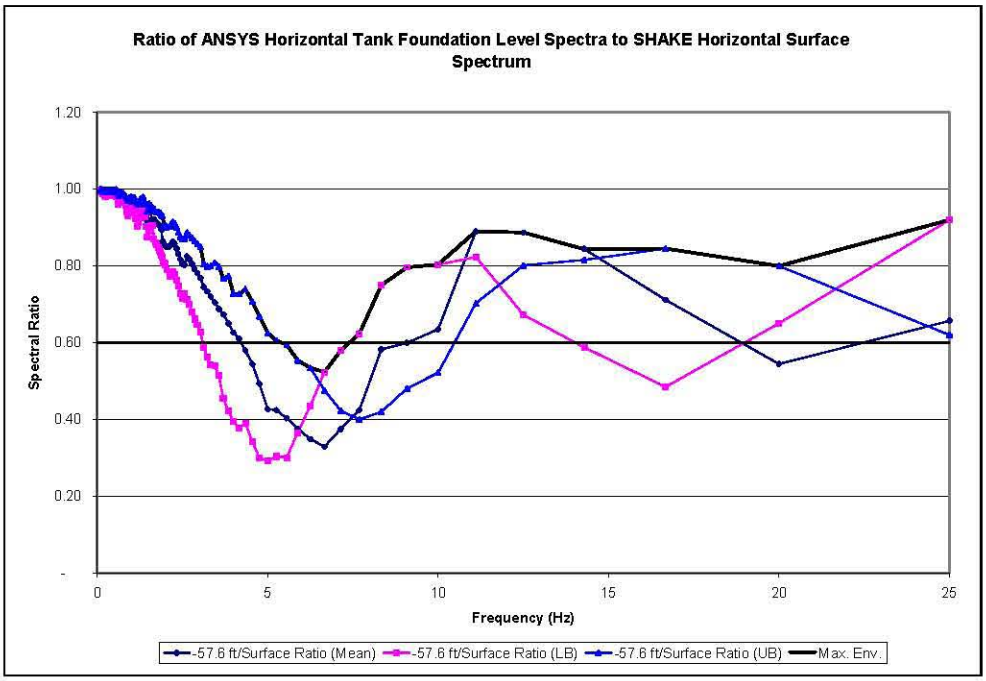


Figure 3-39. Ratio of the ANSYS® Tank Foundation Level Spectra to the SHAKE Surface Spectrum for Horizontal Excitation

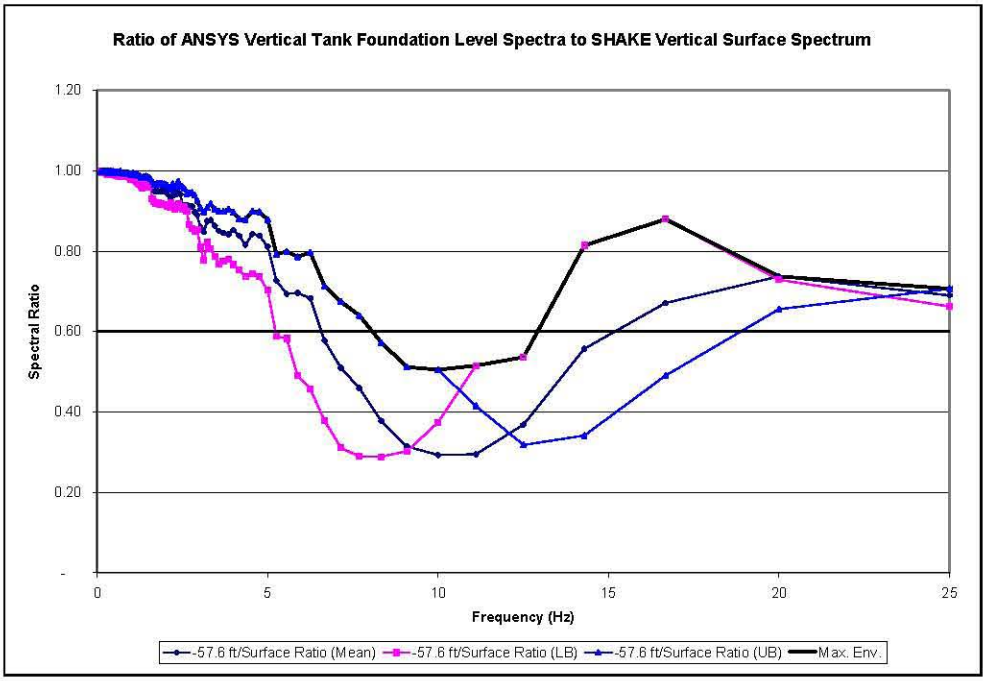


Figure 3-40. Envelope of the Ratio of the ANSYS® Tank Foundation-Level Spectra to the SHAKE Surface Spectrum for Vertical Excitation

3.6.2 Modification to ANSYS® Base Time Histories

Comparison of the ANSYS® soil column spectra at the tank foundation level to the SHAKE surface spectra for horizontal and vertical excitation (Figures 3-39 and 3-40) showed that the tank foundation spectra do not meet the first criterion. The envelope of the best estimate, lower bound, and upper bound response spectra at the tank foundation level (−57.6 feet) should be at least 60% of the surface control motion. This applies to both horizontal and vertical motion. To ensure that the envelope of the tank foundation level spectra is at least 60% of the SHAKE surface spectrum, the horizontal lower and upper bound base time histories used as input to the ANSYS® soil column model were scaled up by factors of 1.175 and 1.12, respectively. The vertical lower and upper bound base time histories were scaled up by factors of 1.12 and 1.19, respectively. Comparisons of the tank foundation-level spectra to the SHAKE surface spectra for the modified base time histories are shown in Figures 3-41 and 3-42. Increasing the base time histories by the above factors results in the ratio of the tank foundation-level spectra to SHAKE surface spectra meeting the 60% criterion.

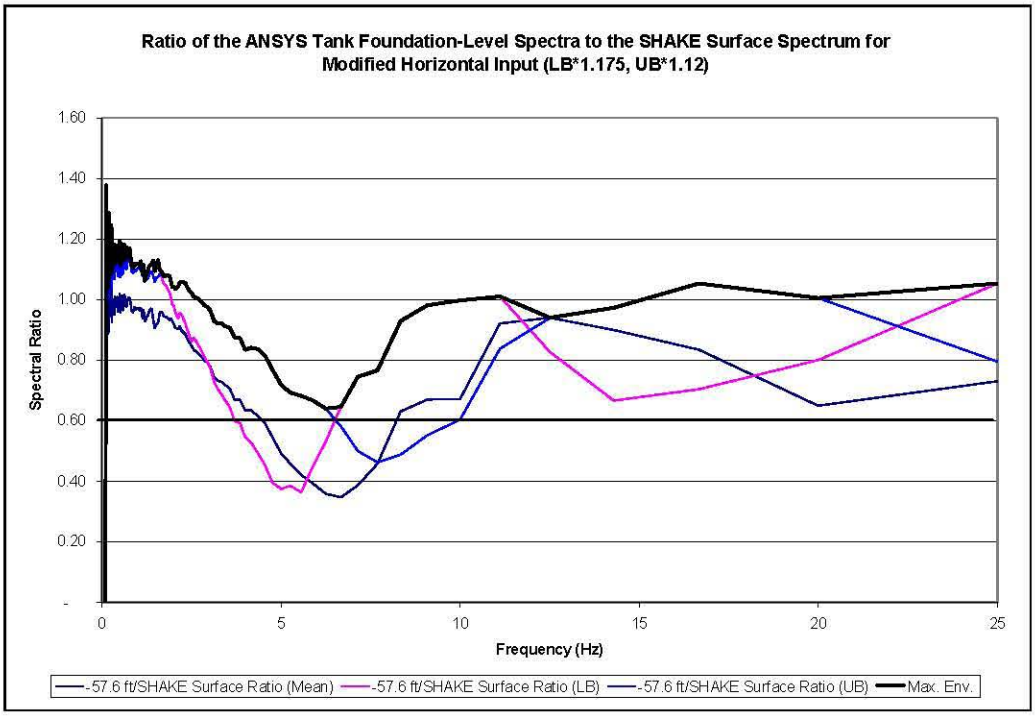


Figure 3-41. Ratio of the ANSYS® Tank Foundation Level Spectra to the SHAKE Surface Spectrum for Modified Horizontal Excitation

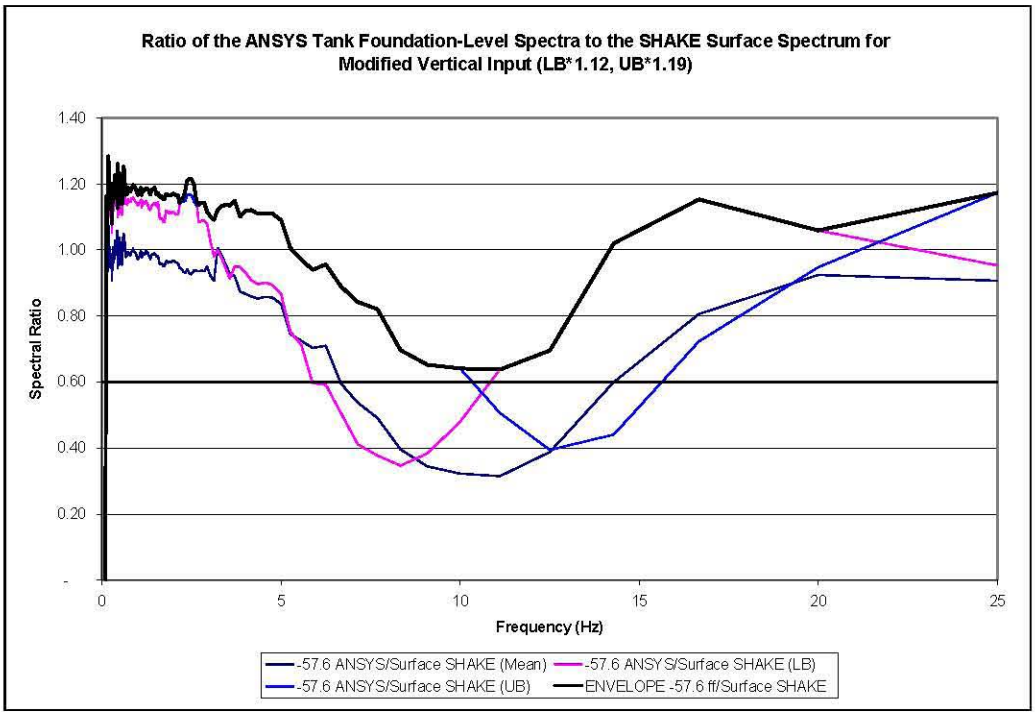


Figure 3-42. Envelope of the Ratio of the Tank Foundation Level Spectra to the SHAKE Surface Spectrum for Modified Vertical Excitation

3.6.3 ANSYS® Base Acceleration Time Histories

Individual time histories are applied for each different soil condition. Lower Bound, Best Estimate, and Upper Bound soil horizontal and vertical acceleration time histories are shown in Figures 3-43, 3-45, and 3-47, respectively. Lower Bound, Best Estimate, and Upper Bound soil horizontal and vertical displacement time histories are shown in Figures 3-44, 3-46, and 3-48, respectively.

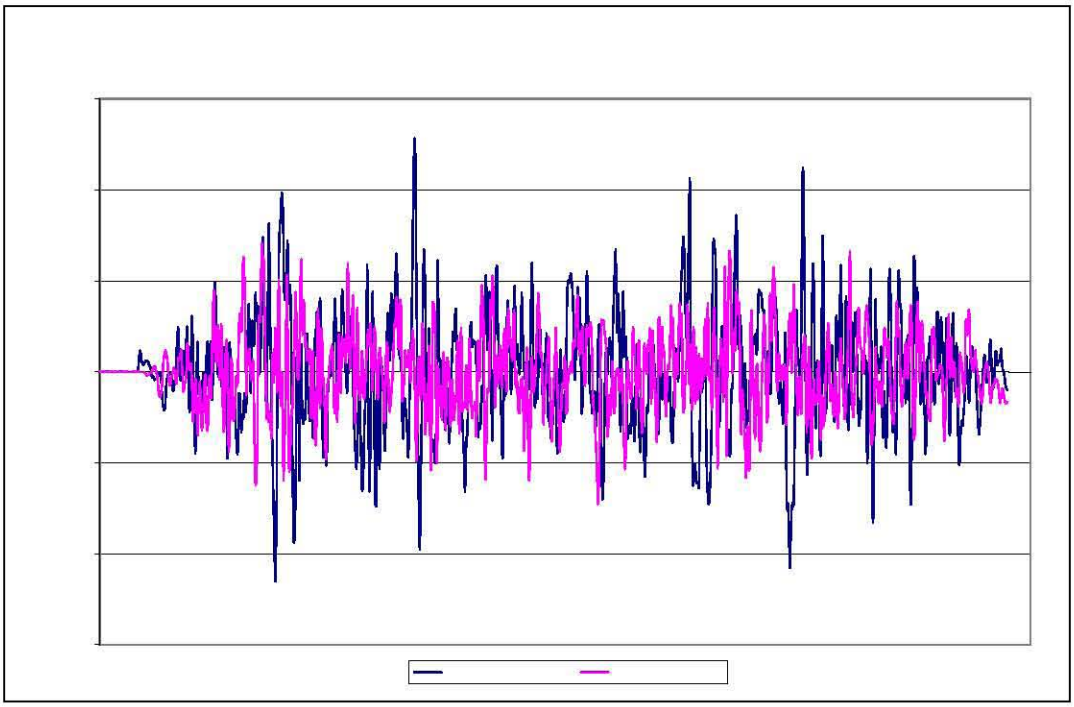


Figure 3-43. Horizontal and Vertical Base Acceleration Time History, −266 feet, Lower Bound Soil

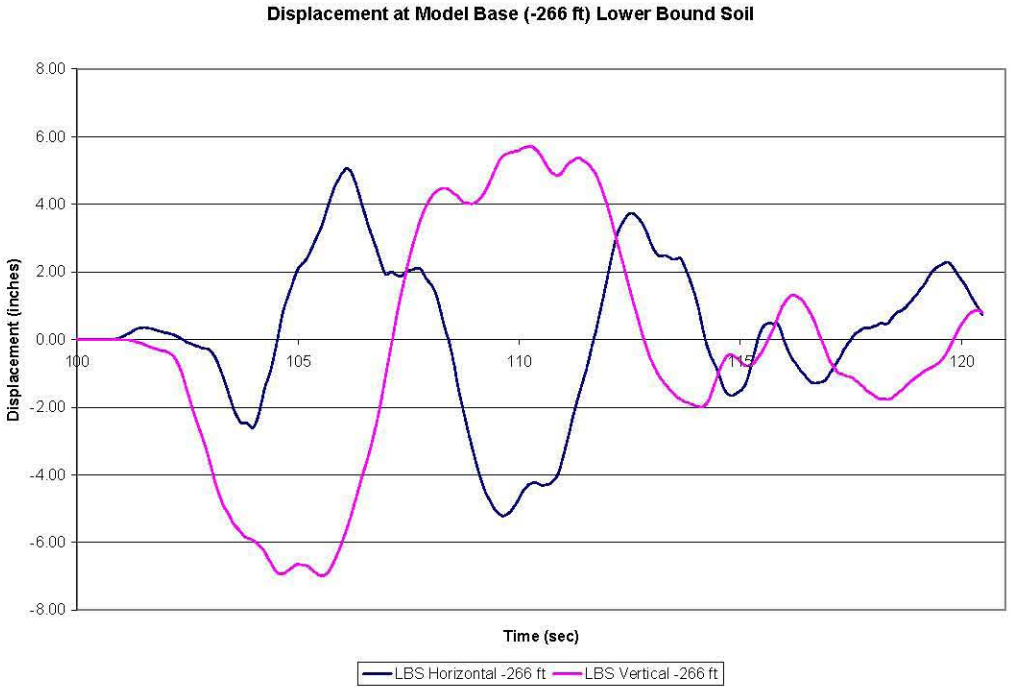


Figure 3-44. Horizontal and Vertical Base Displacement Time History, −266 feet, Lower Bound Soil

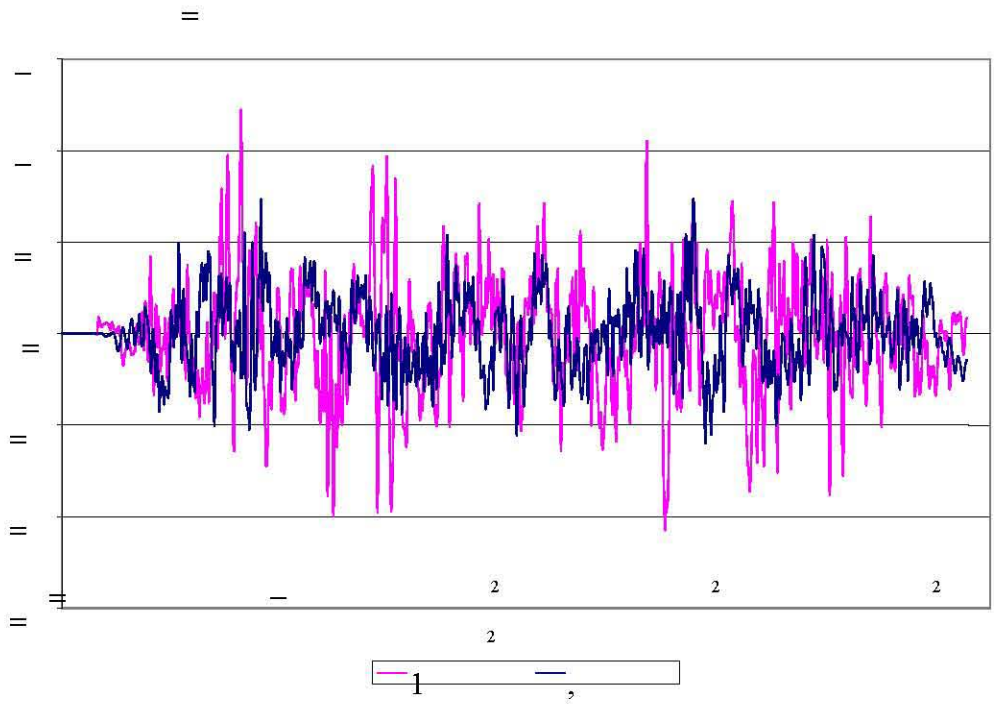


Figure 3-45. Horizontal and Vertical Base Acceleration Time History, −266 feet, Best Estimate Soil

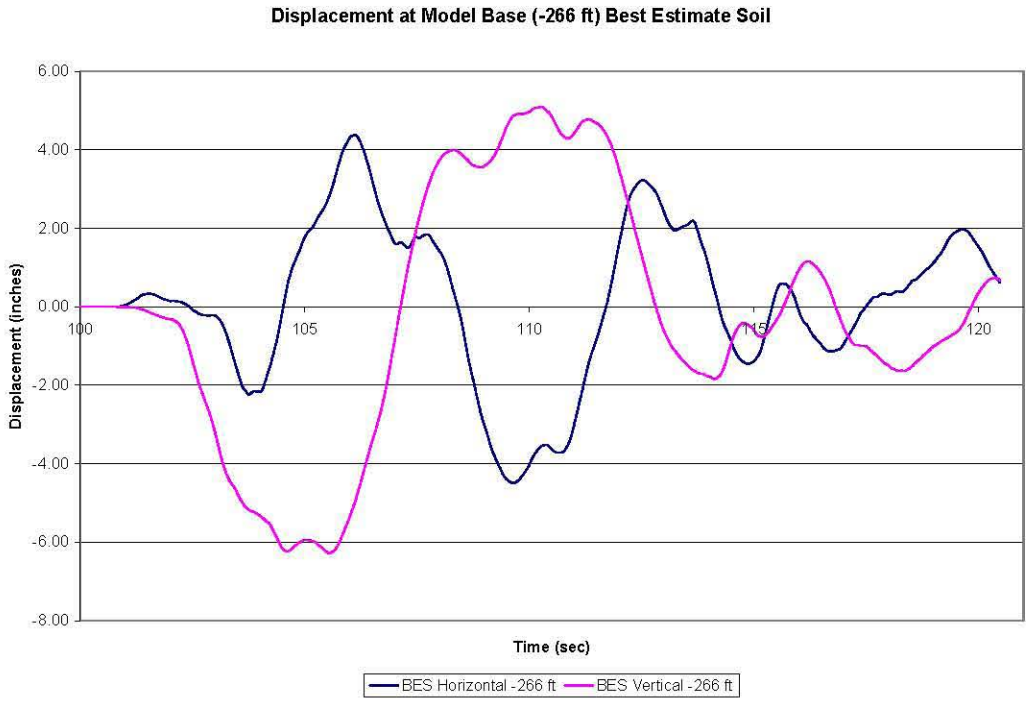


Figure 3-46. Horizontal and Vertical Base Displacement Time History, −266 feet, Best Estimate Soil

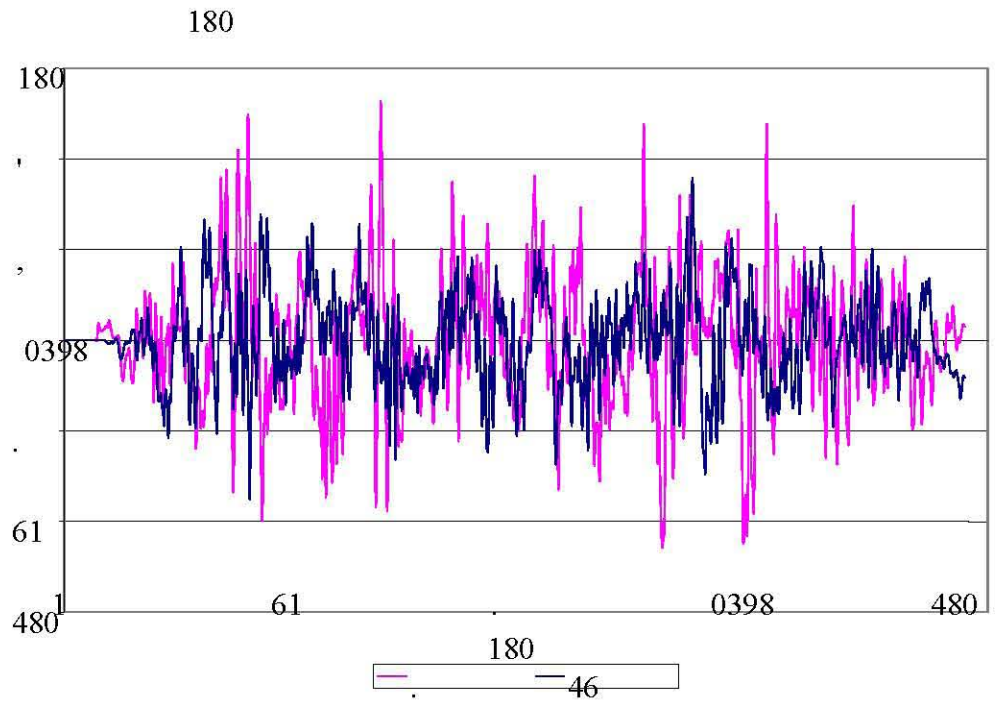


Figure 3-47. Horizontal and Vertical Base Acceleration Time History, −266 feet, Upper Bound Soil

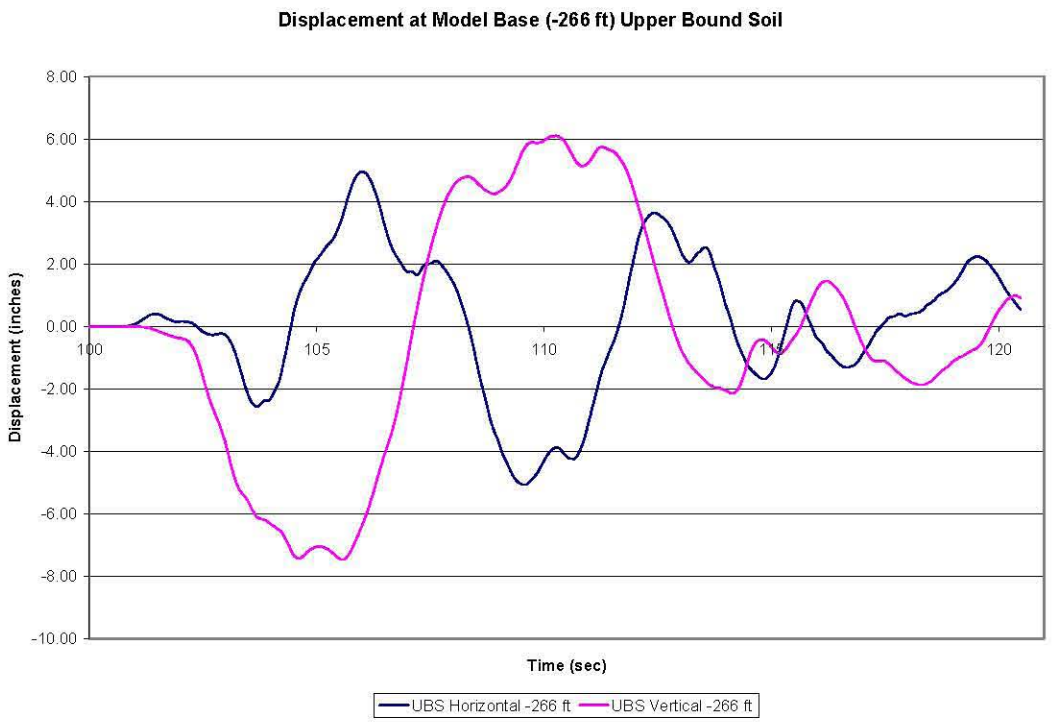


Figure 3-48. Horizontal and Vertical Base Displacement Time History, −266 feet, Upper Bound Soil

3.7 Model Excitation

An acceleration time history extracted from SHAKE at the −266-foot level is used for the excitation of the full model. A very large mass element is located at the bottom of the soil model (−266 feet), and a force is applied to that node. The force is the product of the point mass and the acceleration for that time step of the time history. The point mass used is greater than 100 times the mass of the full model to faithfully simulate the seismic excitation.

4.0 Model Reconciliation

The finite element models used in the TOLA and seismic analyses are significantly different. Reviewing the figure and model description in Chapters 2 and 3 readily demonstrates the dissimilarities (e.g., the TOLA model represents a 2.9° section of the tank and the seismic model represents a 180° section of the tank). The non-axisymmetric nature of the earthquake load requires the seismic model to encompass at least 180°. The acceleration time history used to represent the earthquake-comprised 2048 load steps to achieve the 20.48 seconds of the transient analysis. Minimizing the model size was important in achieving a reasonable solution run-time on the computer. Consequently, the element size is quite large in comparison to the TOLA model.

In contrast, the TOLA analysis has no inherent non-axisymmetric features. The 3-D model was made necessary only by the desire to use SOLID65 concrete element in ANSYS®. A refined mesh was implemented to obtain better resolution of stress throughout the model, particularly in the knuckle region.

The disparity between models required a mapping procedure in order to combine the TOLA and seismic results. This section summarizes the mapping for the different evaluations.

- Table 4-1 shows the element correlation for the ACI evaluation.
- Table 4-2 shows the element correlation for the ASME primary tank evaluation.
- Table 4-3 shows the element correlation for the ASME concrete-backed liner evaluation. As shown in Figure 3-12, the secondary liner in the seismic model extended only across the floor and up to the second element in the tank wall. Consequently, seismic strain in the wall and haunch was taken from the concrete shell elements representing the wall. Strain in the dome was taken from the steel liner.
- Table 4-4 shows the correlation for the J-bolts.

Table 4-1. Element Correlation for ACI Evaluation

Seismic Element #	R (in.)	Z (in. up)	TOLA Section #
7	22.5		
57	67.6998		2
77	105.5598		3
97	136.812		4
117	182.154		6
137	225.252		8
157	272.862		9
177	321.114		11
197	364.65		13
217	411.198		17
237	449.298		20
257	478.398	431.244	21
277	487.95	398.598	24
297	489	362.55	26
317	489	312	30
337	489	262.746	33
357	489	215.646	35
377	489	170.148	38
397	489	111.744	41
417	489	48.996	43
437	489	12	46
457	510		48
477	463.5		52
497	424.002		54
517	384		55
537	317.85		57
557	248.1		59
577	199.248		60
597	154.95		61
617	112.8		62
637	65.85		63

Table 4-2. Element Correlation for Primary Tank Evaluation

Seismic Element #		R (in.)	Z (in.)	TOLA Element #
762	dome	44.74	560.50	15276
782		89.87	558.32	15264
802		120.00	555.74	15303
822		151.97	552.26	15258
842		210.05	543.32	15247
862		237.53	537.87	15227
882		304.42	520.51	15211
902		333.05	511.15	15185
922	dome	390.22	487.86	15197
942	haunch	422.26	466.92	15180
962		432.00	460.00	15176
982		444.36	448.70	15172
1002	haunch	448.66	437.40	15168
1022	wall	450.00	426.13	15162
1042		450.00	402.13	15156
1062		450.00	378.13	15150
1082		450.00	354.13	15144
1102		450.00	329.88	15138
1122		450.00	306.78	15132
1142		450.00	283.68	15126
1162		450.00	260.58	15120
1182		450.00	237.38	15115
1202		450.00	214.28	15109
1222		450.00	191.18	15103
1242		450.00	168.08	15097
1262		450.00	144.88	15092
1282		450.00	123.28	15086
1302		450.00	101.68	15081
1322		450.00	80.08	15076
1342		450.00	58.48	15070
1362		450.00	37.00	15064
1382	wall	450.00	12.00	15061
1402	knuckle	446.49	3.51	15056
1422	knuckle	438.00	0.00	15050
1442	floor	423.00	0.00	15037
1462		400.00	0.00	15018
1482		340.00	0.00	15000
1502		280.00	0.00	14981
1522		220.00	0.00	14962
1542		160.00	0.00	14943
1562	floor	100.00	0.00	14927

Table 4-3. Element Correlation for Concrete-Backed Liner Evaluation

Seismic Element #		R (in.)	Z (in. up)	TOLA Element #
762	dome	68.02		15276
782		105.91		15264
802		136.01		15324
822		180.6		15303
842		224.26		15258
862		272.27		15247
882		318.015		15227
902		362.525		15211
922		405.475		15185
237		448.92		15804
257		471.63		15814
277		479.165		15798
297	wall	480	353.5	15912
317		480	302.5	15897
337		480	254.5	15877
357		480	206.5	15866
377		480	161.5	15851
397		480	107.5	15837
2062		480	41.5	15819
2052	wall	480	8.4125	15953
2042	knuckle	478.99	7.752	15785
2032	knuckle	472.555	1.752	15788
477	floor	448.5	0	15795
497		416.665		15654
517		378.355		15666
537		311.305		15687
557		244.255		15708
577		196.36		15723
597		151.66		15737
617		110.155		15750
637		65.4535		15764

Table 4-4. Element Correlation for J-Bolt Evaluation

Seismic J-Bolt	Seismic Radius	TOLA Radius	TOLA scale factor
Radius 4	120.0	107.5	4.465
Radius 5	152.0	167.6	2.864
Radius 6	210.1	208.5	2.302
Radius 7	237.5	243.3	1.973
Radius 8	304.4	300.5	1.597
Radius 9	333.1	325.2	1.476
Radius 10	390.2	391.7	1.225
Radius 11	422.3	413.4	1.161

5.0 Structural Acceptance Criteria

5.1 Introduction

This chapter describes the code-based acceptance criteria that are used to evaluate the AP tanks for the Increased Liquid Level Analysis. A complete description of the evaluation criteria is found in the Thermal and Operating Loads Analysis report (Rinker et al. 2004).

Day et al. (1995) provides a definitive summary of code-based structural acceptance criteria that govern the current and future uses of the Hanford double-shell tanks (DSTs). The document covers the primary objectives of any reevaluation of the existing waste storage tanks for continued operation or remediation, namely: 1) to show that the tank structures remain within code-based limits for the original design-based loads, 2) to evaluate if the actual service conditions or changes in requirements will exceed the design conditions, or 3) to evaluate current operating loads and future remediation activity loads.

The structural acceptance criteria document by Day et al. (1995) describes the tank designs, loads that must be sustained, potential failure modes, and the recommended approaches to protect against such failure. The application of code-based evaluation methods is discussed in detail. Alternate methods to the code-based approach are recommended to account for localized overstressing, load redistribution, and reduction in section capacities due to material degradation. Code reconciliation issues and material degradation under aging conditions also are addressed.

The purpose of this chapter is to identify a) the design and construction standards that were used for the double-shell tank designs, b) the allowable stresses for the steels and the minimum specified strengths of the concrete that were specified in the design, and c) the analysis methods that will be used to evaluate the structural adequacy of the AP tank design. Because Day et al. (1995) specifically identifies the recommended code-based methods for tank evaluation, they are not reproduced in this document.

5.2 Design and Construction Specifications for 241-AP Tanks

The 241-AP Tank Farm was constructed as part of Project B-340, 241-AP Tank Farm Project. For that project, the design and construction specifications list the standards that were used in the design and construction of the 241-AP tank farm. Specifications that are pertinent to the steel and concrete structure include:

- B-340-C4, Primary and Secondary Steel Tanks
- B-340-C3, Tank Foundations
- B-340-C5, Side Walls and Dome.

B-340-C4 documents that the 241-AP tanks were designed, fabricated, and inspected to the intent of the 1980 ASME Boiler and Pressure Vessel Code, Section VIII, Division 2. (Note: Although the ASME code standards were followed, the tanks were not registered as ASME vessels due to the non-standard nature of their design, use, and contents.) The steel plate used to construct the primary and secondary liners is specified as ASTM A537 Class 1. Abatt (1996) lists the ASME S_m allowables that were specified for the pressure vessel steels for each of the DST designs (see Table 5-1).

B-340-C3 and B-340-C5 document that the 241-AP tanks were constructed to the 1977 ACI 318 building code requirements for reinforced concrete (ACI 1977). In addition, structural concrete for the foundation was required to have a minimum allowable compressive strength of 4500 psi at 28 days. The concrete in the walls and dome was specified at 5,000 psi.

5.3 Applicable Codes

5.3.1 Design Codes of Record for the DSTs

Abatt (1996) identifies SDC 4.1, *Standard Arch-Civil Design Criteria - Design Loads for Facilities*, as the standard for the design of tanks at the Hanford Site. This standard has been in existence since the original document was published in April 1957, and it has been revised since then to comply with current DOE orders. More recently, SDC 4.1 was superseded by HNF-PRO-097, *Engineering Design and Evaluation (Natural Phenomena Hazard)* (HNF-PRO-097 2002). However, HNF-PRO-097 (2002) is a more general standard in use by the Project Hanford Management Contractor and a similar standard, TFC-ENG-STD-06, *Design Loads for Tank Farm Facilities* (Mackey 2004) is used by the Tank Farm Contractor.

5.3.2 Steel Design Codes of Record

Abatt (1996) summarized the codes of record that were used during the design of the various DST farms. The codes pertaining to the steel liner and tank components are listed in Table 5-1.

5.3.3 Concrete Design Codes of Record

Abatt (1996) also summarized the codes of record that pertain to the reinforced concrete structure of the tanks. These codes are listed in Table 5-2. This table shows that the 241-AY tanks were designed to the standards of the 1963 revision of ACI 318.

5.3.4 Contemporary Codes for Structural Evaluation of the DSTs

Day et al. (1995) lists the following DOE orders as applicable to the analysis and structural qualification of the existing DSTs for continued operation:

- DOE Order 6430.1A, *General Design Criteria* (DOE 1989)
- DOE Order 5480.28, *Natural Phenomena Hazard Mitigation* (DOE 1993)

Note that DOE Order 420.1, *Facility Safety*, Section 4.4, Natural Phenomena Hazard Mitigation (DOE 2000), superseded DOE Order 5480.28. In addition, DOE Order 6430.1A has been canceled.

Day et al. (1995) further states that the analysis and structural qualification of the existing DSTs for continued operation must be performed using the following codes and standards as guidance:

- BNL 52527, *Guidelines for Development of Structural Integrity, Programs for DOE High-Level Waste Storage Tanks* (Bandyopadhyay 1997)

Table 5-1. Summary of the S_m Allowables that were Specified for Each of the DST Designs (Abatt 1996)

Tank Farm 241-	Construction Years	Max. Temp, °F	Primary Tank Design Code	ASTM Plate Spec.	Minimum Specification	Temperature, °F					
						100	200	250	300	350	400
AY	1968–1970	350	ASME Section VIII, Div. 2 (1965)	A515	S_y (ksi) = 32	32	29.2	28.8	28.3	27.9	27.4
				Gr. 60	S_{ult} (ksi) = 60	60	60	60	60	60	60
					S_m (ksi)	20	19.5	19.2	18.9	18.6	18.3
AZ	1971 &1977	350	ASME Section III, (1968)	A515	S_y (ksi) = 32	32	29.2	28.8	28.3	27.9	27.4
				Gr. 60	S_{ult} (ksi) = 60	60	60	60	60	60	60
					S_m (ksi)	20	19.5	19.2	18.9	18.6	18.3
SY	1974–1976	250	ASME Section III, Div. 1 (1971 & 1973 addenda)	A516	S_y (ksi) = 35	35	31.9	31.5	31.0	30.5	30.0
				Gr. 65	S_{ult}(ksi) = 65	65	65	65	65	65	65
					S_m (ksi)	21.7	21.3	21.0	20.7	20.3	20.0
AW	1978–1980	350	ASME Section VIII, Div. 2 (1974 & summer 1975 addenda)	A537	S_y (ksi) = 50	50	44.1	42.3	40.5	39.0	37.5
				Class 1	S_{ult} (ksi) = 70	70	70	70	70	70	70
					S_m (ksi)	23.3	23.3	23.1	22.9	22.9	22.9
AN	1980–1981	350	ASME Section VIII, Div. 2 (1974 & 1976 addenda)	A537	S_y (ksi) = 50	50	44.1	42.3	40.5	39.0	37.5
				Class 1	S_{ult} (ksi) = 70	70	70	70	70	70	70
					S_m (ksi)	23.3	23.3	23.1	22.9	22.9	22.9
AP	1983–1986	210	ASME Section VIII, Div. 2 (1980 & winter 1981 addenda)	A537	S_y (ksi) = 50	50	44.1	42.3	40.5	39.0	37.5
				Class 1	S_{ult} (ksi) = 70	70	70	70	70	70	70
					S_m (ksi)	23.3	23.3	23.1	22.9	22.9	22.9

Table 5-2. Summary of Hanford Double-Shell Tank Structural Concrete Design Basis (Abatt 1996)

Tank Farm 241-	Const. Years	Design Code: Specified 28-day Compressive Strength (10^3 lbf/in.^{2}): Dome & Haunch	Wall	Basemat Foundation	Insulation Concrete[a]	Reinforcing Steel: Rebar (ASTM)	Cross-Ties (ASTM)	Welds
AY	1968–70	ACI 318 (1963)				A15-65 FDN Gr. 40 A432-66 Shell Gr .60	A432-66 Gr. 60	NA
		3 (Type III)	3 (Type II)	3	0.200			
AZ	1971 & 77	ACI 318 (1963)				A615-68 Gr .60	A615-72 Gr. 60	NA
		3	3	3 (Type V)	0.200			
SY	1974–76	ACI 318 (1971)				A615-72 Gr. 60	A615-72 Gr. 40	AWS D12.1
		4.5 (Type III)	4.5 (Type II)	3(4.5)[b] (Type V)	0.130			
AW	1978–80	ACI 318 (1971)				A615-76a Gr. 60	A615-76a Gr. 40	AWS D12.1 HPS-220-W
		5 (Type III)	5 (Type II)	4.5 (Type II)	0.130			
AN	1980–81	ACI 318 (1971)				A615-75 Gr. 60	A615-75 Gr. 40	AWS D12.1 HPS-220-W
		5 (4.5)[c] (Type III)	5 (4.5)[c] (Type II)	4.5 (Type II)	0.130			
AP	1983–86	ACI 349 (1976)				A615-81a Gr. 60	A615-81a Gr. 60	AWS D1.4
		5	5	4.5 (Type II)	0.130			

(a) The insulating concrete material is a cast-in-place lightweight refractory concrete material.
(b) From H-2-37704.
(c) From H-2-71907.
Type II = Low-alkali Portland cement – used where moderate exposure to sulfate attack is anticipated. Type II cement is in common use in western United States. Type II cement gains strength a little more slowly than general-purpose Type I cement, but ultimately attains strength of Type I cement.
Type III = High-early-strength cement – develops in 7 days the same strength that is achieved at 28 days for concrete made from Types I or II cement, but may not achieve the long-term strength of Types I or II.
Type V = Sulfate-resisting cement – strength characteristics are equivalent to Type II.
ACI = American Concrete Institute
ASTM = American Society of Testing and Materials
AWS = American Welding Society
FDN = Foundation (basemat)
HPS = Hanford Plant Standard
NA = Not applicable

- U.S. DOE Report UCRL 15910, *Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards* (UCRL 1990) (superseded by DOE-STD-1020-2002)
- ASCE Standard 4-86, *Seismic Analysis of Safety Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety Related Nuclear Structures* (ASCE 1986)
- Hanford Plant Standards, HPS-SDC-4.1, Rev. 12, *Standard Arch-Civil Design Criteria, Design Loads for Facilities* (SDC-4.1 1993) (superseded by TFC-ENG-STD-06)

- TFC-ENG-STD-06, *Design Loads for Tank Farm Facilities*, CH2M Hill Hanford Group, Inc. (Mackey 2004)
- BNL 52361, *Seismic Design and Evaluation Guidelines for the Department of Energy High Level Waste Tanks and Appurtenances* (Bandyopadhyay et al. 1995)

Specific guidance is given by Day et al. (1995) on the code analysis methods to be used in evaluating the major components of the tank, namely:

Primary Tank: The primary tank shall be evaluated against the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NC, Article NC-3200 (ASME 1992a). (Note: The design by analysis methods of Section III, Article XIII-1000, "Design Based on Stress Analysis," are equivalent to the analysis requirements of Section VIII, Division 2 (ASME 1992b). The primary difference between Section III [nuclear vessels and piping] and Section VIII [non-nuclear vessels and piping] involves the increased level of material qualification and fabrication inspection required by Section III.

Secondary Concrete Structure: The secondary concrete structure shall be evaluated against the requirements of ACI 349-90, Code Requirements for Nuclear Safety Related Concrete Structures (ACI 1992). While the AY tanks were designed to ACI-318, ACI-349 provides essentially the same technical design provisions. Mackey (2004a) notes that using ACI-349 as the evaluation criteria would not change the calculation results.

Secondary Tank Liner: The secondary tank liner shall be evaluated using the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division 2, Subsection CC (ASME 1992c). Those portions of the liner which are not backed by concrete shall be evaluated to the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division 2, Subsection NC (ASME 1992a). (Note: The evaluation methods of Section III, Division 2, Subsection CC are recommended because the steel-lined, reinforced concrete tanks are similar in construction to concrete nuclear containment vessels, which Subsection CC covers. Section VIII does not provide specific guidance on the evaluation of steel liners backed by concrete. Therefore, the analysis methodology recommended in Section III will be adopted [as recommended by Day et al. (1995)], even though the tanks were not strictly designed, constructed, and inspected to Section III standards.)

Insulating Concrete Pad: The insulating concrete pad shall be evaluated against the bearing stress requirements of ACI 349-90, *Code Requirements for Nuclear Safety Related Concrete Structures* (ACI 1992).

Primary Tank Dome and Secondary Liner Anchorage System: The anchorage systems for that portion of the tank steel which is backed by concrete shall meet the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division 2, Subsection CC (ASME 1992c).

Abatt (1996) presents a compilation of the ASME allowable stresses and the load factor combinations that were used in performing "design by analysis" evaluations of the DST primary tanks. Later sections of Day et al. (1995) give detailed guidance on how to apply these codes to analyze the tanks. Section 2 of Day et al. (1995) provides guidance on defining the tank loads (normal, abnormal, and extreme loads) for consideration in the analysis.

Potential failure modes are identified and discussed in detail in Section 3 of Day et al. (1995) for specific tank components as summarized here in Table 5-3.

Section 4 of Day et al. (1995) presents detailed discussion of the ASME code methods for evaluating the above failure modes in the primary tanks, secondary liner, and the anchor bolts (J-bolts). For J-bolts, Section 4 gives specific guidance on the appropriate liner anchor allowables to use in the code evaluation (see Tables 4.1.4-1, 4.1.4-2, and 4.1.4-3 in Day et al. 1995). Section 4 also presents a similarly detailed discussion of the ACI code methods for evaluating the reinforced concrete tank walls and dome. This includes examples of the load combinations and load scaling factors required by the code.

Section 5 of Day et al. (1995) gives guidance on what to consider in reconciling differences in the current versions of the ASME and ACI codes when reanalyzing the double-shell tanks. The "design by analysis" methods recommended by the ASME code have not changed in their application since the design of the 241-AY tanks. Therefore, the primary and secondary tank steels will be evaluated to the current methods using the S_m allowables and stress intensity classifications listed in Tables 5-1 and 5-4.

Table 5-3. Summary Table of the Local and Global Significance of Failure of the Various DST Components (Day et al. 1995)

Failure Mode	Steel Tank or Liner	Steel Reinforcement	Concrete	Soil
Buckling	L→L		G	
Collapse			G	
Fatigue	L→L	L→G	L→G	
Fracture	L→L			
Bond-Slip		L→G		
Plastic Failure	L→L	L→G	L→G	
Bearing Failure			L→L	L→L

L→L Local failure that could lead to leakage.
L→G Local failure that could lead to a global instability failure.
G Global instability failure.

Table 5-4. Stress Intensity Classification (Abatt 1996)

Vessel Component	Location	Origin of Stress	Type of Stress	Classification
Cylindrical or Spherical Shell	Shell plate remote from discontinuity	Internal pressure	General membrane gradient through plate thickness	P_m Q
		Axial thermal gradient	Membrane bending	Q Q
	Junction with head or flange	Internal pressure	Membrane bending	P_L Q
Any Shell or Head	Any section across entire vessel	External load or moment, or internal pressure	General membrane averaged across full section	P_m
		External load or moment	Bending across full section	P_m
	Near nozzle or other openings	External load or moment, or internal pressure	Local membrane bending	P_L Q
	Any location	Temperature difference between shell and head	Membrane bending	Q Q
Dished Head or Conical Head	Crown	Internal pressure	Membrane bending	P_m P_L
	Knuckle or injection to shell	Internal pressure	Membrane bending	P_L [(a)] Q

P_m = Primary membrane
P_L = Local membrane
Q = Secondary
(a) Consideration shall also be given to the possibility of wrinkling and excessive deformation in vessels with large diameter-to-thickness ratio.

6.0 Analysis Results

6.1 ACI Structural Concrete Evaluation

The Structural Acceptance Criteria document, WHC-SD-WM-DGS-003 (Day et al. 1995), specifies that the reinforced concrete structure of the tanks shall be evaluated to the standards of ACI 349-90, Section 9.2. The requirements of the IBC are satisfied by virtue of meeting the standards of ACI-349. Chapter 19 of the IBC states that structural concrete shall be designed in accordance with the requirements of ACI-318. The commentary on ACI-349 describes the additional conservatisms for nuclear structures that exceed those in ACI-318. Accordingly, a structure that is shown to conform to ACI-349 satisfies the IBC.

The load factors to be applied in the double-shell tank (DST) analyses are a subset of the possible combinations specified in ACI 349-90, that subset being defined by and, further, reduced by the definition of the current work scope. Chapter 7 of the TOLA report (Rinker et al. 2004) indicates that load combinations 1, 4, and 9 are relevant for this study. The seismic loads are considered in load combination 4.

As noted previously, the seismic model contains larger elements than the TOLA model. Accordingly, the ACI evaluation of combined TOLA + seismic loads was conducted at 30 locations in the secondary concrete tank rather than the 63 locations recorded in the TOLA report. Figures 6-1 through 6-3 show the locations of these 30 sections.

The peak loads and moments from the seismic analysis were combined with the loads and moments from each load step of the thermal cycle in such a way as to maximize the demand/capacity ratio. In other words, the direction of the seismic loads and moments was ignored and the results were summed so as to give the worst possible combination of force and moments for that section. The peak seismic loads and moments were extracted from the seismic time history results without regard to location in the tank or time during the seismic event. This simplified the combination of seismic and TOLA demands while maintaining a conservative evaluation.

The capacity of each section was determined according to the reinforcing steel and concrete geometry and properties specified on the 241-AP tank drawings. In other words, the section capacities were increased from the TOLA analysis (Rinker et al. 2004), which was based on the 241-AY Tank Farm design. The 241-AP tanks have more and larger rebar (in some locations), higher strength rebar (foundation), higher concrete nominal strength, and the lower operating temperatures also results in higher concrete strength.

The 3-D seismic analysis generates non-axisymmetric response that requires evaluation of the in-plane shear forces in addition to the cross-section shear forces. The method of ACI 349-90, Section 11.10 was applied to the in-plane shear force.

The concrete in the TOLA analyses is allowed to crack; therefore, there are no distinct Fully Cracked Concrete (FCC) TOLA results. Accordingly, results are presented for the three ACI load combinations for the Best Estimate Soil – Best Estimate Concrete (BES-BEC), Lower Bound Soil (LBS)-BEC, and Upper Bound Soil (UBS) – BEC soil – concrete cases. Only load combination 4 results are presented for the BES-FCC case.

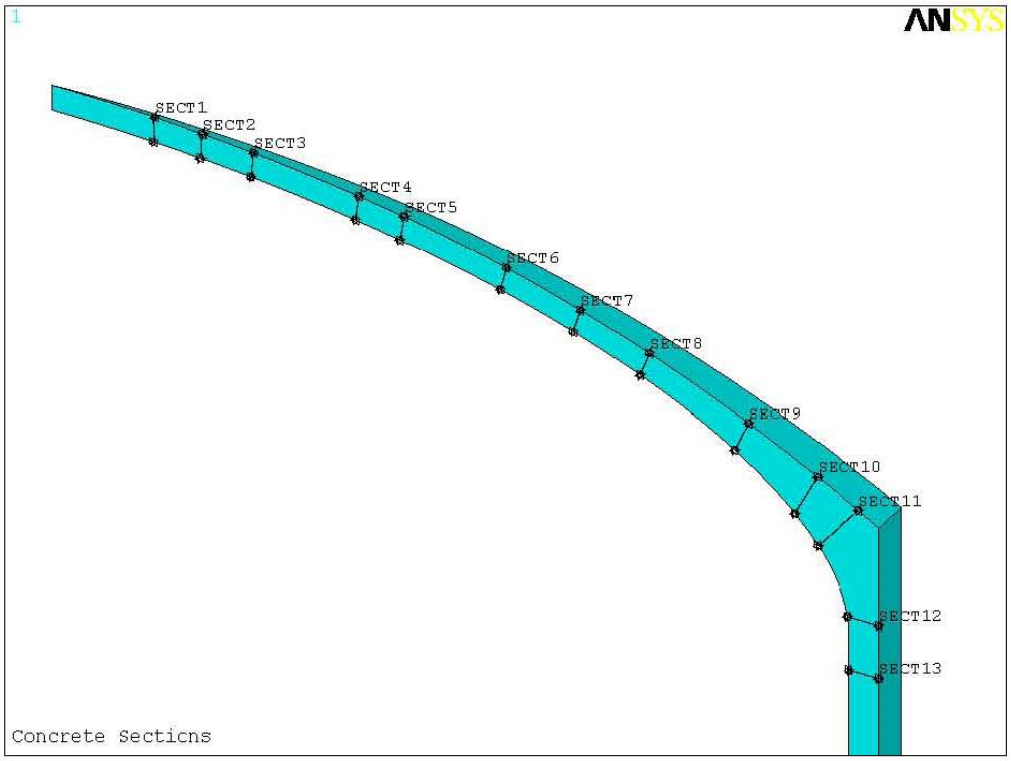


Figure 6-1. Reinforced Concrete Sections – Dome and Haunch Area

6.1.1 Best Estimate Soil – Best Estimate Concrete

Figure 6-4 shows the demand/capacity ratios for load combination 1 of the Best Estimate Soil – Best Estimate Concrete (BES-BEC) material combination. Load combination 4 is shown in Figures 6-5 through 6-8. Load combination 9 is shown in Figures 6-9 through 6-11. The demand/capacity ratios are all less than 1.0 in the meridional, circumferential, and shear directions.

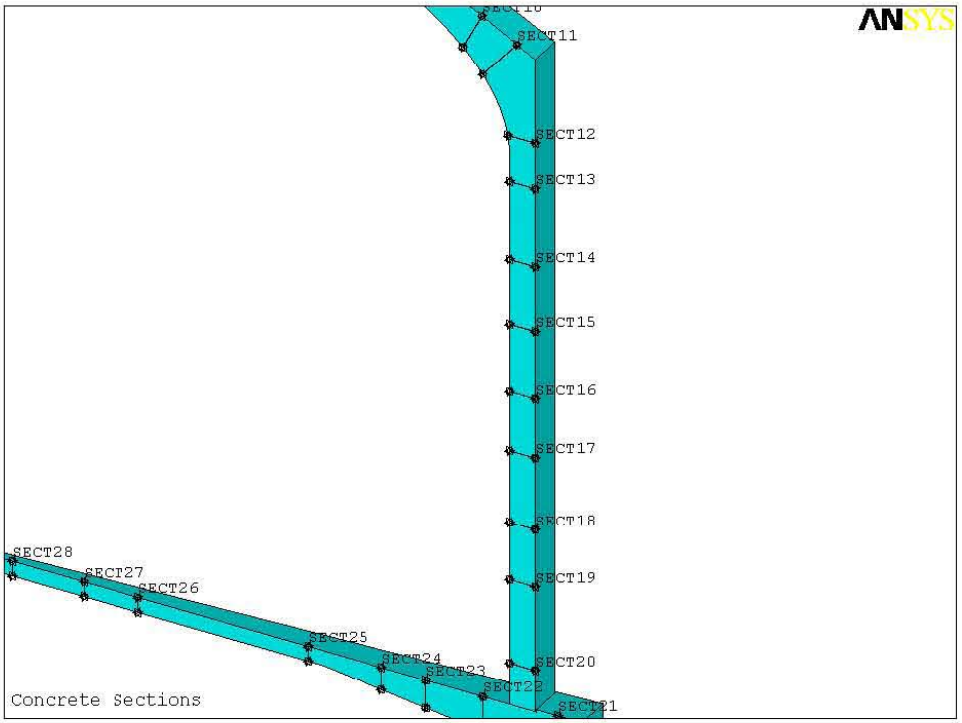


Figure 6-2. Reinforced Concrete Sections – Wall

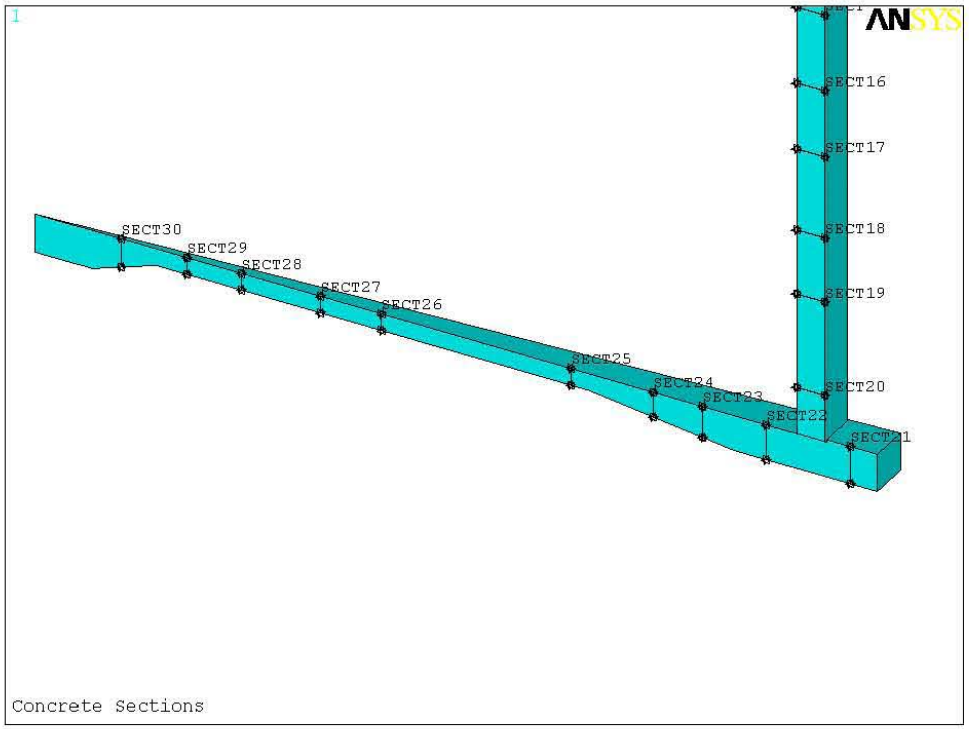


Figure 6-3. Reinforced Concrete Sections – Slab

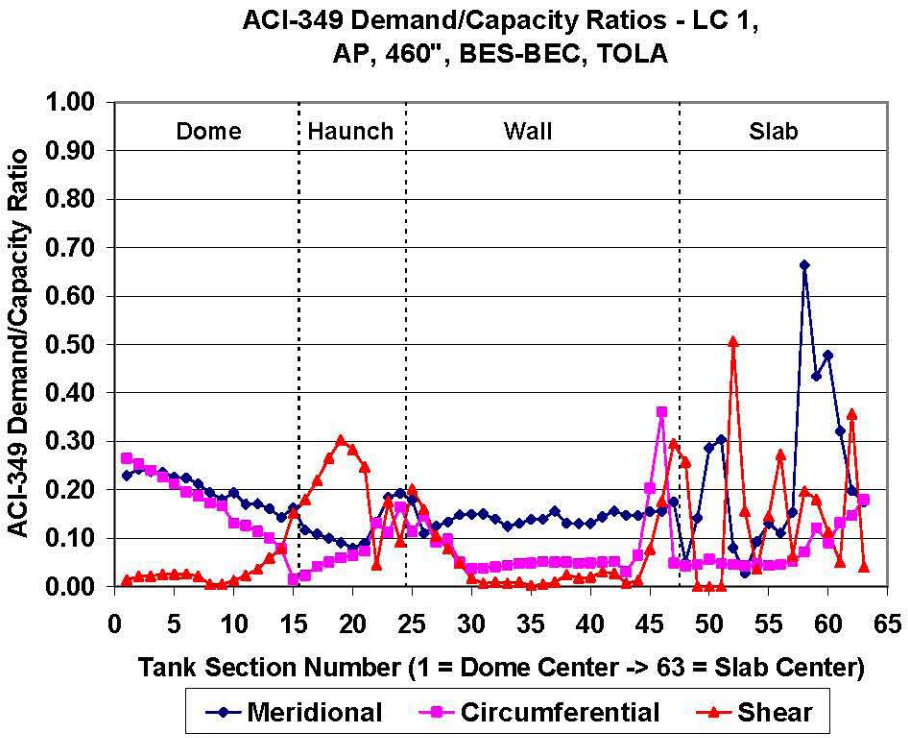


Figure 6-4. BES – BEC, Load Combination 1

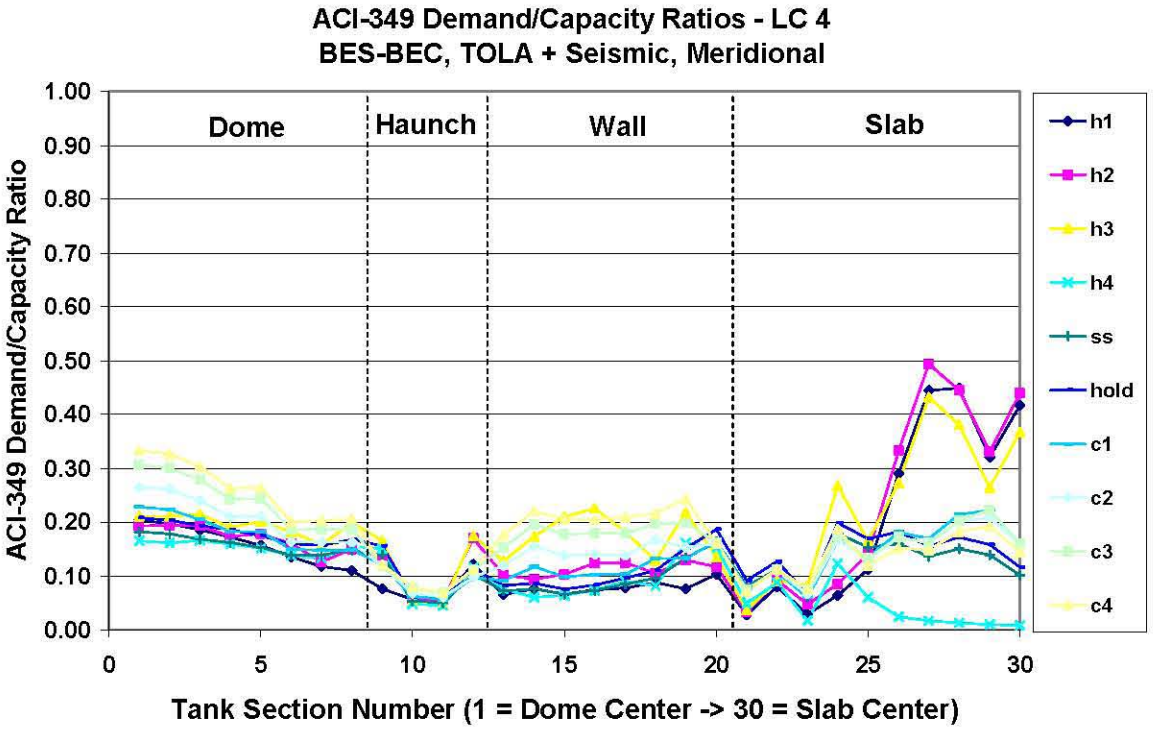


Figure 6-5. BES – BEC, Load Combination 4, Meridional

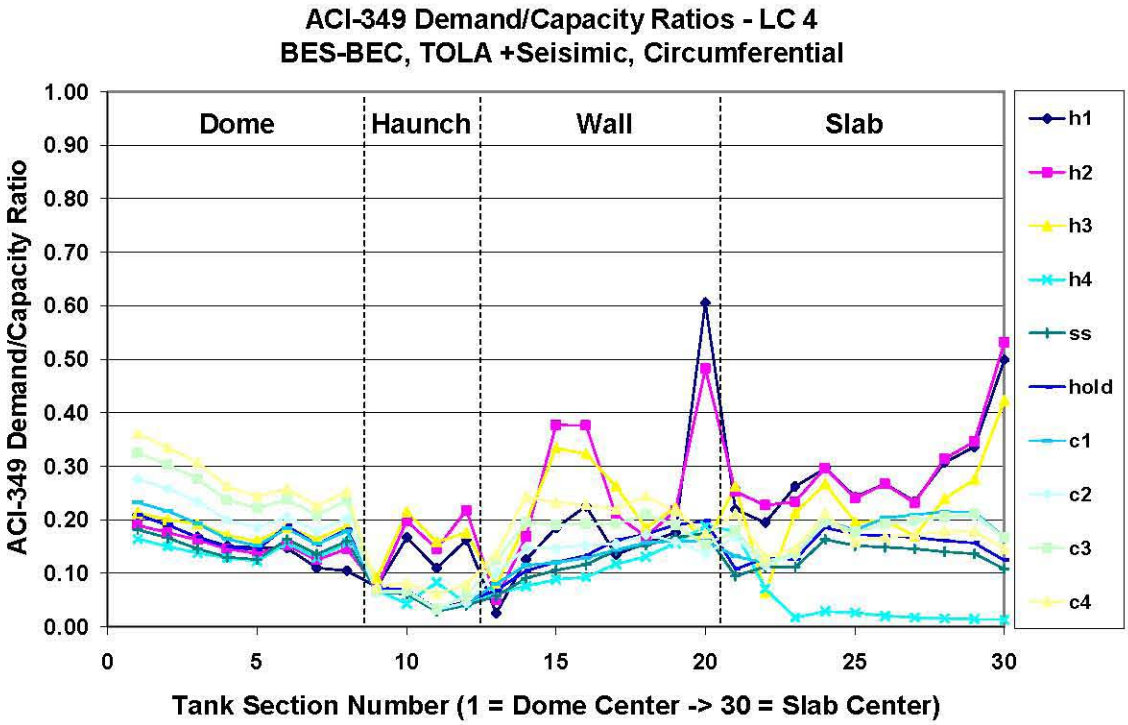


Figure 6-6. BES – BEC, Load Combination 4, Circumferential

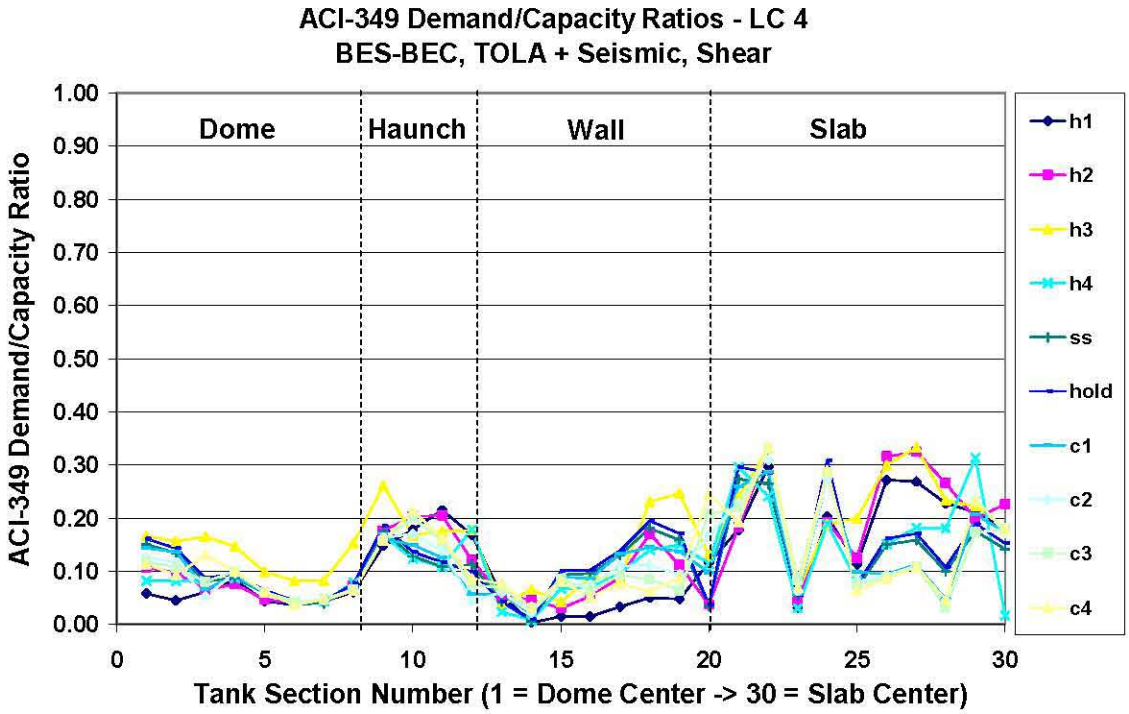


Figure 6-7. BES – BEC, Load Combination 4, Shear

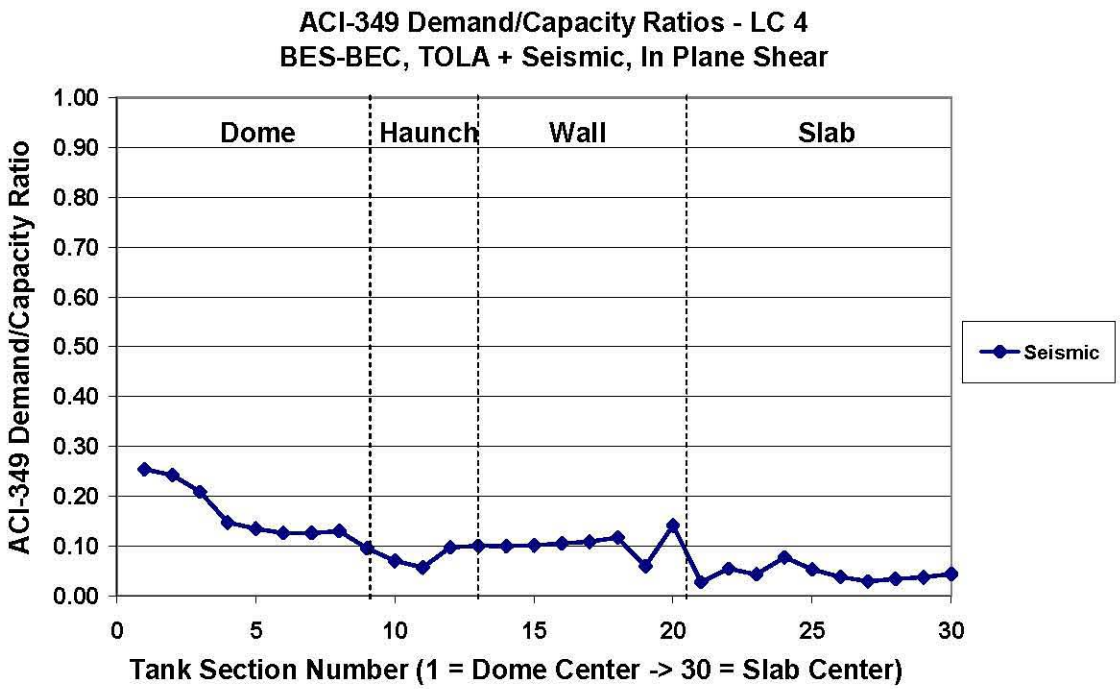


Figure 6-8. BES – BEC, Load Combination 4, In-Plane Shear

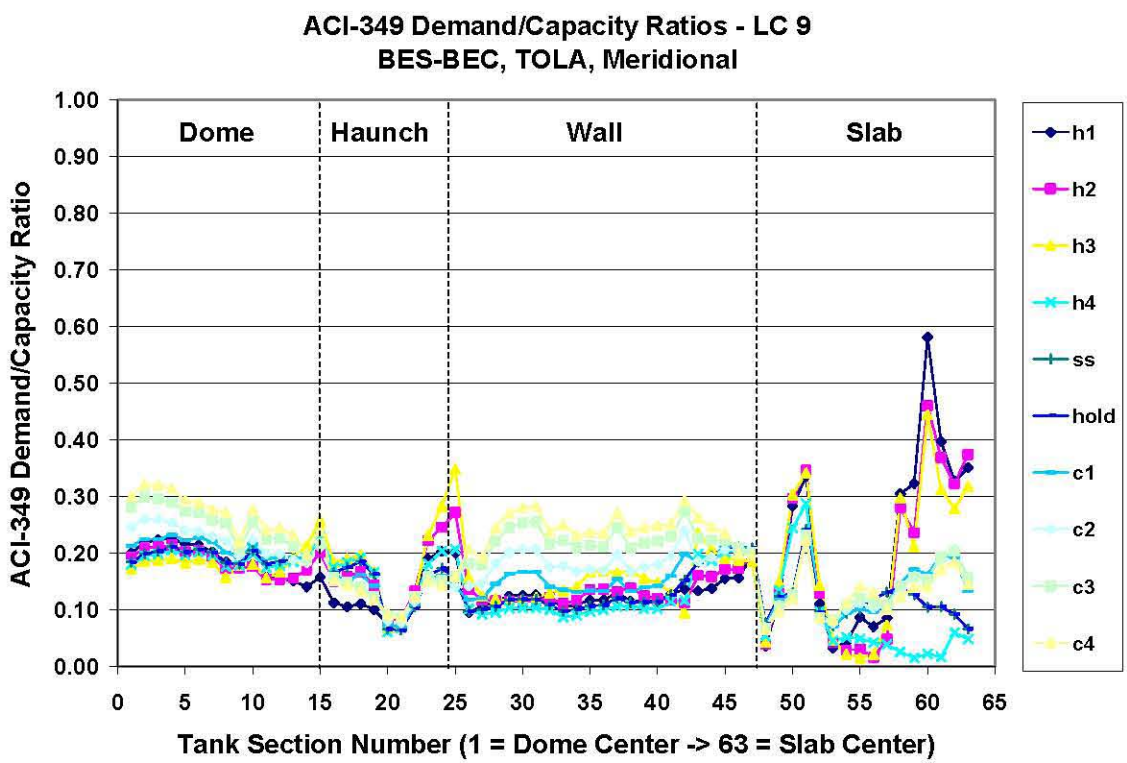


Figure 6-9. BES – BEC, Load Combination 9, Meridional

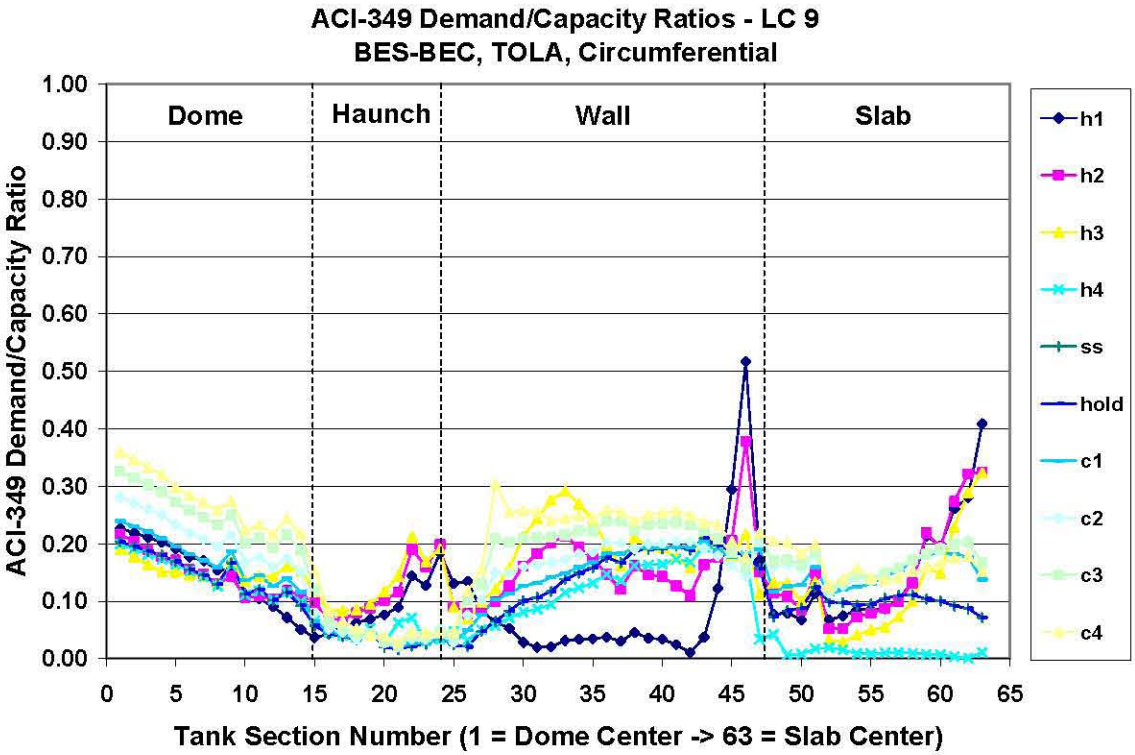


Figure 6-10. BES – BEC, Load Combination 9, Circumferential

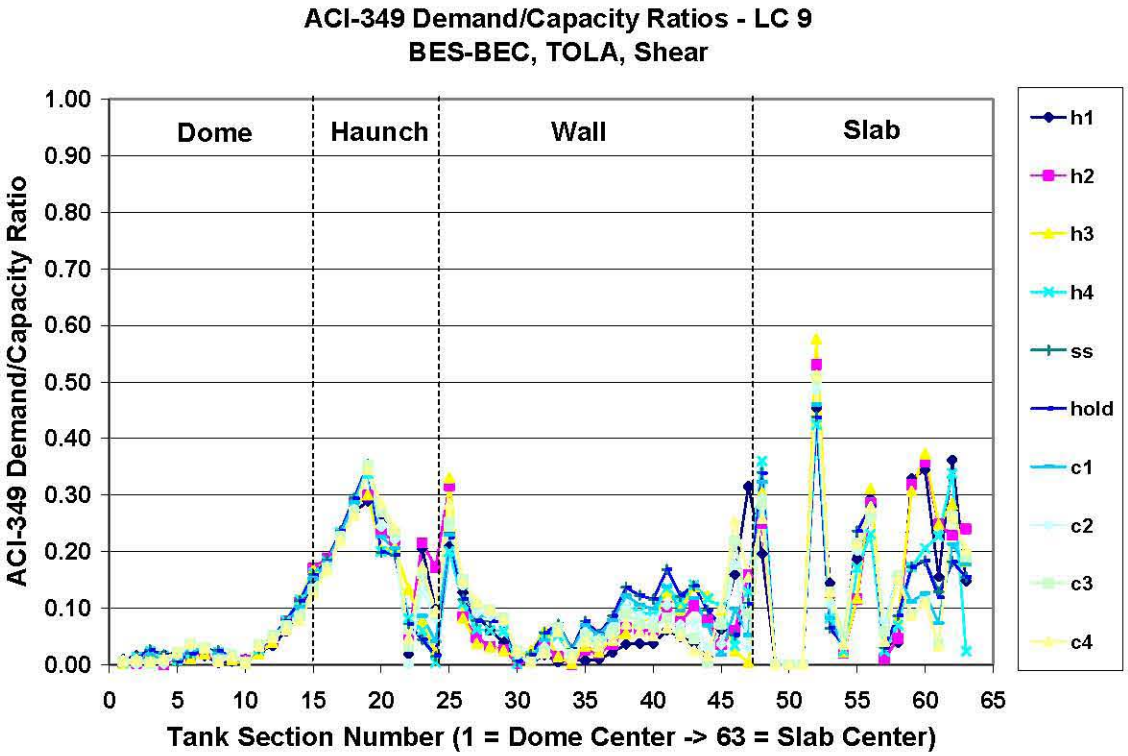


Figure 6-11. BES – BEC, Load Combination 9, Shear

6.1.2 Upper Bound Soil – Best Estimate Concrete

Figures 6-12 through 6-19 show the demand/capacity ratios for load combinations 1, 4, and 9 of the Upper Bound Soil – Best Estimate Concrete (UBS-BEC) material combination. The demand/capacity ratios are all less than 1.0 in all directions.

6.1.3 Lower Bound Soil – Best Estimate Concrete

Figures 6-20 through 6-27 show the demand/capacity ratios for load combinations 1, 4, and 9 of the Lower Bound Soil – Best Estimate Concrete (LBS-BEC) material combination. The demand/capacity ratios are all less than 1.0 in all directions.

6.1.4 Best Estimate Soil – Fully Cracked Concrete

Figures 6-28 through 6-31 show the demand/capacity ratios for load combination 4 of the Best Estimate Soil – Fully Cracked Concrete (BES-FCC) material combination. The demand/capacity ratios are all less than 1.0 in all directions.

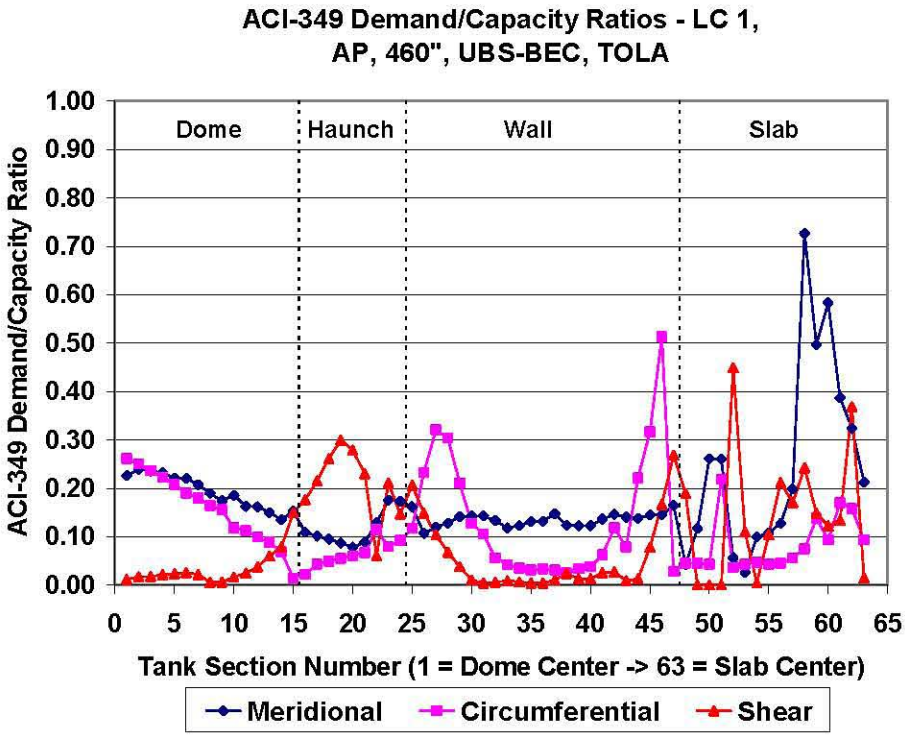


Figure 6-12. UBS – BEC, Load Combination 1

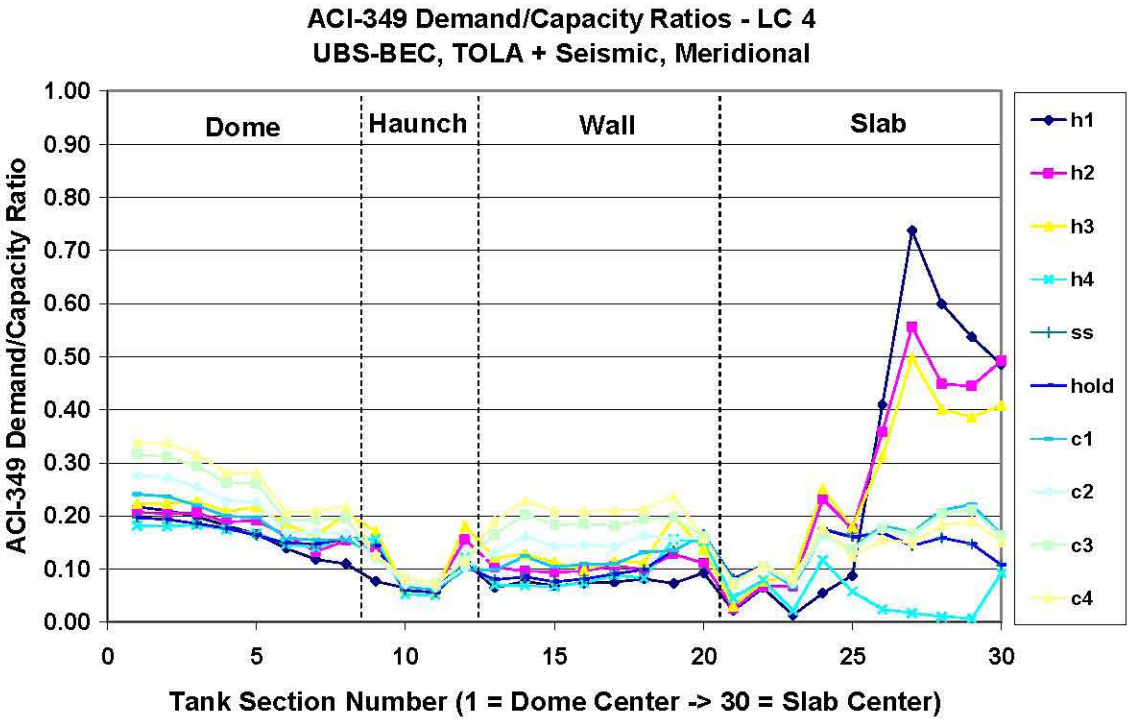


Figure 6-13. UBS – BEC, Load Combination 4, Meridional

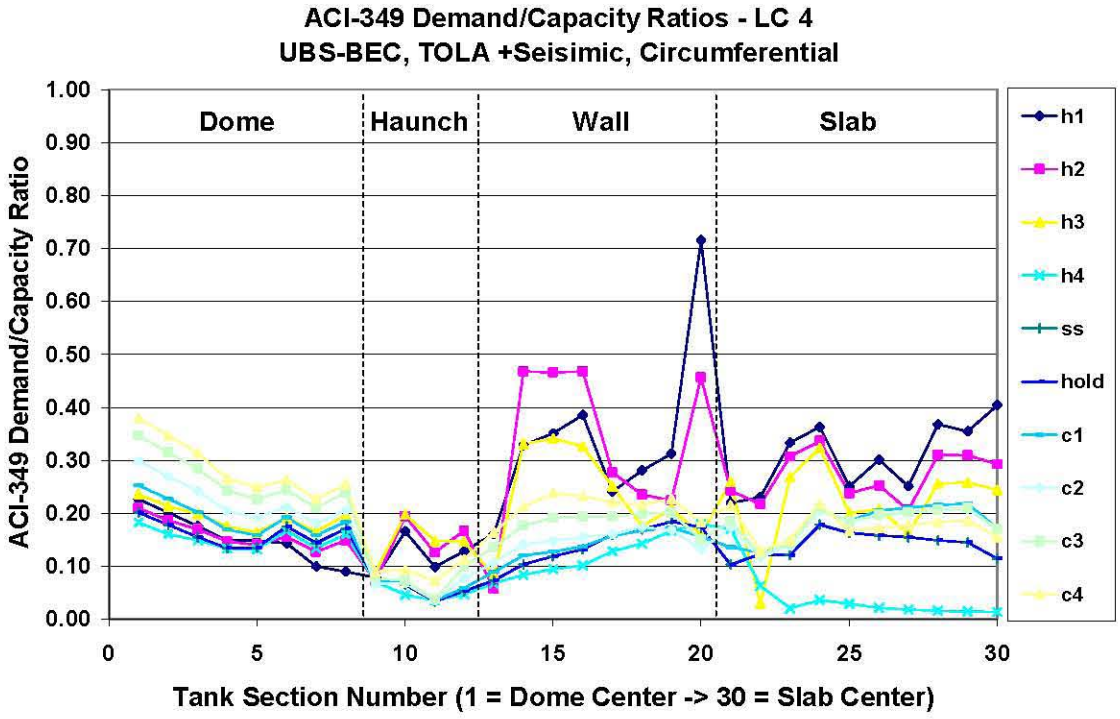


Figure 6-14. UBS – BEC, Load Combination 4, Circumferential

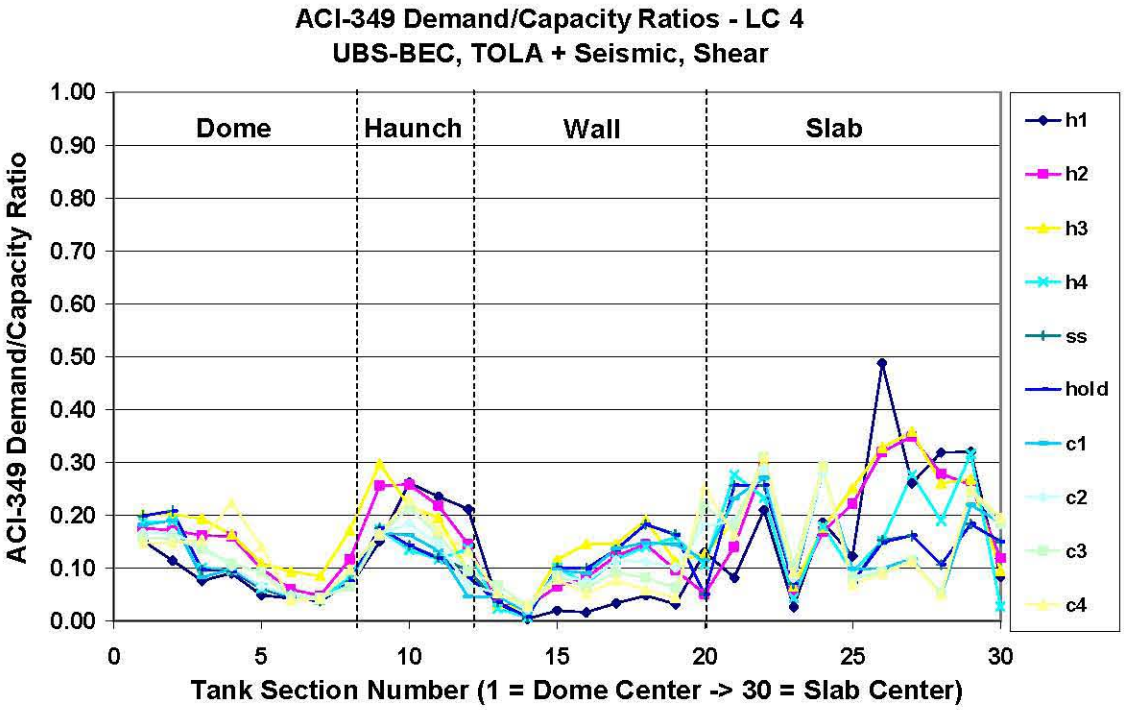


Figure 6-15. UBS – BEC, Load Combination 4, Shear

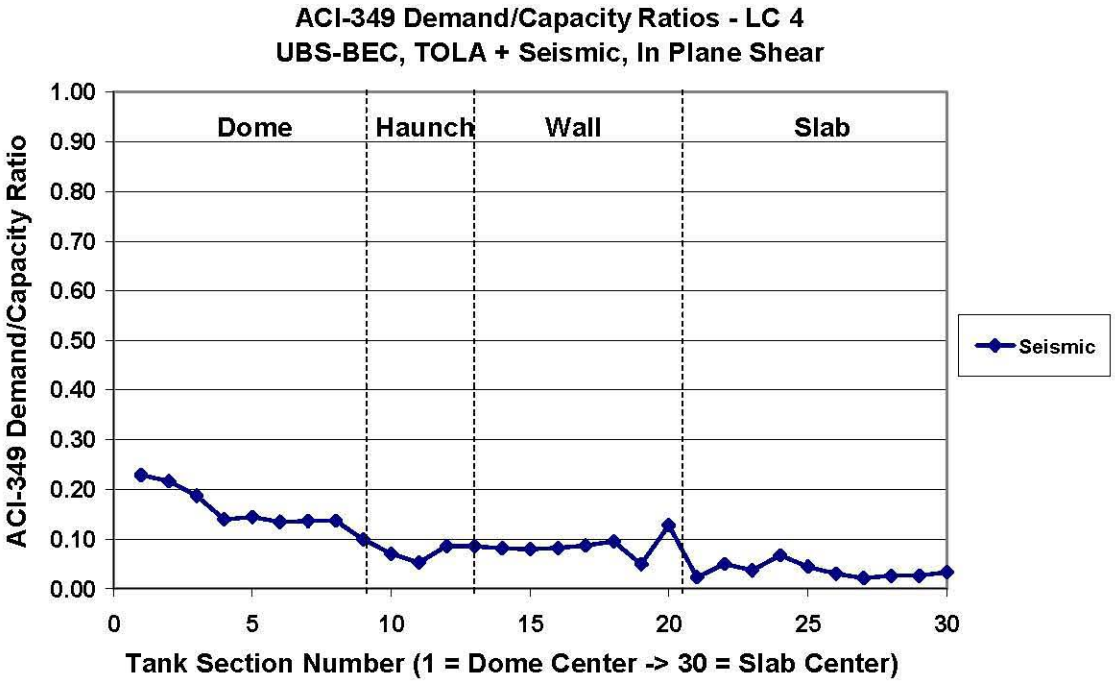


Figure 6-16. UBS – BEC, Load Combination 4, In-Plane Shear

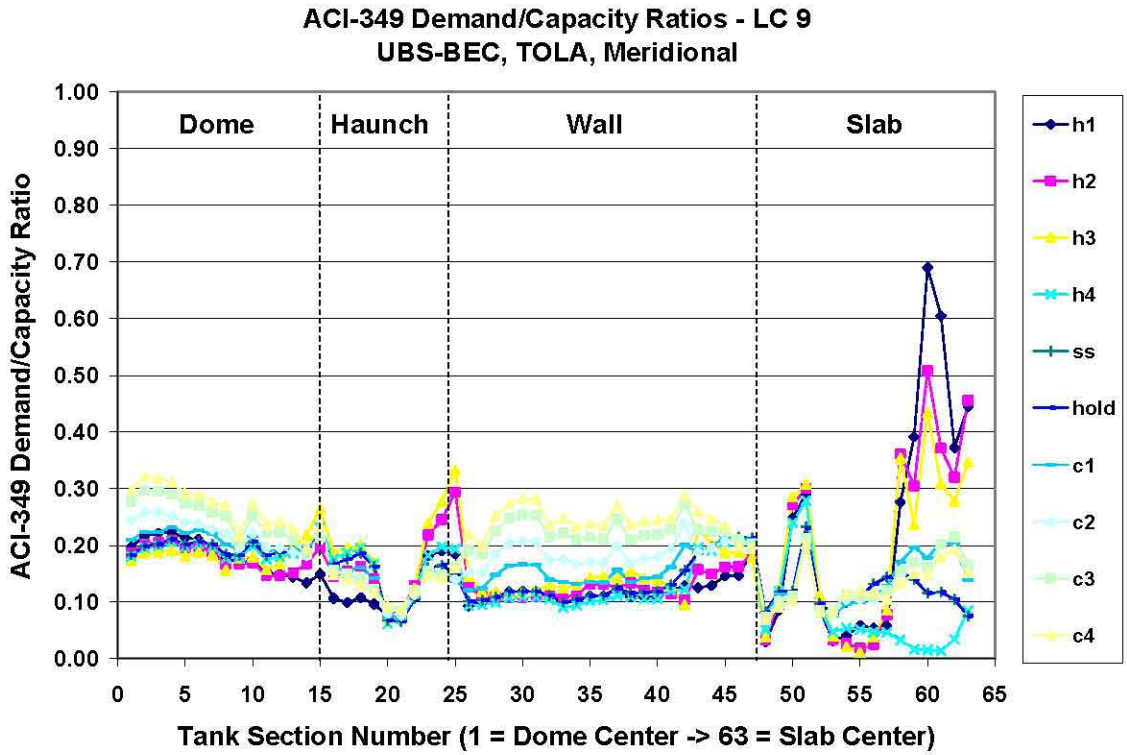


Figure 6-17. UBS – BEC, Load Combination 9', Meridional

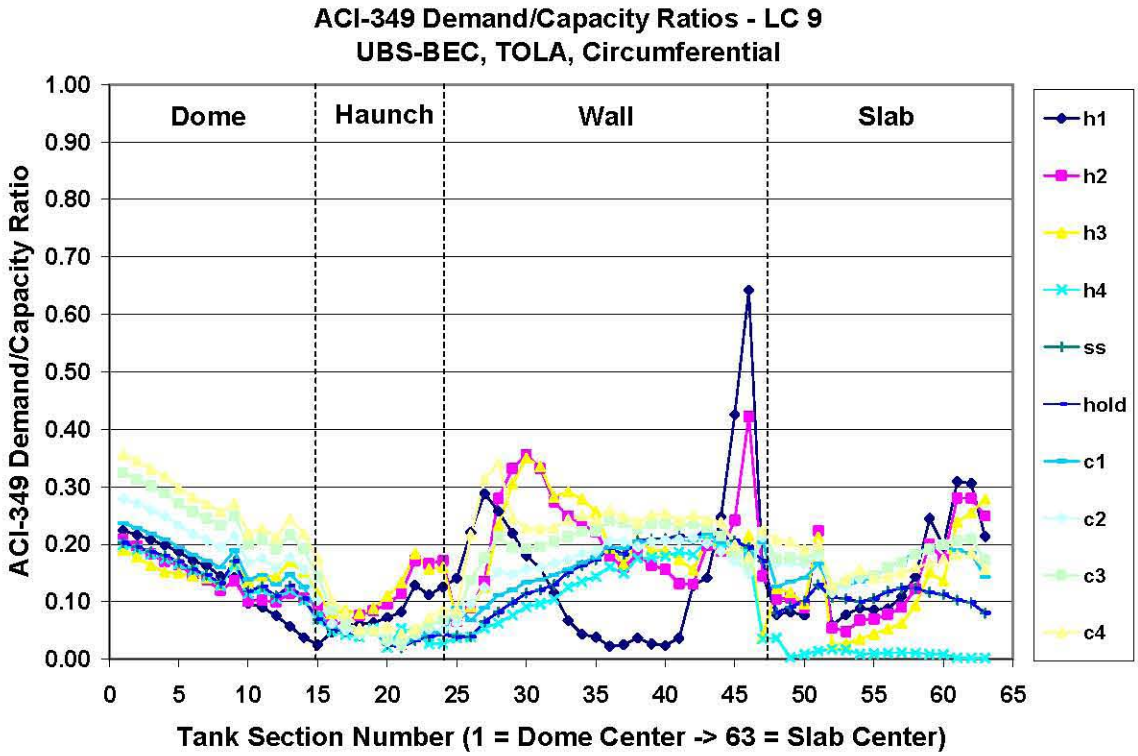


Figure 6-18. UBS – BEC, Load Combination 9', Circumferential

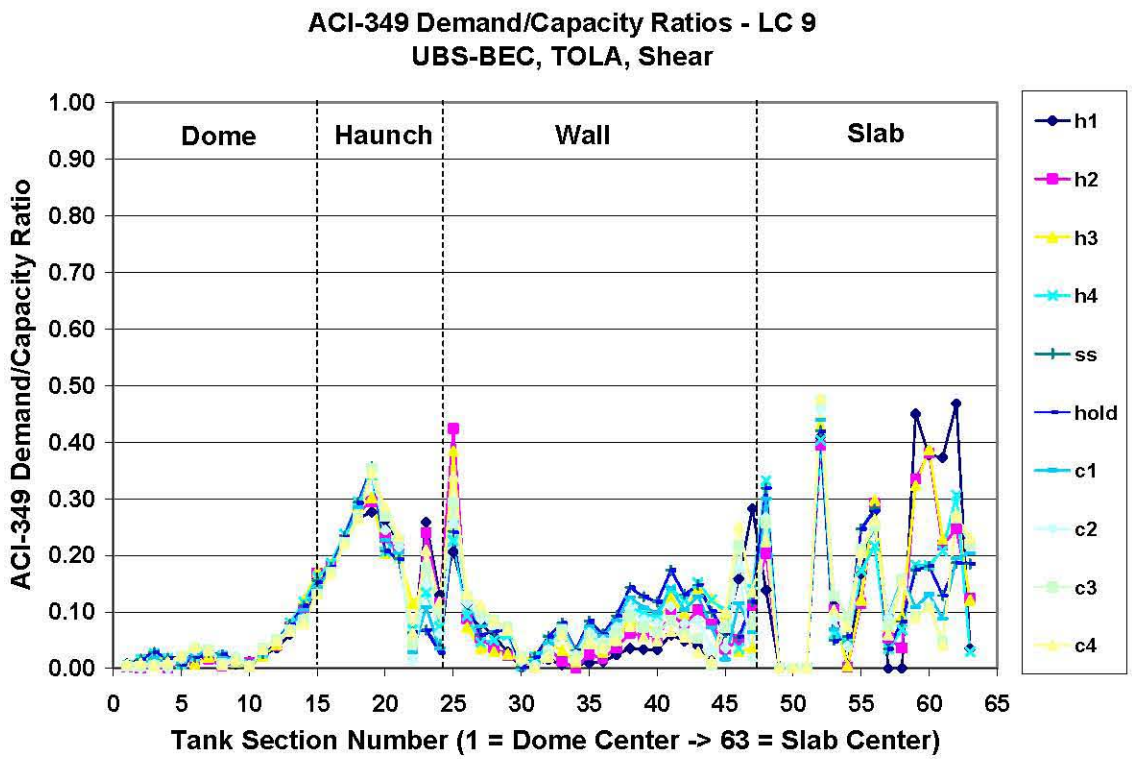


Figure 6-19. UBS – BEC, Load Combination 9', Shear

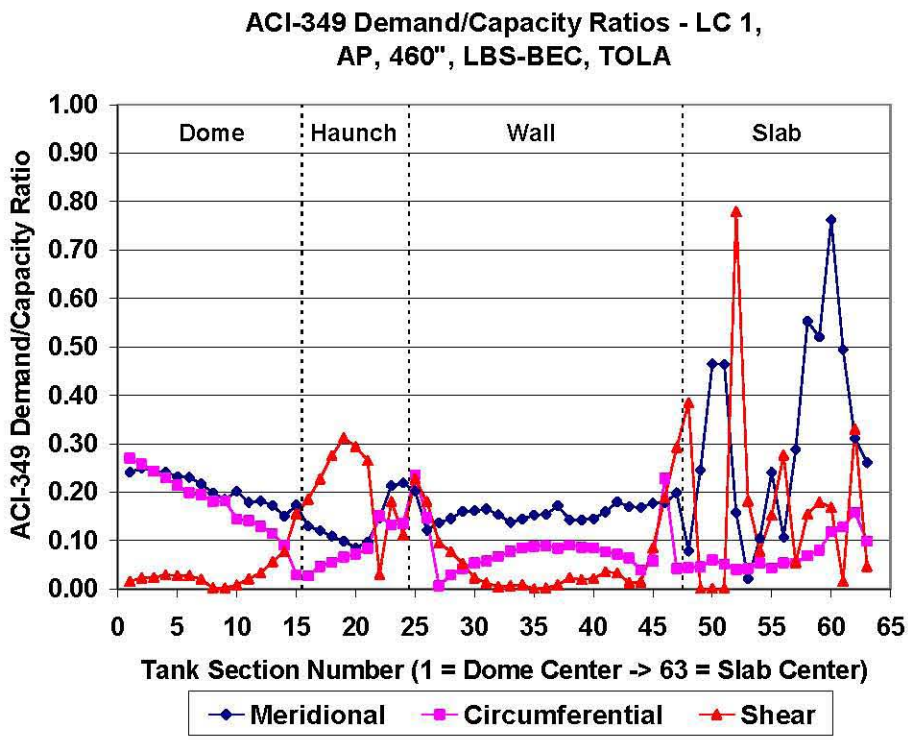


Figure 6-20. LBS – BEC, Load Combination 1

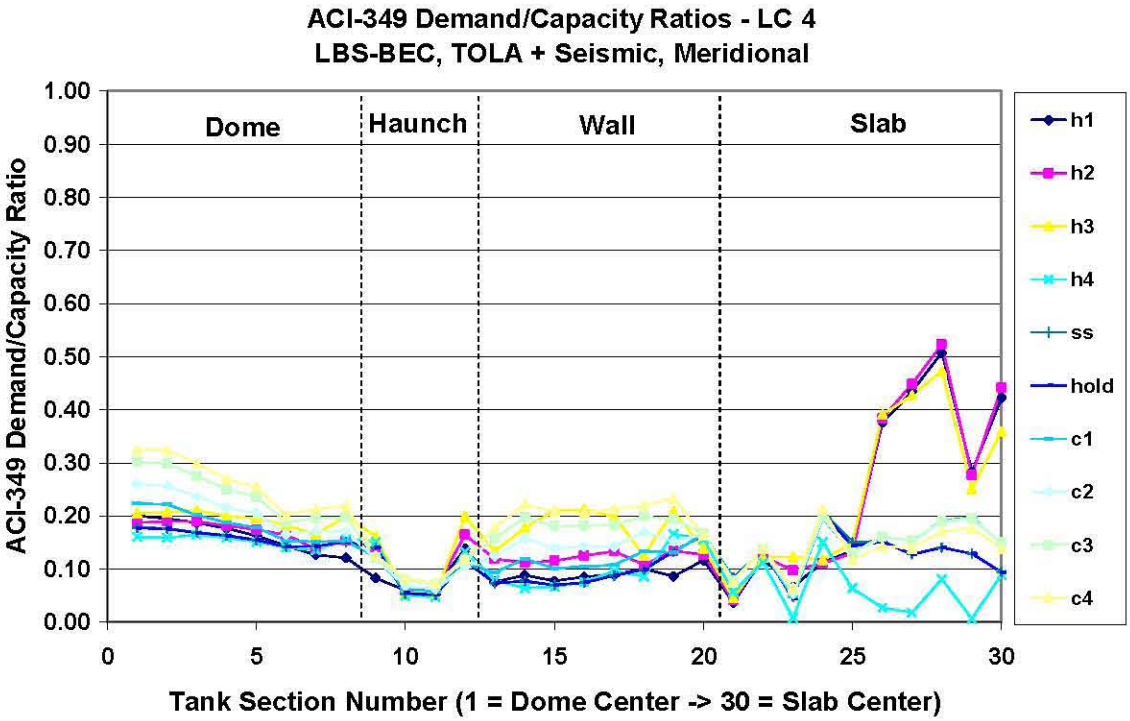


Figure 6-21. LBS – BEC, Load Combination 4, Meridional

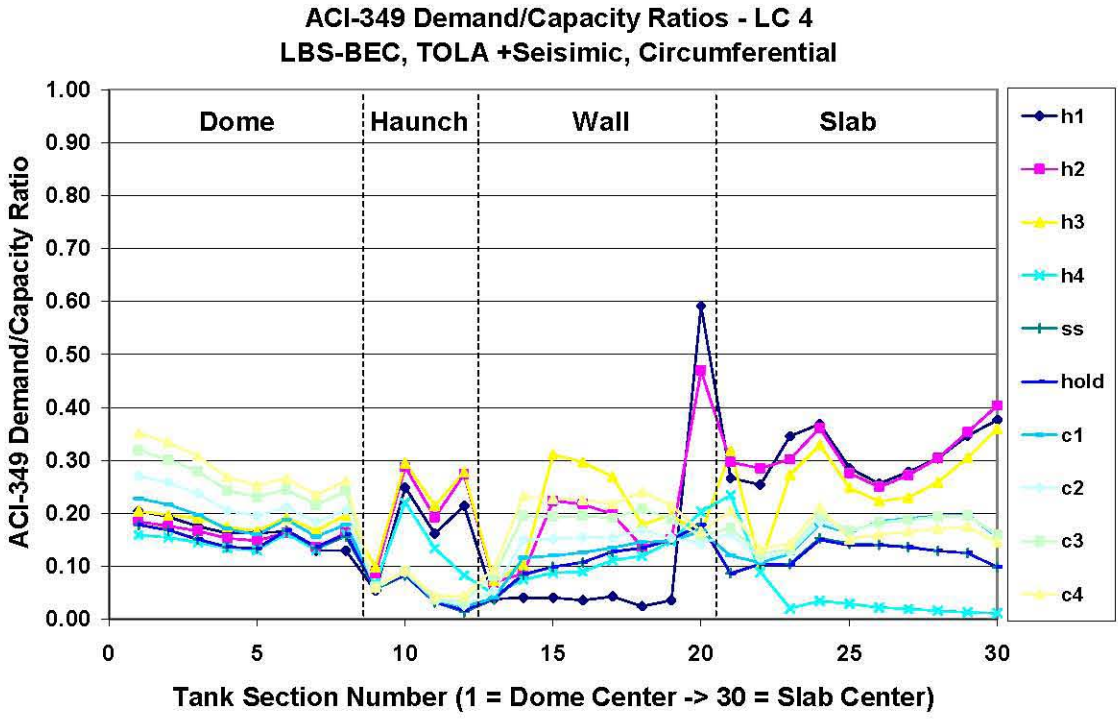


Figure 6-22. LBS – BEC, Load Combination 4, Circumferential

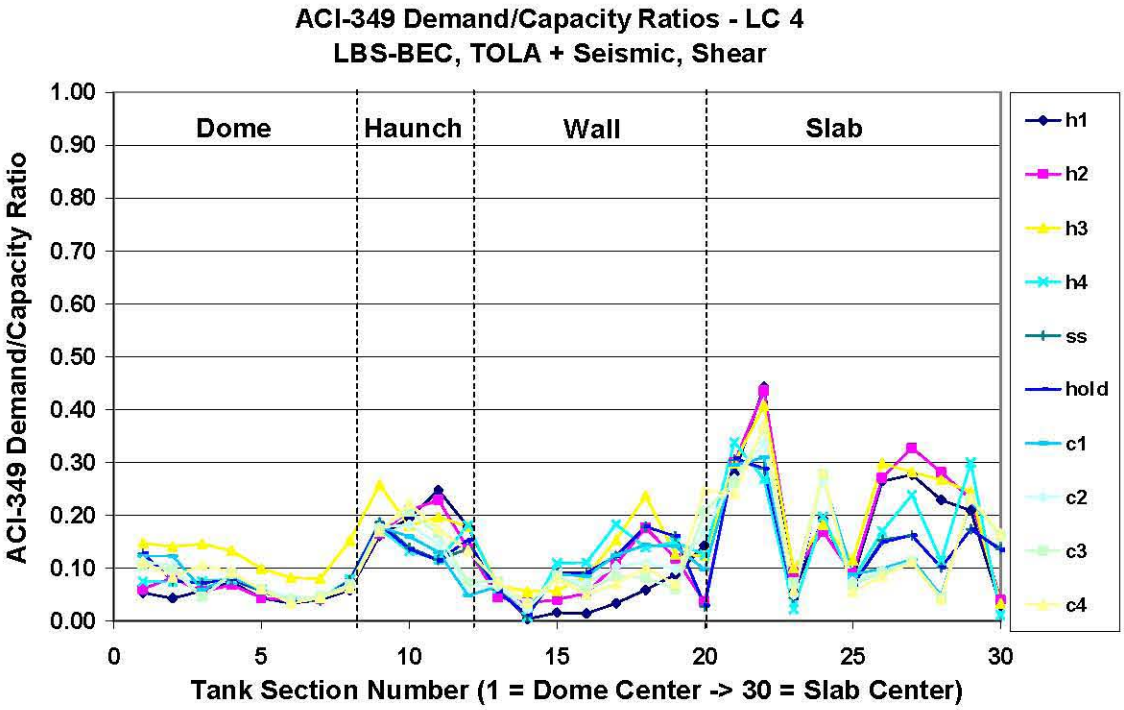


Figure 6-23. LBS – BEC, Load Combination 4, Shear

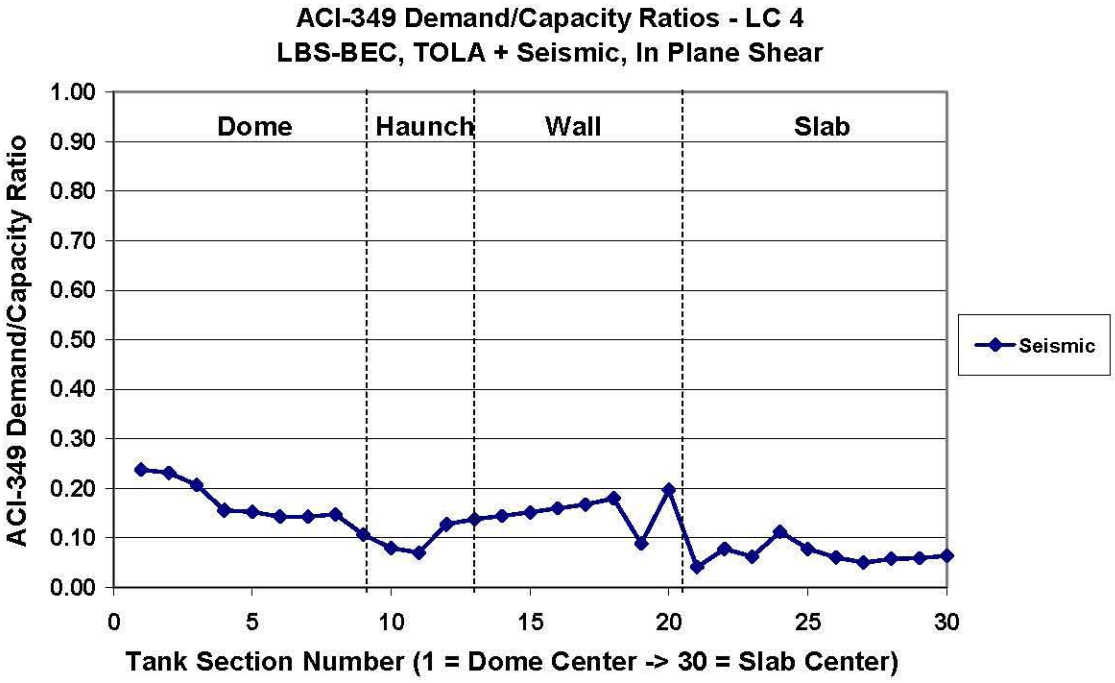


Figure 6-24. LBS – BEC, Load Combination 4, In-Plane Shear

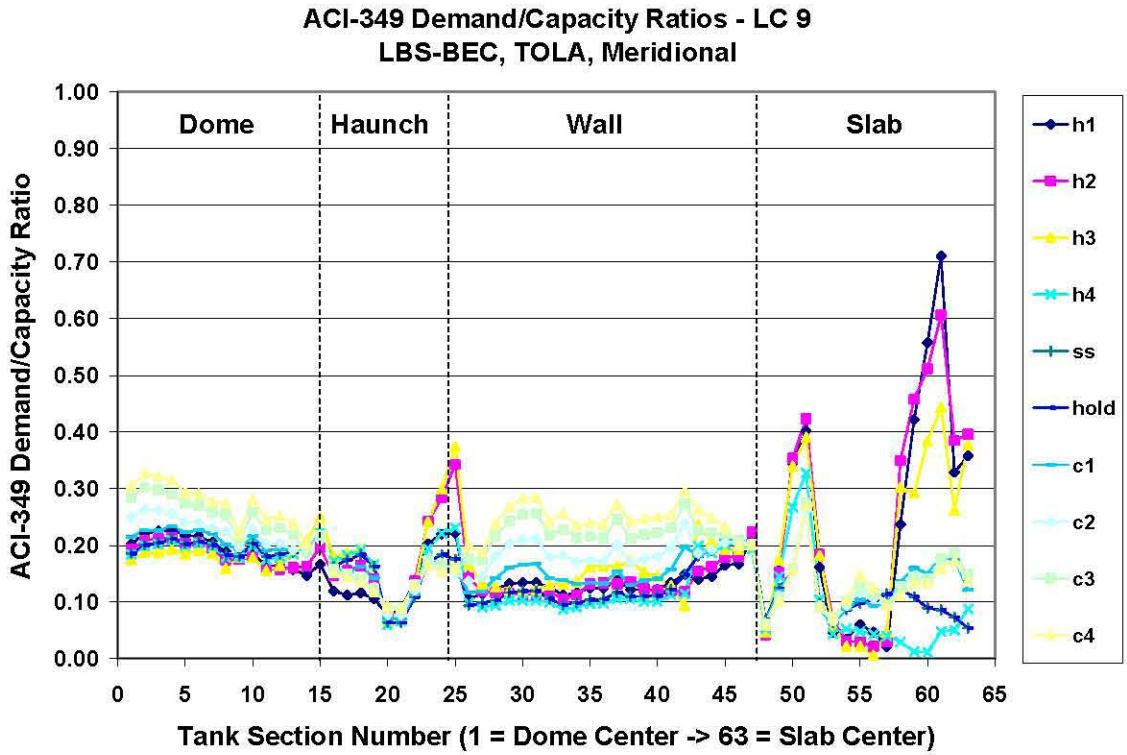


Figure 6-25. LBS – BEC, Load Combination 9', Meridional

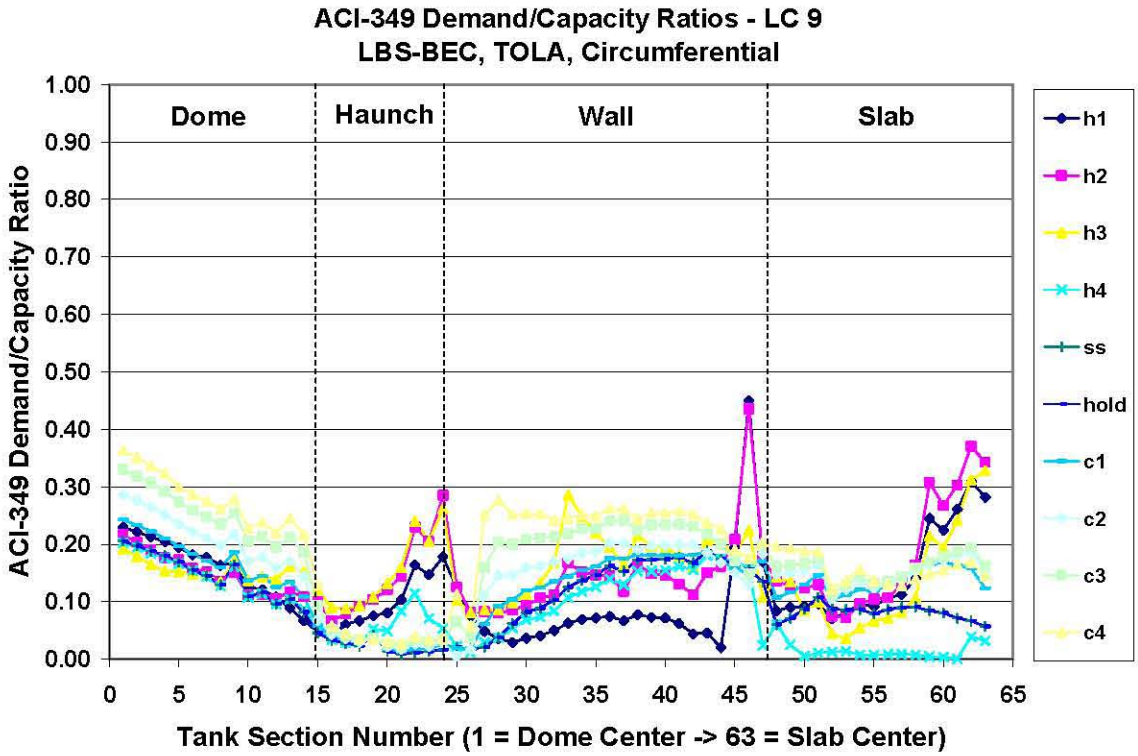


Figure 6-26. LBS – BEC, Load Combination 9', Circumferential

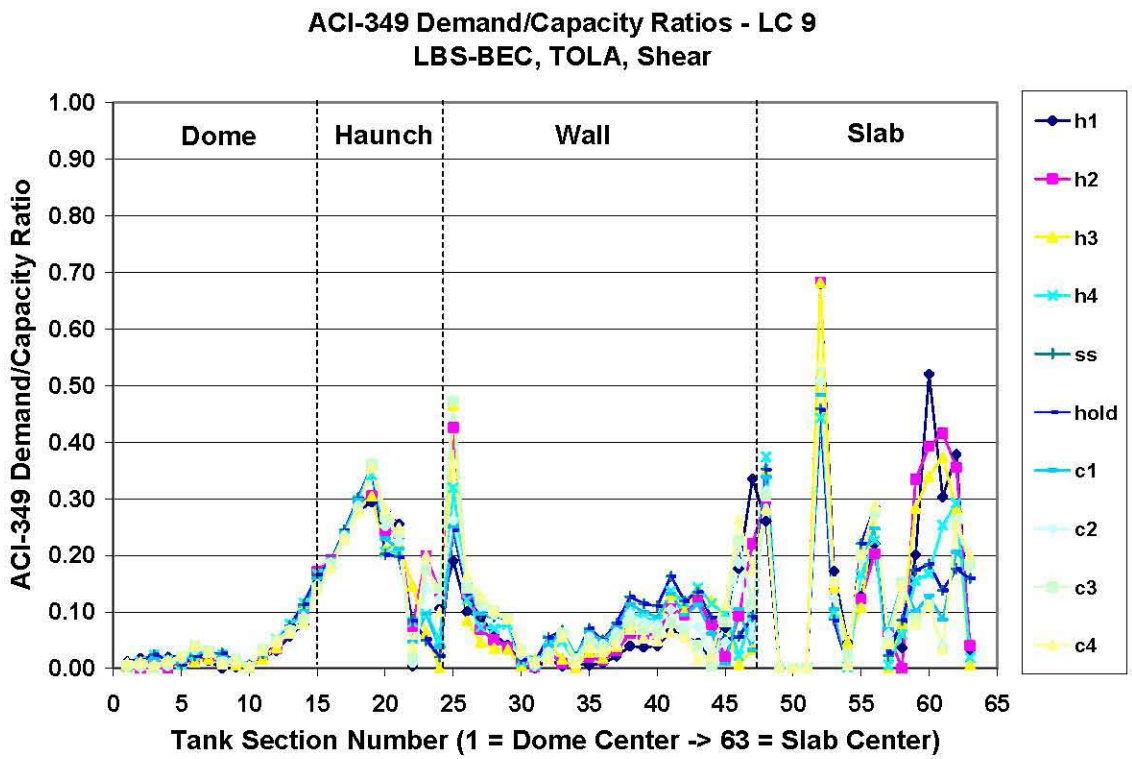


Figure 6-27. LBS – BEC, Load Combination 9', Shear

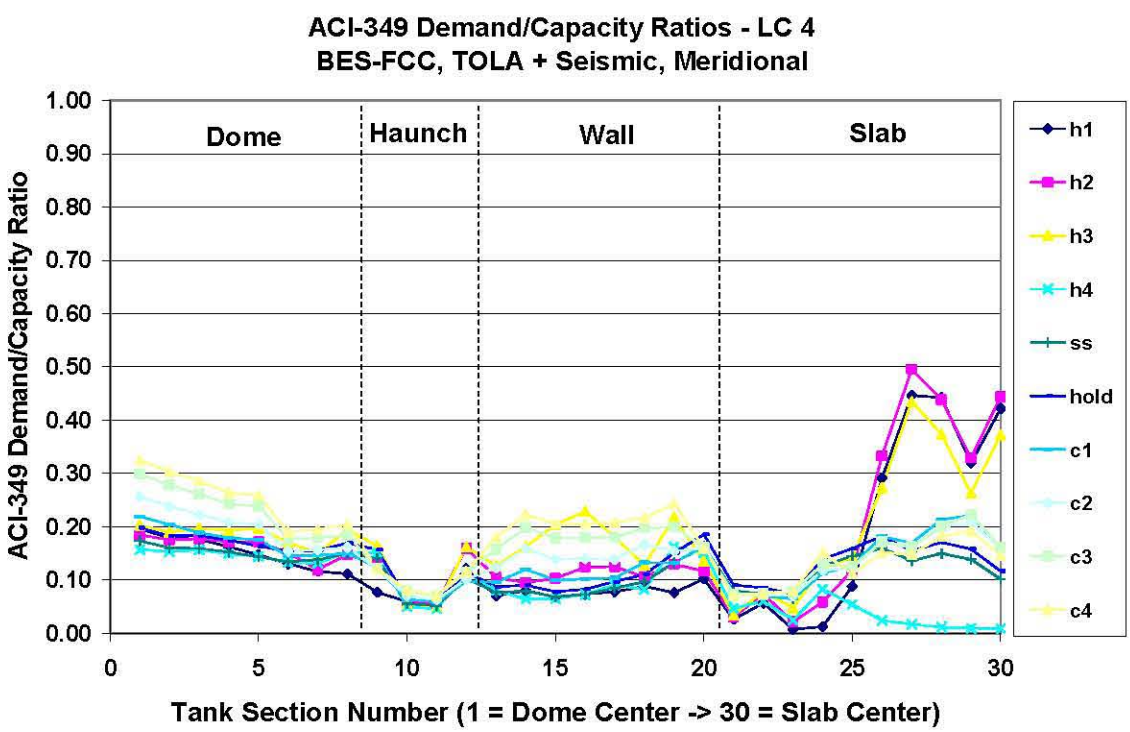


Figure 6-28. BES – FCC, Load Combination 4, Meridional

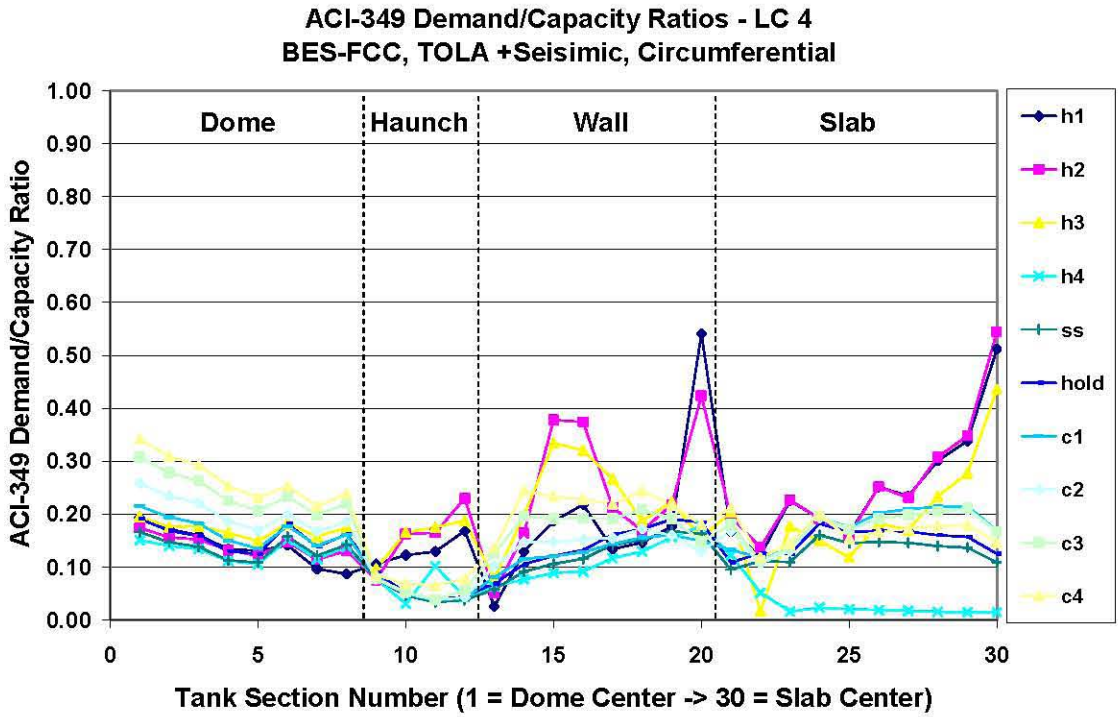


Figure 6-29. BES – FCC, Load Combination 4, Circumferential

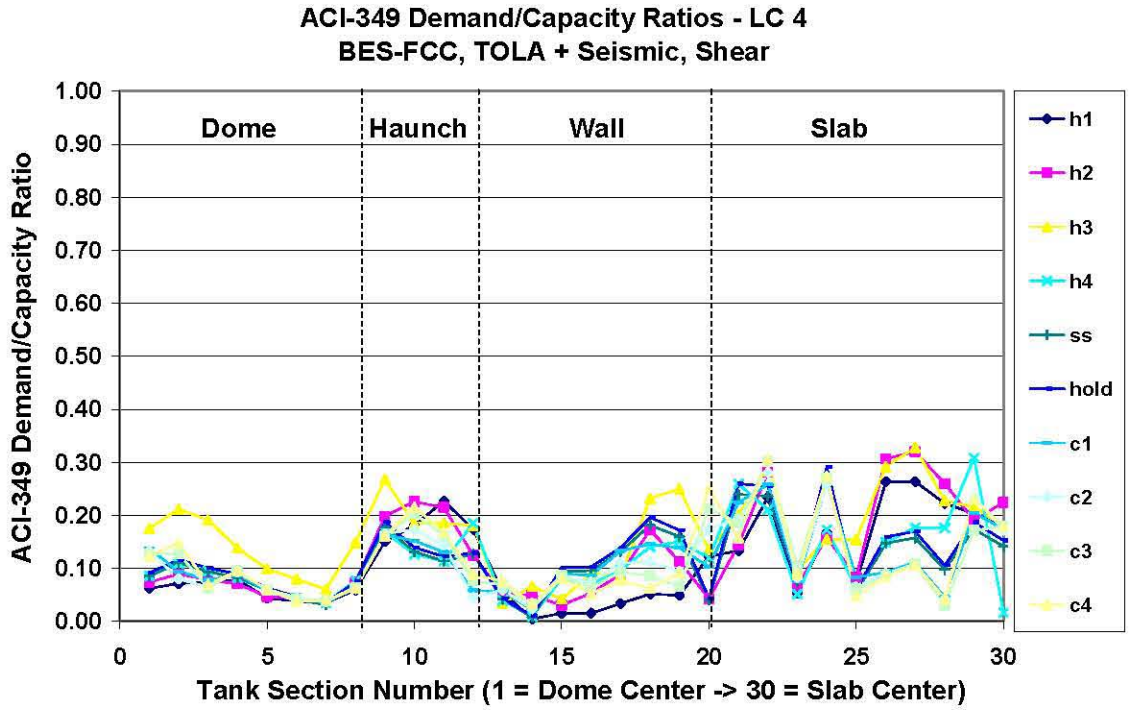


Figure 6-30. BES – FCC, Load Combination 4, Shear

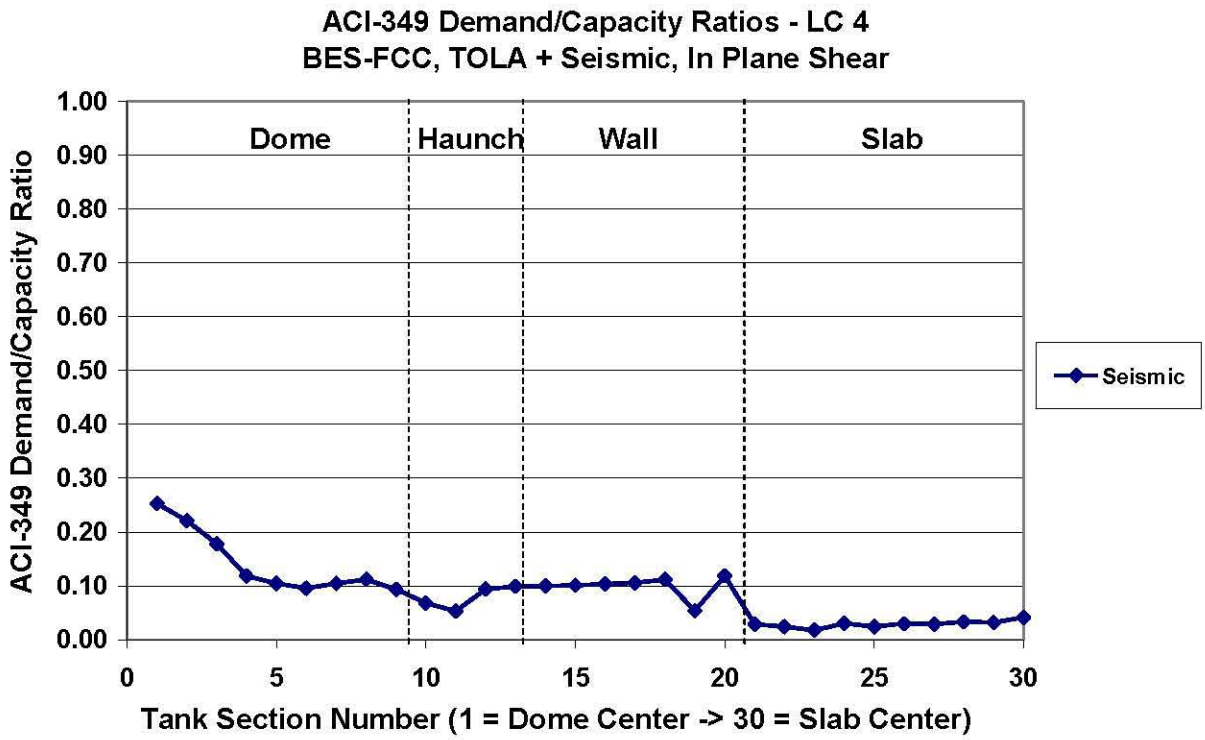


Figure 6-31. LBS – FCC, Load Combination 4, In-Plane Shear

6.2 ASME Primary Tank Evaluation

The primary tank was evaluated against the requirements of ASME B & PV Code, Section III, Division 1, Subsection NC, Article NC-3200 (ASME 1992a). Section 1622 of the IBC mandates that nonbuilding structures comply with the requirements of Section 9.14 of ASCE 7. That document, in turn, references the ASME B&PV Code as the applicable standard. Therefore, while the DST primary tank structure is not specifically addressed in IBC, it can be shown to meet the requirements of IBC by demonstrating its compliance with the ASME code.

The Evaluation Criteria document (Day el al. 1995) states that earthquake loads may be considered as Service Level D loading. The Seismic Design and Evaluation document (Bandyopadhyay et al. 1995) also states that load combinations including the design basis earthquake should use Service Level D capacities.

6.2.1 Primary Tank Results

Appendix E of the Combined Summary report (Rinker et al. 2006d) describes a study of the mesh refinement of the lower knuckle of the primary tank in the seismic FE model. That study concluded that the seismic stress intensities in the primary tank lower knuckle should be multiplied by a factor of 2.0 before being combined with the TOLA results. This factor was applied to the lower knuckle elements in the spreadsheets used to combine the primary tank stress intensities. The general primary membrane stress intensity, the general primary membrane plus bending stress intensity, and the primary plus

secondary stress intensity range are shown in Figures 6-33 through 6-52. The demands are well within the allowable capacity for each of the four material combinations.

It was stated in Section 3.2.7 of this report that the ANSYS seismic model has some limitations for predicting the convective response of the waste. Comparisons of primary tank element hoop stresses near the waste-free surface from Dytran and ANSYS models were presented in Rinker and Abatt (2006), and Rinker et al. (2006b), respectively. The models showed that at the 422-inch waste level, where the interaction of the fluid with the dome curvature is not significant, that the primary tank hoop stresses near the free surface were less than 5 kip/in.^{2} in magnitude, and that the stresses predicted by ANSYS and Dytran were similar. Similarly, the Increased Liquid Level Seismic analysis (Rinker et al. 2007) did not show significantly higher stresses resulting from increased interaction at the 460-inch waste level. Accordingly, because of the low demand-to-capacity ratio near the free surface and the conservative nature of the stresses reported by ANSYS relative to Dytran, the stresses extracted from the ANSYS simulation are sufficient to evaluate the stresses in the primary tank near the free surface.

6.2.2 Evaluation Criteria Discussion

The evaluation of the primary tank capacity was in accord with ASME Section III, Division 1, Service Level D as specified by the Structural Acceptance Criteria document (Day et al. 1995) and the guidance of the Seismic Evaluation document (Bandyopadhyay et al. 1995). The ASME code specifies the following load combinations and capacities for an elastic analysis:

General primary membrane stress intensity $P_m \leq kS_m$ (6.1)

Local primary membrane stress intensity $P_L \leq 1.5kS_m$ (6.2)

Primary membrane + bending stress intensity $(P_m \text{ or } P_L) + P_b \leq 1.5kS_m$ (6.3)

Primary + secondary stress intensity $(P_m \text{ or } P_L) + P_b + Q \leq 3S_m$ (6.4)

In these equations, P_m is the primary membrane stress, P_L is the local primary stress, P_b is the primary bending stress, and Q is a secondary stress (thermal in the case of the DSTs). The factor k is equal to 2.0 for Service Level D capacities.

The general primary membrane stress in the DST primary tank is dominated by hoop tension. Section 5.5 of the Seismic Evaluation document (Bandyopadhyay et al. 1995) imposes the additional condition that the hoop membrane stress capacity should be taken as the ASME Section III, Division 1, Service Level D limit of $2S_m$, or the yield strength, whichever is less. The intent of the additional condition is that kS_m should be limited to the yield strength if credit is taken for inelastic energy absorption in the computation of demands. Accordingly, the general primary membrane stress intensity criterion becomes:

$$P_m \leq \min(kS_m, S_y) \quad (6.5)$$

This additional condition was invoked for each of the DST evaluations shown in Figures 6-24, 6-29, 6-34, and 6-39.

The allowable stresses S_m and S_y were conservatively taken at 250°F for the A537 steel used in the AP tanks as 23.1 ksi and 42.3 ksi, respectively.

6.2.3 ANSYS® Seismic Sloshing Concerns

The comparison of fluid-structure interaction results for the primary tank sub-model reported in Rinker et al. (2007) showed that the global ANSYS seismic model had limitations in predicting accurately the convective response of the liquid within the primary tank. Similar results were also reported in Rinker and Abatt (2006) and Rinker et al. (2006b). Consequently, concerns have been raised over the accuracy of the resulting seismic demand in the upper primary tank. These concerns are amplified with the increased interaction of the liquid waste with the curved dome area at the 460-inch liquid waste level (see Figure 2.1 in Chapter 2).

It was shown in Rinker et al. (2007) that the stresses near the waste-free surface were not governing for the primary tank. Figure 6-32 shows the seismic contribution to the low level of stress in the upper knuckle. That report also demonstrated that the stresses predicted by ANSYS® were higher than those predicted by Dytran. Consequently, the seismic stresses used for the quantitative evaluation of the primary tank for combined loads were from the (more conservative) global ANSYS® model.

6.2.4 Best Estimate Soil – Best Estimate Concrete

Figures 6-33 through 6-37 show the demand/capacity ratios for the primary tank for the BES-BEC material combination. All demand/capacity ratios are less than 1.0.

6.2.5 Upper Bound Soil – Best Estimate Concrete

Figures 6-38 through 6-42 show the demand/capacity ratios for the primary tank for the UBS-BEC material combination. All demand/capacity ratios are less than 1.0.

6.2.6 Lower Bound Soil – Best Estimate Concrete

Figures 6-43 through 6-47 show the demand/capacity ratios for the primary tank for the LBS-BEC material combination. All demand/capacity ratios are less than 1.0.

6.2.7 Best Estimate Soil – Fully Cracked Concrete

Figures 6-48 through 6-52 show the demand/capacity ratios for the primary tank for the BES-FCC material combination. All demand/capacity ratios are less than 1.0.

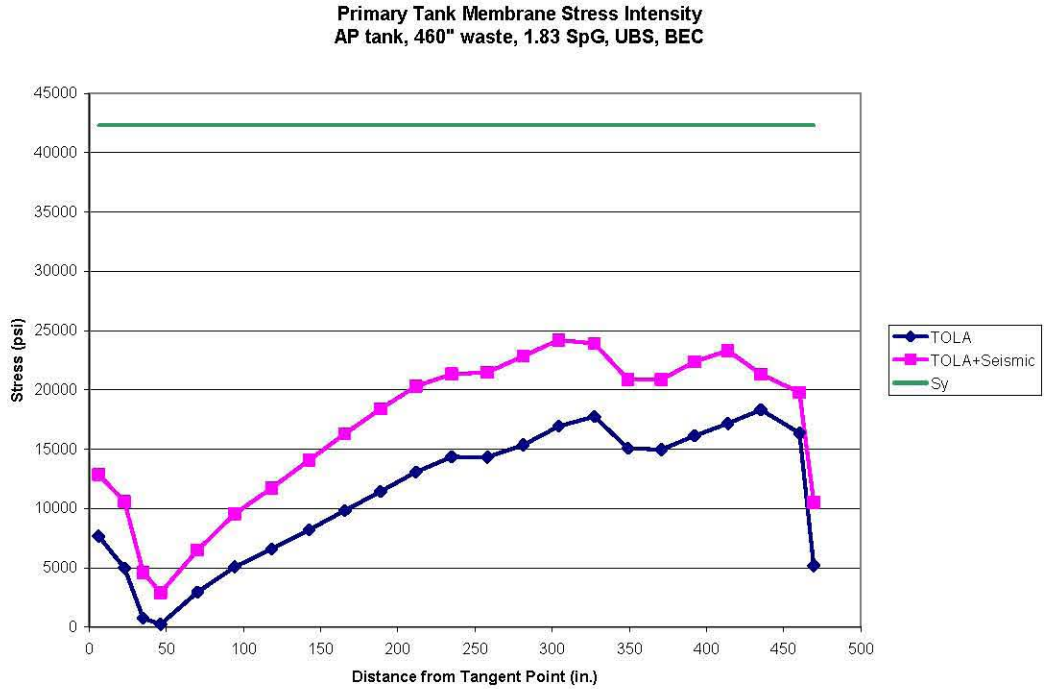


Figure 6-32. Relative Magnitude of TOLA and Seismic Primary Membrane Stress Intensity

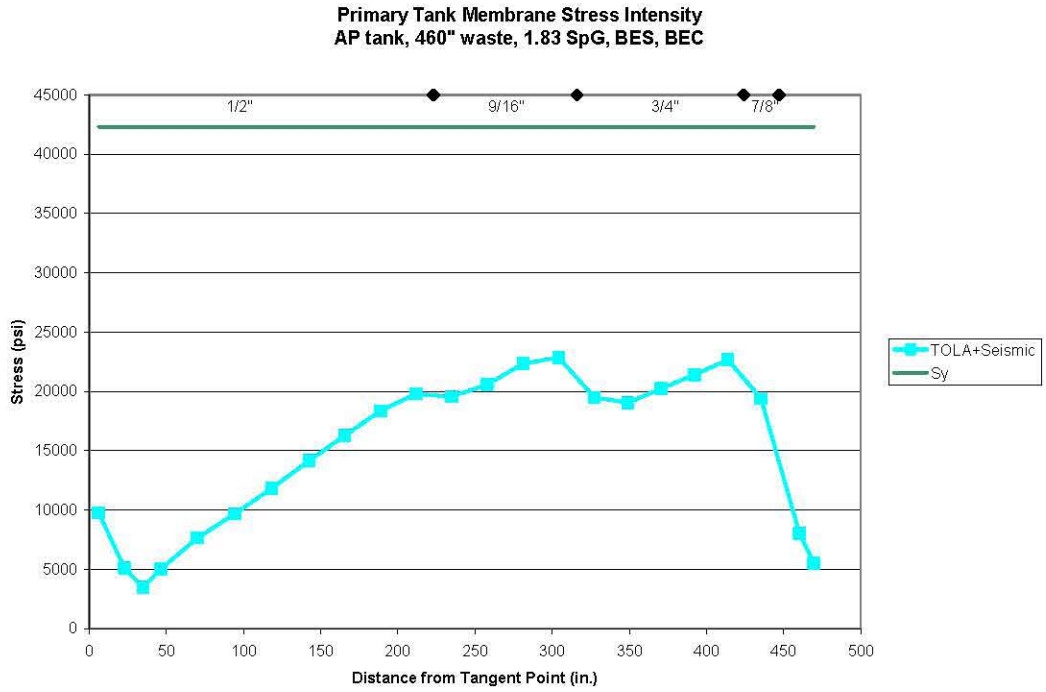


Figure 6-33. BES – BEC Primary Membrane Stress Intensity

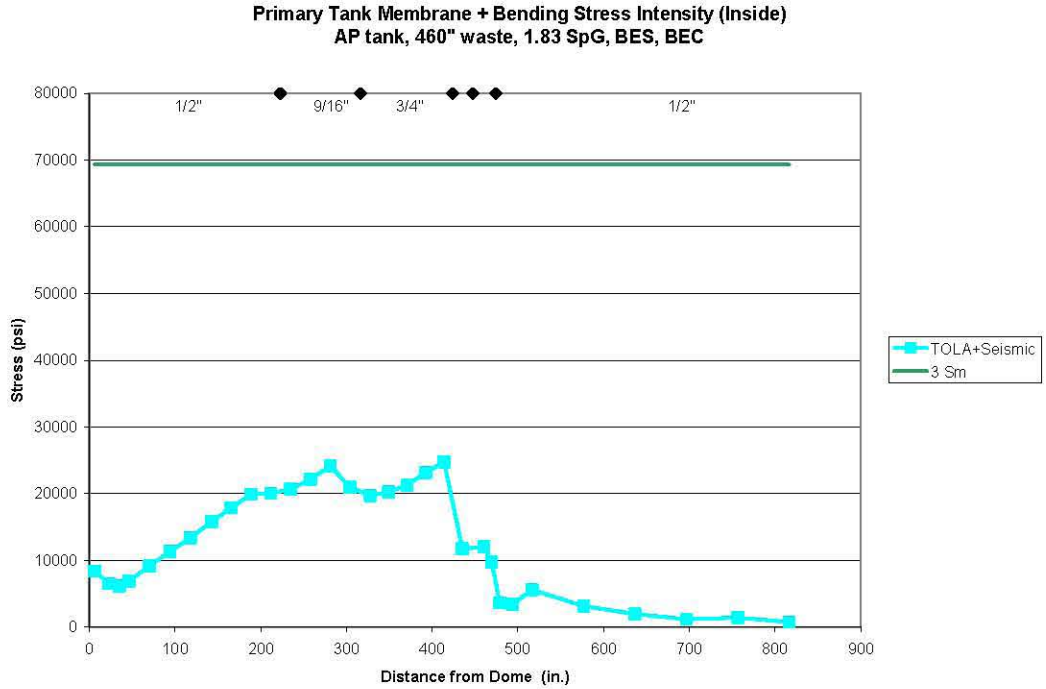


Figure 6-34. BES – BEC Primary Membrane + Bending (inside) Stress Intensity

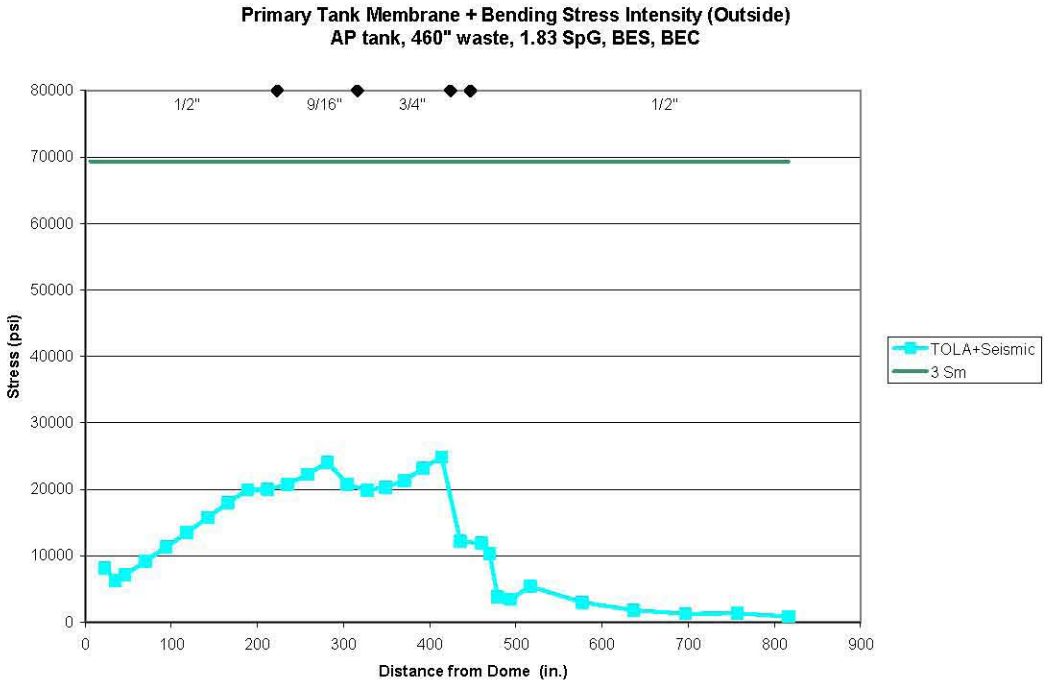


Figure 6-35. BES – BEC Primary Membrane + Bending (outside) Stress Intensity

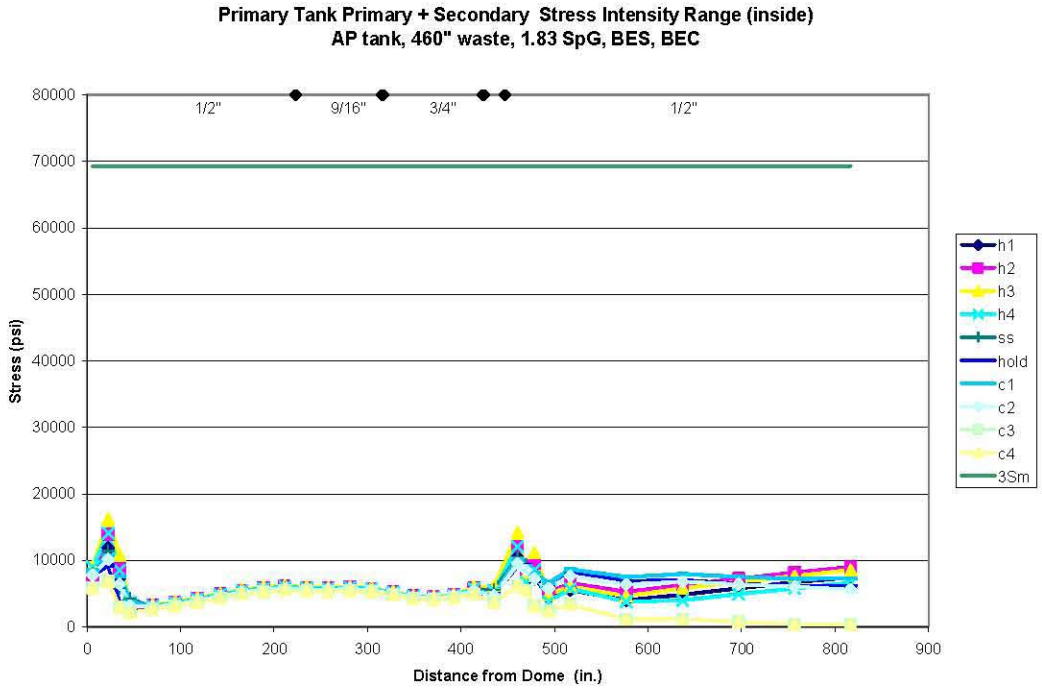


Figure 6-36. BES – BEC Primary + Secondary (inside) Stress Intensity Range

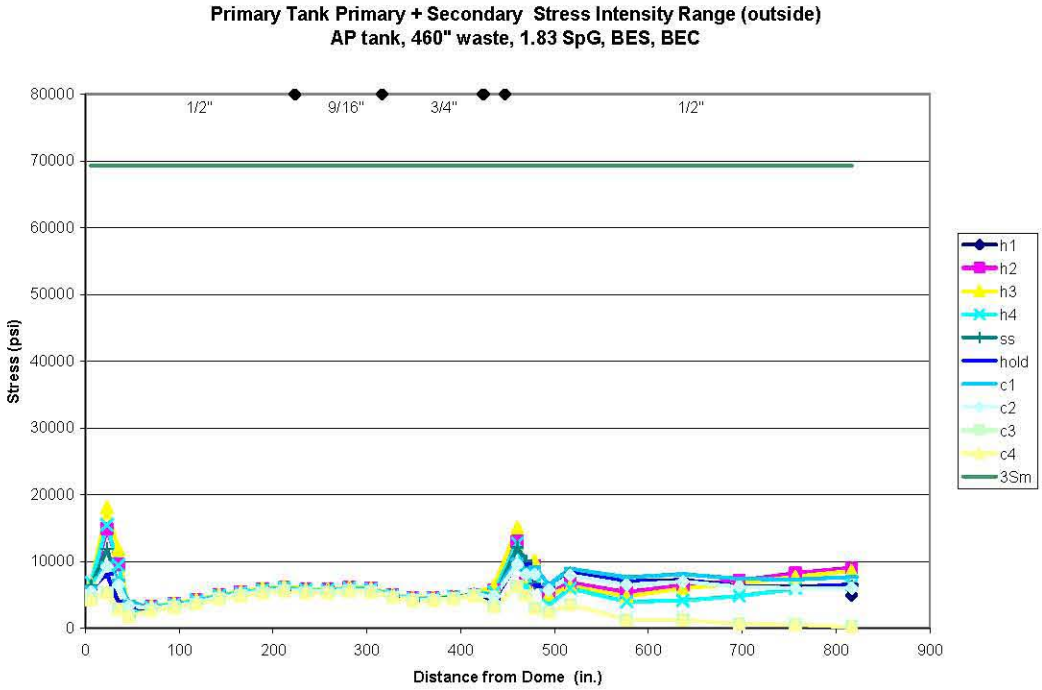


Figure 6-37. BES – BEC Primary + Secondary (outside) Stress Intensity Range

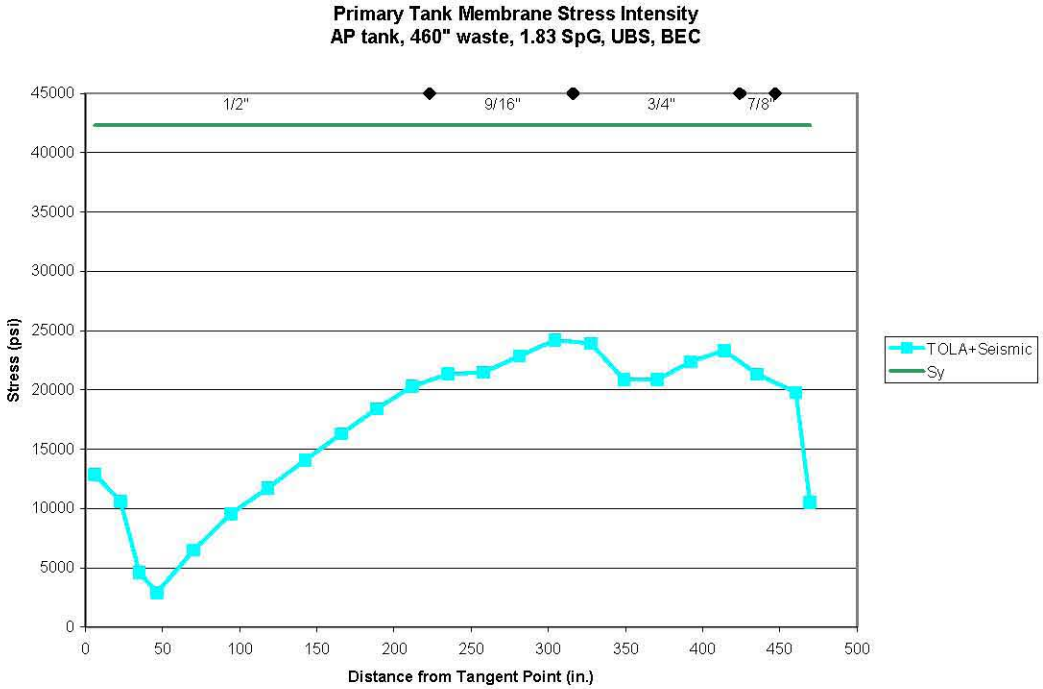


Figure 6-38. UBS – BEC Primary Membrane Stress Intensity

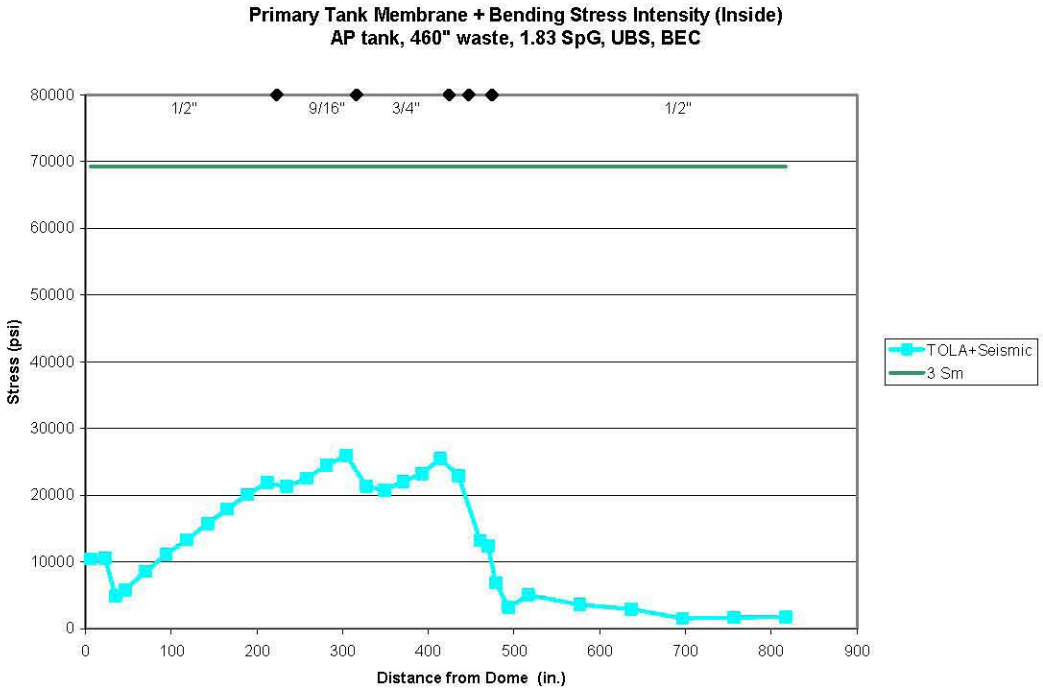


Figure 6-39. UBS – BEC Primary Membrane + Bending (inside) Stress Intensity

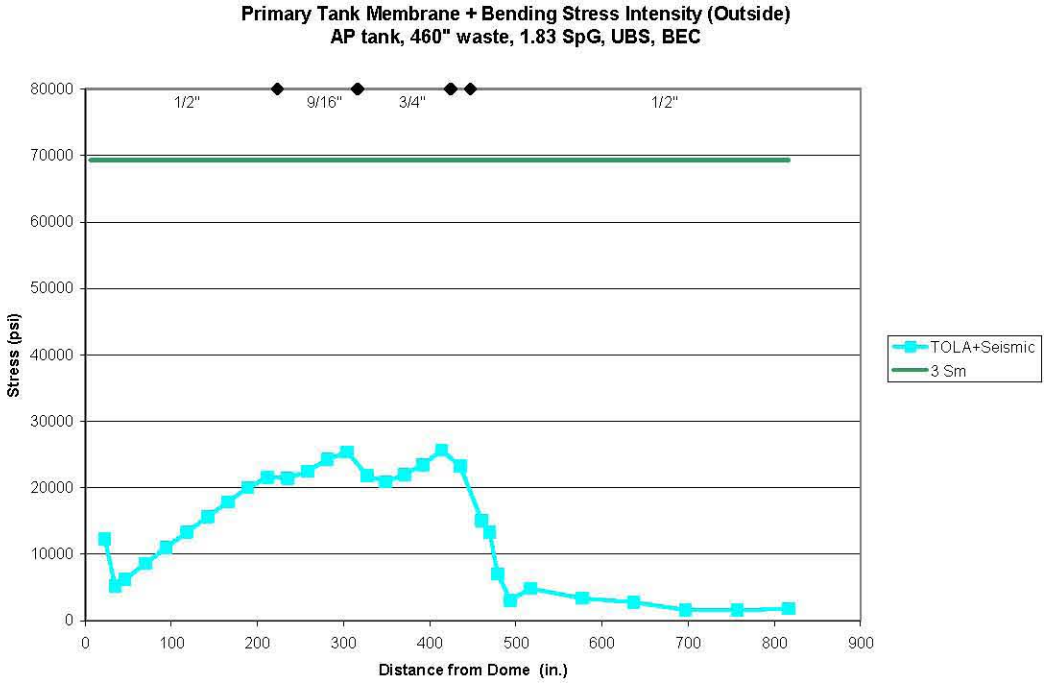


Figure 6-40. UBS – BEC Primary Membrane + Bending (outside) Stress Intensity

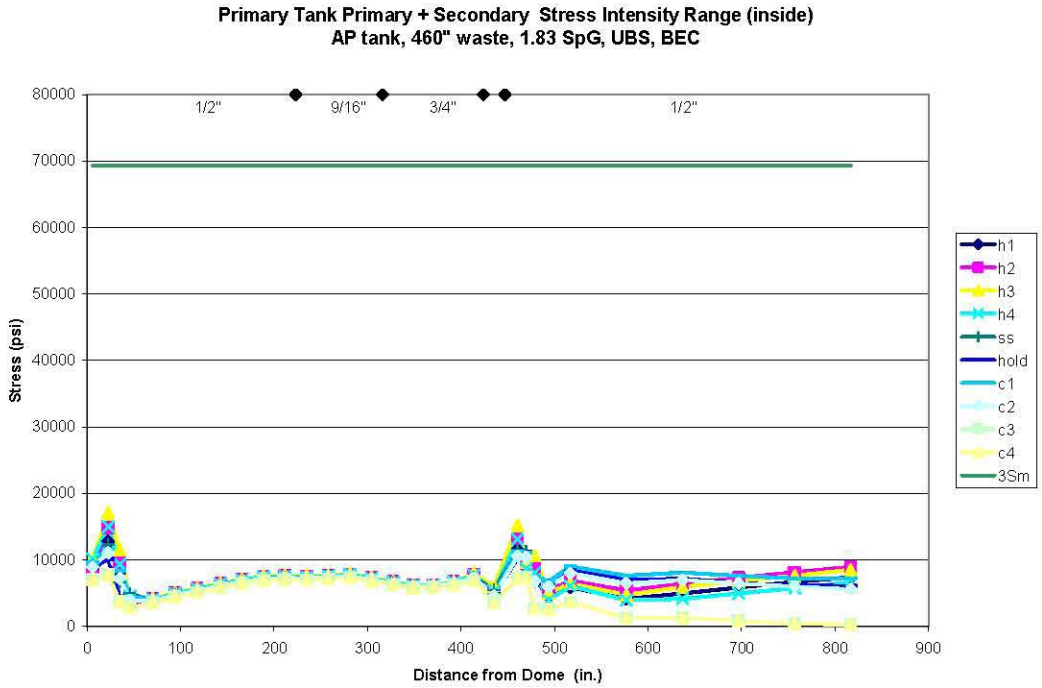


Figure 6-41. UBS – BEC Primary + Secondary (inside) Stress Intensity Range

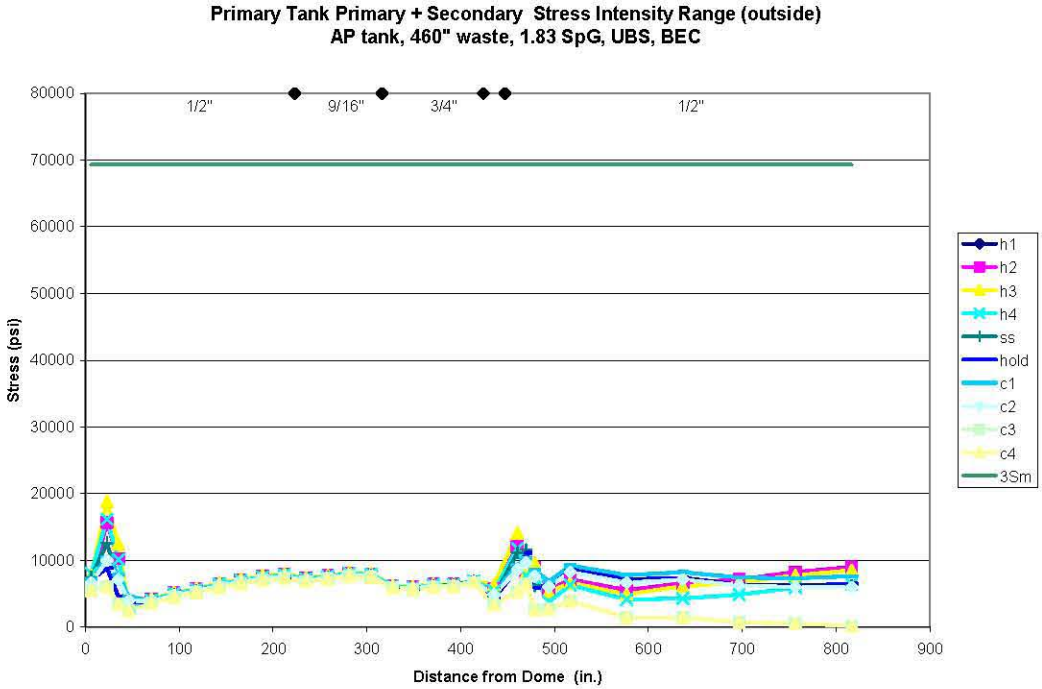


Figure 6-42. UBS – BEC Primary + Secondary (outside) Stress Intensity Range

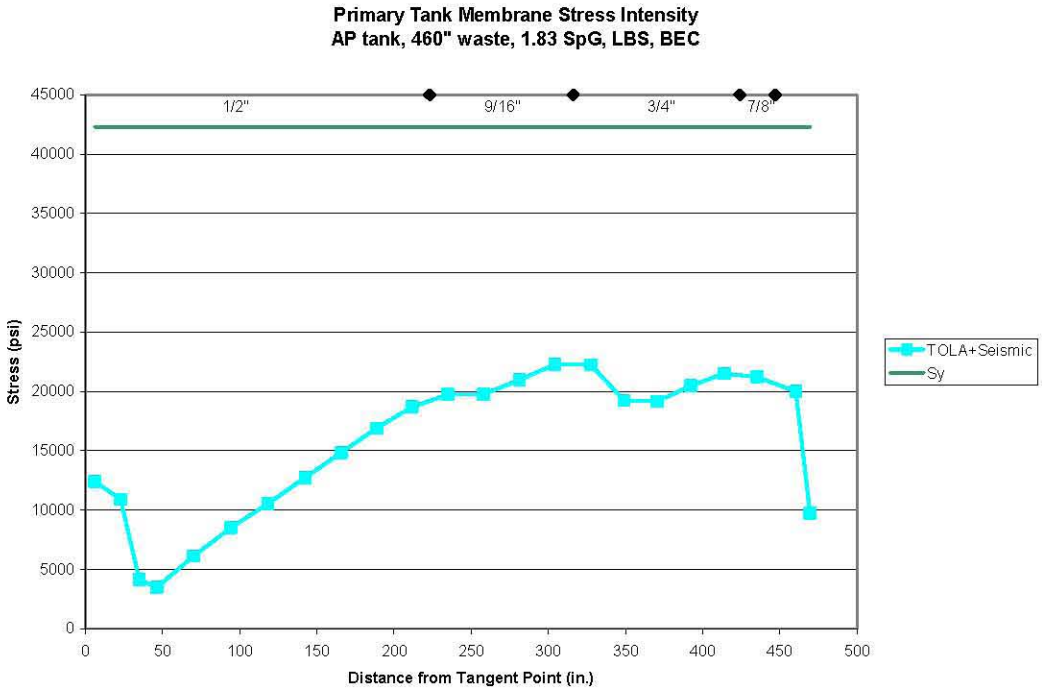


Figure 6-43. LBS – BEC Primary Membrane Stress Intensity

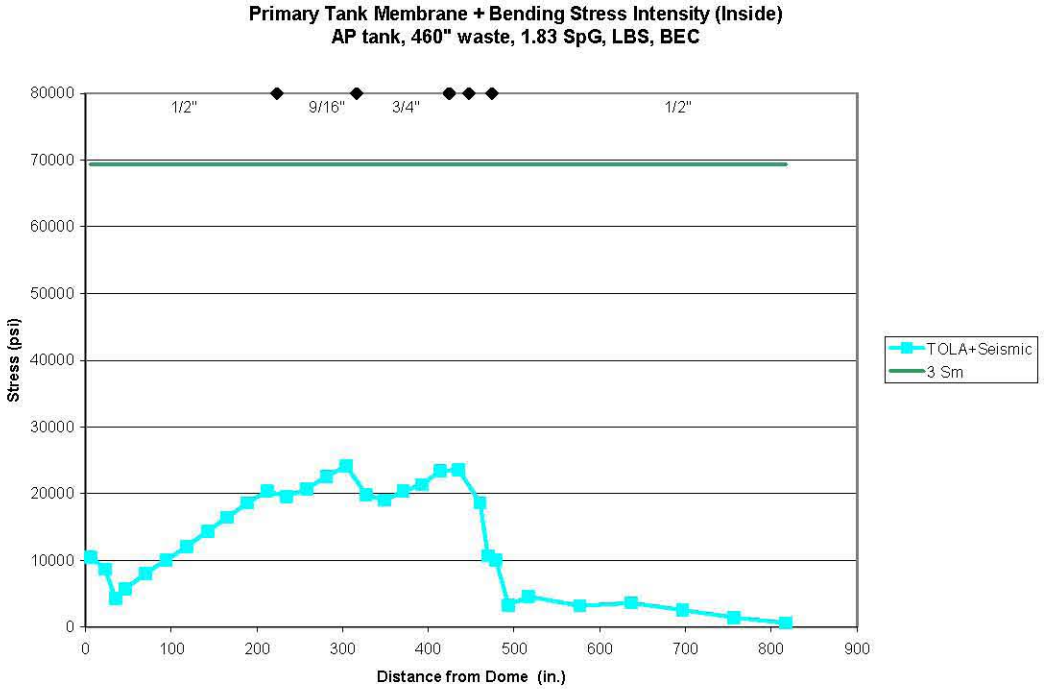


Figure 6-44. LBS – BEC Primary Membrane + Bending (inside) Stress Intensity

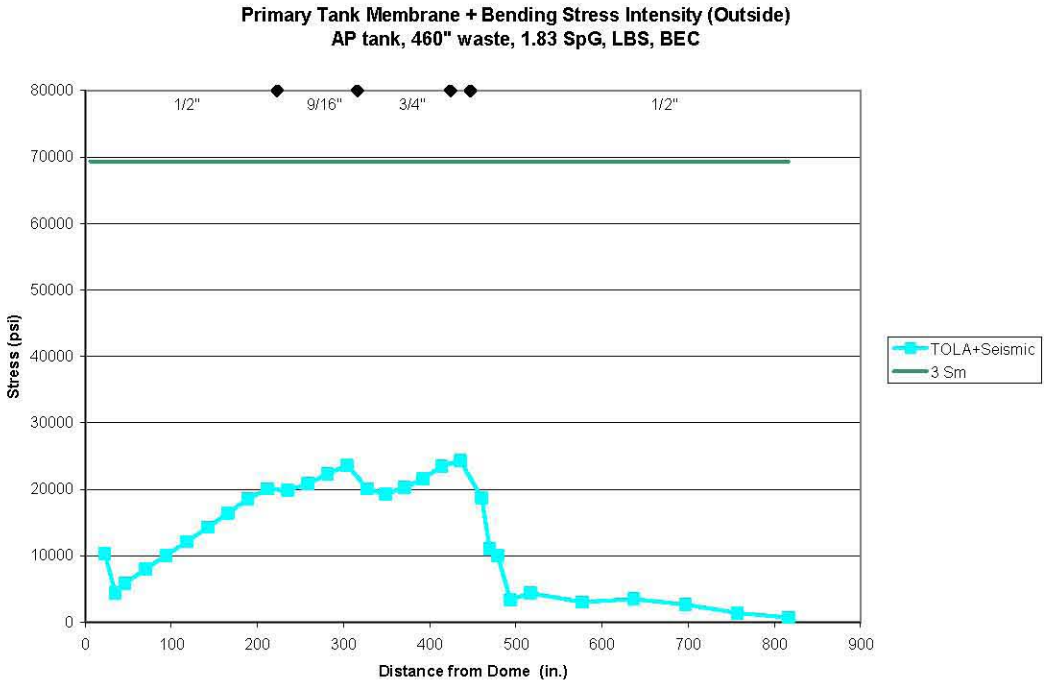


Figure 6-45. LBS – BEC Primary Membrane + Bending (outside) Stress Intensity

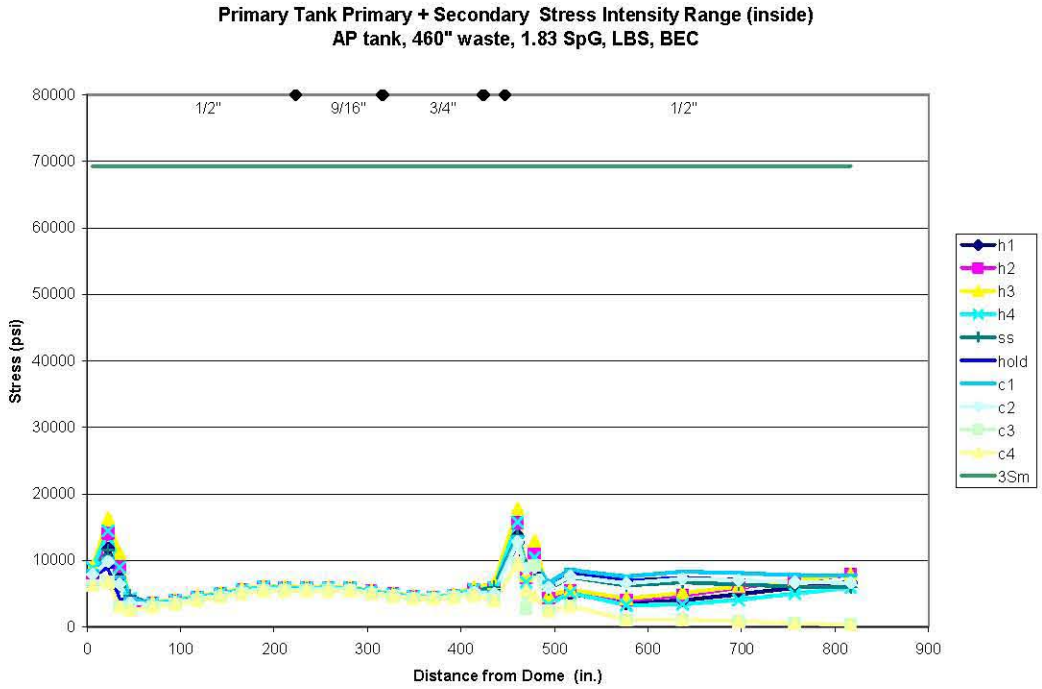


Figure 6-46. LBS – BEC Primary + Secondary (inside) Stress Intensity Range

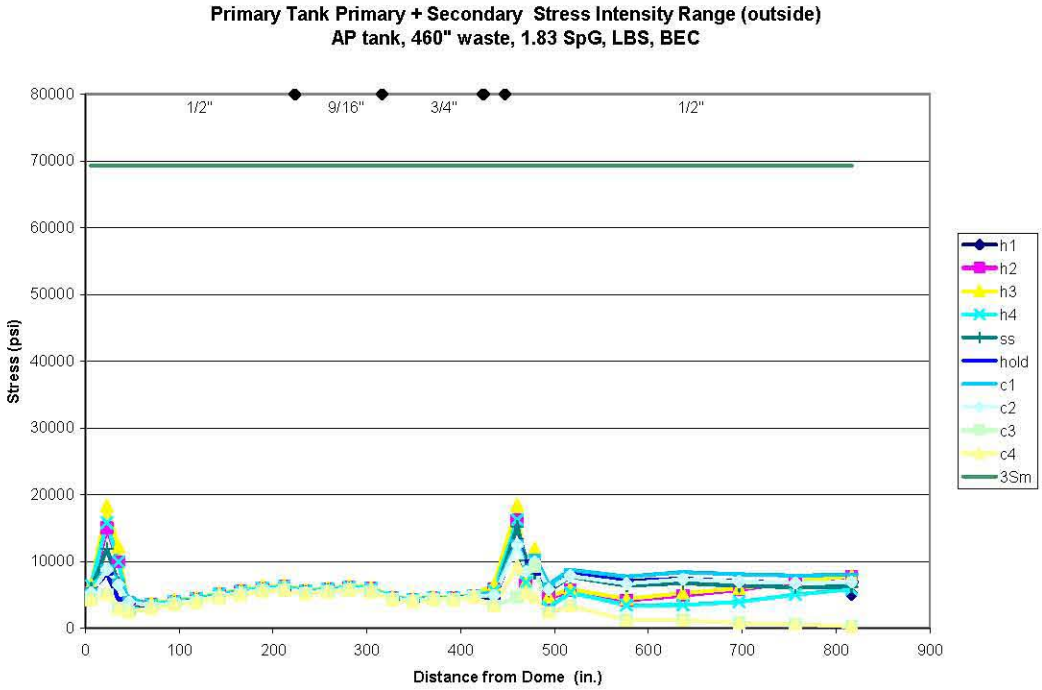


Figure 6-47. LBS – BEC Primary + Secondary (outside) Stress Intensity Range

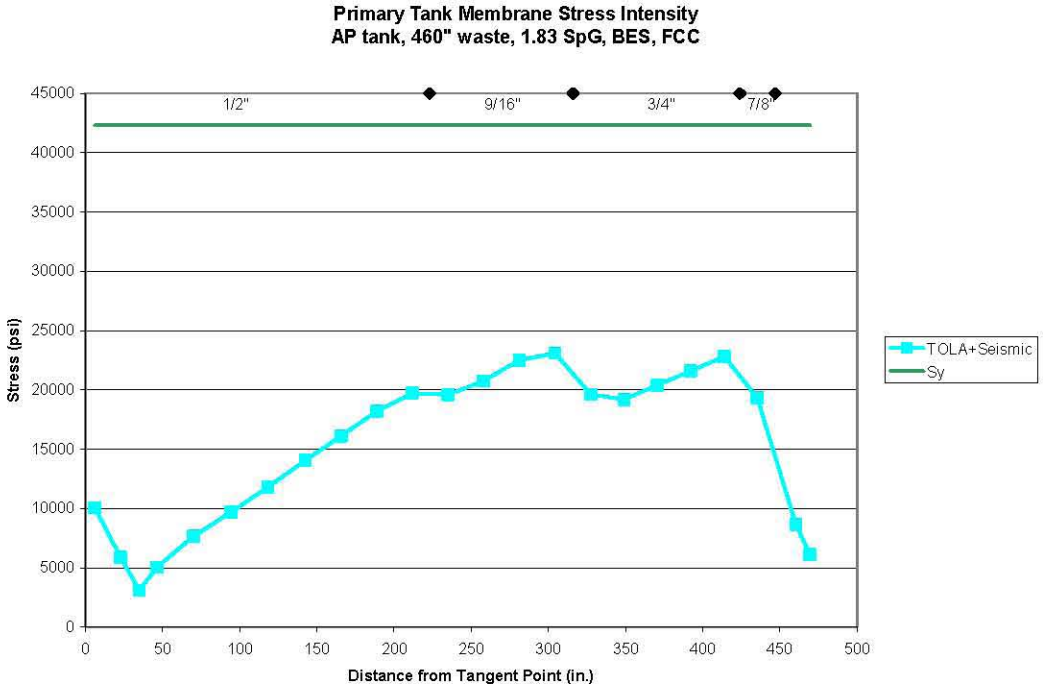


Figure 6-48. BES – FCC Primary Membrane Stress Intensity

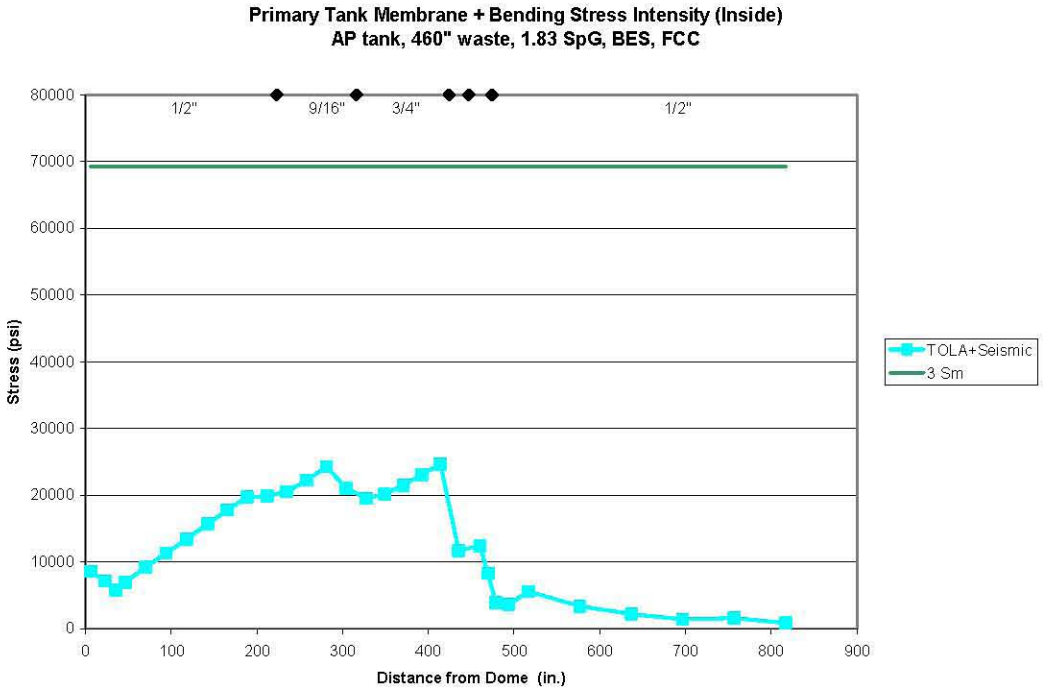


Figure 6-49. BES – FCC Primary Membrane + Bending (inside) Stress Intensity

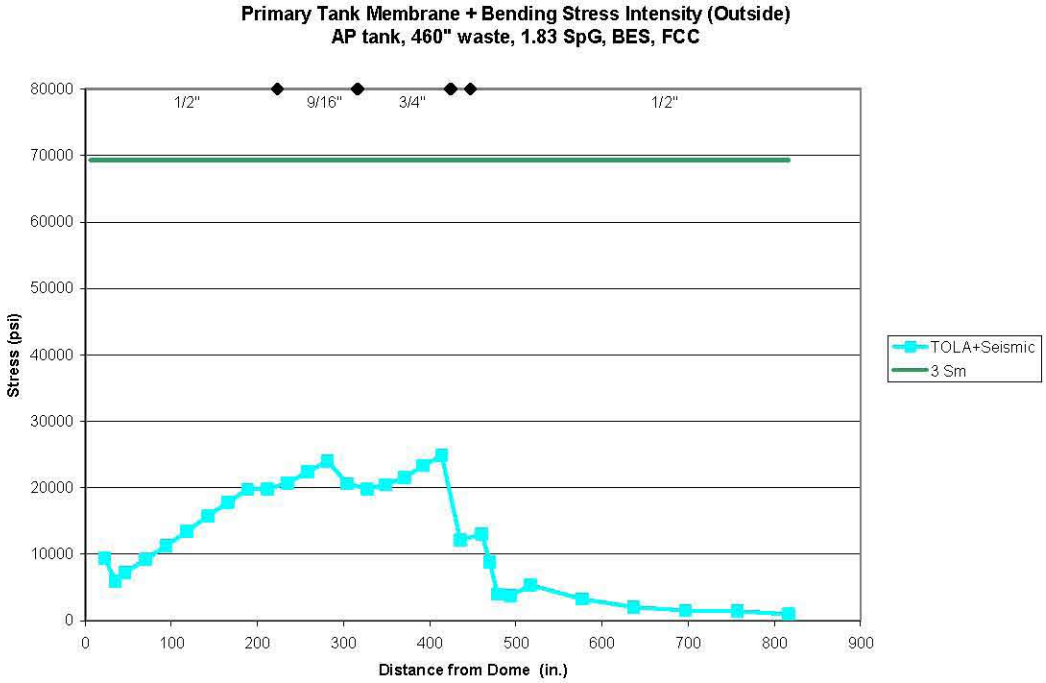


Figure 6-50. BES – FCC Primary Membrane + Bending (outside) Stress Intensity

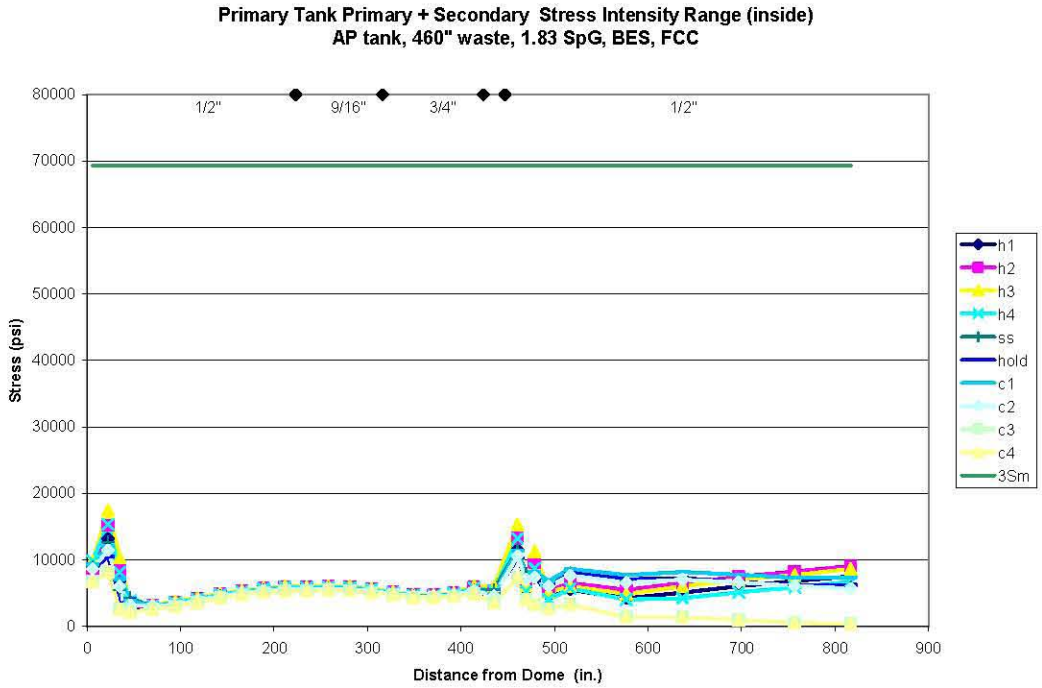


Figure 6-51. BES – FCC Primary + Secondary (inside) Stress Intensity Range

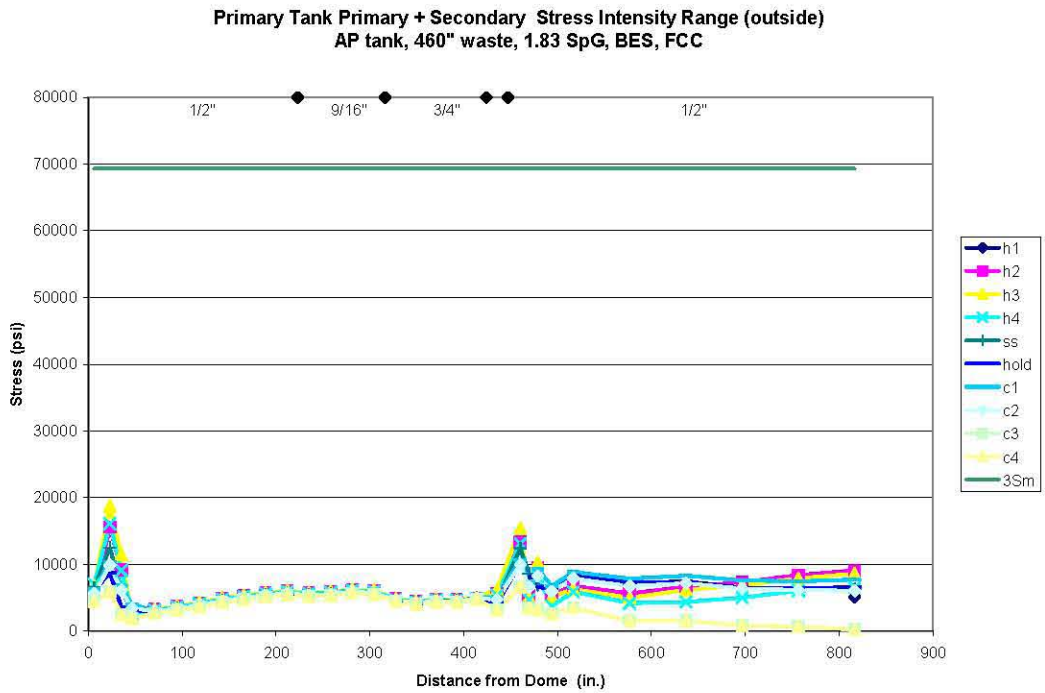


Figure 6-52. BES – FCC Primary + Secondary (outside) Stress Intensity Range

6.3 Primary Tank Stress Corrosion Cracking Evaluation

The Structural Acceptance Criteria document (Day et al. 1995) raised the issue of primary tank fracture by stress corrosion cracking (SCC) as a potential failure mode. However, the report does not set forth a criterion by which to assess the limits on stress, temperature, or waste chemistry to preclude such failure. The TOLA report (Rinker et al. 2004) used the previously postulated limit on the primary tank principal stress on the inner surface to 90% of the yield strength of the tank steel. Perhaps the earliest appearance of this criterion is the AP Tank Farm Functional Design Criteria (Garfield and Guenther 1981). Other indications are that the criterion was "less than yield" prior to construction of the AZ farm, but was changed to "90% of yield" beginning with the AZ tanks.

Intervening analyses, particularly the Expert Panel discussions regarding waste chemistry (Terry et al. 2004), raised concerns regarding the validity of this criterion. The subsequent evaluation of the stress criteria for stress corrosion cracking (Rinker et al. 2005) was unable to establish a technical basis for the 90% yield criterion. That report also observed that while other industries and other design codes are concerned about SCC, they do not address the issue solely on the basis of a stress limit. Other approaches to addressing SCC include reduction of tensile residual stress by post weld heat treatment (PWHT), control of environmental conditions (chemistry and temperature), in-service inspection to confirm the lack of stress corrosion cracks, and fracture mechanics calculations to assess the possibility of crack growth.

6.3.1 Analytical Evaluation

The SCC report (Rinker et al. 2005) developed a damage tolerance approach based on fracture mechanics methods as an alternative means of evaluation. That report focused specifically on Tank AN-107 because

of the historical difficulty of maintaining the desired pH levels in the waste. The fracture mechanics calculations referenced crack growth rate data being developed concurrently (Brongers et al. 2005).

Earlier crack growth testing (Blackburn 1995a,b) in highly aggressive solutions has demonstrated relatively high crack growth rates. It was recognized, however, that these test conditions were very conservative in comparison to the lower temperatures and less aggressive chemical conditions of past and current tank operations. This conservatism was confirmed by recent test results (Brongers et al. 2005) that showed no propensity to crack at equilibrium corrosion potentials, and one to two orders of magnitude lower crack growth rates with an induced voltage to bring the system into the SCC sensitivity range. Only insignificant crack growth was predicted over the projected life of tank operations. Accordingly, conservative values of K_{ISCC} were assigned to facilitate the fracture mechanics calculations.

Application of the fracture mechanics method to Tank AN-107 showed a very low potential for stress corrosion crack growth. There are, however, differences between the loads and tank geometry (wall thickness) of the AN-107 and bounding TOLA analysis described herein. The differences in load are summarized in Table 6-1.

Table 6-1. Comparison of TOLA and AN-107 Analyses

Feature	TOLA	AN-107
Soil overburden (ft.)	8.3	7.4
Overburden density (lb/ft^3)	125	120
Waste height (in.)	422	388
Waste specific gravity	1.70	1.43
Waste temperature (°F)	350	110

The effect of these differences on the lower knuckle inner surface principal stress is shown in Figure 6-53.

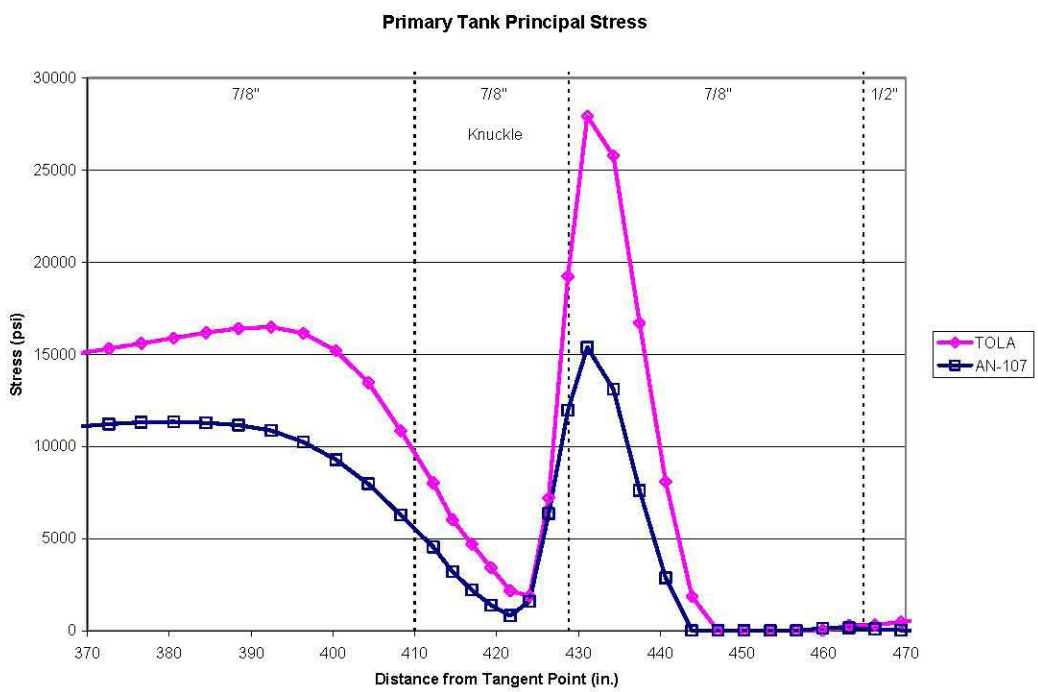


Figure 6-53. Comparison of TOLA and AN-107 Lower Knuckle Principal Stress

A parametric study on the effect of the applied bending stress to the sensitivity to crack growth was conducted as part of the SCC study (Rinker et al. 2005). Figure 5-5 from that report is reproduced here as Figure 6-54. Interpolation of the results to the TOLA bending stress of ±27 ksi suggest that crack growth is unlikely for an existing 0.10-inch crack unless K_{ISCC} is less than 21 ksi-in$^{1/2}$. These results are predicated on the assumption of the lower knuckle steel temperature being more moderate (≤ 150°F) than was historically recorded in the AY/AZ tanks.

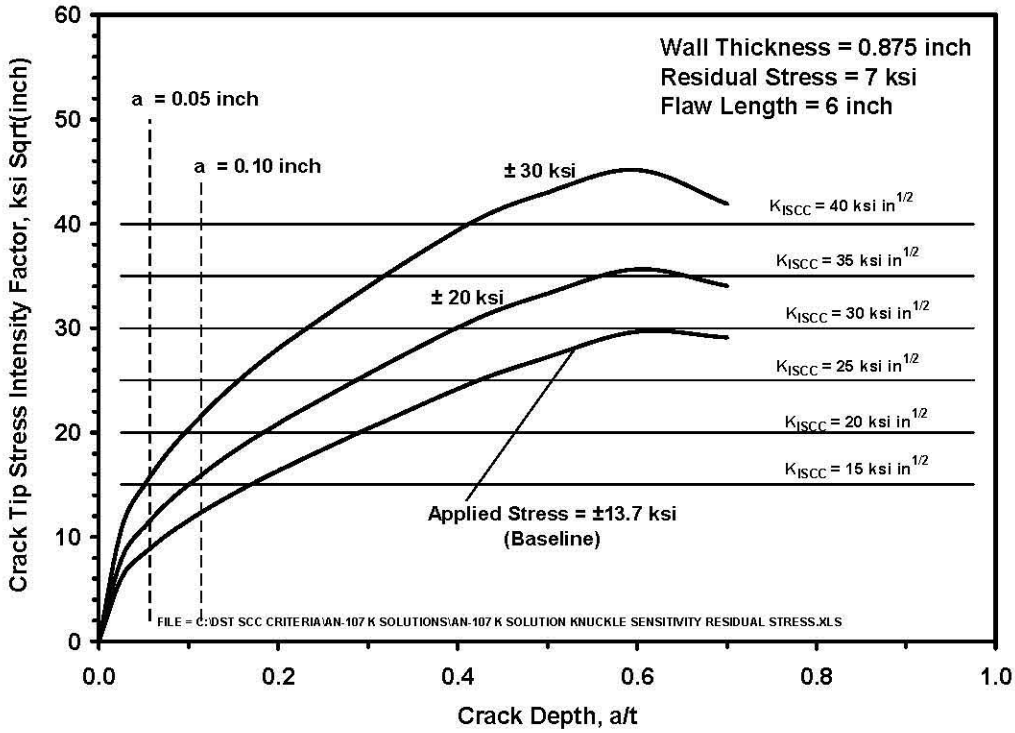


Figure 6-54. Effect of Applied Bending Stress on Calculated Stress Intensity Factor for the Lower Knuckle of Tank AN-107

6.3.2 DST Operating Experience

Appendix C of the SCC report (Rinker et al. 2005) summarized the operating experience with double-shell tanks at both the Hanford Site and the Savannah River Site (SRS). Stress corrosion cracking occurred with some early waste tank designs, without PWHT, at Savannah River. These tanks were constructed of carbon steel but, unlike the Hanford DSTs, were not given post-weld heat treatments to reduce welding residual stresses. The SRS tanks with confirmed SCC were exposed to relatively high-temperature wastes with adverse waste chemistries that were outside the current limits imposed on both SRS and Hanford tanks. Other early SRS tanks (also of low carbon steels and without PWHT) were operated at less severe waste chemistries and temperatures without reported SCC.

SRS initiated research programs in response to the early cracking incidents. Results of this research showed the benefits of PWHTs and improved specifications for waste chemistry. Implementation of these mitigative measures has evidently been effective because there has been no further SCC either in the older tanks (without PWHT) or in newer tanks that used PWHT.

Hanford waste storage tanks have experienced leaks from the older single-shell tanks (no PWHT) but also achieved a record of no leakage from the newer DSTs with PWHT. It is not possible to examine failed liners of single-shell tanks, which precludes the detailed analyses needed to determine whether the failures were caused by corrosion, wall thinning, pitting, or cracking. It is likely that SCC was a factor because none of the older tanks were given PWHT to reduce welding residual stresses. Furthermore, the past service conditions included storage of wastes at high temperatures with chemical compositions known to contribute to SCC.

In contrast, no SCC has been observed in any of the 28 Hanford double-shell tanks over periods of operation that date back to 1971. Detection methods include observation of leakage from through-wall cracks, visual inspections of the outer surface of the tanks, and monitoring for moisture and the increased radiation levels caused by leakage from the primary tank into the outer annulus. Ultrasonic (UT) examinations have been used to look for cracks with less than through-wall depths (present sensitivity can detect very small defects but can only dimension them to 0.050-inch depth), and none have been detected in the lower knuckle region. These crack inspections are done on a 30-inch-wide, top-to-bottom vertical pass (~40 feet), as well as a 20-foot-long segment of the lower knuckle region. However, these UT examinations have covered only a fraction of the tank wall, and depend on the covered fractions being representative of entire tank conditions. Uncertainties aside, it can nevertheless be concluded that the Hanford DSTs appear to have experienced no significant SCC degradation.

There has been no stress corrosion cracking observed in the Hanford DSTs under the present chemistry controls and operating parameters. Recent testing and analysis, and the historical operational record dating back to 1971, shows that SCC is unlikely if the present operating requirements are maintained. Temperature limits are lower and waste chemistry is much less aggressive than those that have caused cracking incidents in laboratory experiments and SRS waste storage tanks.

6.3.3 Seismic Considerations

Implicit in the definition of stress corrosion cracking is the presence of a static tensile stress. A seismic event is by definition a transient event, lasting a much shorter duration than that required to produce SCC. However, it has been posited that seismically induced stresses, when added to the baseline stresses from the thermal and operating loads, may exceed the yield strength of the primary tank steel. Consequently, the stress state following the earthquake may be higher, thus possibly promoting the development of SCC.

A simplified stress analysis of the lower knuckle was conducted to evaluate this scenario. A model of the lower knuckle was loaded with a downward displacement of the wall sufficient to achieve an inside surface stress just below the yield strength (32 ksi) of the steel. This load condition was selected to conservatively represent the nominal operating loads. The displacement was then increased to give an additional 10 ksi compressive stress resulting in yielding of the knuckle such as might occur in an earthquake. The wall stress was then evaluated after returning the load to the nominal operating level. It was observed that the maximum inside surface stress was decreased by nearly 5 ksi following this overstress event.

This analysis demonstrates that yielding of the lower knuckle due to increased meridional compression such as might result from an earthquake does not increase the inside surface stress after the transient event has passed. The model predicts that such an overstress condition may actually decrease the subsequent surface stress due to the load reversal effect in going from the over-stress state back to the normal operating condition.

6.4 Primary Tank Buckling Evaluation

Buckling of the primary tank was considered in Section 8.5 of the TOLA report (Rinker et al. 2004). The evaluation method was based on the method defined in Code Case N-284-1 of the ASME B&PV Code, Section III, Division 1 (ASME 1995b). The buckling evaluation for service Level D was conducted using seismic demands from the original design calculations (Blume and Associates 1974). A separate task of the *DST Integrity Project* was to conduct detailed buckling analyses, in part to "develop an approximate influence function to estimate the effect of changes between the finite element analysis parameters and the tank specific conditions." Accordingly, a new finite element model was developed, distinct from the TOLA model, and buckling evaluations were performed incorporating the results from the current seismic analysis. Complete documentation of the TOLA buckling evaluation is found in the Buckling Analysis report (Johnson et al. 2006).

6.4.1 Evaluation Method

Large displacement finite element analyses were used to predict the limiting vacuum load for the DST primary tanks under combined axial and vacuum loads. Figure 6-55 shows the model of the primary tank used in this analysis. A downward deflection was applied to the dome of the tank (the area in contact with the concrete tank structure) to simulate the displacement controlled axial compression of the tank wall that occurs due to concrete thermal degradation and creep, plus the confined thermal expansion of the steel tank inside the concrete shell. The model includes a geometric imperfection to initiate the buckling instability under the radially symmetric vacuum load. The imperfection was sized to the maximum out of roundness (1-inch deviation in a 7-foot arc length) allowed in the AY tank farm construction specifications (HWS-7789 Hanford Engineering Services 1968). Additional loads on the model include gravity and hydrostatic pressure of the waste at height, h, and specific gravity, SpG (see Figure 6-56).

The onset of the buckling instability was predicted by applying an increasing vacuum load on the inside surface of the tank while monitoring the maximum radial displacement of the tank wall as a function of the increasing vacuum load. The onset of instability is signaled by an increasing rate of radial deflection for a constant increment in the applied vacuum load. Figure 6-57 shows an example load deflection curve from one of the cases that were analyzed. Because vacuum is a primary load, the stresses are not self-limiting and the model eventually fails to converge (numerically) as the physical load carrying capacity of the tank is reached. However, using the final converged vacuum load as the buckling limit is not a reliable measure of the onset of instability because the final convergence is sensitive to non-physical factors including the load step size, the convergence tolerance, and the numerical precision of the computer. Therefore, the ASME code was reviewed to find an appropriate method for defining the limiting vacuum load.

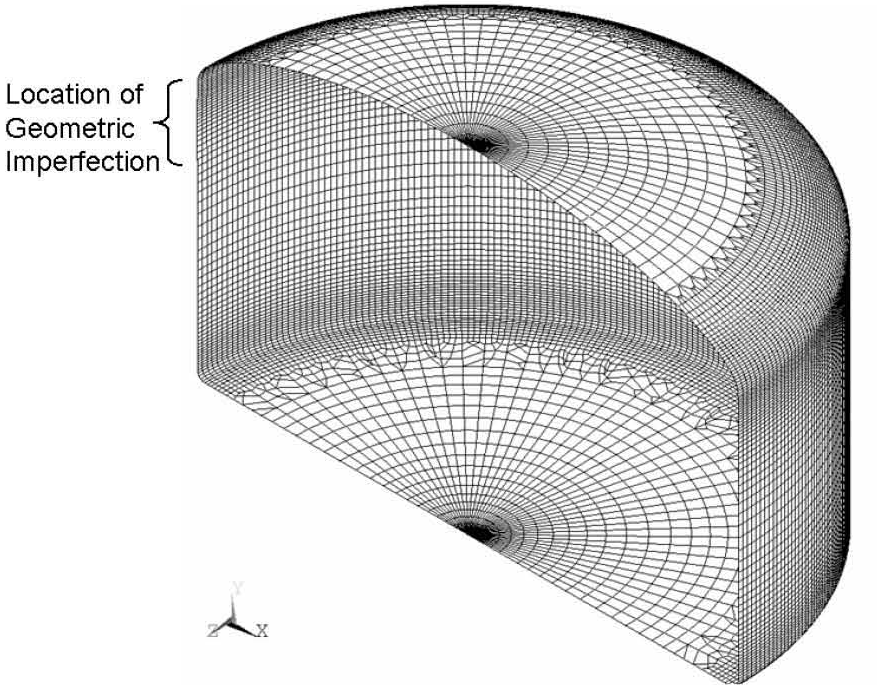


Figure 6-55. Buckling Model

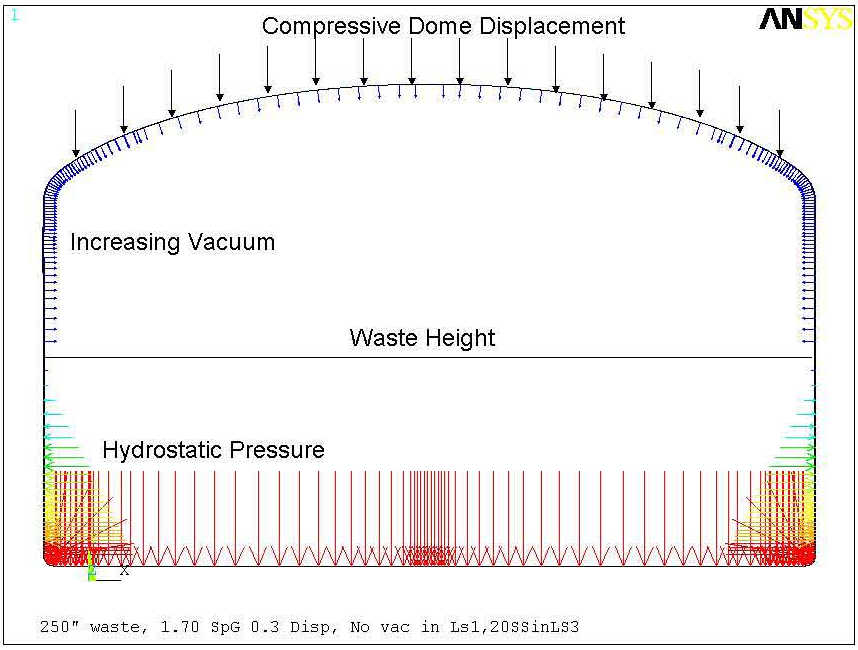


Figure 6-56. Buckling Model Loads

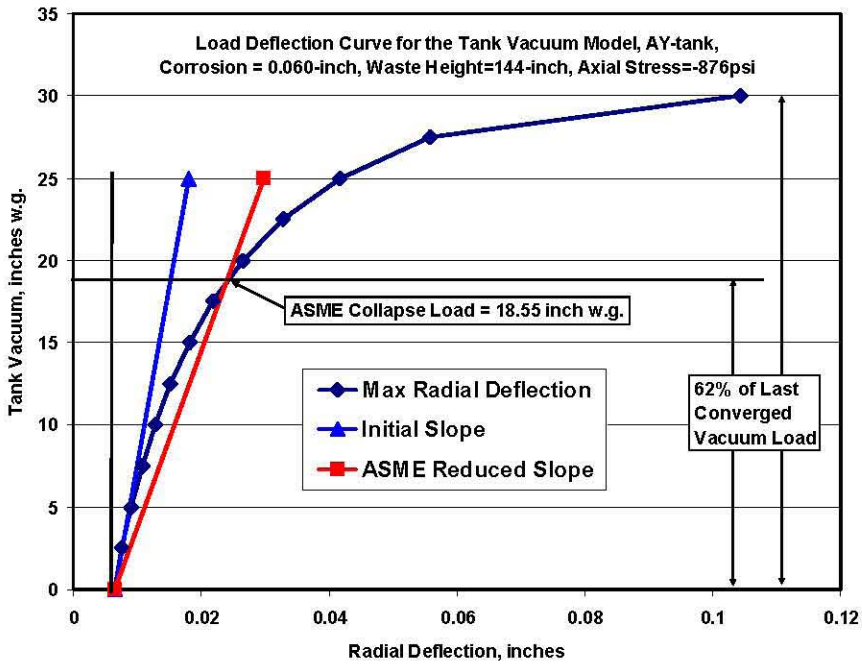


Figure 6-57. Buckling Load Deflection Curve

The ASME Boiler and Pressure Vessel Code, Section III, NB-3213.25, provides guidance on establishing a reasonable collapse load for a structure undergoing controlled plastic deformation (ASME 1995b). Although an elastic buckling phenomenon is being evaluating (the buckling models predict that the tank membrane stresses are well below the elastic limit), the increasing rate of distortion in the tank wall (for a constant increasing vacuum load) represents a gradual decrease in structural stiffness that is similar to a structure undergoing progressive plastic deformation. In the former case, the stiffness reduction is due to the large deformations of the tank geometry that progressively decrease the load-carrying capacity of the tank. In the latter case, it is due to plastic softening. The ASME code method establishes the collapse load by limiting the reduction in structural stiffness under increasing load.

> ***NB-3213.25 Plastic Analysis — Collapse Load.*** *A plastic analysis may be used to determine the collapse load for a given combination of loads on a given structure. The following criterion for determination of the collapse load shall be used. A load–deflection or load–strain curve is plotted with load as the ordinate and deflection or strain as the abscissa. The angle that the linear part of the load–deflection or load–strain curve makes with the ordinate is called* θ*. A second straight line, hereafter called the collapse limit line, is drawn through the origin so that it makes an angle of* $\tan^{-1}(2 \tan \theta)$ *with the ordinate. The collapse load is the load at the intersection of the load–deflection or load–strain curve and the collapse limit line. If this method is used, particular care should be given to ensure that the strains or deflections that are used are indicative of the load carrying capacity of the structure.*

Figure 6-57 graphically illustrates the ASME code method based on the factor of two stiffness reduction. The radial displacement is offset from zero (at zero vacuum) because the initial loads (axial compression, hydrostatic pressure, and gravity) cause an initial radial deflection in the tank wall. The initial load/ deflection slope was calculated and a second line was drawn at an angle with twice the tangent measured from the vertical axis. The vacuum limit was then calculated by interpolating to find the vacuum load

where the second line crossed the load/deflection curve (Figure 6-57). In this case, the ASME collapse load is about 62% of the last converged vacuum load. Figure 6-58 shows the displaced shape of the tank model at the ASME collapse load. The displacements are magnified by a factor of 50 for visual effect. For the tank geometry, the ASME method results in a minor amount of tank distortion.

A matrix of tank models was run to develop equations for the tank vacuum limit as a function of waste height, specific gravity, wall thickness, and axial compressive load. Influence functions were developed to estimate the applied axial force in the primary tank wall that is required for evaluating buckling of the primary tank. The axial force contributions from the applied loads were evaluated, giving the total axial force as the sum of the following loads:

- Differential thermal expansion,
- Gravity,
- Surface loads,
- Concrete thermal degradation and creep,
- Seismic excitation, and
- Effect of hydrostatic waste pressure on the confined axial force.

Once the unfactored axial force and vacuum limits are calculated, the safety factors for the ASME Section III service levels are applied to calculate the allowable tank vacuum limits.

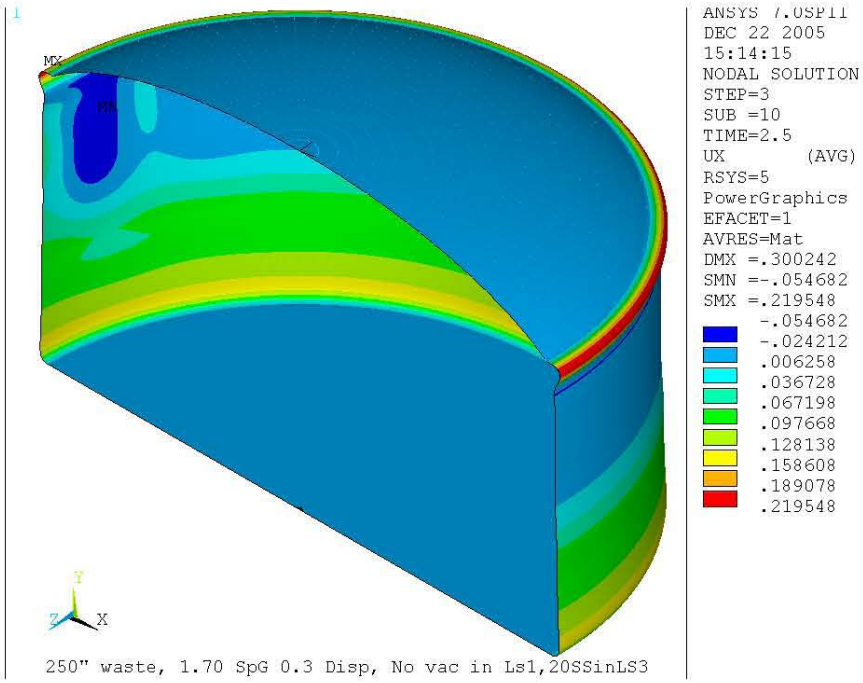


Figure 6-58. Model Displaced Shape at Vacuum Limit

6.4.2 Evaluation Criteria

The buckling calculations are conducted for the four different service levels defined in ASME Section III, each with required factors of safety for local and global buckling:

	Factors of Safety	
	Local Buckling	Global Buckling
Level A = Normal operating conditions	2.0	2.4
Level B = Upset conditions	2.0	2.4
Level C = Emergency conditions	1.67	2.0
Level D = Faulted conditions	1.34	1.61

Attachment B of Julyk (2002) makes the argument that axial compression in the tank cylinder will be relieved by local bowing of the wall before the onset of general instability. This position is justified since the meridional (axial) compressive stresses are displacement-controlled as a result of differential thermal expansion and concrete creep-induced loads on the primary tank. The load deflection response of the large displacement finite element models used in the current buckling analysis confirms that the axial stress in the tank is self-limited by the deformation of the primary tank geometry. This rational leads to the following buckling criteria when combining the effects of axial and hoop loads on the allowable vacuum:

The allowable vacuum (net negative pressure) in the double-shell tanks is controlled by the minimum of two cases:

A. Local Buckling (with *local* buckling safety factors imposed) evaluated considering the interaction of the net internal vacuum load (Δp) combined with the meridional compressive stress (σ_ϕ).

B. General Instability (with *global* buckling safety factors imposed) evaluated considering the net internal vacuum load (Δp) acting alone. No interaction with the meridional compressive stress shall be considered ($\sigma_\phi = 0$).

These criteria were used by Julyk (2002), and they are they also used in the current buckling evaluation.

Julyk (2002) states that activation of the tank relief valves at the limiting vacuum load should be classified as a Level C (emergency) load condition. This is justified because the normal vacuum imposed by the tank ventilation systems is about 3 inch w.g. compared to the vacuum limit of 6.6 inch w.g. for the AY, SY, AN, AW, and AZ tanks and 12 inch w.g. for the AP primary tank. The relief valves (set at the limit values) are not expected to activate over the operating life of the tanks and at worst this would occur no more than 25 times. Therefore, activation of the relief valves would be an off-normal occurrence, which is consistent with the ASME Service Load Classification for Level C events.

It is assumed in this analysis that the design basis loads used in the thermal and operating loads analysis conservatively represent Service Levels A, B, and C. This is consistent with the loading conditions assumed by Julyk (2002). Service Level D, however, requires that the incremental seismic stresses be added to the design basis stresses for evaluating the faulted condition.

6.4.3 Buckling Results

An Excel™ spreadsheet was constructed using the relationships documented in detail in the Buckling report (Johnson et al. 2006), and it applies the Section III service level safety factors to calculate the vacuum allowable for the primary tanks. Table 6-2 shows a summary of the allowable vacuum calculations that are based on the current 210°F operating limits for waste temperature, 460-inch waste height, and waste-specific gravity of 1.83. A corrosion allowance of 0.060 inch was assumed in these calculations. This table shows that the specified vacuum limit of 12 inch w.g. is greater than the current vacuum allowable to prevent buckling of 10.46 inch w.g.

Table 6-3 summarizes the additional analyses that showed that the allowable vacuum was above the 12-inch limit for corrosion allowances less than 0.025 inch. Little or no corrosion has been observed in the primary tanks (Jensen 2003 and 2005) such that this wall thickness is appropriate for the buckling calculation. With this assumption, the AP tank passes the buckling criteria. Additional consideration may be given to the operational capabilities of the ventilation equipment.

Table 6-2. Primary Tank Buckling Evaluation

	AP
Approx. Operating History	
Temp, F	120
Hwaste, inch	422
Operating Limits	
Temp, F	210
Hwaste, inch	460
SpG	1.83
Corrosion Allowance, inch	0.060
Yield at Temp, ksi	43.8
Calculated Axial Forces	
Operating Axial Force, kip/inch	-0.355
Oper+Seismic Force, kip/inch	-0.869
Axial Force Limit, kip/inch	-2.842
Calculated AllowableVacuum Limits, inches w.g.	
Local Buckling	
Service Level A&B	9.61
Service Level C	11.51
Service Level D	13.37
Global Buckling	
Service Level A&B	8.71
Service Level C	10.46
Governing Allowable Vacuum, inch w.g.	8.71
Governing Allowable when vacuum = Level C load	10.46
Current Vacuum Limit, inches w.g.	12

Table 6-3. Summary of Primary Tank Buckling Evaluation

	AP
Approx. Operating History	
Temp, F	120
Hwaste, inch	422
Maximum Expected Future Operating Conditions	
Temp, F	210
Hwaste, inch	460
SpG	1.83
Yield at Temp, ksi	43.80
Corrosion Allowance, inch	0.000
Level C Vacuum Limit, inch w.g.	13.35
Corrosion Allowance, inch	0.010
Level C Vacuum Limit, inch w.g.	12.85
Corrosion Allowance, inch	0.025
Level C Vacuum Limit, inch w.g.	12.11
Corrosion Allowance, inch	0.060
Level C Vacuum Limit, inch w.g.	10.46

6.5 ASME Concrete-Backed Steel Evaluation

The evaluation criteria for the concrete-backed steel liner (both primary and secondary liner) are specified by Day et al. (1995) in WHC-SD-WM-DGS-003. These requirements were taken from the ASME B & PV Code, Section III, Division 2, Subsection NC-3700 (ASME 1992c). The seismic load component is added to the factored load combination under the abnormal/extreme environmental category.

6.5.1 Best Estimate Soil – Best Estimate Concrete

Figures 6-59 through 6-64 show the demand/capacity ratios for the primary tank for the BES-BEC material combination. All demand/capacity ratios are less than 1.0.

6.5.2 Upper Bound Soil – Best Estimate Concrete

Figures 6-65 through 6-70 show the demand/capacity ratios for the primary tank for the UBS-BEC material combination. All demand/capacity ratios are less than 1.0.

6.5.3 Lower Bound Soil – Best Estimate Concrete

Figures 6-71 through 6-76 show the demand/capacity ratios for the primary tank for the LBS-BEC material combination. All demand/capacity ratios are less than 1.0.

6.5.4 Best Estimate Soil – Fully Cracked Concrete

Figures 6-77 through 6-82 show the demand/capacity ratios for the primary tank for the LBS-FCC material combination. All demand/capacity ratios are less than 1.0.

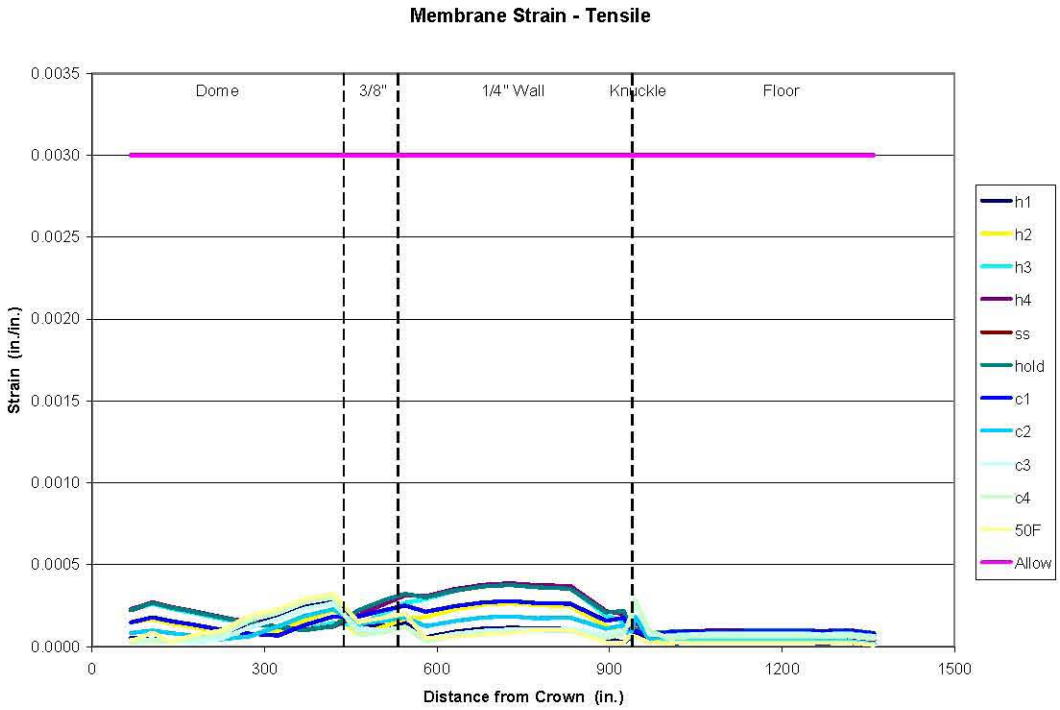


Figure 6-59. BES – BEC, Principal Membrane Strain – Tension (ε_1)

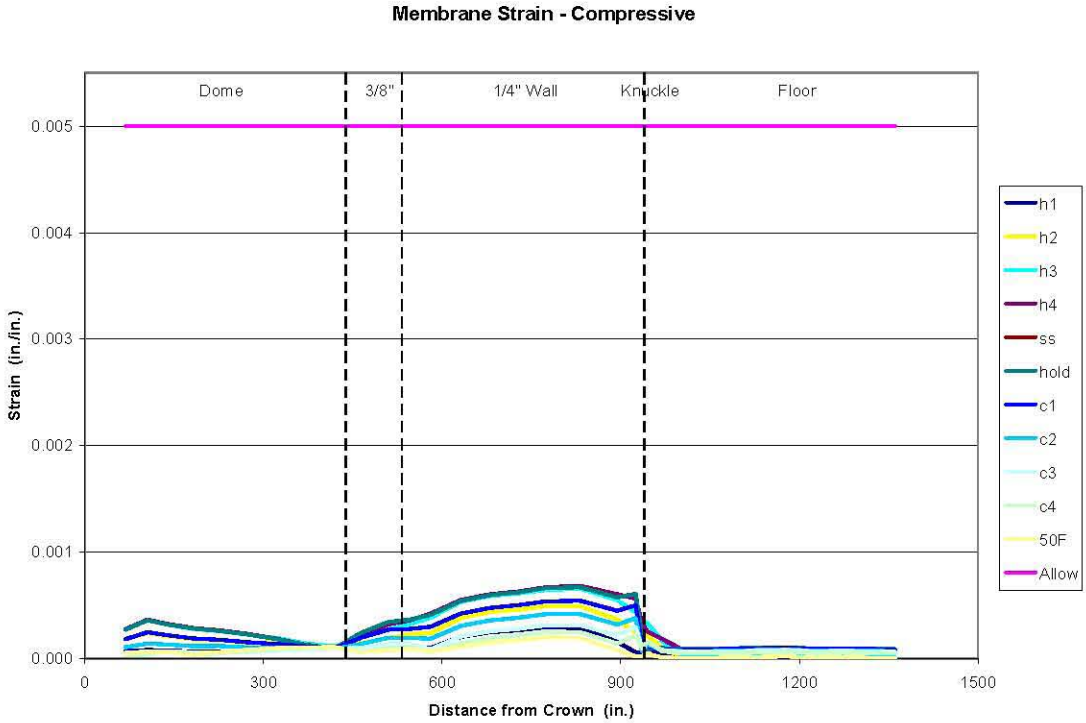


Figure 6-60. BES – BEC, Principal Membrane Strain – Compression (ε_3)

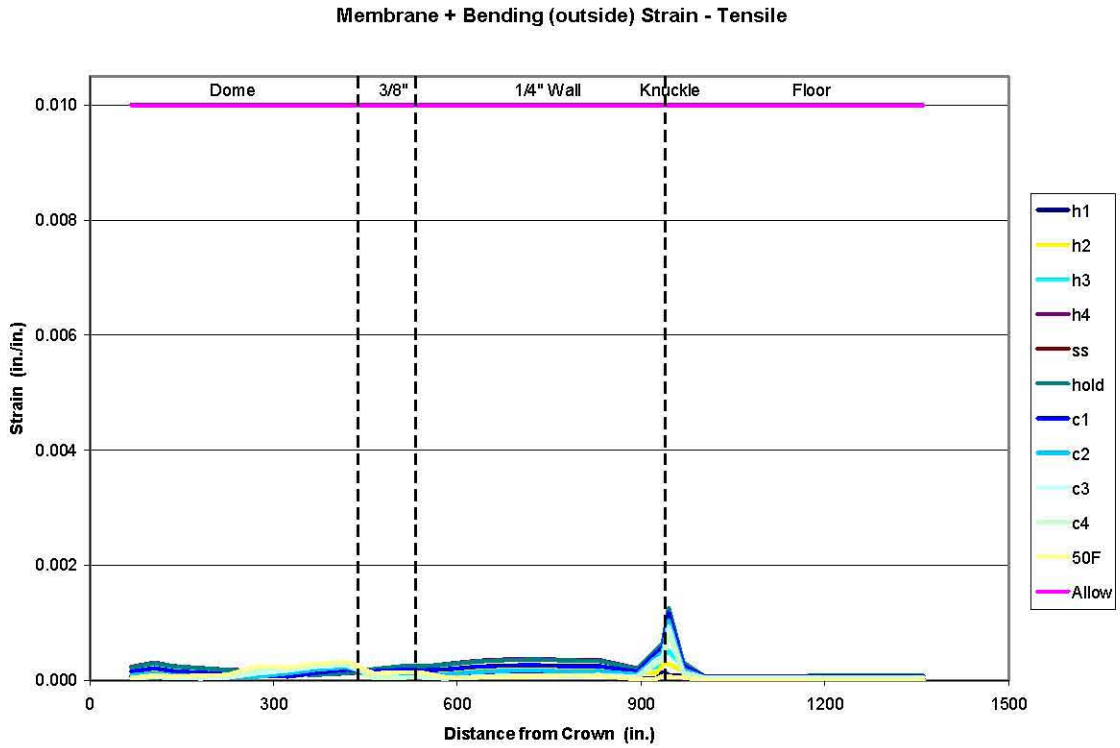


Figure 6-61. BES – BEC, Principal Membrane + Bending Strain Outer Surface – Tension (ε_1)

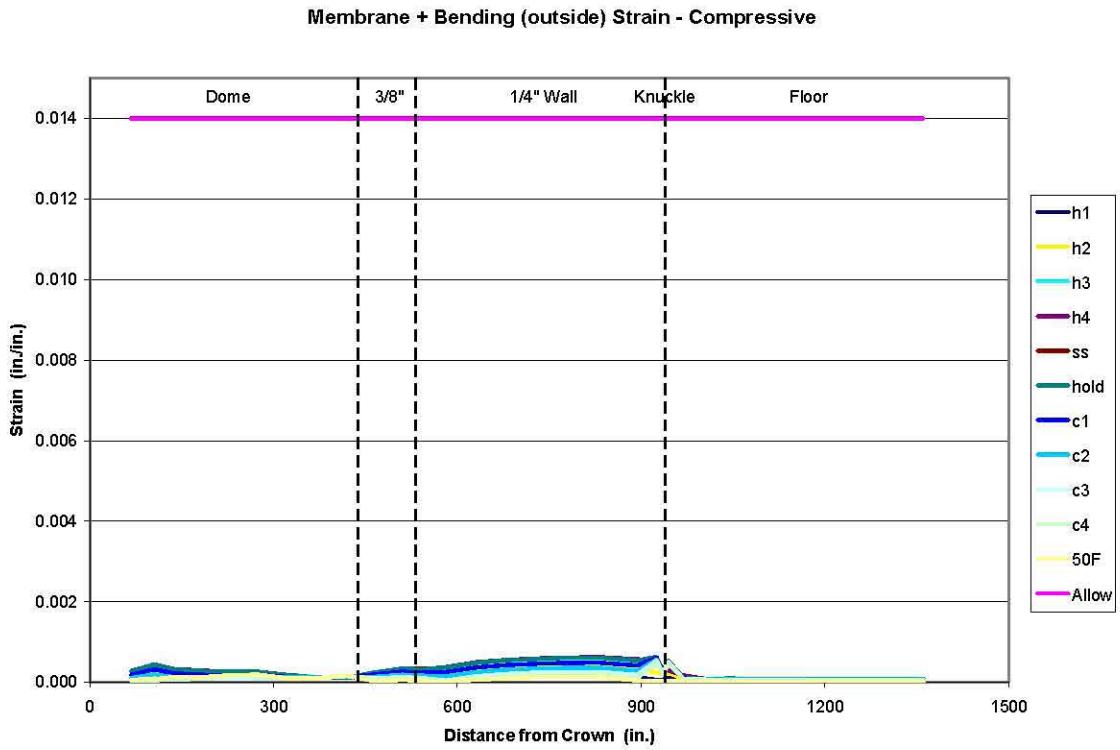


Figure 6-62. BES – BEC, Principal Membrane + Bending Strain Outer Surface – Compression (ε_3)

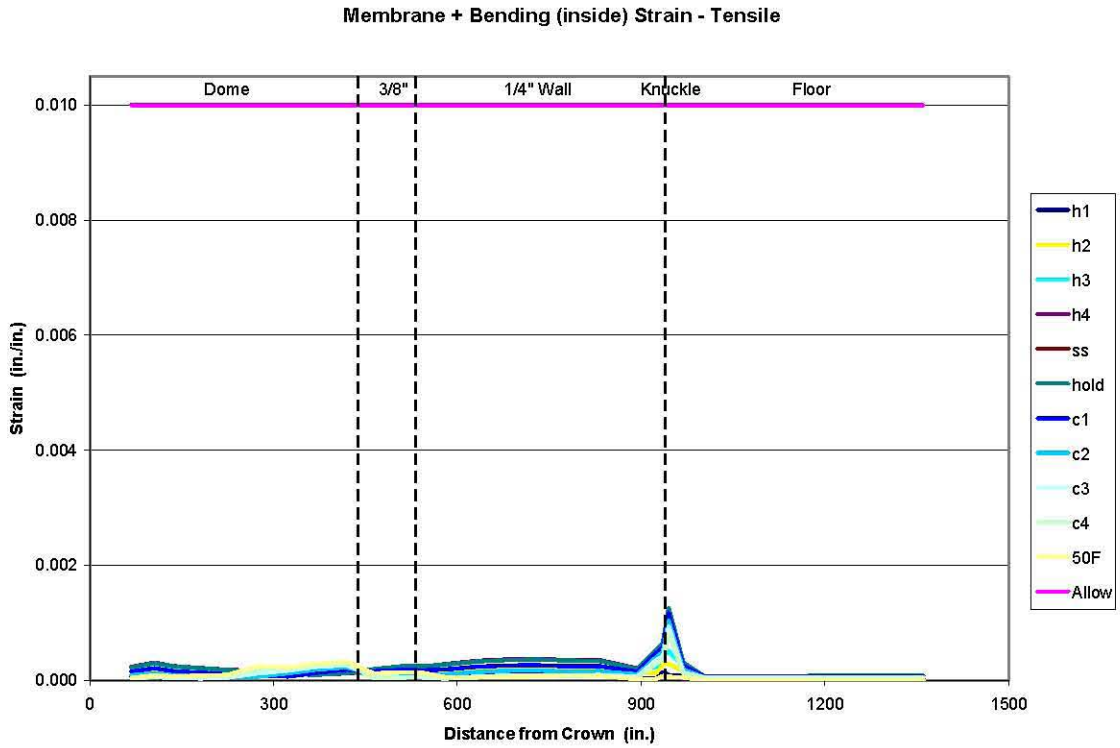


Figure 6-63. BES – BEC, Principal Membrane + Bending Strain Inner Surface – Tension (ε_1)

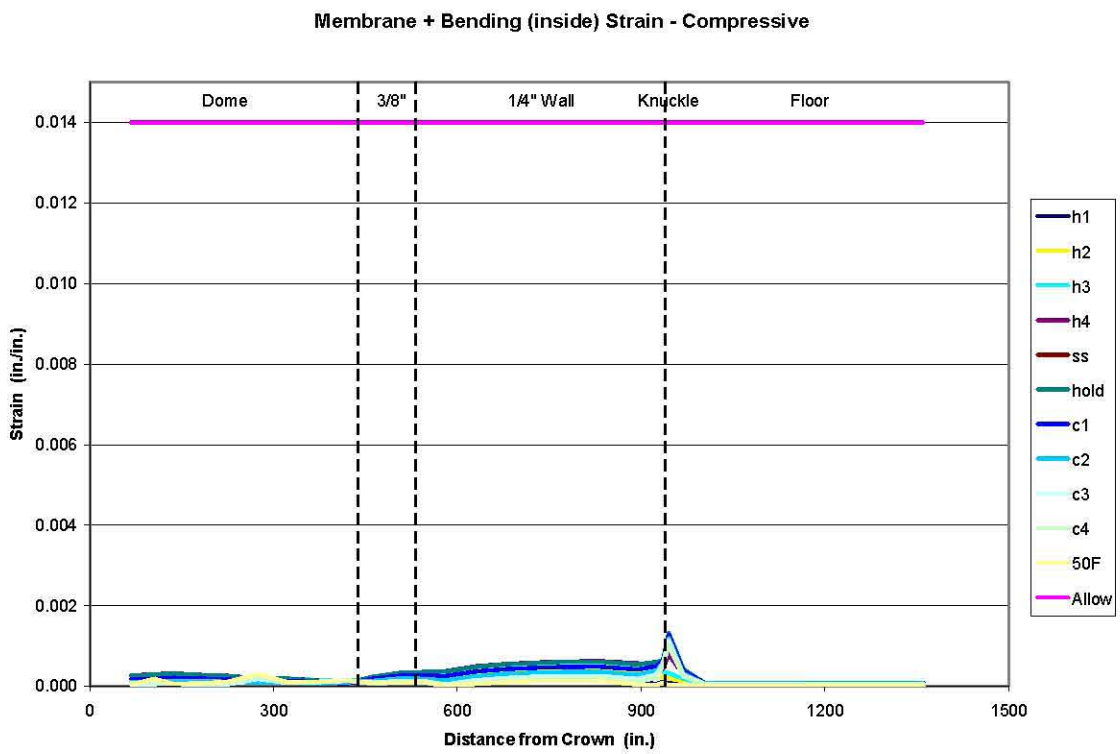


Figure 6-64. BES – BEC, Principal Membrane + Bending Strain Inner Surface – Compression (ε_3)

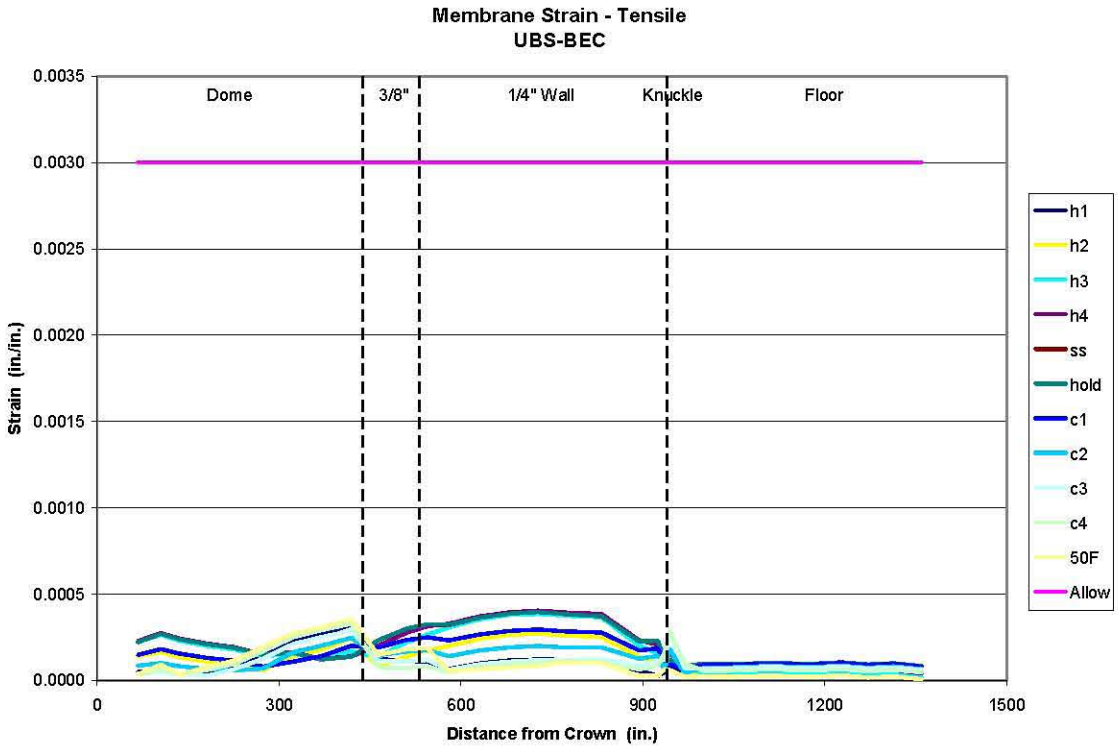


Figure 6-65. UBS – BEC, Principal Membrane Strain – Tension (ε_1)

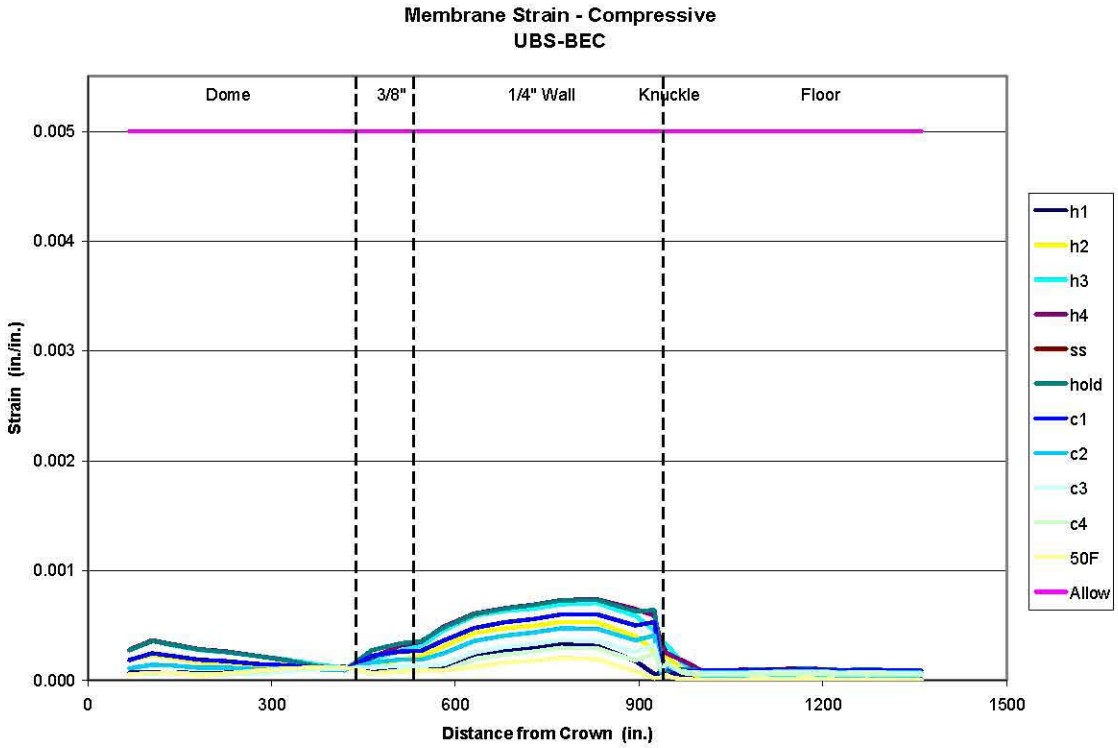


Figure 6-66. UBS – BEC, Principal Membrane Strain – Compression (ε_3)

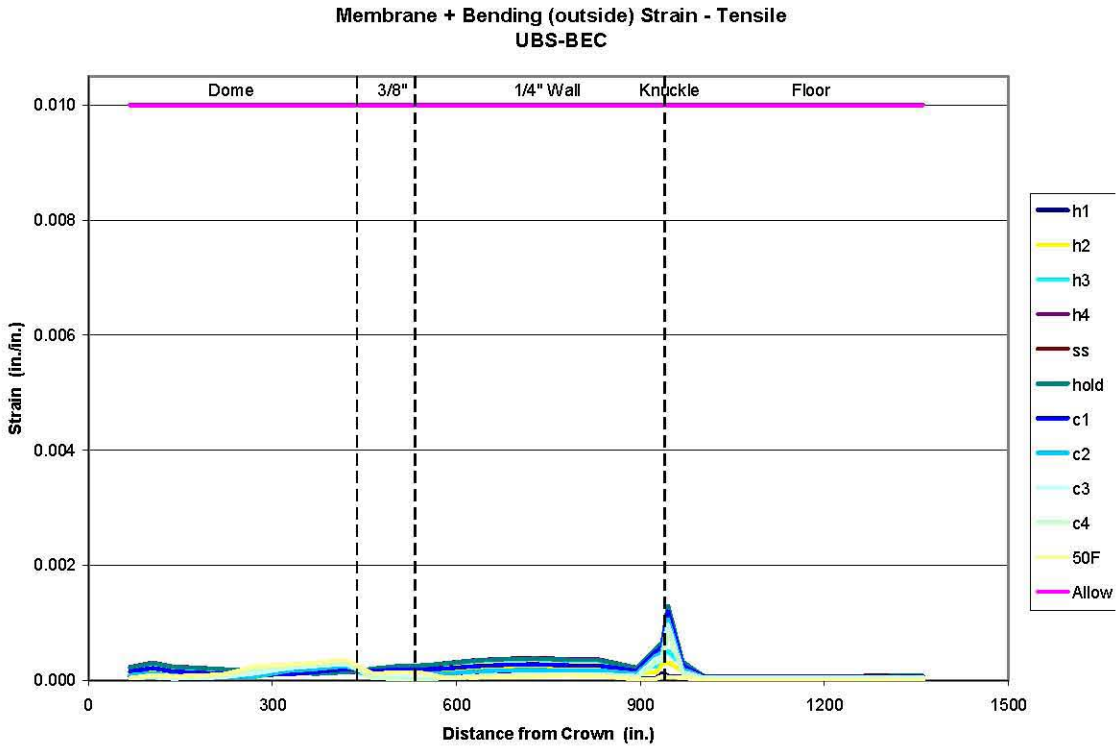


Figure 6-67. UBS – BEC, Principal Membrane + Bending Strain Outer Surface – Tension (ε_1)

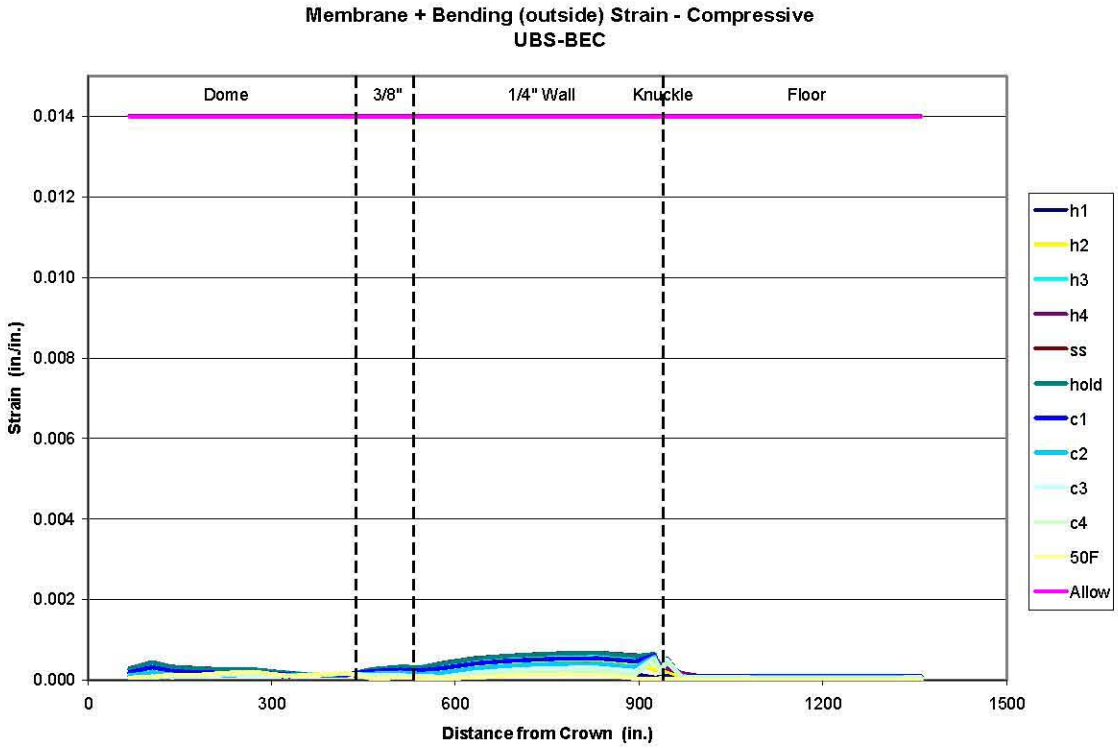


Figure 6-68. UBS – BEC, Principal Membrane + Bending Strain Outer Surface – Compression (ε_3)

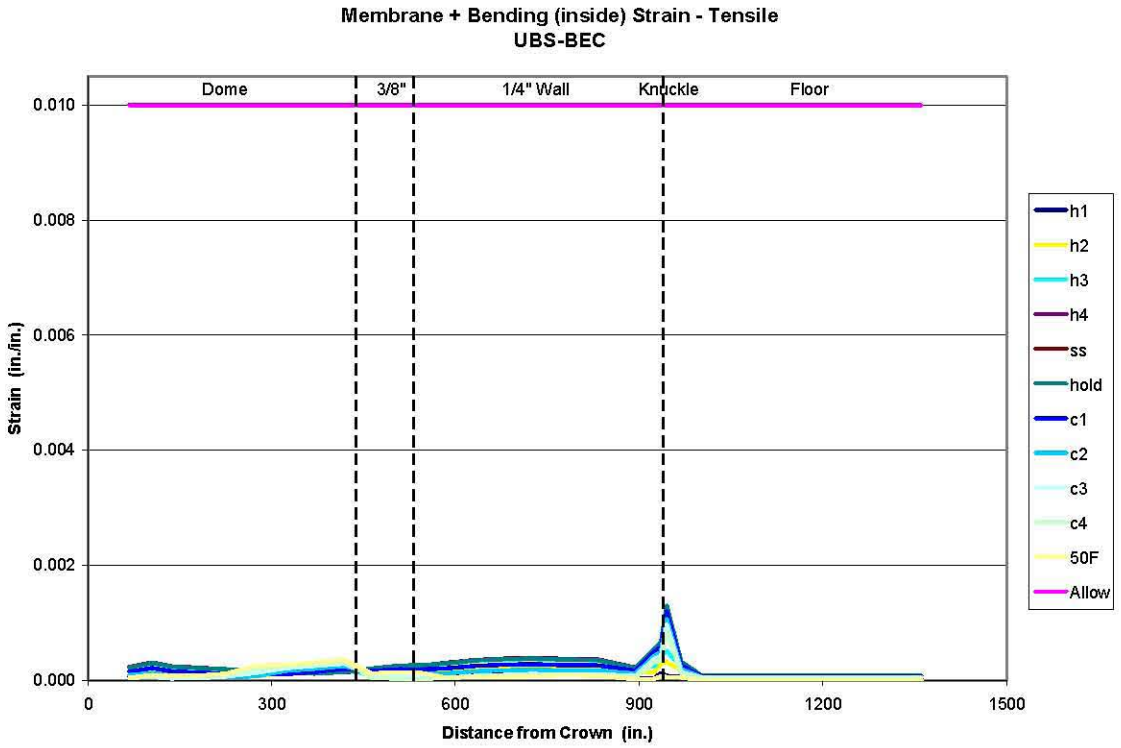


Figure 6-69. UBS – BEC, Principal Membrane + Bending Strain Inner Surface – Tension (ε_1)

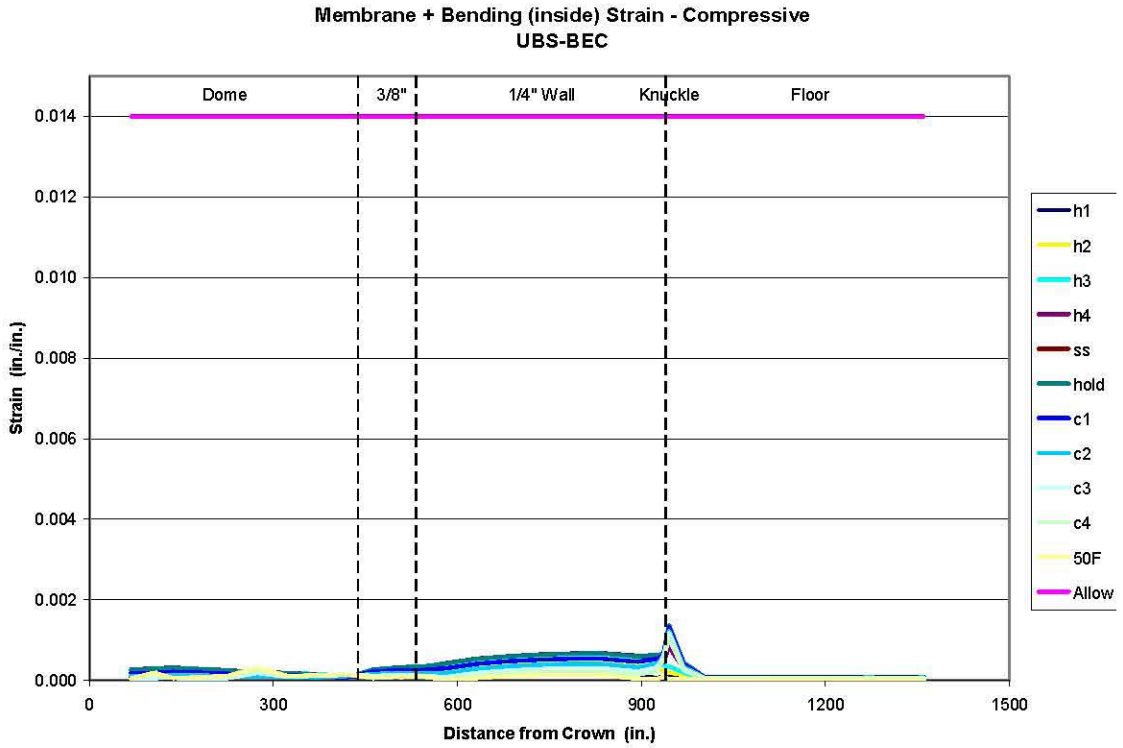


Figure 6-70. UBS – BEC, Principal Membrane + Bending Strain Inner Surface – Compression (ε_3)

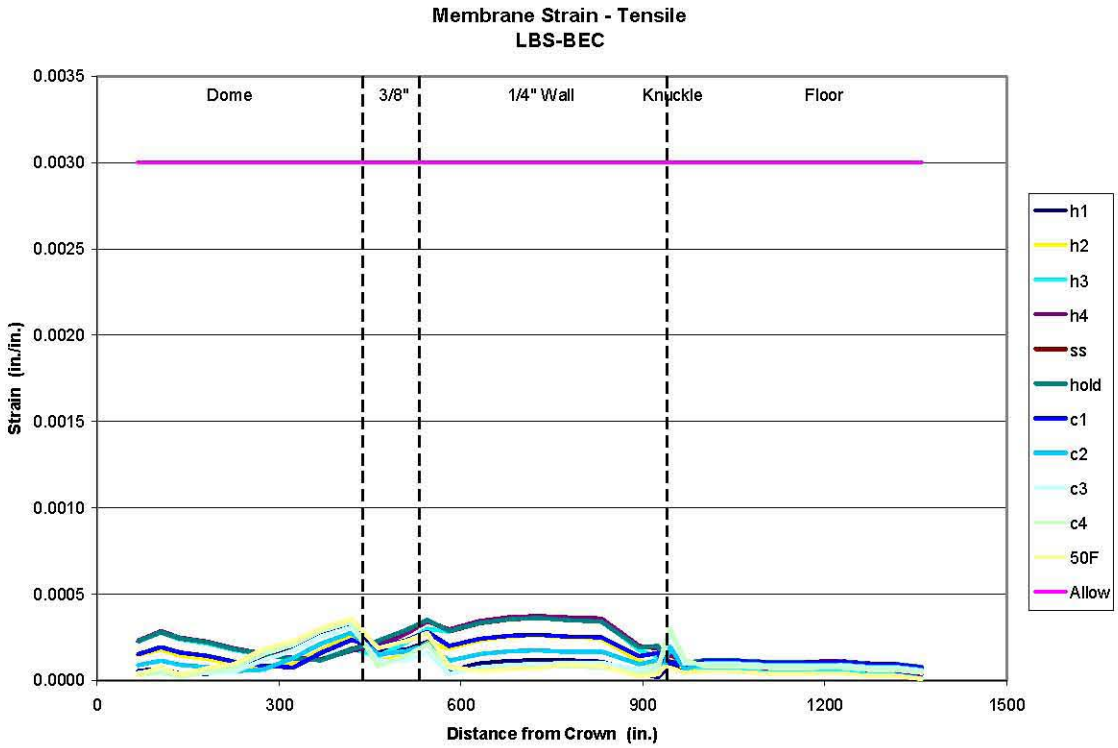


Figure 6-71. LBS – BEC, Principal Membrane Strain – Tension (ε_1)

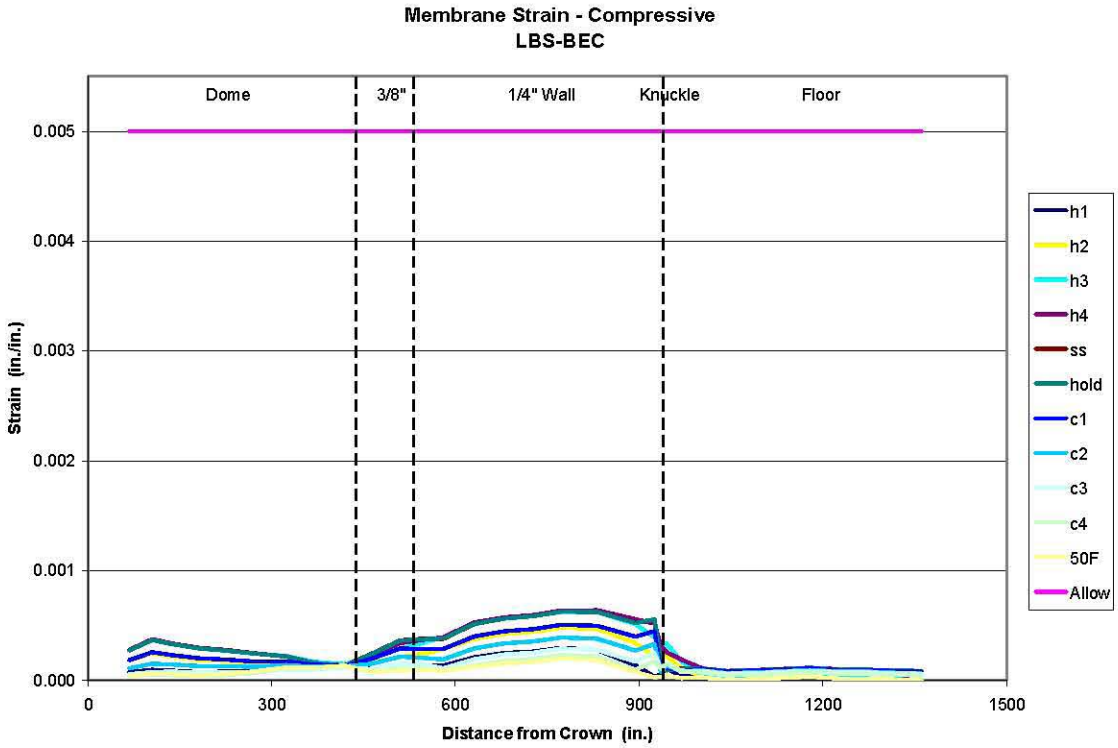


Figure 6-72. LBS – BEC, Principal Membrane Strain – Compression (ε_3)

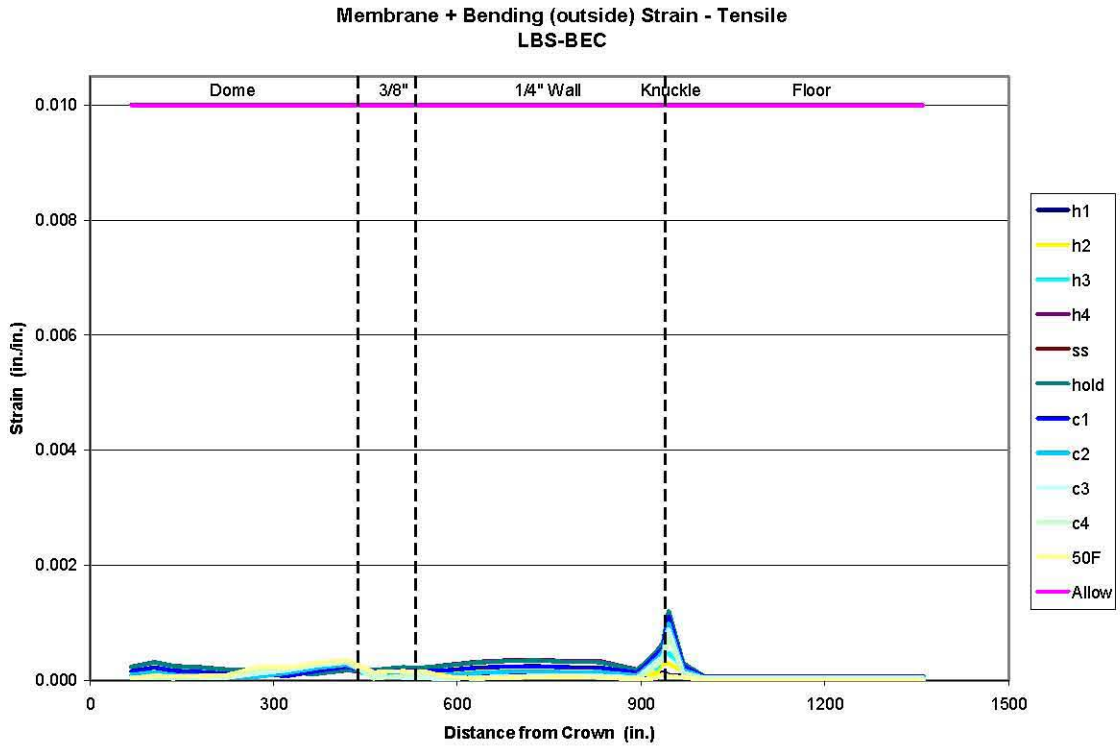


Figure 6-73. LBS – BEC, Principal Membrane + Bending Strain Outer Surface – Tension (ε_1)

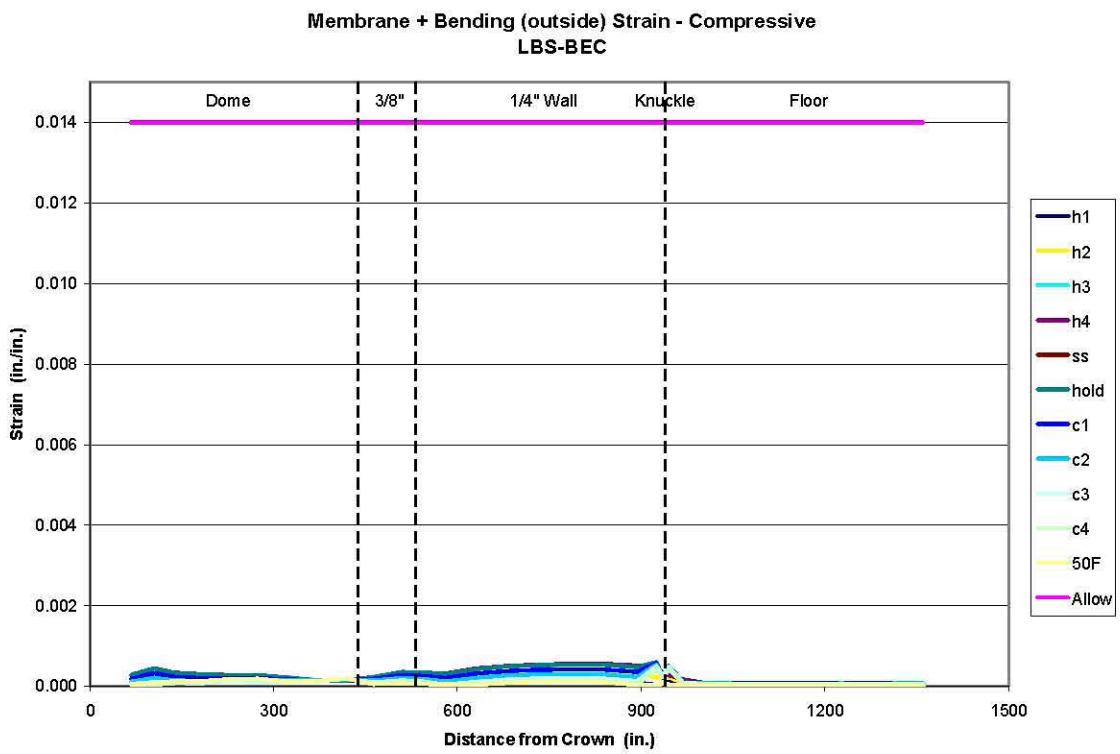


Figure 6-74. LBS – BEC, Principal Membrane + Bending Strain Outer Surface – Compression (ε_3)

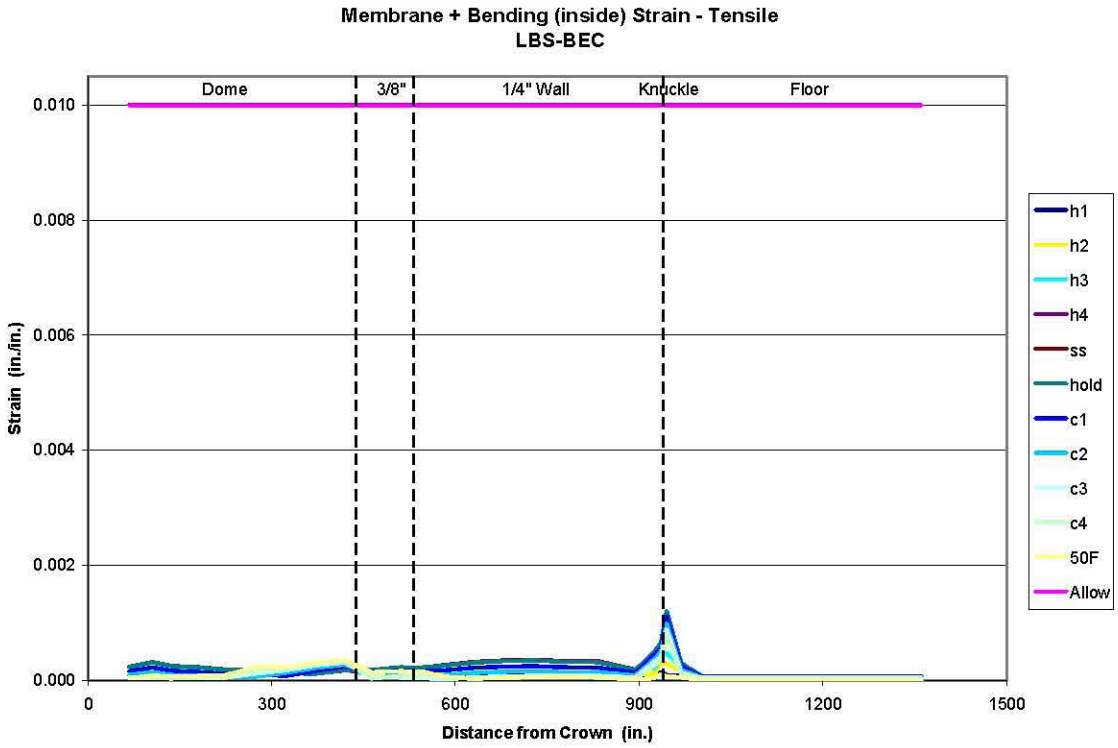


Figure 6-75. LBS – BEC, Principal Membrane + Bending Strain Inner Surface – Tension (ε_1)

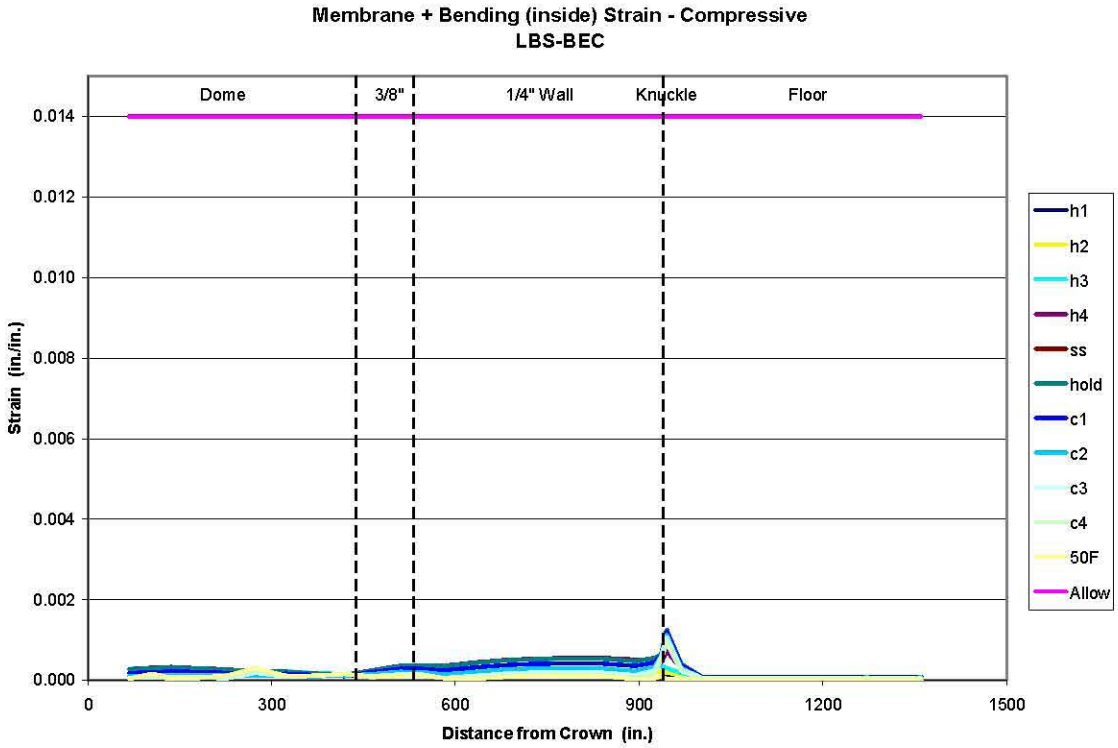


Figure 6-76. LBS – BEC, Principal Membrane + Bending Strain Inner Surface – Compression (ε_3)

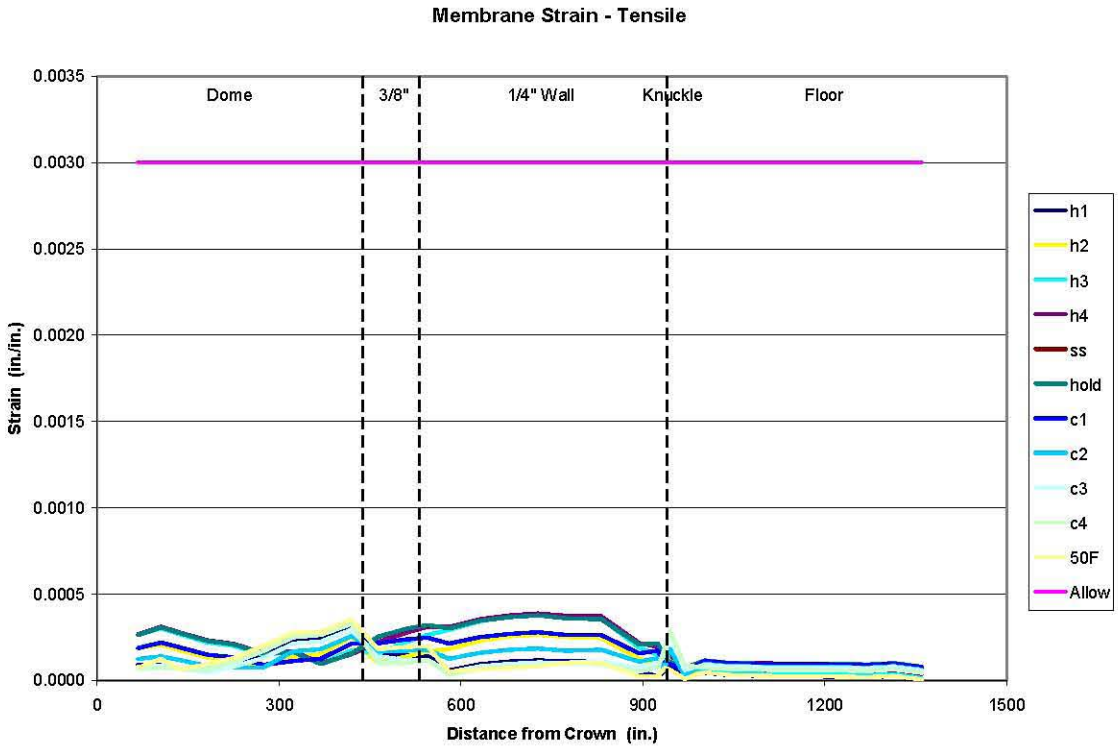


Figure 6-77. BES – FCC, Principal Membrane Strain – Tension (ε_1)

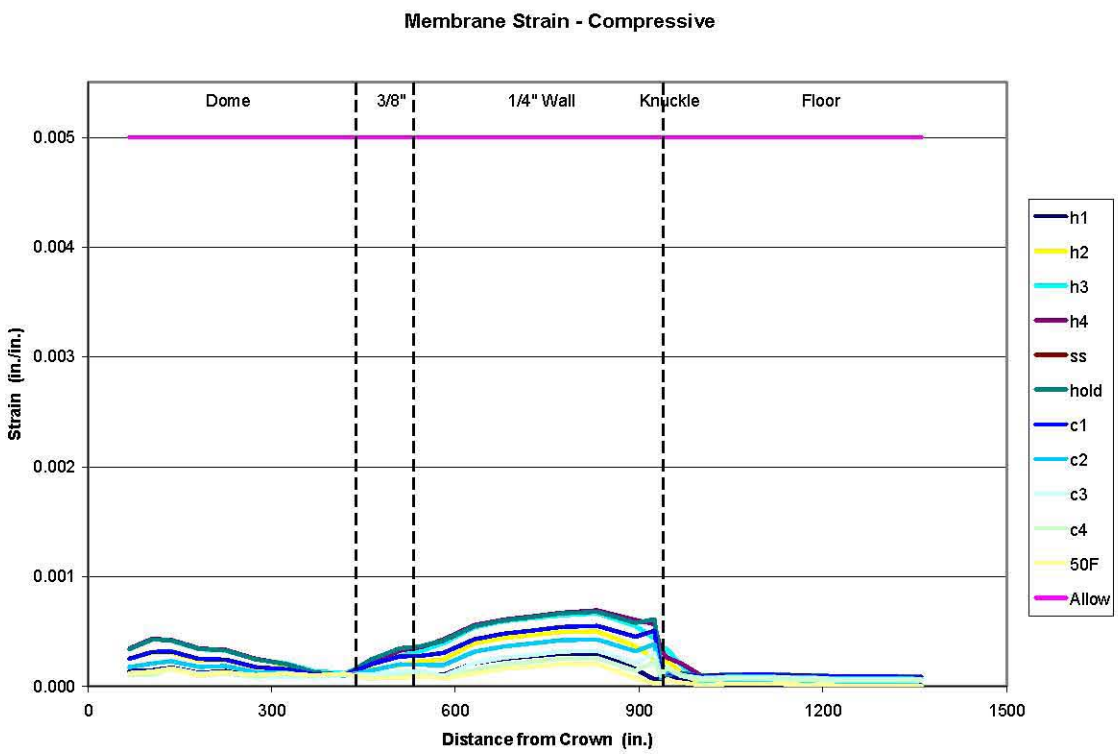


Figure 6-78. BES – FCC, Principal Membrane Strain – Compression (ε_3)

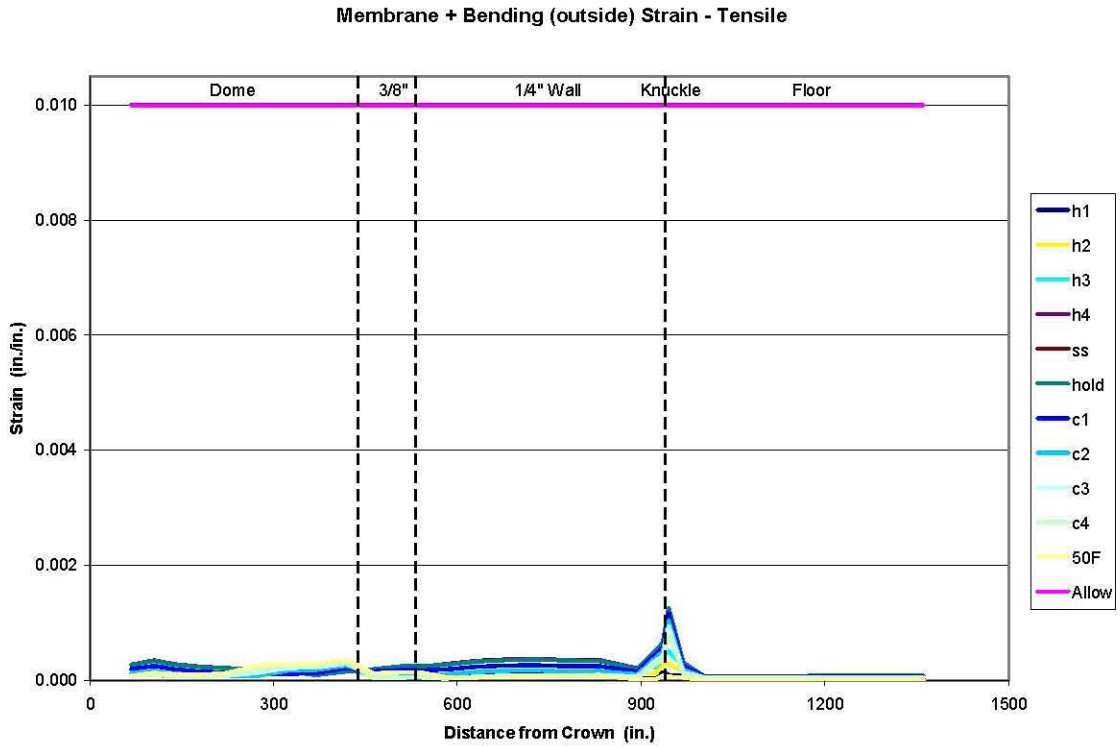


Figure 6-79. BES – FCC, Principal Membrane + Bending Strain Outer Surface – Tension (ε_1)

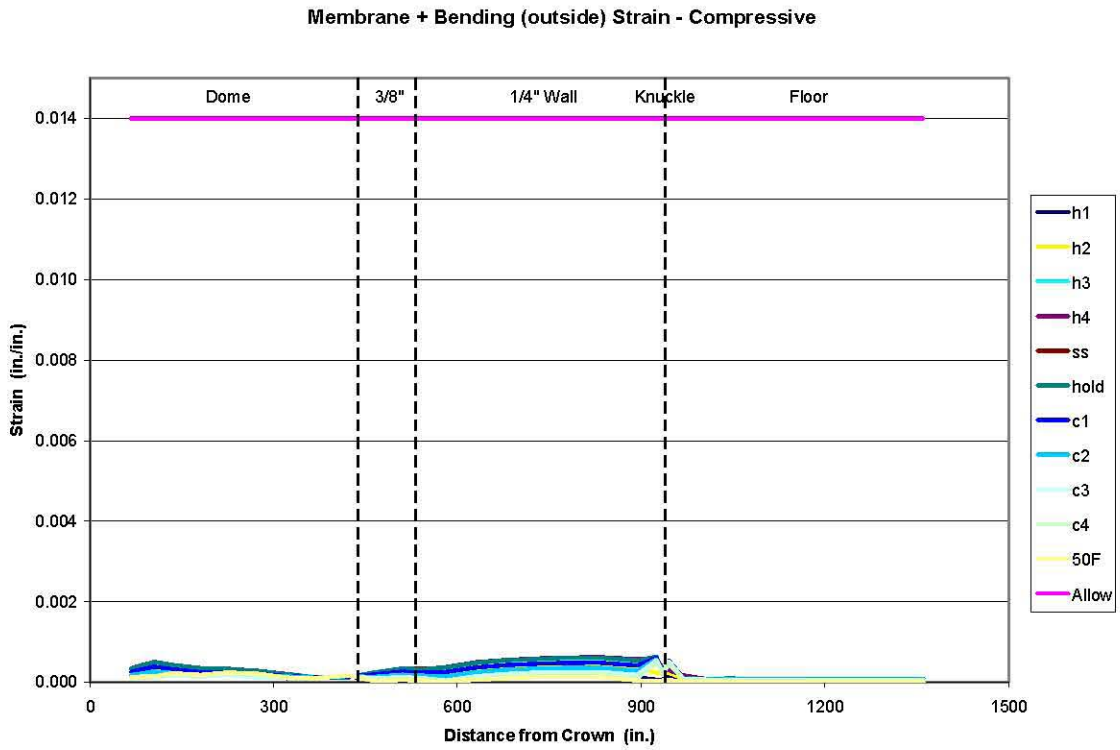


Figure 6-80. BES – FCC, Principal Membrane + Bending Strain Outer Surface – Compression (ε_3)

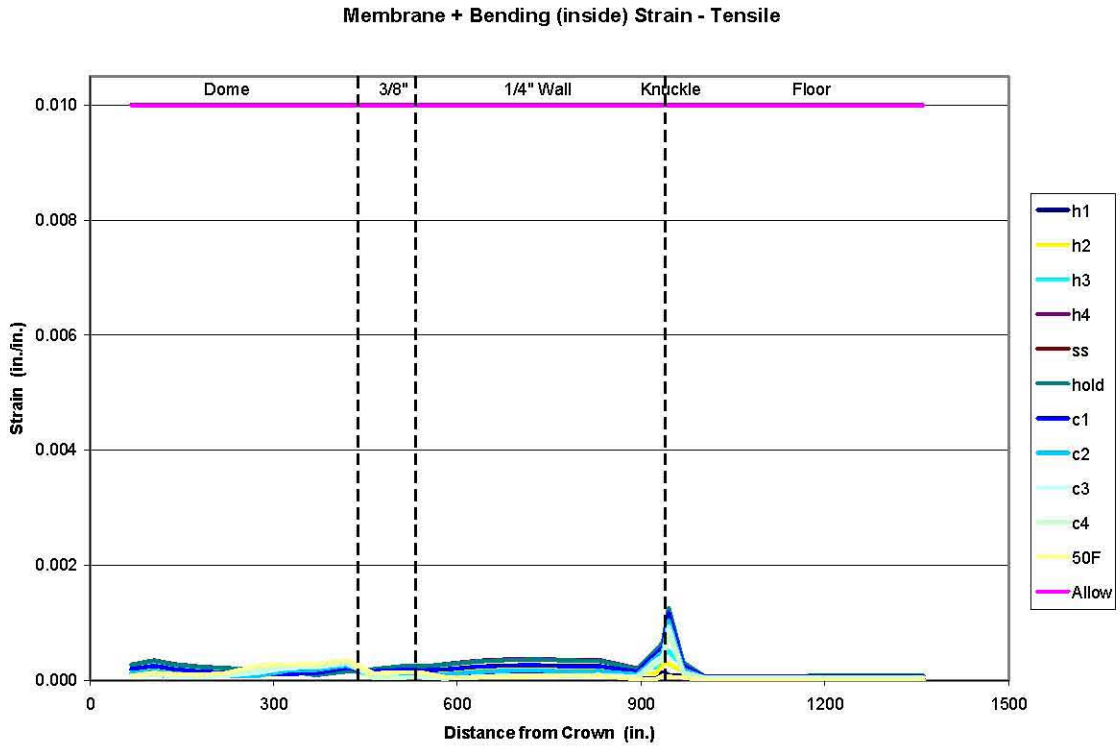


Figure 6-81. BES – FCC, Principal Membrane + Bending Strain Inner Surface – Tension (ε_1)

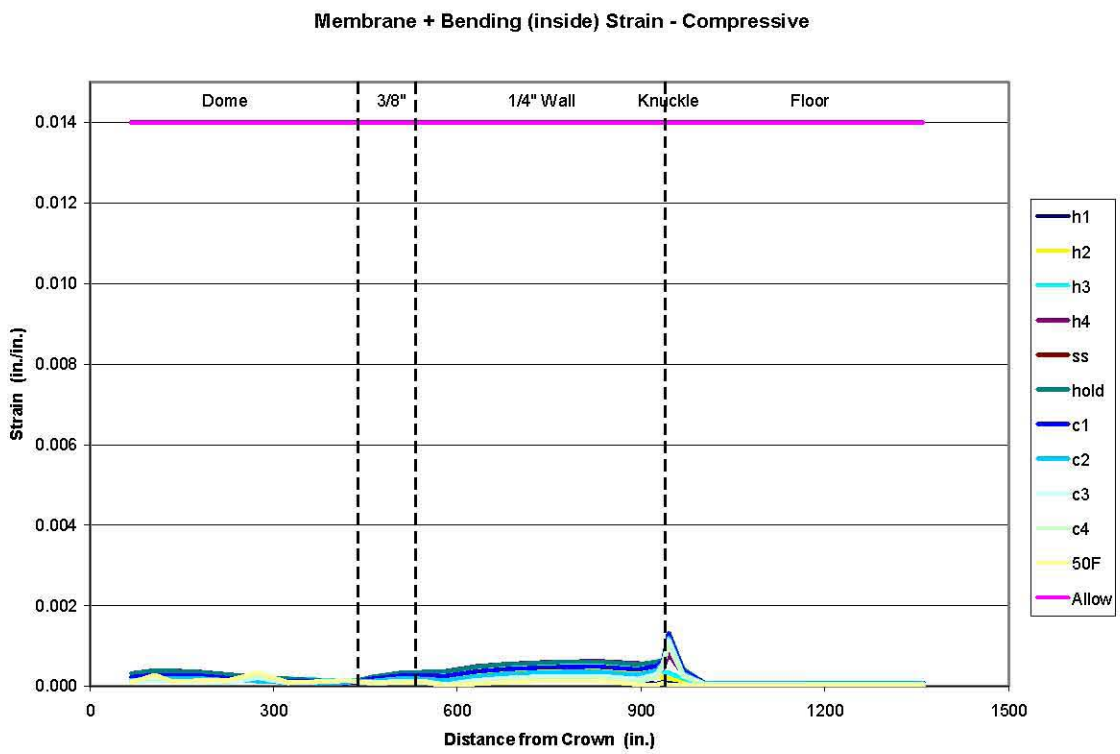


Figure 6-82. BES – FCC, Principal Membrane + Bending Strain Inner Surface – Compression (ε_3)

6.6 J-Bolt Evaluation

Evaluation of the primary tank dome J-bolts was conducted in accordance with ASME Section III, Division 2, Subsection CC-3730 (ASME 1992b). Table 6-4 on page 6.59 summarizes the calculation for the J-bolt allowable loads. The mechanical (non-self-limiting) loads are evaluated against a force criterion after 60 years of tank operation. The thermal loads are included in the displacement-limited load evaluation, so this evaluation is conducted at each load step of the final thermal transient. The J-bolt evaluations are shown in Figures 6-83 through 6-90.

The primary tank dome J-bolt forces and displacements are within the allowable limit for all combinations of soil and concrete.

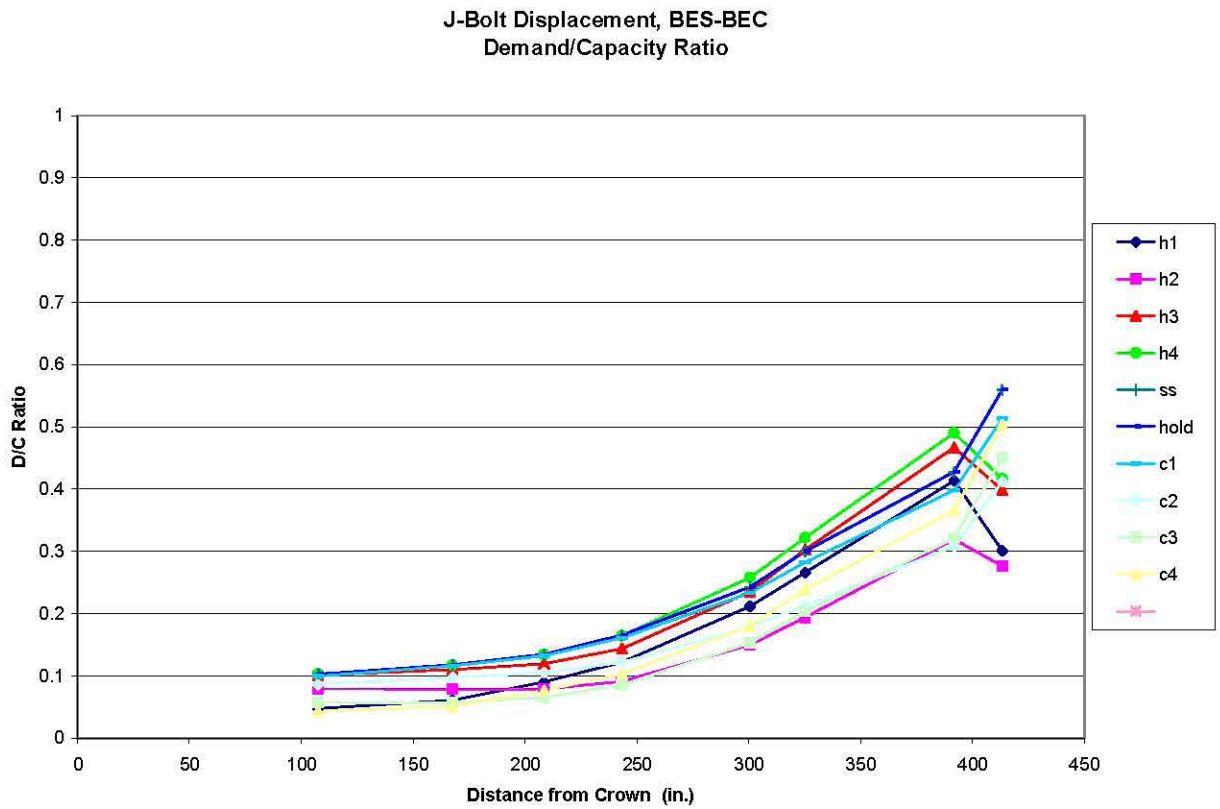


Figure 6-83. BES – BEC, J-Bolt Displacement Evaluation

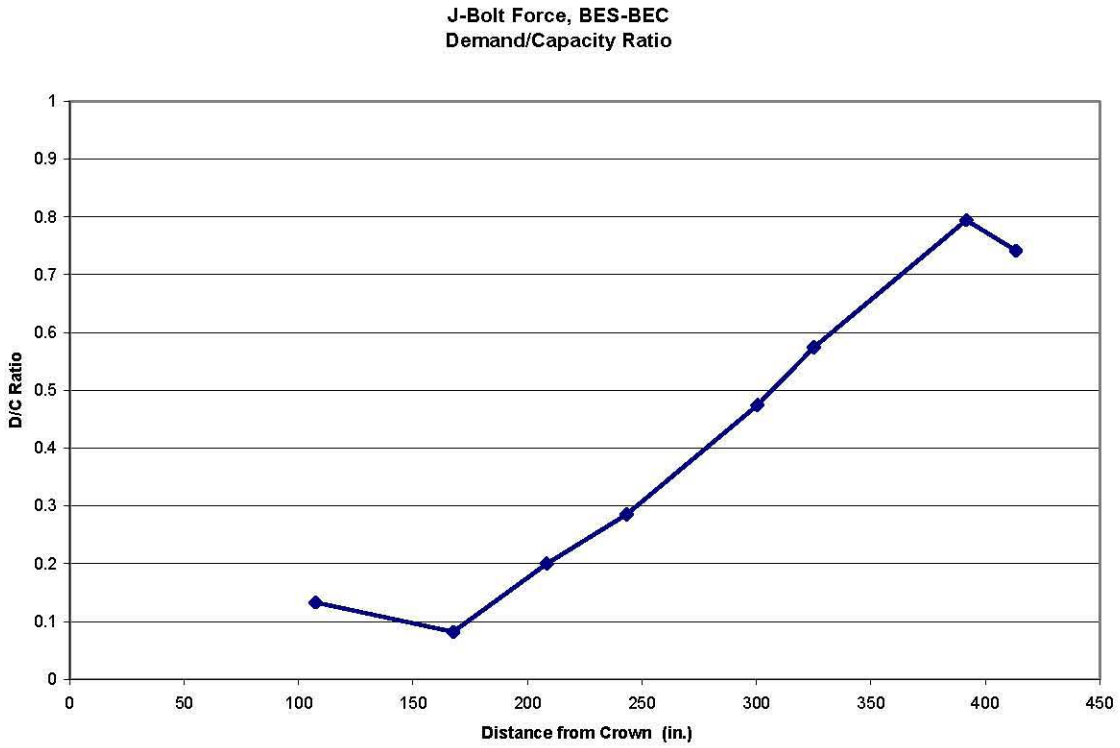


Figure 6-84. BES – BEC, J-Bolt Force Evaluation

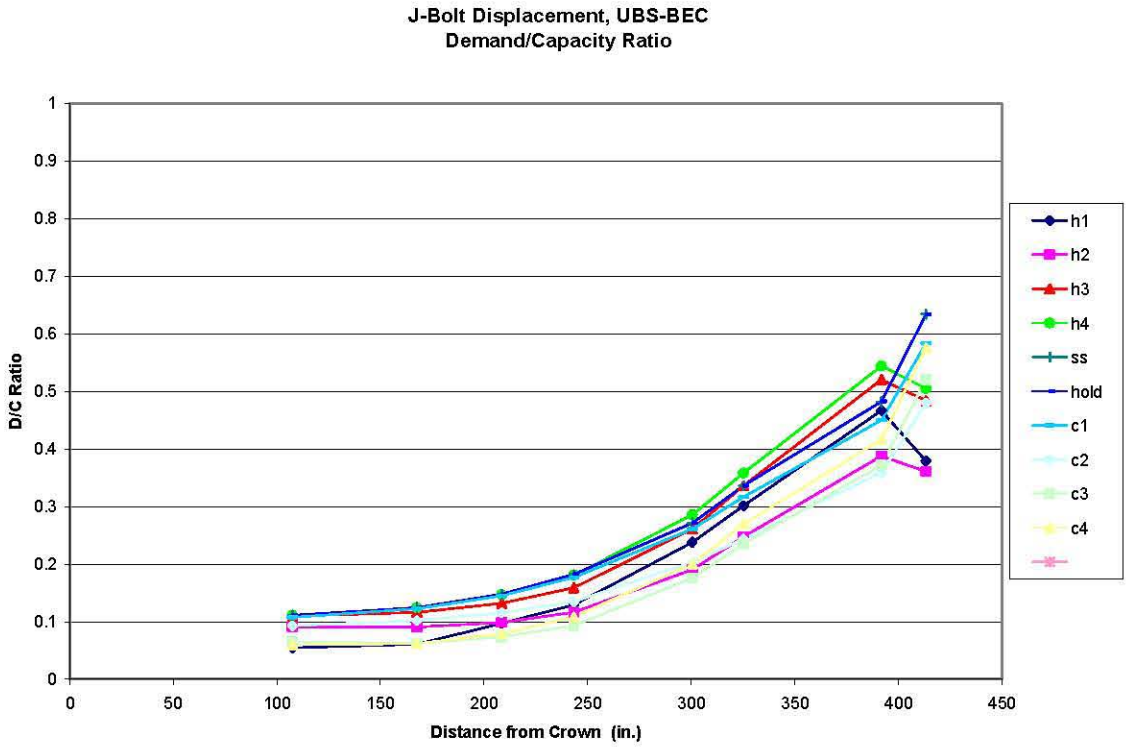


Figure 6-85. UBS – BEC, J-Bolt Displacement Evaluation

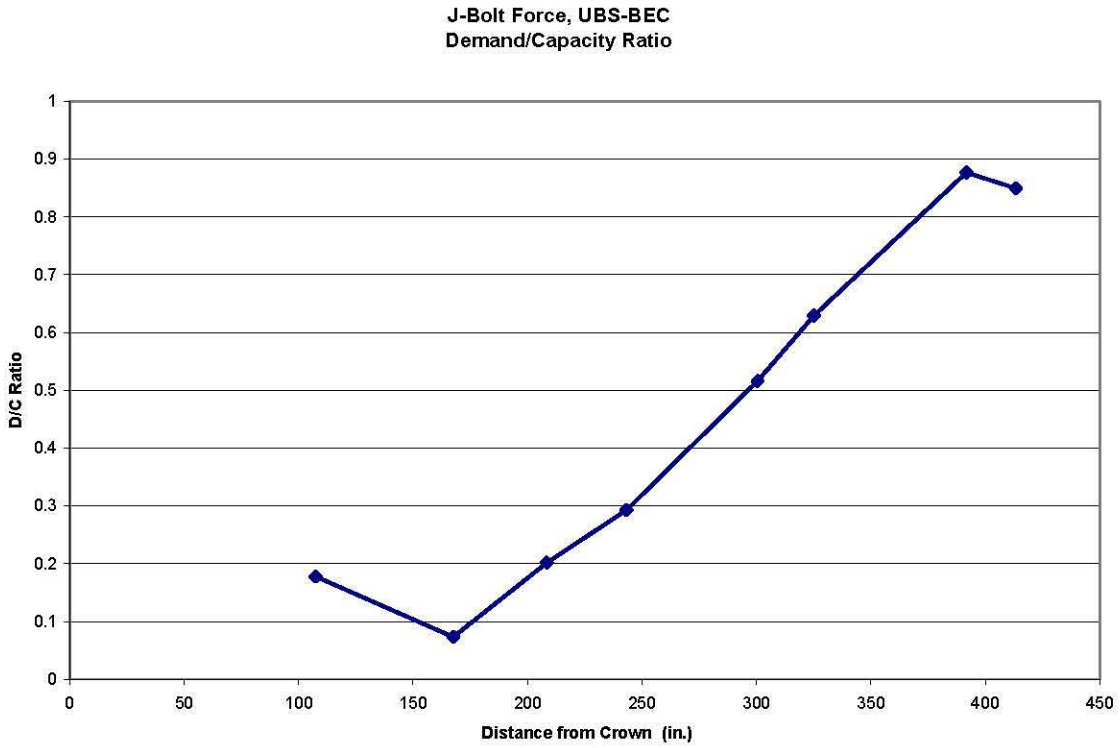


Figure 6-86. UBS – BEC, J-Bolt Force Evaluation

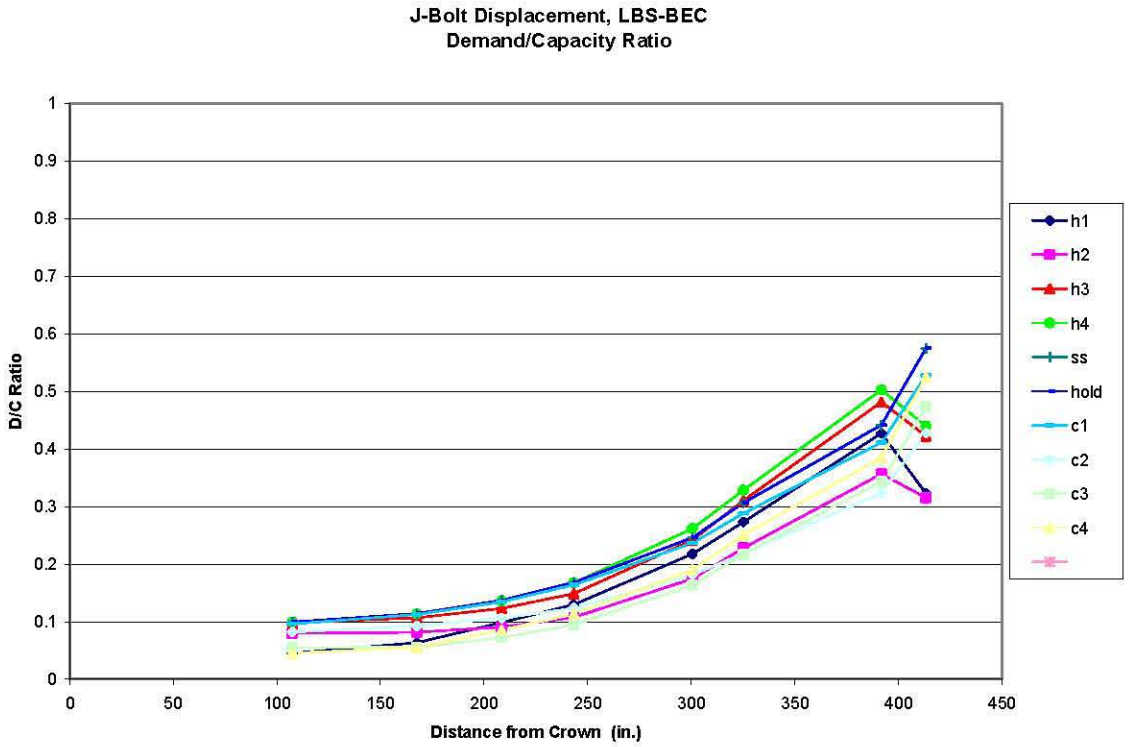


Figure 6-87. LBS – BEC, J-Bolt Displacement Evaluation

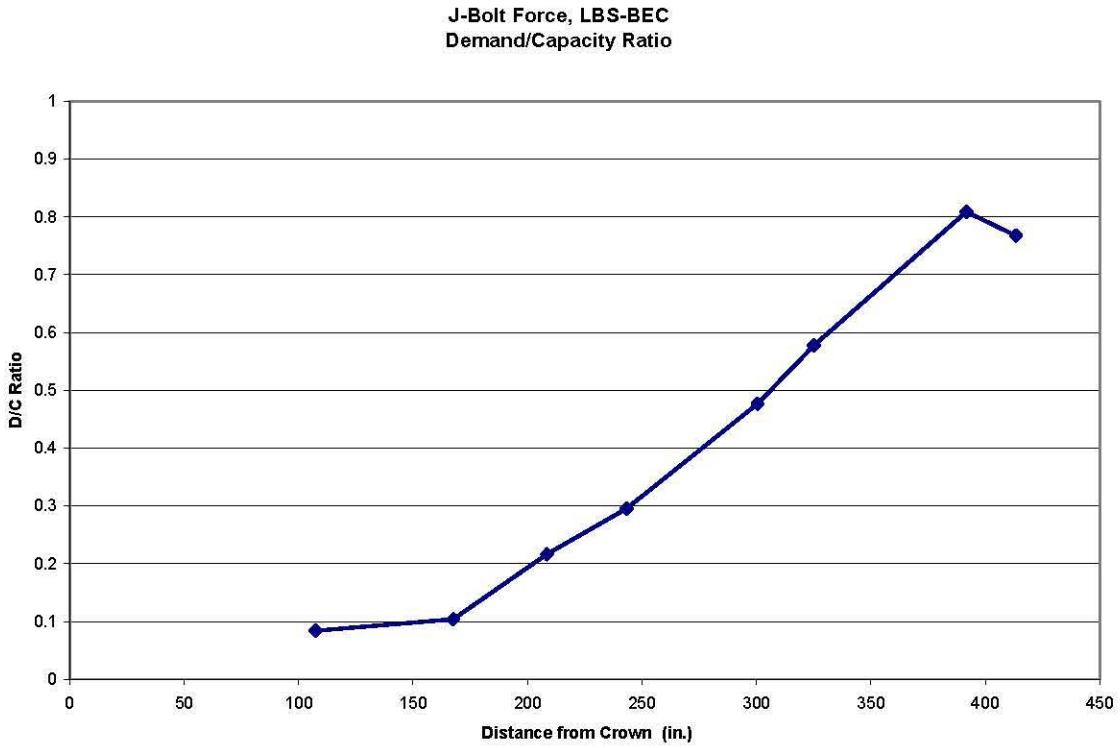


Figure 6-88. LBS – BEC, J-Bolt Force Evaluation

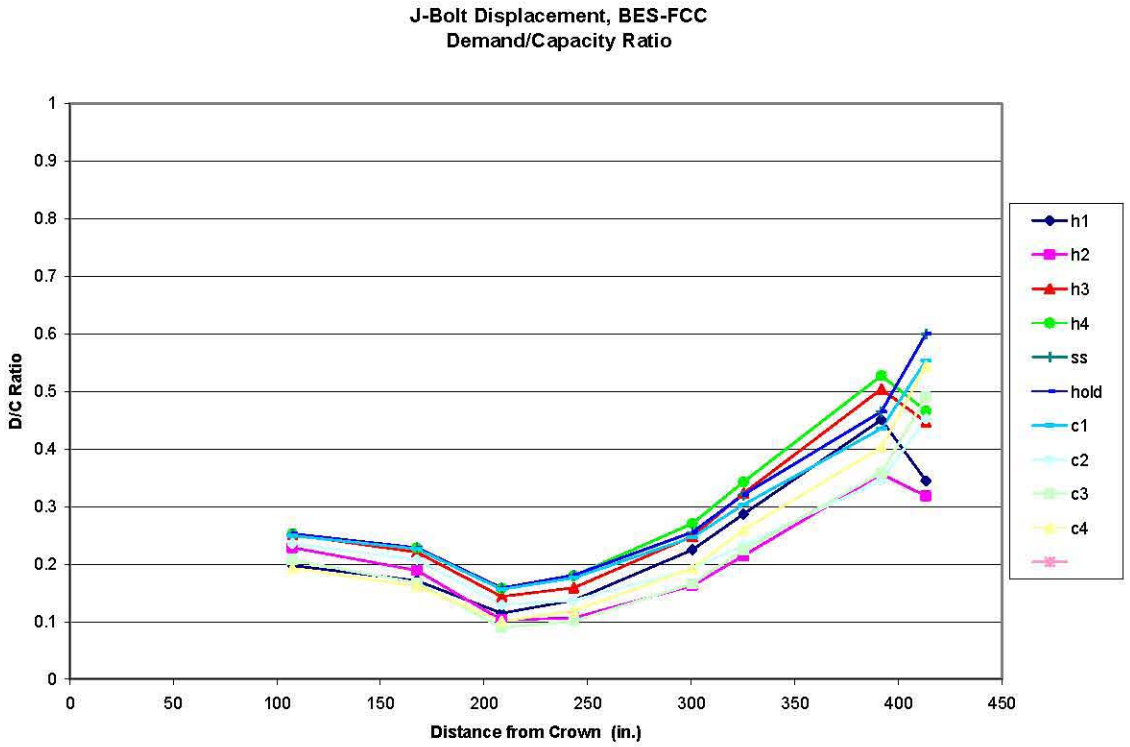


Figure 6-89. BES – FCC, J-Bolt Displacement Evaluation

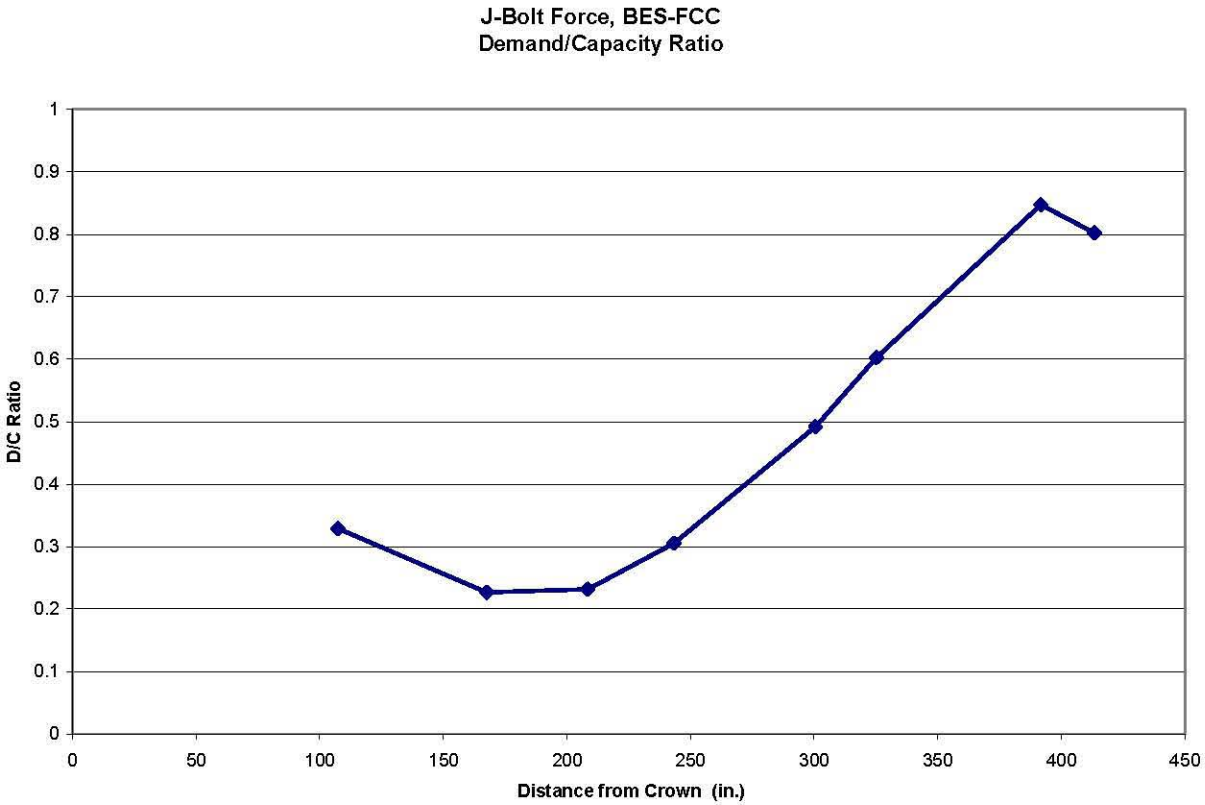


Figure 6-90. BES – FCC, J-Bolt Force Evaluation

Table 6-4. J-Bolt Allowable Loads

J-Bolt Allowables for Combined Loading

$(P/F_{ap})^{5/3} + (S/F_{as})^{5/3} <= 1$

P = Applied tension load
S = Applied Shear load
F_{ap} = Allowable for an appled Tension load
F_{as} = Allowable for an applied Shear Load

J-Bolt Allowables for Tension/Shear only Loading

$F_a = 0.9F_y$
$F_a = 0.5F_u$
} Lesser of both values

F_a = Allowable force
F_y = Force to reach anchor yield strength
F_u = Force to reach anchor ultimate strength

J-Bolt Steel Properties

f_y	36000	Yield Strength, psi		
f_u	60000	Ultimate Strength, psi		
Concrete Properties, 3-ksi Hanford Mix				
f_c'	4860	Compressive Strength, psi, Mean value, 60 yrs at T=250F		
E	3.257E+06	Elastic Modulus, psi, Mean value, 60 yrs at 250F		
Shear and Tensile Areas				
A_s Tensile	0.196	Bolt Shank area, in^2		
A_s Shear	0.442	Stud Base area, in^2		
Shear F_y		**Shear F_u**		
$A_s f_y$	15904	**$0.9A_s f_u$**	23856	**Steel Failure Limit**
		$5.66A_s f_c^{0.3} E_c^{0.44}$	23424	**Concrete Failure Limit**
Tensile F_y		**Tensile F_u**		
$A_s f_y$	7069	**$2/3A_s f_u$**	7854	
$1/2A_s f_u$	5890			

J-Bolt Allowables for Combined Loading

$(P/F_{ap})^{5/3} + (S/F_{as})^{5/3} <= 1$

(Unfactored Yield and Ultimate Limits)

F_y		F_u	
Tension	Shear	Tension	Shear
5890	15904	7854	23424

J-Bolt Allowables for Tension/Shear only Loading

F_y		F_u	
Tension	Shear	Tension	Shear
5890	15904	7854	23424

(Abnormal Load Allowables)

$0.9F_y$		$0.5F_u$			$0.9F_y$		$0.5F_u$	
Tension	Shear	Tension	Shear		Tension	Shear	Tension	Shear
5301	14314	3927	11712		5301	14314	3927	11712
F_{ap} =	**3927**	**F_{as} =**	**11712**		**$F_{a(tension)}$ =**	**3927**	**$F_{a(shear)}$ =**	**11712**

7.0 Conclusions and Recommendations

The code evaluations reported in Chapter 6 for the AP tank model with 460 inches of 1.83 SpG waste do not reveal any structural deficiencies with the integrity of the double-shell tanks. The analyses represent 60 years of use, which corresponds to an additional 40 years of use beyond the current date. The loads imposed on the model for the finite element analyses are significantly more severe than any service to date or proposed for the future. The material properties were selected to be lower bound and in the most severe combinations.

7.1 Reinforced Concrete

The reinforced concrete structure was evaluated in the manner required by ACI-349. Load combinations 1, 4 (which includes the seismic load), and 9 of the ACI code were evaluated for each combination of soil and concrete properties. The axial load and moment were evaluated on the load-moment interaction diagram for each individual cross section. The demand was demonstrated to be lower than the capacity at all locations for all load combinations. The cross-section shear demand was less than the capacity for all sections. The in-plane shear demand/capacity ratios were evaluated for the seismic loads and showed low values.

7.2 Primary Tank

The primary tank is governed by ASME B & PV Code, Section III, Division 1. The allowable stress value, S_m, is provided by the code at operating temperature, which is defined to be 210°F for operating loads. This value at this temperature was used for all the stress intensity code checks regardless of temperature. All sections of the primary tank were checked to Service Level D requirements with k = 2.0. In all instances the factored inelastic general primary membrane stress intensity remained below the yield stress (which is lower than the allowable $2S_m$). The primary local membrane plus bending stress intensity remained below the code allowable value of 1.5 kS_m, and the primary + secondary (thermal) stress intensity range remained below the code allowable value of 3.0 S_m. Therefore, the primary tank is acceptable according to the established criteria.

7.3 Stress Corrosion Cracking

The use of the criterion limiting the primary tank principal stress on the inside surface to 90% of the yield strength of the steel to prevent stress corrosion cracking (SCC) was discontinued with the Combined Summary analysis (Rinker et al. 2006d). The SCC report (Rinker et al. 2005) discouraged further use of this criterion, citing the lack of a technical basis. The fracture mechanics method developed in that report was extended to evaluate the bounding tank under the thermal and operating loads. The results when considered with the current crack growth rate testing show that SCC is unlikely if the present operating requirements are maintained. Analysis also showed that the propensity for SCC would not be increased after a seismic event.

7.4 Primary Tank Buckling

A large displacement finite element analysis method was developed to evaluate the potential for buckling of the primary tank. The method was shown to have good correlation with the ASME code case N-284

method. The primary tank buckling evaluation showed the current limit on demand of 12 inch water (w.g.) vacuum to exceed the ASME allowable of 10.4 inch. This determination was based on analysis at the full 60-year corrosion allowance on the tank wall of 0.060 inch. However, analysis at a corrosion allowance of 0.025 inch results in an acceptable demand/capacity ratio. Therefore, the current limit of 12 inches w.g. for the AP tanks is acceptable given the current lack of corrosion in the tanks.

7.5 Concrete-Backed Liner

The evaluation criteria for the secondary steel liner are strain-based and taken from the ASME B & PV Code, Section III, Division 2, Subsection NC for normal service loads. The results in all cases demonstrate that the secondary liner strains are all well below the allowable strain levels. Therefore, the secondary liner is judged to be adequate.

7.6 J-Bolts

Evaluation of the J-bolts in the dome was conducted in accordance with ASME Section III, Division 2, Subsection CC-3730. Mechanical (non-self-limiting) loads were evaluated against a force criterion after 60 years of tank operation. The thermal loads were included in the displacement limited load evaluation so that the evaluation was conducted at each load step of the final thermal transient. In all cases for the force and displacement evaluations, the J-bolts were within the allowable range. Therefore, the dome J-bolts are considered to be satisfactory.

8.0 References

Abatt FG. 1996. *Double-Shell Tank Useful Life Analysis*, WHC-SD-WM-ER-556, Revision 0, Westinghouse Hanford Company, Richland, Washington.

ACI. 2001. *American Concrete Institute Code Requirements for Nuclear Safety Related Concrete Structures*. ACI 349-01. American Concrete Institute, Detroit, Michigan.

ACI. 2002. *American Concrete Institute Building Code Requirements for Structural Concrete*. ACI 318-02. American Concrete Institute, Detroit, Michigan.

American Society of Mechanical Engineers (ASME). 1995a. Code Case N-284-1, 1995, Metal Containment Shell Buckling Design Method, Class MC, Section III, Division 1. *ASME Boiler and Pressure Vessel Code*, American Society of Mechanical Engineers, New York, New York.

American Society of Mechanical Engineers (ASME). 1995b. Section III, Division 2, Subsection NC. *ASME Boiler and Pressure Vessel Code*. ASME, New York.

American Society of Mechanical Engineers (ASME). 1995c. Section III, Division 2, "Rules for Inservice Inspection of Nuclear Power Plant Components." *ASME Boiler and Pressure Vessel Code*. ASME, New York.

American Society of Mechanical Engineers (ASME). 1992. Section VIII, Division 2, "Pressure Vessels – Alternative Rules." *ASME Boiler and Pressure Vessel Code*. ASME, New York.

ASCE. 1998. *Seismic Analysis of Safety-Related Nuclear Structures and Commentary,* ASCE 4-98, American Society of Civil Engineers, Reston, Virginia.

ASTM. 1965. *American Society for Testing and Materials Standard Specification for Pressure Vessel Plates, Carbon Steel, for Intermediate- and Higher-Temperature Service*. American Society for Testing and Materials, West Conshohocken, Pennsylvania.

Bandyopadhyay K, A Cornell, C Costantino, R Kennedy, C Miller, and A Veletsos. 1995. *Seismic Design and Evaluation Guidelines for the Department of Energy High Level Waste Tanks and Appurtenances*. BNL 52361, Brookhaven National Laboratory, Associated Universities, Inc., Upton, New York.

Bandyopadhyay K. 1997. *Guidelines for Development of Structural Integrity, Programs for DOE High-Level Waste Storage Tanks*. BNL 52527, Brookhaven National Laboratory, Associated Universities, Inc., Upton, New York.

Blackburn LD. 1995a. *Recommended Test Program to Determine Crack Growth Rate in Double-Shell Tank Materials*. WHC-SD-WM-ETP-137 Rev. 0, prepared by ICF Kaiser Hanford Company for Westinghouse Hanford Company, Richland, Washington.

Blackburn LD. 1995b. *Nitrate Stress Corrosion Crack Growth Rate in Plain Carbon Steels*. WHC-SD-WM-ES-349 Rev. 0, prepared by ICF Kaiser Hanford Company for Westinghouse Hanford Company, Richland, Washington.

Blume and Associates. 1974. *Analysis of Underground Waste Storage Tanks 241-SY at Hanford, Washington.* ARH-R-172. URS/John A. Blume and Associates, Atlantic-Richfield Hanford Company, Richland, Washington.

BNFL. 2000. *Free-Field Analysis of HLW Vitrification Building,* CALC-W375HV-ST00004, Rev. 0, BNFL, Inc., Richland, Washington.

Brongers MP, CS Brossia, and C Mendez. 2005. *Investigation of Chemistry Factors Influencing Stress Corrosion Cracking Susceptibility of High-Level Waste in Double Shell Tank 241-AN-107.* RPP-RPT-28063, Rev.0, prepared by CC Technologies Laboratories, Dublin, Ohio for ARES Corporation, Richland, Washington.

Day JP, AD Dyrness, LJ Julyk, CJ Moore, WS Peterson, MA Scott, HP Shrivastava, JS Shulman, and TN Watts. 1995. *Structural Acceptance Criteria for the Evaluation of Existing Double-Shell Waste Storage Tanks Located at the Hanford Site, Richland, Washington.* WHC-SD-WM-DGS-003. Westinghouse Hanford Company, Richland, Washington.

DOE STD. 2002. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities.* DOE-STD-1020-2002, U.S. Department of Energy, Washington, D.C.

Duncan GP. 2003. *Double-Shell Tank Integrity Program Plan*, RPP-7574, Rev. 1A, CH2M HILL Hanford Group, Inc., Richland, Washington.

Ecology. 2003. *Federal Facility Agreement and Consent Order,* 89-10 Rev. 6. Milestone Series M48, Washington State Department of Ecology, U.S. Environmental Protection Agency, and U.S. Department of Energy, Olympia, Washington.

Fisher TW, LL Hyde, CJ Moore, SW Peterson, and WW Chen. 1994. *Structural Sensitivity Evaluations of Single- and Double-Shell Waste Tanks for Accelerated Safety Analysis - Phase I,* WHC-SD-WM-DA-150, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Garfield JS and RB Guenther. 1981. *Functional Design Criteria 214-AP Tank Farm Project B-340 Line Item FY-1983.* RHO-CK951-FDC-1, Rockwell Hanford Operations, Richland, Washington.

Han FC. 1996. *Structural Integrity and Potential Failure Modes of the Hanford High-Level Waste Tanks.* WHC-SD-TWR-RPT-002, Revision 0A, Westinghouse Hanford Company, Richland, Washington.

HNF-PRO-097. 2002. *Engineering Design and Evaluation (Natural Phenomena Hazard).* Project Hanford Management System, Fluor Hanford Company, Richland, Washington.

IBC. 2003. International Building Code 2003. International Code Council, Inc.

Jensen CE. 2003. *Supplement 2 to Inspection Results for Double Shell Tank 241-AY-101 FY2003.* RPP-15763. CH2M HILL Hanford Group, Inc., Richland, Washington.

Jensen CE. 2005. *Ultrasonic Inspection Results for DST 241-AP-106 FY2005.* RPP-RPT-23205. CH2M HILL Hanford Group, Inc., Richland, Washington.

Johnson KI, SP Pilli, NK Karri, JE Deibler, and MW Rinker. 2006. *Hanford Double-Shell Tank Thermal and Seismic Project – Buckling Evaluation Methods and Results for the Primary Tanks.* RPP-RPT-28967, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Julyk LJ. 2002. *Assessment of Double-Shell Tank Internal Vacuum Specification Limits on Primary Tanks.* HNF-1838 Rev. 0-A, CH2M HILL Hanford Group, Inc., Richland, Washington.

M&D. 2001a. *SASSI Analysis – HLW Preliminary SSI Evaluation*, Rev. 0, M&D Calculation No. 01-0010-HLW-2, M&D Professional Services, Richland, Washington.

M&D. 2001b. *SASSI Analysis – PT Preliminary SSI Evaluation*, Rev. 0, M&D Calculation No. 01-0010-PT-2, M&D Professional Services, Richland, Washington.

Mackey TC. 2004. *Design Loads for Tank Farm Facilities.* TFC-ENG-STD-06. CH2M HILL Hanford Group, Inc., Richland, Washington.

NUREG-0800. USNRC Standard Review Plan 3.7.1, Seismic Design Parameters, Revision 2, August 1989. U.S. Nuclear Regulatory Commission, Washington, D.C.

Rinker MW, FG Abatt, and BG Carpenter. 2007. *Hanford Double Shell Tank Thermal and Seismic Project – Seismic Analysis of Increased Liquid Level for 241-AP Tank Farms*, RPP-RPT-32239, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW and FG Abatt. 2006a. *Hanford Double Shell Tank Thermal and Seismic Project - Dytran Benchmark Analysis of Seismically Induced Fluid-Structure Interaction in a Hanford Double Shell Primary Tank*, RPP-RPT-28963, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW and FG Abatt. 2006b. *Hanford Double Shell Tank Thermal and Seismic Project - Dytran Benchmark Analysis of Seismically Induced Fluid-Structure Interaction Analysis in Flat-Top Tanks*, RPP-RPT-30807, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW, FG Abatt, BG Carpenter, and CA Hendrix. 2006a. *Hanford Double Shell Tank Thermal and Seismic Project - Establishment of Methodology for Time Domain Soil-Structure Interaction Analysis of a Hanford Double Shell Tank*, RPP-RPT-28964, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW, Carpenter BG and FG Abatt. 2006b. *Hanford Double Shell Tank Thermal and Seismic Project - ANSYS Benchmark Analysis of Seismically Induced Fluid-Structure Interaction in a Hanford Double Shell Primary Tank*, RPP-RPT-28965, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW, BG Carpenter, C Hendrix, and FG Abatt. 2006c. *Hanford Double Shell Tank Thermal and Seismic Project - ANSYS Seismic Analysis of Hanford Double Shell Primary Tank.* RPP-RPT-28966, Rev. 0, M&D Professional Services, Richland, Washington.

Rinker MW, JE Deibler, KI Johnson, NK Karri, SP Pilli, Abatt FG, BG Carpenter,and CA Hendrix. 2006d. *Hanford Double-Shell Tank Thermal and Seismic Project – Summary of Combined Thermal and Operating Loads with Seismic Analysis*. RPP-RPT-28968, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW and RR Youngs. 2006. *Development of PC2 Surface Spectra for Double-Shell Tank Facilities, DOE Hanford Site in Washington State*. RPP-RPT-27570, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW, FA Simonen, JE Deibler, KI Johnson, SR Gosselin, SP Pilli, and AB Johnson. 2005. *Evaluation and Recommendation of Stress Criteria for Stress Corrosion Cracking of Hanford Double-Shell Tanks*. RPP-RPT-27574, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Rinker MW, JE Deibler, KI Johnson, SP Pilli, CE Guzman-Leong, and OD Mullen. 2004. *Hanford Double-Shell Tank Thermal and Seismic Project – Thermal and Operating Load Analysis*. RPP-RPT-23308, Rev. 0, Pacific Northwest National Laboratory, Richland, Washington.

Scott MA and WS Peterson. 1995. *Accelerated Safety Analyses, Structural Analyses Phase II, ACI Code Evaluations of the Maximum Loads in the Concrete Dome, Haunch and Upper Wall of Double-Shell Waste Storage Tanks*. WHC-SD-WM-SARR-032, Westinghouse Hanford Company, Richland, Washington.

SDC-4.1. 1993. *Standard Arch-Civil Design Criteria, Design Loads for Facilities*. Hanford Plant Standards, HPS-SDC-4.1, Rev. 12, U.S. Department of Energy, Richland, Washington.

Terry M, J Beavers, C Czajkowski, G Frankel, B Gordon, T Jones, R Jones, L Stock, B Wiersma, and P Zapp. 2004. *Expert Panel Workshop for Hanford Site Double-Shell Tank Waste Chemistry Optimization*. RPP-RPT-22126 Rev. 0, CH2M HILL Hanford Group, Inc., Richland, Washington.

Tomaszewski TA. 2004. *Tank Farms Documented Safety Analysis, Rev. 1*. RPP-13033, Rev. 1, CH2M HILL Hanford Group, Inc., Richland, Washington.

UCRL. 1990. *Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards*. U.S. DOE Report UCRL 15910, Lawrence Livermore National Laboratory, Livermore, California.

Appendix A

Software Acceptance

Appendix A

Software Acceptance

The software acceptance documentation is recorded in the Combined Summary report (Abatt et al. 2006).

Appendix B

ANSYS® Model Files

® ANSYS is a registered trademark of ANSYS, Inc., Canonsburg, Pennsylvania

Appendix B

ANSYS® Model Files

B.1 Introduction

This appendix contains the ANSYS® model input files for the thermal and operating load analyses. The input files for the seismic analyses are available in the seismic report (Carpenter et al. 2006) To conserve space and avoid duplication of the same data multiple times, some of the files listed will be used multiple times, but they are only included one time in this document.

There are twenty-six files needed to actually build the model and run the initial mechanical loads. The key file for this phase of the analysis is the "set_slicea.mac" macro file. The set_slicea.mac file calls all of the other necessary files for the actual ANSYS® run. At the end of this initial phase, the ANSYS® database file is copied into a new subdirectory along with the eighteen temperature distribution macro files that apply the temperatures via body forces to each node point in the model and a short input macro file to restart the ANSYS® run. The actual nodal temperature values are not included in this appendix, as it would take over three thousand pages to do so. The actual nodal temperatures are included separately on electronic media. The ACI load factors are applied at the end of the 60 years of thermal cycling in a separate restart analysis. Section B.2 contains all the input files needed for the Best Estimate Soil – Best Estimate Concrete analysis. Sections B.3 and B.4 contain only the files that are different to run the Lower Bound Soil – Best Estimate Concrete and Upper Bound Soil – Best Estimate Concrete analyses.

The post-processing files required to extract the results from the TOLA model in preparation for combination with the seismic results are shown in Section B.5.

B.2 Best Estimate Soil Model Input Files

1.1.2 Model Files

Input file: set_slicea.mac

```
!***    AP 210F, Waste Height=422 SpG =1.83 for 20 years
10/11/2006
!***      AP 210F, Waste Height=460 SpG =1.83 for 40 years
10/11/2006

!***AP modifications 8/9/04
!***Liquid level 460", SpG 1.83 8/11/04
!***Liquid level 460", SpG 2.0     7/26/04
!***Liquid level 460", SpG 1.7     7/19/04
!***2nd liner extension 0.25 thick                    7/21/04
!***2nd liner extension contact <> concrete   7/21/04
!*** Augmented stiffness 5% Econc (350)   7/19/04
!*** 5% pivot, bcso,mmd           6/25/04
!***Use nsub              6/24/04
!***cnvtol,f(m),,.005,0   6/16/04
!*** Augmented stiffness 2% Econc (350)   6/14/04
!*** Augmented stiffness 30000   6/11/04
!***6/10/04 changes
!***    Do not merge insulating concrete <> 2nd liner @ OD
of concrete
!***    Add 1st radius element to contact of 1st liner <> ins
conc
!***    Add contact 2nd liner <> slab concrete
!***Correct node select for type,61 real,70   6/9/04
!***Reorient Beam188 on z=/= 0 face
!***Fix Liner-Dome common nodes   5/6/04
!***Delete "j-bolts" in wall    5/6/04
!***Move j-bolt real definition to pnnla6.mac  3/30/04
!***Changed Liner Coupling per J. Deibler 3/29/04
!!***      Augmented stiffness 15000   3/24/04
!***Default convergence criteria  3/22/04
!***Best estimate soil properties  3/19/04
!***Soil-Concrete - 5 regions  2/23/04
!***Correct Drucker-Prager - soil
!***Correct mat,1 temperature dependent modulus
!***Replace shell64 with shell181
!***Primary tank pressure -12" H2O (was -6)
!***125 pcf overburden, 110 pcf undisturbed soil
!***10/30/03
!***Define additional soils for load factor restart
!***No cracking insulating concrete
!***fix mpch (esel,r,mat,,2)
!***1 yr + 15 day creep  5/14/03
!***    Load step 5 creep for 330 days
!***New load step 6 => mpch +5 days
!***  "sets" degraded concrete properties
!***
!***   Turn off concrete crushing 5/5/03
!***
!*** Run 2, Load Step 1, 2 & thermal
!***   (8.3' soil, 125 lb/ft3)
!***   (0.06" primary tank corrosion wall, floor)
!*** 4/16/03
!***
!***
!*** JED mods 3/29/03
!***

i_rebuild=1
```

```
*if,i_rebuild,eq,1,then
 pnnla
 pnnla2
 pnnla3
 pnnla4
 pnnla5
 pnnla6
 pnnla7
 pnnla8
 pnnla9
*else
 resume,pnnla9,db
*endif

/prep7

allsel
cpdele,all,all

!get misc area components for applying loads, etc.
/input,set_areas_slice,mac

!add steel plate below wall (on slab)
r,45,1/4
csys,22
vsel,s,mat,,2
aslv
asel,r,loc,z,-8.125
asel,r,loc,x,480,498
aatt,1,45,22
mat,1
real,45
amesh,all

!define contact elements (all have default friction of 0.3)
et,60,170
et,61,173
mp,mu,61,.3            !Soil-concrete dome
,mu,62,.4
,mu,63,.4
,mu,64,.4
,mu,65,.3
,mu,66,.2
,mu,67,.05             !soil-concrete wall
,mu,68,.3              !soil-concrete footing/top
,mu,69,.05             !soil-concrete footing/side
,mu,70,.6              !soil-concrete foundation
,mu,71,.4              !2nd liner-insulating concrete
6/10/04

!soil_concrete contact - dome
r,61,,,1,.1
real,61
type,61
mat,61
cmsel,s,aconc_soil
nsla,,1
nsel,r,loc,z,452,600
esln
esurf
type,60
cmsel,s,asoil
nsla,,1
nsel,r,loc,z,452,600
esln
esurf
```

```
!soil_concrete contact - wall
r,67,,,1,.1
real,67
type,61
mat,67
cmsel,s,aconc_soil
nsla,,1
nsel,r,loc,z,-3,453
esln
esurf
type,60
cmsel,s,asoil
nsla,,1
nsel,r,loc,z,-3,453
esln
esurf

!soil_concrete contact - Footing - top
r,68,,,1,.1
real,68
type,61
mat,68
cmsel,s,aconc_soil
nsla,,1
nsel,r,loc,z,-7,-6
esln
esurf
type,60
cmsel,s,asoil
nsla,,1
nsel,r,loc,z,-7,-6
,r,loc,x,496,530
esln
esurf

!soil_concrete contact - Footing - side
r,69,,,1,.1
real,69
type,61
mat,69
cmsel,s,aconc_soil
nsla,,1
nsel,r,loc,x,531
esln
esurf
type,60
cmsel,s,asoil
nsla,,1
nsel,r,loc,x,531
esln
esurf

!soil_concrete contact - Foundation
r,70,,,1,.1
real,70
type,61
mat,70
cmsel,s,aconc_soil
nsla,,1
nsel,r,loc,z,-31,-30
,r,loc,x,440,531
cm,foundconc,node
nsla,,1
nsel,r,loc,x,,440
,r,loc,z,-33,-8              !** was -32  6/9/04
```

```
cmse,a,foundconc
esln
esurf
type,60
cmsel,s,asoil
nsla,,1
nsel,r,loc,z,-31,-30
,r,loc,x,440,531
cm,foundsoil,node
nsla,,1
nsel,r,loc,x,,440
,r,loc,z,-33,-8
cmse,a,foundsoil
esln
esurf


!secondary liner contact
r,62,,,1,.1
real,62
type,60
mat,62
cmsel,s,aconc_shell
csys,0
asel,u,loc,y,459,99999
nsla,,1
esln
esel,r,mat,,2
esurf
type,61
cmsel,s,area_secon
csys,0
asel,u,loc,y,-99999,3.87
nsla,,1
esln
esurf

!primary liner contact with dome
r,63,,,1,.1
real,63
type,60
mat,63
cmsel,s,aconc_shell
asel,r,loc,y,459,99999
nsla,,1
esln
esel,r,mat,,2
esurf
type,61
cmsel,s,area_prim
asel,r,loc,y,459,99999
nsla,,1
esln
esurf

!primary liner contact with insulating concrete
r,64,,,1,.1
real,64
type,60
mat,64
cmsel,s,area_insul_top
nsla,,1
esln
esel,r,mat,,4
esurf
type,61
```

```
cmsel,s,area_prim
csys,0
asel,r,loc,y,0
nsla,,1
esln
nsle      !*6/10/04
esurf

!secondary liner contact with foundation concrete  6/10/04
r,71,,,1,.1
real,71
type,60
mat,71
cmse,,slab_top
asel,r,loc,x,-480,-440
nsla,,1
esln
esur
type,61
cmse,,area_secon
asel,r,loc,x,-470,-440
,r,loc,y,-9,-8
nsla,,1
esln
nsle
esur

!merge insulating concrete bottom nodes and secondary liner
nodes
cmsel,s,area_insul_bot
cmsel,a,area_secon
csys,0
asel,u,loc,y,20,9999
nsla,,1
cpintf,uz,.1

!slab top/insulating concrete
r,65,,,1,.1
real,65
type,60
mat,65
cmsel,s,slab_top
nsla,,1
esln
esurf
type,61
cmsel,s,area_insul_bot
nsla,,1
esln
esurf

!wall/slab contact
r,66,,,1,.1
real,66
type,60
mat,66
asel,,,,986,992
cm,slab_top_wall,area
nsla,,1
esln
esel,r,mat,,2
esurf
type,61
asel,,,,214
,a,,,706
,a,,,913,918,5
```

```
,a,,,934
cm,wall_bot,area
nsla,,1
esln
esel,r,mat,,2
esurf

allsel
!esel,s,type,,60
!nsle
!nummrg,node
!nummrg,elem
!esel,s,type,,61
!nsle
!nummrg,elem

max_mat=100
max_real=1000

!define the local coordinate systems and rebar orientations
/input,set_esys_3d,mac

!apply loads
/input,apply_loads_slice,mac
allsel

!apply axisymmetric boundary conditions
csys,22
nsel,s,loc,y,180
nsel,a,loc,y,180+swp_th-.001,183
csys,0
nsel,a,loc,x,0
d,all,uy,0
d,all,rotx,0
d,all,rotz,0
allsel

nsel,s,loc,x,0
d,all,roty,0

!merge liner/concrete nodes at dome centerline
ksel,s,,,2
ksel,a,,,329
nslk
nummrg,node
allsel

!copy jbolts, etc for slice model
csys,22
esel,s,type,,20,21
cm,e_bolt0,elem
egen,2,500000,all,,,0,0,0,0,0,,swp_th
esel,s,mat,,1
esel,u,real,,45
nsle
nsel,u,,,22789,22790      !*** 5/6/04
,u,,,20260,20261!*** 6/10/04
nummrg,node

!divide jbolt/bottom anchors properties by 2 for slice model
r,30,.19635/2,.3068e-2/2,.3068e-2/2,.5,.5

esel,s,type,,20,21
cmsel,u,e_bolt0
nsle
nsel,r,,,500000,999999
```

```
cm,ntemp,node

vsel,s,mat,,2
vsel,a,mat,,6
csys,0
vsel,u,loc,y,-9999,-8.12
cm,vtemp,volu
*get,nv,volu,,count
*do,i,1,nv
 *get,iv,volu,,num,min
 eslv
 nsle
 cmsel,a,ntemp
 nummrg,node
 cm,ntemp,node
 cmsel,s,vtemp
 vsel,u,,,iv
 cm,vtemp,volu
*enddo

!***
!***  Delete primary-secondary tank coupling at tangent
!***   JED 3/31/03
!***

r,41,3/16                    !insulating concrete confining ring
thickness

/prep7

esel,s,mat,,5
nsle,,1
csys,0
*get,top_elev,node,,mxloc,y
cm,soil_elem,elem

*do,i,1,16
 set_slayer,soil_z0(i),soil_z1(i),soil_emod(i),soil_pr(i)
*enddo

max_mat=100
!set backfill/overburden material
*do,i,1,8
 set_backfill,bf_z0(i),bf_z1(i),bf_emod(i),bf_pr
*enddo

!Don't do this!! 5/6/04
!make sure anchors/jbolts/studs etc are merged with concrete
!esel,,type,,12,13
!,a,type,,20,21
!,a,type,,24,25
!nsle
!nsel,u,,,22789,22790      !*** 3/26/04
!numm,node


!***
!*** Augmented Stiffness  2/27/04
!***
et,32,45
*get,ec350,ex,2,temp,350
mp,ex,12,ec350*0.05                !7/19/04
,prxy,12,.15
esel,,type,,12,15
egen,2,0,all,,,10
esel,,mat,,12
```

```
emod,all,type,32

/fil,set_slice_0
save

!***
!***Redefine j-bolts  4/1/04
!***

alls
csys
nod0k=node(-550,575,0)
nod1k=node(-550,575,27)
et,30,188                    !New j-bolts
type,30
mat,1
real,20
secn,2
sect,2,beam,csolid
secd,.25/(2**.5),1,1         !Use 1/2 area for symmetry
esel,,type,,20
nsle
nsel,r,loc,z
esln,,1
*get,jb0,elem,,count
*do,i,1,jb0
*get,jb1,elem,,num,min
*get,jn1,elem,jb1,node,1
*get,jn2,elem,jb1,node,2
e,jn1,jn2,nod0k
esel,u,,,jb1
*enddo
esel,,type,,20
nsle
nsel,u,loc,z
esln,,1
*get,jb2,elem,,count
*do,i,1,jb2
*get,jb3,elem,,num,min
*get,jn3,elem,jb3,node,1
*get,jn4,elem,jb3,node,2
e,jn3,jn4,nod1k
esel,u,,,jb3
*enddo

allsel

!***  2nd liner extension issues   7/21/04
asel,,,,928,,,1
egen,2,100000,all,,,,,4,,,0,0,0
modm,nocheck
alls
emod,15784,-1,114183,104465
,15955,-3,104465,114183
,28878,-3,104465,114183
acle,928
real,62
type,60
mat,62
asel,,,,928,,,1
esln
esel,r,type,,12
esurf
type,61
esel,,type,,23
```

```
,r,real,,45
nsle
esurf
dsym,symm,y,5
alls

!***  AP modifications   8/9/04
!***    Thickness from set_parms.mac
!* r50=1-.06       !shell thickness (in) (R1 of Figure 11 in
RPP-13990)
!* r51=3/8-.06     !shell thickness (in) (R2,R6,R7,R9 of
Figure 11 in RPP-13990)
!* r52=7/8-.06     !shell thickness (in) (R3 of Figure 11 in
RPP-13990)
!* r53=3/4-.06     !shell thickness (in) (R4 of Figure 11 in
RPP-13990)
!* r54=1/2-.06     !shell thickness (in) (R5,R8 of Figure 11 in
RPP-13990)
!* r55=1/4     !shell thickness (in) (R10 of Figure 11 in RPP-
13990)
!* r56=3/8    !shell thickness (in) of secondary liner above
357.5 in

!***    Additional liner thickness
r,57,9/16-.06
,58,15/16-.06
!***    Redefine secondary liner thickness
r,55,3/8
,56,1/2
,59,9/16

!*** Primary liner
csys
esel,,real,,51
nsle
nsel,r,loc,y,380,468.5
esln,,1
esel,r,real,,51
emod,all,real,54
esel,,real,,54
nsle
nsel,r,loc,y,142,238
esln,,1
esel,r,real,,54
emod,all,real,57
esel,,real,,52
nsle
nsel,r,loc,y,,12
,r,loc,x,-450,-437
esln,,1
esel,r,real,,52
emod,all,real,58
esel,,real,,51
nsle
nsel,r,loc,y,-1,1
esln,,1
esel,r,real,,51
emod,all,real,54
!***    Secondary liner
esel,,real,,55,56
nsle
nsel,r,loc,y,24,460
esln,,1
esel,r,real,,55,56
emod,all,real,55
esel,,real,,55
```

```
nsle
nsel,r,loc,y,3.875,24
esln,,1
esel,r,real,,55
emod,all,real,56
esel,,real,,55
nsle
nsel,r,loc,y,-9,3.875
,r,loc,x,-480,-467
esln,,1
esel,r,real,,55
emod,all,real,59
esel,,real,,55
nsle
nsel,r,loc,x,-468,-420
esln,,1
esel,r,real,,55
emod,all,real,56


!***
!***   Temperatures
!***    Uniform 50F  (4/17/03)
!***
tref,50
tunif,50

finish
/filnam,set_slice_0
/sol
!solcontrol,off
neqit,50
time,1
nlgeom,on
nrop,unsym
cnvt,f,,.005,0              !6/16/04
,m,,.005,0                  !6/16/04
crpl,.05
nsub,10,100,5
!delt,.1,.01,.2
!outres,all,all
!nrre,on,250
eqsl,sparse,.05,-1
bcso,mmd
allsel
save
solve

time,2
!***
!***  Add waste and pressure loads
!***
pres_surf=0          !ground surface uniform pressure psf
point_cent=0         !point load at center lb
pres_annulus=-20  !annulus pressure inches h2o
pres_int=-12                 !annulus internal pressure inches
h2o
hwaste=422                   !total waste height
height_waste1=hwaste/3   !height of waste 1 inches
gamma_waste1=1.83        !specific gravity of waste 1
height_waste2=hwaste/3   !height of waste 2 inches
gamma_waste2=1.83        !specific gravity of waste 2
height_waste3=hwaste/3   !height of waste 3 inches
gamma_waste3=1.83        !specific gravity of waste 3

/inp,apply_loads_slice,mac
```

```
delt,.1,.01,.25
solv

time,3
!***
!***  Add surface loads
!***
pres_surf=40                    !ground surface
uniform pressure psf
point_cent=200000               !point load at center
lb
pres_annulus=-20                !annulus pressure
inches h2o
pres_int=-12                    !annulus internal
pressure inches h2o
hwaste=422                      !total waste height
height_waste1=hwaste/3          !height of waste 1
inches
gamma_waste1=1.83               !specific gravity of
waste 1
height_waste2=hwaste/3          !height of waste 2
inches
gamma_waste2=1.83               !specific gravity of
waste 2
height_waste3=hwaste/3          !height of waste 3
inches
gamma_waste3=1.83               !specific gravity of
waste 3

/inp,apply_loads_slice,mac

save
solv
```

Input file: apply_loads_slice.mac

```
!***
!***Eliminate in-plane pressure 2nd liner
!*** Add pressure 1st liner @ connection
!*** 12/4/03
!***

allsel
sfdele,all,all
sfedele,all,all,all
sfgrad,pres
fdele,all,all
esel,s,type,,59
edele,all

!40 psf pressure on ground surface
!***
!*** No pressure - Phase II, Load Case S5
csys,0
*get,ymx,kp,,mxloc,y
asel,s,loc,y,ymx
lsla
nsla,,1
esel,all
sf,all,pres,pres_surf/144

!200K point load at center
!***
!*** No concentrated load - Phase II, Load Case S5
csys,22
nsel,r,loc,x,0,clr
```

```
*get,nnode,node,,count
f,all,fz,-point_cent/nnode*swp_th/360

!liner pressure loads
p_annulus=pres_annulus/12*62.4/144
p_internal=pres_int/12*62.4/144

!waste depth and unit weight
hw1=height_waste1
gammaw1=gamma_waste1
hw2=height_waste2
gammaw2=gamma_waste2
hw3=height_waste3
gammaw3=gamma_waste3

*if,abs(gammaw1),lt,1e-3,then
 gammaw1=1e-6
*else
 gammaw1=gammaw1*62.4/1728
*endif
*if,abs(gammaw2),lt,1e-3,then
 gammaw2=1e-6
*else
 gammaw2=gammaw2*62.4/1728
*endif
*if,abs(gammaw3),lt,1e-3,then
 gammaw3=1e-6
*else
 gammaw3=gammaw3*62.4/1728
*endif

zz4=0
zz3=hw1
zz2=zz3+hw2
zz1=zz2+hw3
zz0=460
pp0=p_internal
pp1=p_internal-p_annulus
pp2=pp1+hw3*gammaw3
pp3=pp2+hw2*gammaw2
pp4=pp3+hw1*gammaw1

allsel

!primary liner
esel,s,real,,50,54
nsle
cm,nliner,node

!top reaches of dome
allsel
csys,0
cmsel,s,nliner
nsel,r,loc,y,zz0-.03,9999
sfgrad,pres
sf,all,pres,pp0

!space between top of fluid and prim/secon liner intersection
cmsel,s,nliner
nsel,r,loc,y,zz1,zz0
sf,all,pres,pp1

!waste region 3
cmsel,s,nliner
nsel,r,loc,y,zz2,zz1
esln
```

```
esel,r,type,,1
nsle,,1
sfgrad,pres,0,y,zz1,(pp1-pp2)/hw3
sf,all,pres,pp1

!waste region 2
cmsel,s,nliner
nsel,r,loc,y,zz3,zz2
esln
esel,r,type,,1
nsle,,1
sfgrad,pres,0,y,zz2,(pp2-pp3)/hw2
sf,all,pres,pp2

!waste region 1
cmsel,s,nliner
nsel,r,loc,y,zz4,zz3
esln
esel,r,type,,1
nsle,,1
sfgrad,pres,0,y,zz3,(pp3-pp4)/hw1
sf,all,pres,pp3

!annulus
esel,s,type,,1
nsle,,1
cmsel,u,nliner
nsel,u,loc,y,-9999,-8.124
esln
esel,r,type,,1
nsle,,1
cm,nsecon,node
esln
esel,r,real,,55,56
sfgrad,pres
sf,all,pres,p_annulus

alls
```

Input file: mesh_size.mac

```
eesize=3.2                      !default element size for
rebar [in]
soil_size=14                    !default element size for soil
elements [in]
swp_th=24/(2*pi*480)*360        !single element sweep angle
[deg]
num_div=6                       !number of divisions per
quadrant
```

Input file: PNNLA.mac

```
set_parms
/prep7
!  3/28/03
! DST - AY

*afun,deg

k,1,0,h6
k,2,0,h5
k,3,0,0
k,4,-ir2,0
k,5,ir2,h3+36+6+13/16
k,6,-r1*sin(th1),h6-r1+r1*cos(th1)    !Intersection of exterior
dome radii
larc,6,1,3,r1                 !Exterior dome radius - center

rectng,-ir2,0,h2,h1
```

```
rectng,-or,-ir,h2,h3            !Wall to tangent point
rectng,-or,-ir,h3,h4

larc,18,6,3,r2                  !Exterior dome radius - outer
local,11,1,0,h3,0,,,,3/8
l,13,2                                  !Interior dome ellipse

csys,0
l,1,2
k,19,-ir2,0
k,20,-ir2,h4+5
l,19,20
lcsl,15,17
lfil,18,20,r3                           !Radius primary tank to
dome
csys,11
l,21,22

nummrg,kp
csys,0

lfil,20,4,12                            !Corner radius primary tank
floor
l,7,12
lfil,23,7,12                            !Corner radius secondary
tank floor

wpcs,-1
wpro,,,-90
wpof,,,icr
asbw,1                                  !Insulating concrete

al,8,19,17,18,16,1,14,13 !Haunch & dome concrete
```

```
adel,3,4
alls
numc,all

!Tank Foundation
*get,ik,kp,,num,max
k,ik+1,0,h2-24
k,ik+2,-36,h2-24
k,ik+3,-76,h2-10.5
k,ik+4,-29*12-1,h2-10.5
k,ik+5,-36*12-9,ky(ik+4)-11.5
k,ik+6,-44*12-3,ky(ik+5)
k,ik+7,kx(ik+6),ky(ik+6)+12+11.5
k,ik+8,-or-1,ky(ik+7)
k,ik+9,kx(ik+8),ky(ik+8)-1.5
k,ik+10,-or,ky(ik+9)
k,ik+11,-ir,ky(ik+9)
k,ik+12,-ir+1,ky(ik+9)
a,ik+1,ik+2,ik+3,ik+4,ik+5,ik+6,ik+7,ik+8,ik+9,ik+10,ik+11,
ik+12,8

!Dome & wall rebar
!Outer rebar
k,37,kx(11)+covext,ky(11)          !Outer edge wall outer
rebar - bottom
k,38,kx(37)+1,ky(37)               !Inner edge wall outer rebar -
bottom
k,39,kx(18)+covext,ky(18)-.707     !Outer edge wall outer
rebar - top
k,40,kx(39)+1,ky(39)-.707          !Inner edge wall outer
rebar - top
```

```
k,41,kx(6),ky(6)-covext          !Outer dome rebar radius
intersection
k,42,kx(41),ky(41)-1             !Outer dome rebar radius
intersection
k,43,kx(1),ky(1)-covext          !Outer dome rebar -
centerline outer
k,44,kx(1),ky(43)-1              !Outer dome rebar - centerline
inner
larc,39,41,3,r2-covext           !Outer edge of outer rebar,
outer radius
larc,41,43,3,r1-covext           !Outer edge of outer rebar,
center radius
larc,40,42,3,r2-covext-1         !Inner edge of outer rebar,
outer radius
larc,42,44,3,r1-covext-1         !Inner edge of outer rebar,
center radius
a,37,38,40,42,44,43,41,39        !Dome outer rebar

!Dome & wall rebar
!Inner rebar
k,45,kx(12)-covint1,ky(12)
,46,kx(45)-1,ky(45)
,47,kx(13)-covint1,ky(13)
,48,kx(47)-1,ky(47)
,55,0,ky(2)+covint2
,56,0,ky(55)+1
loca,12,1,,h3,,,,,(30*12+1.5)/(80*12+1.5)
k,49,ir+1.72,164
,53,ir+2.21,144
l,53,55
loca,13,1,,h3,,,,,(30*12+2.5)/(80*12+2.5)
k,50,ir+2.86,163.9
,54,ir+3.68,143.85
l,54,56
loca,14,1,,h3,,,,,(30*12+4)/(80*12+4)
k,51,ir+5.2,154.8                !Want 4" cover & 7-1/2"
from tangent
loca,15,1,,h3,,,,,(30*12+5.5)/(80*12+5.5)
k,52,ir+6.4,154.65
csys,0
l,45,47
,46,48
csys,11
a,45,47,49,51,53,55,56,54,52,50,48,46
csys,0

!Foundation rebar
covtop=3.5
covbot=3
ssli=(ky(27)-ky(26))/(kx(27)-kx(26))
sslo=(ky(28)-ky(29))/(kx(28)-kx(29))
k,60,kx(30)+3,ky(30)+covbot
k,61,kx(60),ky(60)+1
k,62,kx(31)+3,ky(8)-covtop
k,63,kx(62),ky(62)-1
k,64,0,ky(8)-covtop
k,65,0,ky(64)-1
k,74,0,ky(25)+covbot+1
k,75,0,ky(25)+covbot
k,66,kx(26)-ssli*covbot,ky(26)+covbot
k,67,kx(66)-ssli,ky(66)+1
k,68,kx(27)-ssli*covbot,ky(27)+covbot
k,69,kx(68)-ssli,ky(68)+1
k,70,kx(28)-sslo*covbot,ky(28)+covbot
k,71,kx(70)-sslo,ky(70)+1
k,72,kx(29)-sslo*covbot,ky(29)+covbot
```

```
k,73,kx(72)-sslo,ky(72)+1
a,60,61,73,71,69,67,74,75,66,68,70,72
a,62,64,65,63

!Haunch mid section rebar
k,80,kx(14)+11+.5,ky(14)+36
k,81,kx(80),ky(40)
k,82,kx(80),.5*(ky(80)+ky(81))
k,83,kx(14)+72,ky(14)+98
k,84,kx(14)+103,ky(14)+113
k,85,kx(84),ky(84)+1
k,86,kx(83),ky(83)+1
k,87,kx(82),ky(82)+1
k,88,kx(81)-1,ky(81)
k,89,kx(80)-1,ky(80)
a,80,82,87,81,88,89
a,82,83,84,85,86,87

ldiv,13,.34
csys,0
wpcs,-1
kwpa,57
wpro,,-90
wpro,,,60
asel,,,,1
asbw,all
wpcs,-1
kwpa,14
wpof,,12
wpro,,-90
asbw,all

allsel
aovlap,all

!divide bottom slab rebar at radial locations
*dim,bsr,,4
dl5=27.4
bsr(1)=(7+7.5)/2*12+dl5,(14+15)/2*12+dl5,31*12+6-9,435
asel,s,,,7
csys,0
wpcs,-1
wpro,,,-90
*do,i,1,4
 wpoff,,,bsr(i)
 asbw,all
 wpoff,,,-bsr(i)
*enddo

wpcs,-1
wpoff,kx(68),ky(68)
wpro,,,-90
wpro,,atan(ssli)
asbw,2
wpcs,-1
wpoff,kx(70),ky(70)
wpro,,,-90
wpro,,atan(sslo)
asbw,1
wpcs,-1
wpoff,kx(72),ky(72)
wpro,,,-90
wpro,,atan(sslo)
asbw,7

!divide top slab rebar at radial locations
```

```
*dim,tsr,,7
tsr(1)=kx(69),kx(35),kx(98),kx(71),kx(100),kx(102),kx(73)
asel,s,,,8
csys,0
wpcsys,-1
wprot,,,90
*do,i,1,7
 wpoff,,,tsr(i)
 asbw,all
 wpoff,,,-tsr(i)
*enddo

!divide wall rebar
*dim,wr,,4
wr(1)=10*12+19+h2,17*12,23*12+19+h2,h3-42
asel,s,,,15,16
csys,0
wpcsys,-1
wprot,,-90
kwpave,3
*do,i,1,4
 wpoff,,,wr(i)
 asbw,all
 wpoff,,,-wr(i)
*enddo

!divide dome rebar
*dim,dr,,7
dl6=32.9
dr(1)=7*12+3+dl6,12*12+6+dl6,22*12+6,(24+26.75)/2*12,2
6*12+2,29*12+6,28*12+dl6,
asel,s,,,18,28,10
csys,0
wpcs,-1
wpro,,,-90
kwpa,3
jdcr=h6-3-95*12
*do,i,1,7
 wpof,,jdcr+95*12*cos(asin(dr(i)/(95*12))),dr(i)
 wpro,,asin(dr(i)/(95*12))
 asbw,all
 wpro,,-asin(dr(i)/(95*12))
 wpof,,-(jdcr+95*12*cos(asin(dr(i)/(95*12)))),-dr(i)
*enddo

!divide bent bar, top of haunch
wpcsys,-1
kwpave,17
wpoff,48*cos(30)
wprot,,,-90
asel,s,,,29
asbw,all
allsel
l,40,39
asbl,28,127

allsel
nummrg,all
numcmp,all

!J-bolts
! 32-35 are tank wall stiffeners
*dim,jx,,35
*dim,jy,,35
*dim,jdeg,,35
jx(1)=479,479,479,479,479,479,479,479,479,479
```

```
jx(11)=479,479,479,479,479,479,473,462,450,432
jx(21)=412,391,369,347,324,299,272,241,206,165
jx(31)=107,479,479,479,479
jy(1)=19,43,67,91,115,139,163,187,211,235
jy(11)=259,283,307,331,355,379,402,424,442,460
jy(21)=474,486,496,504,511,515,518,522,525,527
jy(31)=529,89.5,89.5*2,89.5*3,89.5*4
jdeg(1)=90,90,90,90,90,90,90,90,90,90
jdeg(11)=90,90,90,90,90,90,75,55,45,40
jdeg(21)=35,30,25,20,15,10,9,8,7,6,5
jdeg(31)=1,90,90,90,90

csys
asel,,,,24,29,5
,a,,,42,46,4
,a,,,14,16,2
,a,,,19,21,2
,a,,,30,51,21
,a,,,45,49,2
,a,,,50,56,2
,a,,,60,62,2

*do,i,1,35
 wpcsys,-1
 wpave,-jx(i),jy(i)
 wprot,jdeg(i)
 wprot,,,90
 asbw,all
*enddo

!bottom anchors
lanch=5+3/16
ldiv,228,.14
kgen,2,38,,,0,lanch,0
a,12,268,269,38
allsel
aovlap,all

!flange of wall stiffeners - 6"
lsel,,,,175,246,71
,a,,,266,303,37
*do,i,32,35
 wpcsys,-1
 wpave,-jx(i),jy(i)
 wprot,jdeg(i)
 wprot,,,90
 wpoff,,,-6
 lsbw,all
*enddo
lsel,all

! dome stiffener (detail 9)
lang,16,51,90,.8
lsel,,,,414
lsum
lsel,all
*get,stang,line,,ixv,x
wpcs,-1
kwpa,51
wpro,,,-90
wpro,,acos(stang)
wpof,,,6
lsbw,324
asbl,106,414

! line for concentrated load
```

```
wpcs,-1
kwpa,1
wpro,,,-90
wpof,,,clr
lsbw,1

!Identify areas
!inside layer of rebar
asel,,loc,x,-485,-484
,u,,,33,34
,a,,,21,91,70
,a,,,30,100,70
,a,,,104,105
,a,,,102,110,8
,a,,,107,111,4
,a,,,19,62,43
,a,,,51,60,9
,a,,,112,116,2
,a,,,118,120,2
,a,,,50,56,2
,a,,,122,127,5
,a,,,47
cm,as1,area

!outside layer of rebar
asel,,loc,x,-496,-495
,a,,,18,64,46
,a,,,57,59
,a,,,61,63,2
,a,,,53,55,2
,a,,,28,43,15
cm,as2,area

!bottom layer of slab
asel,,,,1,2
,a,,,4,6
,a,,,11,13,2
,a,,,33
cm,as3,area

!top layer of slab
asel,,loc,y,-13,-11
cm,as4,area

!haunch
asel,s,,,32
cm,haunch,area

!concrete insulation
asel,s,,,3
cm,cinsul,area

!slab
asel,s,,,31
cm,slab,area

!haunch vertical steel
asel,s,,,9
cm,hvert,area

!haunch radial
asel,s,,,10
cm,hrad,area

!concrete
allsel
```

```
cmsel,u,hrad
cmsel,u,hvert
cmsel,u,slab
cmsel,u,cinsul
cmsel,u,haunch
cmsel,u,as4
cmsel,u,as3
cmsel,u,as2
cmsel,u,as1
cm,conc,area

allsel
save,pnnla,db
```

Input file: PNNLA2.mac

```
mat_liner=1
mat_conc=2
mat_rebar=3
mat_insul=4
mat_soil=5
mat_haunch=6

type_liner=1          !liner shells
type_tank=2           !tank concrete
type_haunch=3         !haunch concrete
type_slab=4           !slab concrete
type_rebar=5          !rebar
type_insul=6          !insulating concrete
type_soil=7           !soil

et,type_liner,181
et,type_tank,181
et,type_haunch,181
et,type_slab,181
et,type_rebar,181
et,type_insul,181
et,type_soil,181

et,type_liner+10,65
et,type_tank+10,65
et,type_haunch+10,65
et,type_slab+10,65
et,type_rebar+10,65
et,type_insul+10,65
et,type_soil+10,45

!define local element coordinate systems for rebar regions
cmsel,s,as1
cmsel,a,as2
cmsel,a,as3
cmsel,a,as4
cmsel,a,hrad
cmsel,a,hvert
*get,narea,area,,count
cm,atemp,area

*afun,deg
ics=100
*do,i,1,narea
 *get,ia,area,,num,min
 asel,s,,,ia
 lsla
 ksll
 csys,0
 *get,minx,kp,,mnloc,x
 *get,maxx,kp,,mxloc,x
```

```
 *get,miny,kp,,mnloc,y
 *get,maxy,kp,,mxloc,y
 theta=90
 *if,minx,ne,maxx,then
      theta=atan((maxy-miny)/(maxx-minx))
 *endif
 wpcsys,-1
 kwpave,all
 wprot,theta
 cswplan,ics,0
 aatt,mat_rebar,,type_rebar,ics
 cmsel,s,atemp
 asel,u,,,ia
 cm,atemp,area
 ics=ics+1
*enddo

!define spherical coordinate system for haunch, with center at
global origin
csys,0
wpcsys,-1
local,ics,2
asel,s,,,32
aatt,mat_conc,604,type_haunch,ics

!set real constants for rebar
csys,0
wpcsys,-1
!wall external
set_ry,-8,131,201,'as2'
set_ry,131,204,202,'as2'
set_ry,204,287,203,'as2'
set_ry,287,339,204,'as2'
set_ry,339,382,205,'as2'

!wall internal
csys,0
wpcsys,-1
set_ry,-8,131,206,'as1'
set_ry,131,204,207,'as1'
set_ry,204,287,208,'as1'
set_ry,287,339,209,'as1'
set_ry,339,382,210,'as1'

!slab bottom
csys,0
wpcsys,-1
set_rx,-75,0,101,'as3'
set_rx,-115,-75,102,'as3'
set_rx,-202,-115,103,'as3'
set_rx,-350,-202,104,'as3'
set_rx,-369,-350,105,'as3'
set_rx,-435,-369,106,'as3'
set_rx,-442,-435,107,'as3'
set_rx,-531,-442,108,'as3'

!slab top
csys,0
wpcsys,-1
set_rx,-75,0,111,'as4'
set_rx,-115,-75,112,'as4'
set_rx,-202,-115,113,'as4'
set_rx,-350,-202,114,'as4'
set_rx,-369,-350,115,'as4'
set_rx,-435,-369,116,'as4'
set_rx,-442,-435,117,'as4'
```

```
set_rx,-531,-442,118,'as4'

!dome external
csys,0
wpcsys,-1
set_rx,-120,0,301,'as2'
set_rx,-183,-120,302,'as2'
set_rx,-270,-183,303,'as2'
set_rx,-305,-270,304,'as2'
set_rx,-314,-305,305,'as2'
set_rx,-354,-314,306,'as2'
set_rx,-369,-354,307,'as2'
set_rx,-400,-369,308,'as2'

!dome internal
csys,0
wpcsys,-1
set_rx,-120,0,301,'as1'
set_rx,-183,-120,302,'as1'
set_rx,-270,-183,303,'as1'
set_rx,-305,-270,304,'as1'
set_rx,-314,-305,305,'as1'
set_rx,-354,-314,306,'as1'
set_rx,-369,-354,307,'as1'
set_rx,-400,-369,308,'as1'

!haunch external
csys,5
wpcs,-1
cmse,s,as2
asel,r,loc,x,396,450
set_real,401
cmse,s,as2
asel,r,loc,x,450,504
,r,loc,z,381,999
set_real,402
cmse,s,as2
asel,r,loc,z,408,450
set_real,403
cmse,s,as2
asel,r,loc,z,372,410                !Problem??
set_real,404

!haunch_internal
cmse,,as1
set_ry,381,408,405,'as1'
set_ry,408,488,406,'as1'

! Split haunch vertical at top of radial intersection
lsel,all
ksel,all
asel,s,,,9
ldiv,82,.47
l,278,87
*get,ics,area,9,attr,esys
asbl,9,418
cm,hvert,area
aatt,mat_rebar,,type_rebar,ics

!haunch middle (vertical)
asel,,,,67
set_real,500            !Lower
asel,,,,65
set_real,501            !Upper
!haunch middle (radial)
asel,s,,,10
```

```
set_real,502

!insulating concrete
asel,s,,,3
aatt,mat_insul,600,type_insul,0

!haunch concrete
asel,s,,,32
aatt,mat_haunch,503,type_haunch,ics

allsel
asel,u,mat,,mat_insul
asel,u,mat,,mat_rebar
asel,u,mat,,mat_haunch
aatt,mat_conc,700,type_tank,0
cm,atemp,area
asel,r,loc,y,-999,-8.125
aatt,mat_conc,700,type_slab,0
cmsel,s,atemp
asel,u,type,,type_slab
aatt,mat_conc,700,type_tank,0

asel,s,,,27          Outer cover haunch
l,39,18
asbl,27,419
aatt,mat_conc,700,type_tank,0

allsel
save,pnnla2,db
```

Input file: PNNLA3.mac

```
!identify jbolt lines
!***  Remove jbolts from wall 5/6/04
lsel,,,,315,322,7
,a,,,318,327,9
,a,,,92,332,240
,a,,,326,337,11
,a,,,335,342,7
,a,,,209,349,140
,a,,,345,375,5
,a,,,354,379,5
,a,,,382
cm,line_bolt,line

lsel,,,,229,389,160
,a,,,310,394,84
,a,,,399,407,8
,a,,,287,288
,a,,,413
cm,line_wstiff,line

lsel,,,,414,415
cm,line_hstiff,line

lsel,,,,3,9,6
,a,,,14,19,5
,a,,,330
,a,,,58,59
,a,,,339,341,2
,a,,,348,373,5
,a,,,380,381
,a,,,385
cm,line_prim,line

ksel,,loc,x,-480
,r,loc,y,,382
```

```
lslk,,1
lsel,a,,,16,17
,a,,,21,22
,a,,,25,27,2
,a,,,314,323,9
,a,,,96
,a,,,291,303,12
cm,line_secon,line

lsel,s,,,309
,a,,,406
cm,line_botanch,line

allsel

save,pnnla3,db
```

Input file: PNNLA4.mac

```
!copy areas for overlapping with soil
cm,a_orig,area
agen,2,all
cmsel,u,a_orig
cm,a_new,area

csys,0
ksel,s,loc,x,0
cm,ktemp,kp
*get,ymx,kp,,mxloc,y
*get,ymn,kp,,mnloc,y
ksel,r,loc,y,ymx
*get,iktop,kp,,num,min
cmsel,s,ktemp
ksel,r,loc,y,ymn
*get,ikbot,kp,,num,min

htop=12
radsoil=550
depthsoil=60
csys,0
wpcsys,-1
asel,none
rectng,-radsoil,0,ymn-depthsoil,ymx+htop
cm,as0,area
allsel
asba,as0,a_new
asel,s,,,283
adele,all,,,1
asel,s,,,282
cm,soil,area
aatt,mat_soil,1,type_soil

/input,mesh_size,mac

!***
!***   Clean up mesh 4/1/03
!***

lesi,385,,,20
,380,,,14
,89,,,76
,339,,,4
,246,,,1
,129,,,19
,175,,,3
```

```
,177,,,1
,178,,,1
,171,,,2
,172,,,2
,34,,,9
asel,s,type,,type_rebar
esize,eesize
amesh,all
acle,10
amap,10,82,84,85,87
asel,invert
asel,u,type,,type_soil
esize,eesize
amesh,all
asel,s,type,,type_soil
asel,a,mat,,mat_conc
lsla
ksll
nummrg,kp

asel,s,mat,,mat_soil
smrtsize,8
lsel,s,,,832            !vertical line above dome center
lesize,all,,,4
lsel,s,,,833            !vertical line below dome center
lesize,all,,,8
esize,soil_size  !20
amesh,all

extopt,esize,1
type,17
vrotat,all,,,,,,ikbot,iktop,swp_th,1
asel,s,type,,type_slab
asel,a,type,,type_insul
cm,atemp,area
agen,2,all
cm,aaa,area
cmsel,s,atemp
aclear,all
adele,all,,,1

allsel
aslv,u
*get,na,area,,count
cm,atemp,area
*do,i,1,na
 *get,ia,area,,num,min
 asel,s,,,ia
 *get,imat,area,ia,attr,mat
 *get,ireal,area,ia,attr,real
 *get,itype,area,ia,attr,type
 *get,isys,area,ia,attr,esys
 mat,imat
 real,ireal
 type,itype+10
 esys,isys
 ksel,all
 vrotat,ia,,,,,,ikbot,iktop,swp_th,1
 cmsel,s,atemp
 asel,u,,,ia
 cm,atemp,area
*enddo

allsel
aclear,all
```

```
save,pnnla4,db
```

Input file: PNNLA5.mac

```
vsel,s,mat,,1
cm,vtemp,volu
vgen,2,all
cm,vvv,volu
cmsel,s,vtemp
vclear,all
vdele,all,,,1
cmsel,s,vvv
eslv
emodif,all,mat,mat_soil

!rotate all nodes to cylindrical coordinate system (22)
csys,0
wpcsys,-1
wprot,,-90
cswplan,22,1
allsel
nrotate,all

csys,0
!merge slab/rebar nodes/kps
vsel,s,type,,type_rebar+10
vsel,r,loc,y,-999,-11
vsel,a,type,,type_slab+10
vsel,u,mat,,1
eslv
nsle
aslv
lsla
ksll
nummrg,node
nummrg,kp

!merge tank/rebar nodes/kps
vsel,s,type,,type_rebar+10
vsel,r,loc,y,-8,999
vsel,a,type,,type_tank+10
vsel,a,type,,type_haunch+10
vsel,u,mat,,1
aslv
lsla
ksll
nsla,,1
nummrg,node
nummrg,kp

!couple soil to concrete exterior
esel,s,mat,,mat_soil
nsle
ksln
lslk,,1
asll,,1
cm,asoil,area
vsel,s,type,,type_tank+10
aslv
asel,r,ext
cm,atank,area
vsel,s,type,,type_slab+10
aslv
asel,r,ext
cm,aslab,area
vsel,s,type,,type_insul+10
aslv
```

```
cm,ainsul,area

!top of dome
csys,0
cmsel,s,atank
cmsel,a,asoil
asel,r,loc,y,452,999
lsla
nsla,,1
cpintf,uz,.1

!side of tank
cmsel,s,atank
cmsel,a,asoil
asel,r,loc,y,-8.125,452
lsla
nsla,,1
cpintf,ux,.1

!top of slab
cmsel,s,aslab
cmsel,a,asoil
asel,r,loc,y,-6.7,-6.6
lsla
nsla,,1
cpintf,uz,.1

!side of slab
cmsel,s,aslab
cmsel,a,asoil
asel,r,loc,y,-31,-6.7
asel,r,loc,x,-999,-529
lsla
nsla,,1
cpintf,ux,.1

!bottom of slab
cmsel,s,aslab
cmsel,a,asoil
asel,r,loc,x,-530,0
asel,r,loc,y,-999,-18.5
lsla
nsla,,1
cpintf,uz,.1

!couple top of slab / bottom of wall
cmsel,s,aslab
cmsel,a,atank
lsla
nsla,,1
cpintf,uz,.1

!couple top of slab / bottom of insulating concrete
vsel,s,mat,,mat_insul
cm,vtemp,volu
vgen,2,all
cm,volu_insul,volu
cmsel,s,vtemp
vclear,all
vdele,all,,,1
cmsel,s,volu_insul
aslv
cm,ainsul,area
cmsel,s,aslab
cmsel,a,ainsul
lsla
```

```
nsla,,1
cpintf,uz,.1

save,pnnla5,db
```

Input file: PNNLA6.mac

```
!***  mesh J-bolt @ liner w/separate node 5/6/04

!***  Use mesh200 for J-bolts  4/1/04
!***   redefine as beam188 in set_slicea.mac
resu,pnnla5,db
!generate J-bolts
type_bolt=20
et,type_bolt,200,2
mat,mat_liner
type,type_bolt
csys,0
cmsel,s,line_bolt
csys,11
lsel,r,loc,x,480,483
lgen,2,all,,,,,,3000
ksll
ksel,r,loc,x,481,486
numm,kp
cmse,,line_bolt
lsel,u,loc,x,480,483
,a,,,423,435
lmesh,all
csys

!generate studs
type_stud=21
et,type_stud,4
area_stud=pi*.5**2/4
iy=pi*.5**4/64
iz=iy
ty=.5
tz=.5
r,30,area_stud,iy,iz,ty,tz
cmsel,s,line_botanch
real,30
mat,mat_liner
type,type_stud
lmesh,all

!generate wall base plate
asel,s,,,214
,a,,,706
,a,,,913,918,5
,a,,,934
cm,baseplate,area
type_baseplate=22
et,type_baseplate,63
r,40,.375
mat,mat_liner
type,type_baseplate
real,40
amesh,all

!generate confining ring below 12" secondary liner fillet
ksel,s,loc,x,-480-.01,-480+.01
ksel,r,loc,y,-8.2,6.9
lslk,,1
asll
asel,u,loc,z,0
cm,confineplate,area
```

```
type_confine=23
et,type_confine,63
r,41,3/16
type,type_confine
real,41
mat,mat_liner
amesh,all

!generate confining ring for insulating concrete
csys,0
ksel,s,loc,x,-447
lslk,,1
asll,,1
cm,confinering,area
type_confine=23
type,type_confine
real,41
mat,mat_liner
amesh,all

!generate construction stiffeners
cmsel,s,line_wstiff
asll
asel,u,loc,z,0
cm,stiff_area,area
type_stiff=24
et,type_stiff,63
type,type_stiff
r,42,.5
real,42
mat,mat_line
amesh,all

!generate detail #9
cmse,,line_hstiff
asll
asel,u,loc,z,0
cm,detail9,area
type_anchor=25
et,type_anchor,63
type,type_anchor
r,43,.375*1.1
real,43
mat,mat_liner
amesh,all

allsel
save,pnnla6,db
```

Input file: PNNLA7.mac

```
!primary liner
allsel
aslv
lsla
cmsel,s,line_prim
lsel,a,,,34
cm,ltemp,line

asll
asel,u,loc,z,0
ksll
nummrg,kp
cm,line_prim,line
cm,area_prim,area
! Reverse normals - dome
```

```
asel,r,loc,y,459,999
arev,all
asel,none
ksel,s,loc,x,0
ksel,r,loc,y,ymx
*get,iktop,kp,,num,min
ksel,s,loc,x,0
ksel,r,loc,y,ymn
*get,ikbot,kp,,num,min
ksel,all
cmsel,s,ltemp
cmsel,s,area_prim
lsla,u
arotat,all,,,,,,ikbot,iktop,swp_th,1
lsla
ksll
nummrg,kp
aatt,mat_liner,,type_liner
esize,4
smrt,off
lsel,s,,,9,436,427!radiused part of primary liner
lesi,all,,,8,,1
lsel,s,,,440,441
lesize,all,,,1,,1
amesh,all

cm,atemp,area
agen,2,all
cm,area_liner_prim,area
cmsel,s,atemp
aclear,all
vsel,all
aslv,u
adele,all,,,1

r,50,r50
r,51,r51
r,52,r52
r,53,r53
r,54,r54
r,55,r55

!1" lid at tank bottom
cmsel,s,area_liner_prim
esla
cm,etemp,elem
nsla,,1
cm,ntemp,node
nsel,r,loc,x,-24,0
nsel,r,loc,y,-999,10
esln
cmsel,r,etemp
emodif,all,real,50

!3/8" bottom (on top of insulating concrete)
cmsel,s,ntemp
nsel,r,loc,x,-450+48,-24
nsel,r,loc,y,-999,10
esln
cmsel,r,etemp
emodif,all,real,51

!7/8" at fillet
cmsel,s,ntemp
nsel,r,loc,x,-450,-450+48
nsel,r,loc,y,-999,36.89
```

```
esln
cmsel,r,etemp
emodif,all,real,52

!3/4" vertical run
cmsel,s,ntemp
nsel,r,loc,x,-450
nsel,r,loc,y,36.88,144.89
esln
cmsel,r,etemp
emodif,all,real,53

!1/2" vertical run
cmsel,s,ntemp
nsel,r,loc,x,-450
nsel,r,loc,y,144.88,381.5
esln
cmsel,r,etemp
emodif,all,real,54

!3/8" upper reaches of liner
cmsel,s,ntemp
nsel,r,loc,x,-450,-72.1
nsel,r,loc,y,381.6,999
esln
cmsel,r,etemp
emodif,all,real,51

!1/2" at top/center
cmsel,s,ntemp
nsel,r,loc,x,-72,0
nsel,r,loc,y,381.6,999
esln
cmsel,r,etemp
emodif,all,real,54

!couple vertical displacements at liner bottom
!(first rotate the shell nodes)
esel,s,type,,type_liner
nsle
csys,22
nrotate,all
csys,0
asel,s,loc,y,0
nsla,,1
cpintf,uz,.1
cm,liner_insul_cp_z,node

allsel
save,pnnla7,db
```

Input file: PNNLA8.mac

```
!create shell elements for secondary liner
cmsel,s,line_secon
asll
asel,u,loc,z,0
cm,atemp,area
! Reverse normals - upper section
asel,r,loc,y,381,999
arev,all
lsel,,,,21,22
,a,,,25
arotat,all,,,,,,ikbot,iktop,swp_th,1
cmsel,a,atemp
asel,a,,,27
```

```
cm,area_secon,area
lsla
ksll
nummrg,kp

lesi,437,,,1
,438,,,1
,9,,,6
,22,,,6
aatt,mat_liner,55,type_liner
amesh,all

cm,atemp,area
agen,2,all
cm,area_secon,area
cmsel,s,atemp
aclear,all
aslv,u
adele,all,,,1

ksel,s,loc,x,0
ksel,r,loc,y,ymx
*get,iktop,kp,,num,min
ksel,s,loc,x,0
ksel,r,loc,y,ymn
*get,ikbot,kp,,num,min
ksel,all

!couple vertical displacements at liner bottom
!(first rotate the shell nodes)
esel,s,type,,type_liner
nsle
csys,22
nrotate,all

csys,0

!couple shell horizontal displacements to sidewall

esel,s,type,,type_liner
nsle
cm,ntemp,node
esel,s,mat,,mat_conc
nsle
cmsel,a,ntemp
cm,ntemp,node
nsel,r,loc,y,-2,460
cpintf,ux,.1
cm,liner_wall_cp_x,node

!couple shell vertical displacement to dome
cmsel,s,ntemp
nsel,r,loc,y,460,999
cpintf,uz,.1
cm,liner_dome_cp_z,node

!merge secondary liner nodes with slab top nodes
asel,,loc,y,-8.125
,r,loc,x,-465,1
lsla
nsll,,1
cpdele,all,all
cpintf,uz,.1

allsel
save,pnnla8,db
```

Input file: PNNLA9.mac

```
!*** Do not common node intersection of
!*** primary & secondary liner JED 3/19/04

allsel
mpdele,all,all
tbdele,all,all
set_materials
set_options

acel,0,1,0

allsel

!merge coincident nodes between liners and
jbolts/studs/anchors
esel,s,type,,type_bolt
esel,a,type,,type_stiff
esel,a,type,,type_anchor
esel,a,type,,type_stud
esel,a,type,,type_liner
nsle,,1
nsel,u,,,22789,22790      !*** 3/19/04
nummrg,node

set_soil

allsel
ddele,all,all

!contrain boundaries
csys,0
nsel,s,loc,x,0
d,all,ux,0
d,all,uy,0

allsel
*get,xmn,node,,mnloc,x
*get,ymn,node,,mnloc,y
*get,ymx,node,,mxloc,y

nsel,s,loc,y,ymn
d,all,ux,0,,,,uy,uz

ksel,s,loc,x,xmn
ksel,r,loc,z,0
lslk,,1
asll
asel,u,loc,z,0
nsla,,1
d,all,ux,0
d,all,uy,0
asel,s,loc,y,ymn
nsla,,1
d,all,ux,0,,,,uy,uz

csys,22
nsel,s,loc,y,180-.01,180+.01
nsel,a,loc,y,180+swp_th-.01,180+swp_th+.01
d,all,uy,0
allsel

save,pnnla9,db
```

Input file: set_areas_slice.mac

```
asel,,,,150,161
,a,,,177,179,2
,a,,,184,212,28
,a,,,224,226,2
cm,area_prim,area

vsel,,,,1,199,,1
asel,inve
cmse,u,area_prim
cm,area_secon,area

cmsel,a,area_prim
nsla,,1
esln
sfdele,all,all
sfedele,all,all,all

asel,s,,,239
nsla,,1
esln
arev,all

cmse,,avert
,a,ahorz
cm,asoil,area

asel,,,,314,316
,a,,,700
,a,,,196
,a,,,221,261,40
,a,,,978,984
cm,aconc_soil,area

asel,s,,,993,994
cm,slab_top,area

asel,,,,929
,a,,,552,563,11
,a,,,870,876,6
,a,,,583,593,10
,a,,,605,625,20
,a,,,881,887,6
,a,,,636,646,10
,a,,,892,898,6
,a,,,671,677,6
,a,,,651,693,42
,a,,,641,656,15
,a,,,231,238,7
,a,,,710
,a,,,333
,a,,,243,244
,a,,,190,191
,a,,,723,733,10
,a,,,756,762,6
,a,,,784,796,12
,a,,,806,818,12
,a,,,828,839,11
,a,,,853,864,11
,a,,,844
cm,aconc_shell,area

asel,,,,106,143,37
cm,area_insul_top,area

asel,s,,,27
cm,area_insul_bot,area
```

Input file: set_backfill.mac

```
!***
!***Dilation angle 8   6/4/04
!*** Add materials for load factor restart 8/2/03
!***  JED mod 4/1/03
!***   Define backfill/overburden
!***
max_mat=max_mat+1
cmse,,soil_elem
nsle
hsub=top_elev-arg2-h2+24
rsub=-(68*12+hsub/1.5)
nsel,r,loc,y,top_elev-arg1,top_elev-arg2
,r,loc,x,rsub,0
esln
esel,r,mat,,max_mat
emod,all,mat,max_mat+20

soil_ex=arg3                    !elastic modulus [psi]
soil_prxy=arg4                  !Poisson ratio
soil_alpx=0                     !thermal expansion
coefficient [me/F]
soil_cohesion=1                 !drucker-prager constant
(assume small number) [psi]
soil_friction=35                !internal friction angle [deg]
soil_dilat=8                    !dilatancy angle [deg]

soil_alpx=soil_alpx*1e-6        !in/in/F
soil_dens=b_gam/1728            !lb/in^3

mp,ex,max_mat+20,soil_ex
mp,dens,max_mat+20,soil_dens
mp,prxy,max_mat+20,soil_prxy
mp,alpx,max_mat+20,soil_alpx
tb,dp,max_mat+20
tbdata,1,soil_cohesion,soil_friction,soil_dilat

!*** materials max_mat+70 for load factor restart

mp,ex,max_mat+70,soil_ex
mp,dens,max_mat+70,soil_dens*1.7/1.4
mp,prxy,max_mat+70,soil_prxy
mp,alpx,max_mat+70,soil_alpx
tb,dp,max_mat+70
tbdata,1,soil_cohesion,soil_friction,soil_dilat
```

Input file: set_csys.mac

```
*get,ia,area,,num,min
*get,iareal,area,ia,attr,real
*get,iamat,area,ia,attr,mat
*get,iatype,area,ia,attr,type
aatt,iamat,iareal,iatype,arg1
```

Input file: set_esys.mac

```
!***
!***  Set wall & dome rebar to material 3   6/4/04
!***

/prep7
!define reinforced concrete real constants

!---Create local coordinate systems for esys
!--spherical 1
wpcsys,-1,0                 !spherical
kwpave,1
```

```
wpoff,,-1260
cswpla,200,2

wpcsys,-1,0                !spherical
kwpave,1
wpoff,,-892
cswpla,201,2

csys,0                     !ellipcal coordinate
wpcsys,-1
rat=40/15
k,10000,0,h3,0
kwpave,10000
wprot,90
cswplan,202,2,rat,rat

esel,s,real,,100,118  !slab
esel,r,type,,15
emodif,all,esys,22

esel,s,real,,200,210       !vertical wall
esel,r,type,,15
emodif,all,esys,22

esel,s,real,,300,308    !inner exterior dome
esel,r,type,,15
nsle
csys,22
nsel,r,loc,x,0,170
esln
esel,r,type,,15
emodif,all,esys,200

esel,s,real,,300,308    !outer exterior dome
esel,r,type,,15
nsle
csys,22
nsel,r,loc,x,170,9999
esln
esel,r,type,,15
emodif,all,esys,201

esel,s,real,,401,402       !exterior haunch
esel,r,type,,15
emodif,all,esys,201

esel,s,real,,403,404       !vertical haunch
esel,r,type,,15
emodif,all,esys,22

esel,s,real,,405,406       !interior haunch
esel,r,type,,15
emodif,all,esys,202

esel,s,real,,500,501       !vertical mid haunch
esel,r,type,,15
emodif,all,esys,22

esel,s,real,,502   !spherical mid haunch
esel,r,type,,15
emodif,all,esys,201

esel,s,real,,503   !tie bar haunch
emodif,all,esys,ics
```

```
! Slab bottom
r,101,6,.0256,,,6,.0256          ! Center to 6'3"
rmor,90,,,,90,90
r,102,6,.0258,,,6,.0256          ! 6'3" to 7'6"+ld
rmor,90,,,,90,90
r,103,6,.0316,,,6,.0256          ! 7'6"+ld to 14'6"+ld
rmor,90,,,,90,90
r,104,6,.0360,,,6,.0256          ! 14'6"+ld to 29'2"
rmor,90,,,,90,90
r,105,6,.0326,,,6,.0256          ! 29'2" to 30'9"
rmor,90,,,,90,90
r,106,6,.0293,,,6,.0256          ! 30'9" to 36'3"
rmor,90,,,,90,90
r,107,6,.0267,,,6,.0552          ! 36'3" to 37'
rmor,90,,,,90,90
r,108,6,.1016,,,6,.0552          ! 37' to OD
rmor,90,,,,90,90

! Slab top
r,111,6,.0256,,,6,.0256          ! Center to 6'3"
rmor,90,,,,90,90
r,112,6,.0242,,,6,.0256          ! 6'3" to 7'6"+ld
rmor,90,,,,90,90
r,113,6,.0330,,,6,.0256          ! 7'6"+ld to 14'6"+ld
rmor,90,,,,90,90
r,114,6,.0377,,,6,.0256          ! 14'6"+ld to 29'2"
rmor,90,,,,90,90
r,115,6,.0269,,,6,.0256          ! 29'2" to 30'9"
rmor,90,,,,90,90
r,116,6,.0313,,,6,.0256          ! 30'9" to 36'3"
rmor,90,,,,90,90
r,117,6,.0284,,,6,.0552          ! 36'3" to 37'
rmor,90,,,,90,90
r,118,6,.0259,,,6,.0552          ! 37' to OD
rmor,90,,,,90,90

! Wall external
r,201,,,,,3,.0982                ! Base to 10'3" + 1/2 splice
rmor,90,,3,.0368,90,90
r,202,,,,,3,.0982                ! 10'3" to 17'
rmor,90,,3,.0491,90,90
r,203,,,,,3,.0655                ! 17' to 23'3" + 1/2 splice
rmor,90,,3,.0491,90,90
r,204,,,,,3,.0655                ! 23'3" to 28'3-1/2"
rmor,90,,3,.0655,90,90
r,205,,,,,3,.0655                ! 28'3-1/2" to tangent height
rmor,90,,3,.0655,90,90

! Wall internal
r,206,,,,,3,.0982                ! Base to 10'3" + 1/2 splice
rmor,90,,3,.0368,90,90
r,207,,,,,3,.0982                ! 10'3" to 17'
rmor,90,,3,.0491,90,90
r,208,,,,,3,.0655                ! 17' to 23'3" + 1/2 splice
rmor,90,,3,.0491,90,90
r,209,,,,,3,.0655                ! 23'3" to 28'3-1/2"
rmor,90,,3,.0655,90,90
r,210,,,,,3,.0655                ! 28'3-1/2" to tangent height
rmor,90,,3,.0655,90,90

! Dome top & bottom
r,301,,,,,3,.0453                ! Center to 7'3"
rmor,90,,3,.0368,90,90
r,302,,,,,3,.0490                ! 7'3" to 12'6" +
rmor,90,,3,.0368,90,90
r,303,,,,,3,.0661                ! 12'6" to 22'9"
```

```
rmor,90,,3,.0368,90,90
r,304,,,,,3,.0496          ! 22'9" to 25'4-1/2"
rmor,90,,3,.1309,90,90
r,305,,,,,3,.1399          ! 25'4-1/2" to 26'2"
rmor,90,,3,.1309,90,90
r,306,,,,,3,.1300          ! 26'2" to 29'9
rmor,90,,3,.1657,90,90
r,307,,,,,3,.1197          ! 28' to 29'6"
rmor,90,,3,.2485,90,90
r,308,,,,,3,.1139          ! 29'6" to 32'6"
rmor,90,,3,.2485,90,90

! Haunch external
!   Dome (csys,201)
r,401,,,,,3,.2209          ! 33'3" to 37'6"
rmor,90,,3,.1534,90,90
r,402,,,,,3,.2209          ! 37'6" to 41'4"
rmor,90,,3,.1375,90,90
!   Wall (csys,22)
r,403,,,,,3,.2485          ! Height: 34' to corner
rmor,90,,3,.2045,90,90
r,404,,,,,3,.1309          ! Height: tangent to 34'
rmor,90,,3,.2700,90,90

! Haunch internal
!  (csys,202)
r,405,,,,,3,.1309          ! Height: tangent to 34'
rmor,90,,3,.1309,90,90
r,406,,,,,3,.2209          ! 33'3" radius to 34' height
rmor,90,,3,.1489,90,90

!haunch middle
!   (csys,202)
r,502,3,.0007,,,3,.0261          ! 33'3" to vertical
rmor,90,,3,.2209,90,90
!   (csys,22)
r,500,3,.0007,,,3,.1243          ! lower vertical
rmor,90,,3,.0236,90,90
r,501,3,.0007,,,3,.1243          ! upper vertical
rmor,90,,3,.0109,90,90

!haunch ties
r,503,3,.0006
rmore,90,,,,90,90

!secondary liner above 357.5"
r,56,r56
esel,s,real,,55
nsle,,1
csys,0
nsel,r,loc,y,357.5,99999
esln,,1
esel,r,type,,1
emodif,all,real,56
```

Input file: set_mat.mac

```
*get,ia,area,,num,min
*get,iareal,area,ia,attr,real
*get,iatype,area,ia,attr,type
*get,iacsys,area,ia,attr,esys
aatt,arg1,iareal,iatype,iacsys
```

Input file: set_materials.mac

```
!***
!***6/7/04  Add 205F & 215F degraded concrete
!***6/4/04  MISO rebar (mats 3 & 6)
```

```
!*** 10/9/03 Fill out temperature dependent steel modulus
table
!*** 7/23/03 Elastic insulating concrete (no cracking)
!*** 6/17/03 Correct alpx,mat_liner
!***
!***      5/14/03
!*** Add 6 concrete materials: mats 21 - 26
!***    Constant (degraded) properties @
230,250,270,290,310,330
!***  to be used after t=3+15+330 days
!***
!***Remove concrete crushing 5/5/03
!***
!***  Temperature dependent Materials
!***    Best estimate = mean values
!***     All steel elastic
!***      Run 2 (nocreep)  4/16/03
!***
!specify all material properties
/prep7

![1]                    steel (for liner, jbolts, studs, anchors,
bearing plates)
steel_alpx=steel_alpx*1e-6                !in/in/F
steel_dens=steel_gamma/1728               !lb/in^3

mpte
mpte,1,50,70,100,125,150,175
mpte,7,200,225,250,275,300,325
mpte,13,350
mpda,ex,mat_liner,1,29.5e6,29.5e6,29.34e6,29.20e6,29.07e6,
28.93e6
mpda,ex,mat_liner,7,28.8e6,28.68e6,28.55e6,28.43e6,28.3e6,
28.15e6
mpda,ex,mat_liner,13,28.0e6
mp,dens,mat_liner,steel_dens
mp,prxy,mat_liner,steel_prxy
mpda,alpx,mat_liner,1,5.73e-6,5.73e-6,5.73e-6,5.82e-
6,5.91e-6,6.0e-6
mpda,alpx,mat_liner,7,6.09e-6,6.18e-6,6.27e-6,6.35e-
6,6.43e-6,6.51e-6
mpda,alpx,mat_liner,13,6.59e-6
tb,biso,mat_liner
tbdata,1,steel_yield,steel_tan*steel_ex

![2]                    structural concrete
conc_alpx=conc_alpx*1e-6                  !in/in/F
conc_dens=conc_gamma/1728                 !lb/in^3

mp,ex,mat_conc,7.434e6,-30.09e3,71.16,-.0709
mpda,ex,mat_conc,1,5.083e6,5.083e6,5.083e6
mp,dens,mat_conc,conc_dens
mp,prxy,mat_conc,conc_prxy
mp,alpx,mat_conc,conc_alpx
tb,concr,mat_conc,5
tbte,50,1
tbda,1,.1,.98,519,-1
tbte,200,2
tbda,1,.1,.98,519,-1
tbte,225,3
tbda,1,.1,.98,427,-1
tbte,250,4
tbda,1,.1,.98,335,-1
tbte,350,5
tbda,1,.1,.98,335,-1
```

```
tb,creep,mat_conc
tbda,1,.2545e-6,1,-.838,320,,1

![21]     degraded structural concrete (205F)
mp,ex,21,3.652e6
,dens,21,conc_dens
,prxy,21,conc_prxy
,alpx,21,conc_alpx
tb,concr,21
tbda,1,.1,.98,501,-1
tb,creep,21
tbda,1,.2545e-6,1,-.838,320,,1

![22]     degraded structural concrete (215F)
mp,ex,22,3.557e6
,dens,22,conc_dens
,prxy,22,conc_prxy
,alpx,22,conc_alpx
tb,concr,22
tbda,1,.1,.98,465,-1
tb,creep,22
tbda,1,.2545e-6,1,-.838,320,,1

![23]     degraded structural concrete (225F)
mp,ex,23,3.467e6
,dens,23,conc_dens
,prxy,23,conc_prxy
,alpx,23,conc_alpx
tb,concr,23
tbda,1,.1,.98,427,-1
tb,creep,23
tbda,1,.2545e-6,1,-.838,320,,1

![24]     degraded structural concrete (235F)
mp,ex,24,3.380e6
,dens,24,conc_dens
,prxy,24,conc_prxy
,alpx,24,conc_alpx
tb,concr,24
tbda,1,.1,.98,390,-1
tb,creep,24
tbda,1,.2545e-6,1,-.838,320,,1

![25]     degraded structural concrete (245F)
mp,ex,25,3.297e6
,dens,25,conc_dens
,prxy,25,conc_prxy
,alpx,25,conc_alpx
tb,concr,25
tbda,1,.1,.98,354,-1
tb,creep,25
tbda,1,.2545e-6,1,-.838,320,,1

![26]     degraded structural concrete (255F)
mp,ex,26,3.217e6
,dens,26,conc_dens
,prxy,26,conc_prxy
,alpx,26,conc_alpx
tb,concr,26
tbda,1,.1,.98,335,-1
tb,creep,26
tbda,1,.2545e-6,1,-.838,320,,1

![27]     degraded structural concrete (265F)
mp,ex,27,3.141e6
```

```
,dens,27,conc_dens
,prxy,27,conc_prxy
,alpx,27,conc_alpx
tb,concr,27
tbda,1,.1,.98,335,-1
tb,creep,27
tbda,1,.2545e-6,1,-.838,320,,1

![28]     degraded structural concrete (275F)
mp,ex,28,3.067e6
,dens,28,conc_dens
,prxy,28,conc_prxy
,alpx,28,conc_alpx
tb,concr,28
tbda,1,.1,.98,335,-1
tb,creep,28
tbda,1,.2545e-6,1,-.838,320,,1

![29]     degraded structural concrete (285F)
mp,ex,29,2.996e6
,dens,29,conc_dens
,prxy,29,conc_prxy
,alpx,29,conc_alpx
tb,concr,29
tbda,1,.1,.98,335,-1
tb,creep,29
tbda,1,.2545e-6,1,-.838,320,,1

![30]     degraded structural concrete (295F)
mp,ex,30,2.927e6
,dens,30,conc_dens
,prxy,30,conc_prxy
,alpx,30,conc_alpx
tb,concr,30
tbda,1,.1,.98,335,-1
tb,creep,30
tbda,1,.2545e-6,1,-.838,320,,1

![31]     degraded structural concrete (305F)
mp,ex,31,2.860e6
,dens,31,conc_dens
,prxy,31,conc_prxy
,alpx,31,conc_alpx
tb,concr,31
tbda,1,.1,.98,335,-1
tb,creep,31
tbda,1,.2545e-6,1,-.838,320,,1

![32]     degraded structural concrete (315F)
mp,ex,32,2.796e6
,dens,32,conc_dens
,prxy,32,conc_prxy
,alpx,32,conc_alpx
tb,concr,32
tbda,1,.1,.98,335,-1
tb,creep,32
tbda,1,.2545e-6,1,-.838,320,,1

![33]     degraded structural concrete (325F)
mp,ex,33,2.734e6
,dens,33,conc_dens
,prxy,33,conc_prxy
,alpx,33,conc_alpx
tb,concr,33
tbda,1,.1,.98,335,-1
tb,creep,33
```

```
tbda,1,.2545e-6,1,-.838,320,,1

![34]      degraded structural concrete (335F)
mp,ex,34,2.673e6
,dens,34,conc_dens
,prxy,34,conc_prxy
,alpx,34,conc_alpx
tb,concr,34
tbda,1,.1,.98,335,-1
tb,creep,34
tbda,1,.2545e-6,1,-.838,320,,1

![35]      degraded structural concrete (345F)
mp,ex,35,2.615e6
,dens,35,conc_dens
,prxy,35,conc_prxy
,alpx,35,conc_alpx
tb,concr,35
tbda,1,.1,.98,335,-1
tb,creep,35
tbda,1,.2545e-6,1,-.838,320,,1

![3]                rebar
rebar_alpx=rebar_alpx*1e-6              !in/in/F
rebar_dens=rebar_gamma/1728             !lb-sec^2/in^4

mp,ex,mat_rebar,rebar_ex
mp,dens,mat_rebar,rebar_dens
mp,prxy,mat_rebar,rebar_prxy
mp,alpx,mat_rebar,rebar_alpx
tb,miso,mat_rebar,4,4
tbte,100,1
tbpt,,2069e-6,60000
,,3770e-6,67331
,,9555e-6,73035
,,20129e-6,76967
tbte,200,2
tbpt,,1896e-6,54978
,,3770e-6,61720
,,9555e-6,66882
,,20129e-6,70582
tbte,300,3
tbpt,,1896e-6,53304
,,3770e-6,59850
,,9555e-6,64831
,,20129e-6,68453
tbte,400,4
tbpt,,1780e-6,51630
,,3770e-6,57979
,,9555e-6,62780
,,20129e-6,66325

![4]                insulating concrete
insul_alpx=insul_alpx*1e-6              !in/in/F
insul_dens=insul_gamma/1728             !lb/in^3

mp,ex,mat_insul,insul_ex
mp,dens,mat_insul,insul_dens
mp,prxy,mat_insul,insul_prxy
mp,alpx,mat_insul,insul_alpx
!tb,concr,mat_insul
!tbda,1,insul_open,insul_closed,insul_crack,-1


![5]                soil
! These soil properties for material 5 are overwritten later
```

```
!soil_ex=575000          !elastic modulus [psi]
!soil_prxy=0.1           !Poisson ratio
!soil_alpx=0             !thermal expansion coefficient
[me/F]
!soil_gamma=125          !unit weight [lbf/ft^3]
!soil_cohesion=0         !drucker-prager constant (assume
small number) [psi]
!soil_friction=35.4      !internal friction angle [deg]
!soil_dilat=35.4         !dilatancy angle [deg]

!soil_alpx=soil_alpx*1e-6        !in/in/F
!soil_dens=soil_gamma/1728       !lb2/in^3

!mp,ex,mat_soil,soil_ex
!mp,dens,mat_soil,soil_dens
!mp,prxy,mat_soil,soil_prxy
!mp,alpx,mat_soil,soil_alpx
!tb,dp,mat_soil
!tbdata,1,soil_cohesion,soil_friction,soil_dilat

!set mat_haunch materials equal to mat_conc material
vsel,s,mat,,mat_haunch
eslv
emodif,all,mat,mat_conc
mpdele,all,mat_haunch

!set slab rebar material properties
vsel,s,mat,,mat_rebar
eslv
nsle
nsel,r,loc,y,-999,-8.125
esln,,1
esel,r,mat,,mat_rebar
mat_srebar=6
emodif,all,mat,mat_srebar

![6]                slab rebar
srebar_alpx=srebar_alpx*1e-6            !in/in/F
srebar_dens=srebar_gamma/1728           !lb/in^3

mp,ex,mat_srebar,srebar_ex
mp,dens,mat_srebar,srebar_dens
mp,prxy,mat_srebar,srebar_prxy
mp,alpx,mat_srebar,srebar_alpx
tb,miso,mat_srebar,4,4
tbte,100,1
tbpt,,1379e-6,40000
,,2513e-6,44887
,,6370e-6,48690
,,13419e-6,51311
tbte,200,2
tbpt,,1264e-6,36652
,,2513e-6,41147
,,6370e-6,44588
,,13419e-6,47055
tbte,300,3
tbpt,,1225e-6,35536
,,2513e-6,39900
,,6370e-6,43221
,,13419e-6,45636
tbte,400,4
tbpt,,1187e-6,34420
,,2513e-6,38653
,,6370e-6,41853
,,13419e-6,44217
```

```
allsel
esel,s,mat,,3
esel,a,mat,,6
emodif,all,mat,2
allsel
```

Input file: set_options.mac

```
!***Turn on creep, turn on steel plasticity 6/8/04

/prep7

!remove structural concrete CONCR material model
!tbdele,concr,mat_conc

!remove concrete CREEP material model
!tbdele,creep,mat_conc

!remove insulating concrete CONCR material model
!tbdele,concr,mat_insul

!remove insulating concrete CREEP material model
tbdele,creep,mat_insul

!remove liner BISO material model
!tbdele,BISO,mat_liner

!remove rebar BISO material model
!tbdele,BISO,mat_rebar
!tbde,biso,mat_srebar

!remove soil DP material model
!tbdele,DP,mat_soil
```

Input file: set_parms.mac

```
!***
!***  Best estimate soil properties  3/19/04
!***
!*** Run 2, Load Case 1 - 4
!***   (8.3' soil, 125 lb/ft3)
!***   (0.06" primary tank corrosion)
!*** 4/16/03
!***
!***
!***  JED mods 3/20/03
!***  add clr - concentrated load radius
!***  add backfill properties 3/24
!***  backfill properties f(depth)  4/1

finish
/clear
/fil,pnnla
/prep7
/titl,AP 422"(20yr)/460"(40yr), 210F, 1.83SpG, BES
!
! DST - AY

pi=acos(-1)

clr=10*12          !Concentrated load radius
or=12*41.5         !Outside radius concrete wall
ir=12*40           !Inside radius concrete wall
ir2=12*37.5        !Radius primary tank
icr=37*12+3                !Radius insulating concrete
h1=0
```

```
h2=-8.125
h3=381.5                !Height dome tangent  (31'9-1/2")
h4=h3+70.875            !Height exterior corner  (+ 5'10-7/8" =
37'8-3/8")
h5=h3+15*12             !Height interior center dome
h6=h5+15                !Height exterior center dome

covext=2                !Concrete cover - exterior dome
covint1=4               !Concrete cover - wall
covint2=1.5             !Concrete cover - interior dome

r1=105*12+.25           !Exterior dome radius - center
th1=7+(45+14/60)/60     !Angle at tangent of external radii
r2=74*12+4              !Exterior dome radius - outer
r3=3*12+8.375           !Radius primary tank to dome


! This file sets the values of all parameters that may be changed

! These were originally defined in define_soil_layers.mac:

overburden=8.3*12  !overburden height above dome apex (ft)
subdepth=168*12    !subgrade soil depth (ft)
totalwidth=240*12  !total soil width (radius) from tank centerline
to edge (ft)


! These were originally defined in dstay7.mac:

r50=1-.06       !shell thickness (in) (R1 of Figure 11 in RPP-
13990)
r51=3/8-.06     !shell thickness (in) (R2,R6,R7,R9 of Figure 11 in
RPP-13990)
r52=7/8-.06     !shell thickness (in) (R3 of Figure 11 in RPP-
13990)
r53=3/4-.06     !shell thickness (in) (R4 of Figure 11 in RPP-
13990)
r54=1/2-.06     !shell thickness (in) (R5,R8 of Figure 11 in RPP-
13990)
r55=1/4     !shell thickness (in) (R10 of Figure 11 in RPP-13990)


! This was originally defined in set_esys_3d.mac:

r56=3/8    !shell thickness (in) of secondary liner above 357.5 in


! These were originally defined in set_materials.mac:

![1]            steel (for liner, jbolts, studs, anchors, bearing plates)
steel_ex=27.7e6                !elastic modulus [psi]
steel_prxy=0.3                 !Poisson ratio
steel_alpx=6.38                !thermal expansion coefficient
[microstrain/degree F]
steel_gamma=490                !unit weight [lbf/ft^3]
steel_yield=36000              !yield strength [psi]
steel_tan=0.01                 !rebar tangent modulus [% of elastic
modulus]

![2]       structural concrete
conc_ex=3.8e6                  !elastic modulus [psi]
conc_prxy=0.15                 !Poisson ratio
conc_alpx=3.7                  !thermal expansion coefficient
[microstrain/degree F]
conc_gamma=145                 !unit weight [lbf/ft^3]
```

```
conc_open=0.1                !shear transfer coefficient for open
crack
conc_closed=0.98             !shear transfer coefficient for closed
crack
conc_crush=3000              !uniaxial crushing stress [psi]
conc_crack=0.1*conc_crush !tensile cracking stress [psi]

![3]          rebar
rebar_ex=29.0e6              !elastic modulus [psi]
rebar_prxy=0.3               !Poisson ratio
rebar_alpx=6.                !thermal expansion coefficient
[microstrain/degree F]
rebar_gamma=490              !unit weight [lbf/ft^3]
rebar_yield=71000            !yield strength [psi]
rebar_tan=0                  !rebar tangent modulus [psi]

![4]      insulating concrete
insul_ex=165e3               !elastic modulus [psi]
insul_prxy=0.15              !Poisson ratio
insul_alpx=3.7               !thermal expansion coefficient
[me/F]
insul_gamma=50               !unit weight [lbf/ft^3]

insul_open=0.1               !shear transfer coefficient for open
crack
insul_closed=0.98            !shear transfer coefficient for closed
crack
insul_crush=200              !uniaxial crushing stress [psi]
insul_crack=20               !tensile cracking stress [psi]

![6]          slab rebar
srebar_ex=29.0e6             !elastic modulus [psi]
srebar_prxy=0.3              !Poisson ratio
srebar_alpx=6.               !thermal expansion coefficient
[microstrain/degree F]
srebar_gamma=490             !unit weight [lbf/ft^3]
srebar_yield=49000           !yield strength [psi]
srebar_tan=0                 !rebar tangent modulus [psi]


!*** Backfill
! These were originally defined in define_loads.mac:
! [5]          backfill soil
backfill_phi=34.5            !soil friction angle deg
backfill_dil=34.5            !backfill dilatancy angle deg
backfill_cte=0               !thermal expansion coef me/f

!*** No waste, pressures or ext. load
pres_surf=0                  !ground surface uniform pressure
psf
point_cent=0                 !point load at center lb
pres_annulus=0               !annulus pressure inches h2o
pres_int=0                   !annulus internal pressure inches
h2o
hwaste=35.17*12              !total waste height
height_waste1=hwaste/3       !height of waste 1 inches
gamma_waste1=0               !specific gravity of waste 1
height_waste2=hwaste/3       !height of waste 2 inches
gamma_waste2=0               !specific gravity of waste 2
height_waste3=hwaste/3       !height of waste 3 inches
gamma_waste3=0               !specific gravity of waste 3


!define soil layers
*dim,soil_emod,,16
*dim,soil_pr,,16
```

```
*dim,soil_z0,,16
*dim,soil_z1,,16
*dim,bf_emod,,8
!*dim,bf_pr,,8
*dim,bf_z0,,8
*dim,bf_z1,,8
bfdinc=(h6+overburden+18.5)/8
sdinc=(subdepth+60)/8

*do,i,1,8
soil_z0(i)=i*bfdinc  !vertical distance from surface
soil_z1(i)=(i-1)*bfdinc
soil_z0(i+8)=i*sdinc+bfdinc*8
soil_z1(i+8)=(i-1)*sdinc+bfdinc*8
bf_z0(i)=i*bfdinc
bf_z1(i)=(i-1)*bfdinc
*enddo

!Elastic modulus
soil_emod(1)=58000,62000,64618,67236,69563,72180,74798,77
125,82117,90000
soil_emod(11)=109697,129650,151456,172835,191000,200000
bf_emod(1)=12000,15000,19500,24000,28000,32500,37000,400
00

!Poisson's ratio
soil_pr(1)=.24,.24,.24,.24,.19,.19,.19,.19,.19,.19
soil_pr(11)=.19,.19,.28,.28,.28,.28
bf_pr=.27

!*** Soil 110 pcf - undisturbed
!*** Soil 125 pcf - backfill/overburden
s_gam=110                    !lbf/ft^3 density of soil layers
(excluding backfill)
b_gam=125                    !lbf/ft^3 density of soil layers
(excluding backfill)

save
```

Input file: set_real.mac

```
*get,ia,area,,num,min
*get,iamat,area,ia,attr,mat
*get,iatype,area,ia,attr,type
*get,iacsys,area,ia,attr,esys
aatt,iamat,arg1,iatype,iacsys
```

Input file: set_rx.mac

```
cmsel,s,arg4
csys,0
asel,r,loc,x,arg1,arg2
set_real,arg3
```

Input file: set_ry.mac

```
cmsel,s,arg4
csys,0
asel,r,loc,y,arg1,arg2
set_real,arg3
```

Input file: set_slayer.mac

```
!***
!***Dilation angle 8   6/4/04
!***Add materials for load factor restart 8/2/03
!***  JED mod 3/24/03
!***    Define soil
!***     (redefine backfill/overburden in set_backfill)
!***
```

```
max_mat=max_mat+1

/prep7

cmsel,s,soil_elem
nsle

csys,0
hsub=top_elev-arg2-h2+24
nsel,r,loc,y,top_elev-arg1,top_elev-arg2
esln,
esel,r,mat,,5
emodif,all,mat,max_mat
emodif,all,real,7


soil_ex=arg3            !elastic modulus [psi]
soil_prxy=arg4          !Poisson ratio
soil_alpx=0             !thermal expansion coefficient
[me/F]
soil_cohesion=1         !drucker-prager constant [psi]
soil_friction=35        !internal friction angle [deg]
soil_dilat=8            !dilatancy angle [deg]

soil_alpx=soil_alpx*1e-6        !in/in/F
soil_dens=s_gam/1728            !lb/in^3

mp,ex,max_mat,soil_ex
mp,dens,max_mat,soil_dens
mp,prxy,max_mat,soil_prxy
mp,alpx,max_mat,soil_alpx
tb,dp,max_mat
tbdata,1,soil_cohesion,soil_friction,soil_dilat
```

```
!*** materials max_mat+50 for load factor restart

mp,ex,max_mat+50,soil_ex
mp,dens,max_mat+50,soil_dens*1.7/1.4
mp,prxy,max_mat+50,soil_prxy
mp,alpx,max_mat+50,soil_alpx
tb,dp,max_mat+50
tbdata,1,soil_cohesion,soil_friction,soil_dilat
```

Input file: set_soil.mac

```
!***
!***  JED mod 3/24/03
!***    define subdepth (depth of soil below foundation
!***
/prep7

csys,0
vsel,s,mat,,1
aslv
asel,u,loc,z,0
cm,aold,area
aslv
asel,r,loc,z,0
cm,anew,area
eslv
nsle
cpdele,all,all
vclear,all
vdele,all
cmsel,s,aold
adele,all,,,1
```

```
cmsel,s,anew
lsla
lesize,all,,,-1,,1
esize,16

adrag,1986,,,,,,1989
aovlap,all
cm,asoil,area
asel,s,,,147
adele,all,,,1
cmsel,s,asoil
lcomb,14,1983
aatt,mat_soil,,type_soil
amesh,all

allsel
*get,km,kp,,num,max
dy=overburden-12

k,km+1,kx(1112)-dy,ky(1110)+dy
k,km+2,kx(1075)-dy,ky(1075)-dy
k,km+3,0,ky(km+2)
k,km+4,kx(km+2),ky(1077)-subdepth
k,km+5,0,ky(km+4)
k,km+6,0,ky(km+1)
k,km+7,-totalwidth,ky(km+1)
k,km+8,kx(km+7),ky(km+2)
k,km+9,kx(km+8),ky(km+4)
k,km+10,-clr,ky(km+1)
asel,none
a,1112,1110,km+6,km+10,km+1
a,km+1,km+2,1075,1112
a,km+2,km+3,1077,1075
a,km+2,km+4,km+5,km+3
a,km+1,km+7,km+8,km+2
a,km+2,km+8,km+9,km+4
lsla
lsel,r,loc,x,kx(km+7)+1,kx(km+1)-1
lesize,all,,,40,1/10
lsel,r,loc,y,ky(km+1)
lesize,all,,,40,10,1
lsla
lsel,r,loc,y,ky(km+9)+1,ky(km+8)-1
lesize,all,,,40,10
lsel,r,loc,x,0
lesize,all,,,40,.1,1
lsla
aatt,mat_soil,,type_soil
amap,147,1112,1110,3261,3256
asel,u,,,147
mshkey,1
amesh,all

asel,s,mat,,mat_soil
type,type_soil+10
mat,mat_soil
ksel,all
vsel,none
vrotat,all,,,,,,ikbot,iktop,swp_th,1
aclear,all

csys,22
nrotate,all

!couple to concrete DOFs
asel,,,,462,466,4
```

```
,a,,,473
,a,,,469,471
,a,,,482,483
,a,,,488,491,3
cm,avert,area
asel,,,,472,481,9
,a,,,478,479
cm,ahorz,area

esel,s,mat,,2
nsle
nsel,r,ext
cm,nconc,node

cmsel,s,avert
nsla,,1
cm,nsoil,node
*get,nnode,node,,count
*do,i,1,nnode
 *get,inode,node,,num,min
 cmsel,s,nconc
 incoup=node(nx(inode),ny(inode),nz(inode))
 nsel,s,,,incoup
 nsel,a,,,inode
 cp,next,uz,all
 cmsel,s,nsoil
 nsel,u,,,inode
 cm,nsoil,node
*enddo

cmsel,s,ahorz
nsla,,1
cm,nsoil,node
*get,nnode,node,,count
*do,i,1,nnode
 *get,inode,node,,num,min
 cmsel,s,nconc
 incoup=node(nx(inode),ny(inode),nz(inode))
 nsel,s,,,incoup
 nsel,a,,,inode
 cp,next,ux,all
 cmsel,s,nsoil
 nsel,u,,,inode
 cm,nsoil,node
*enddo

/eof
csys,22
nsel,s,loc,y,180-.01,180+.01
nsel,a,loc,y,180+swp_th-.01,180+swp_th+.01
nrotate,all
d,all,uy,0
allsel
```

Input file: set_type.mac

```
*get,ia,area,,num,min
*get,iareal,area,ia,attr,real
*get,iamat,area,ia,attr,mat
*get,iacsys,area,ia,attr,esys
aatt,iamat,iareal,arg1,iacsys
```

1.1.3 Thermal Cycling Files

There are six input files required to run the full 60 years of thermal cycling and creep. These are listed sequentially below.

Input file: set_sliceb.inp

```
/fil,set_slice_0
resu
/sol
anty,,rest
!*** Thermal load - Initial ramp
!***
fhrt=7.5/24
time,3+fhrt                    !LS 4
!***
!***  Fast heat to 125F
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
/gopr
nsub,3,10,2
solv

time,2.125+3+fhrt                    !LS 4
!***
!***  One of Two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
nsub,3,10,2
solv

time,4.25+3+fhrt                    !LS 4
!***
!***  Two of Two steps to 210F
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
nsub,3,10,2
solv

time,26                    !LS 9
!***  150F
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
nsub,150,1000,10
solv

time,41                    !LS 10
!***  Steady state @ 210F
/nopr
/inp,frss1,temp
/inp,bkss1,temp
/gopr
nsub,150,1000,15
solv

time,353            !LS 11
!***  Hold for 1 Year
nsub,300,10000,10
save
solv
```

```
time,353+1                !LS 12
!***  mpchg and 1.0 days
*do,i,1,14
esel,,type,,12,15
nsle
nsel,r,bf,temp,190+i*10,200+i*10
esln
esel,r,mat,,2
mpch,20+i,all
*enddo
esel,,type,,12,15
nsle
nsel,r,bf,temp,330,345
esln
esel,r,mat,,2
mpch,35,all
esel,all
nsel,all
nsub,10,100,2
solv

time,354+2.125            !LS 13
!***  Cool to ambient
!***
!***  First of Two steps to 125F
!***
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
nsub,15,200,5
solv

time,354+4.25             !LS 14
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
nsub,15,200,5
solv

time,354+4.25+fhrt                !LS 17
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
nsub,7,100,3
solv

time,354+4.25+fhrt+1              !LS 18
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
nsub,5,100,2
solv
```

```
time,368            !LS 19
!****  Uniform 50F
nsub,47,150,20
bf,all,temp,50
solv

!***  Cycle  4 More Years
*do,i,1,4

time,3+fhrt+365*i                !LS 20
!***
!***  Thermal load - Initial ramp
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
/gopr
nsub,3,10,2
solv

time,3+2.125+fhrt*365*i          !LS 21
!***
!***  First of two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
nsub,20,100,6
solv

time,3+4.25+fhrt+365*i  !LS 22
!***
!***  Second of two steps to 210F
!***
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
nsub,20,100,6
solv

time,3+23+365*i          !LS 25
!***
!***  350F
!***
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
nsub,150,1000,10
solv

time,3+38+365*i                  !LS 26
!***
!***  Steady state @ 210F
!***
/nopr
/inp,frss1,temp
/inp,bkss1,temp
/gopr
nsub,150,1000,30
solv

time,3+351+365*i                 !LS 27
!***
```

```
!***  Creep for 1 Year
!***
nsub,300,10000,6
solv

!***  Cool to ambient
time,3+351+2.125+365*i                !LS 28
!***
!***  First of two steps to 125F
!***
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
nsub,15,200,5
solv

time,3+351+4.25+365*i            !LS 29
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
nsub,15,200,5
solv

time,3+351+4.25+fhrt+365*i                !LS 32
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
nsub,7,100,3
solv

time,3+351+4.25+fhrt+1+365*i  !LS 33
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
nsub,5,100,2
solv

time,3+365+365*i                  !LS 34
!***
!****  Uniform 50F
!***
nsub,47,150,20
bf,all,temp,50
save
solv

*enddo
! End of 5 Year Thermal Cycles
```

Input file: Extended13yr.inp

```
/fil,set_slice_0
resu
```

```
/sol
anty,,rest
!*** Thermal load - Initial ramp
!***
fhrt=7.5/24
time,3+fhrt+365*5
!***
!***  Fast heat to 125F
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
/gopr
nsub,3,10,2
solv

time,2.125+3+fhrt+365*5
!***
!***  One of Two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
nsub,3,10,2
solv

time,4.25+3+fhrt+365*5
!***
!***  Two of Two steps to 210F
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
nsub,3,10,2
solv

time,26+365*5
!***  Steady State @ 210
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
nsub,150,1000,10
solv

time,41+365*5
!***  Steady state @ 210F
/nopr
/inp,frss1,temp
/inp,bkss1,temp
/gopr
nsub,150,1000,15
solv

time,354+365*17
!***  Hold for 13 Years
nsub,300,10000,10
save
solv

time,354+2.125+365*17
!***  Cool to ambient
!***
!***  First of Two steps to 125F
!***
```

```
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
nsub,15,200,5
solv

time,354+4.25+365*17
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
nsub,15,200,5
solv

time,354+4.25+fhrt+365*17
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
nsub,7,100,3
solv

time,354+4.25+fhrt+1+365*17
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
nsub,5,100,2
solv

time,368+365*17
!****  Uniform 50F
nsub,47,150,20
bf,all,temp,50
solv
```

Input file: TwoYrCycle.inp

```
/fil,set_slice_0
resu
/sol
anty,,rest
!*** Thermal load - Initial ramp
!***
fhrt=7.5/24

!***  Cycle
*do,i,18,19

time,3+fhrt+365*i
!***
!***  Thermal load - Initial ramp
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
```

```
/gopr
nsub,3,10,2
solv

time,3+2.125+fhrt*365*i
!***
!***  First of two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
nsub,20,100,6
solv

time,3+4.25+fhrt+365*i
!***
!***  Second of two steps to 210F
!***
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
nsub,20,100,6
solv

time,3+23+365*i
!***
!***  350F
!***
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
nsub,150,1000,10
solv

time,3+38+365*i
!***
!***  Steady state @ 210F
!***
/nopr
/inp,frss1,temp
/inp,bkss1,temp
/gopr
nsub,150,1000,30
solv

time,3+351+365*i
!***
!***  Creep for 1 Year
!***
nsub,300,10000,6
solv

!***  Cool to ambient
time,3+351+2.125+365*i
!***
!***  First of two steps to 125F
!***
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
nsub,15,200,5
solv
```

```
time,3+351+4.25+365*i
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
nsub,15,200,5
solv

time,3+351+4.25+fhrt+365*i
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
nsub,7,100,3
solv

time,3+351+4.25+fhrt+1+365*i
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
nsub,5,100,2
solv

time,3+365+365*i
!***
!****  Uniform 50F
!***
nsub,47,150,20
bf,all,temp,50
save
solv

*enddo
! End of 20 Year Thermal Cycles
```

Input file: TwoYrCycleWith460wh.inp

```
/fil,set_slice_0
resu
/sol
anty,,rest

time,365*20+3+1
!***
!***  Add waste, pressure and surface loads
!***
pres_surf=40              !ground surface uniform pressure
psf
point_cent=200000         !point load at center lb
pres_annulus=-20          !annulus pressure inches h2o
pres_int=-12              !annulus internal pressure inches
h2o
hwaste=460                !total waste height
height_waste1=hwaste/3    !height of waste 1 inches
gamma_waste1=1.83         !specific gravity of waste 1
```

```
height_waste2=hwaste/3  !height of waste 2 inches
gamma_waste2=1.83       !specific gravity of waste 2
height_waste3=hwaste/3  !height of waste 3 inches
gamma_waste3=1.83       !specific gravity of waste 3

/inp,apply_loads_slice,mac
solv

!*** Thermal load - Initial ramp
!***
fhrt=7.5/24

!***  Cycle
*do,i,20,21

time,3+1+fhrt+365*i
!***
!***  Thermal load - Initial ramp
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
/gopr
nsub,3,10,2
solv

time,3+1+2.125+fhrt*365*i
!***
!***  First of two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
nsub,20,100,6
solv

time,3+1+4.25+fhrt+365*i
!***
!***  Second of two steps to 210F
!***
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
nsub,20,100,6
solv

time,3+1+23+365*i
!***
!***  350F
!***
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
nsub,150,1000,10
solv

time,3+1+38+365*i
!***
!***  Steady state @ 210F
!***
/nopr
/inp,frss1,temp
/inp,bkss1,temp
```

```
/gopr
nsub,150,1000,30
solv
time,3+1+351+365*i
!***
!***  Creep for 1 Year
!***
nsub,300,10000,6
solv

!***  Cool to ambient
time,3+1+351+2.125+365*i
!***
!***  First of two steps to 125F
!***
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
nsub,15,200,5
solv

time,3+1+351+4.25+365*i
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
nsub,15,200,5
solv

time,3+1+351+4.25+fhrt+365*i
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
nsub,7,100,3
solv

time,3+1+351+4.25+fhrt+1+365*i
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
nsub,5,100,2
solv

time,3+1+365+365*i
!***
!****  Uniform 50F
!***
nsub,47,150,20
bf,all,temp,50
save
solv

*enddo
```

! End of 22 Year Thermal Cycles with 460" waste height from 20 years

Input file: Extended38yr.inp

```
/fil,set_slice_0
resu
/sol
anty,,rest

!*** Thermal load - Initial ramp
!***
fhrt=7.5/24

time,4+fhrt+365*20
!***
!***  Fast heat to 125F
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
/gopr
nsub,3,10,2
solv

time,2.125+4+fhrt+365*20
!***
!***  One of Two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
nsub,3,10,2
solv

time,4.25+4+fhrt+365*20
!***
!***  Two of Two steps to 210F
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
nsub,3,10,2
solv

time,26+1+365*20
!***  Steady State @ 210
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
nsub,150,1000,10
solv

time,41+1+365*20
!***  Steady state @ 210F
/nopr
/inp,frss1,temp
/inp,bkss1,temp
/gopr
nsub,150,1000,15
solv

time,354+365*57
!***  Hold for 38 Years
```

```
nsub,300,10000,10
save
solv

time,354+2.125+365*57
!***  Cool to ambient
!***
!***  First of Two steps to 125F
!***
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
nsub,15,200,5
solv

time,354+4.25+365*57
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
nsub,15,200,5
solv

time,354+4.25+fhrt+365*57
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
nsub,7,100,3
solv

time,354+4.25+fhrt+1+365*57
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
nsub,5,100,2
solv

time,368+365*57
!****  Uniform 50F
nsub,47,150,20
bf,all,temp,50
solv

! End of 58 year cycle
```

Input file: TwoYrCycTo60Yr.inp

```
/fil,set_slice_0
resu
/sol
anty,,rest

!*** Thermal load - Initial ramp
!***
```

```
fhrt=7.5/24

!***  Cycle
*do,i,58,59

time,3+fhrt+365*i
!***
!***  Thermal load - Initial ramp
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
/gopr
nsub,3,10,2
solv

time,3+2.125+fhrt*365*i
!***
!***  First of two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
nsub,20,100,6
solv

time,3+4.25+fhrt+365*i
!***
!***  Second of two steps to 210F
!***
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
nsub,20,100,6
solv

time,3+23+365*i
!***
!***  210F
!***
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
nsub,150,1000,10
solv

time,3+38+365*i
!***
!***  Steady state @ 210F
!***
/nopr
/inp,frss1,temp
/inp,bkss1,temp
/gopr
nsub,150,1000,30
solv

time,3+351+365*i
!***
!***  Creep for 1 Year
!***
nsub,300,10000,6
solv
```

```
!***  Cool to ambient
time,3+351+2.125+365*i
!***
!***  First of two steps to 125F
!***
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
nsub,15,200,5
solv

time,3+351+4.25+365*i
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
nsub,15,200,5
solv

time,3+351+4.25+fhrt+365*i
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
nsub,7,100,3
solv

time,3+351+4.25+fhrt+1+365*i
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
nsub,5,100,2
solv

time,3+365+365*i
!***
!****  Uniform 50F
!***
nsub,47,150,20
bf,all,temp,50
save
solv

*enddo

! End of 60 Year Thermal Cycles with 460" waste height
from 20 years
```

1.1.4 ACI Load Factors

Input file: set_sliced6a.inp

```
!***
!***     Load factors  12/19/06
```

```
!***    1.4 g
!***    1.4 pressures
!***    1.4 waste
!***    1.83*1.4 soil density
!***    1.7 distributed & concentrated load
!***

/fil,set_slice_0
resu

/sol
anty,,rest

!***
!***

time,365*61+4
nsub,10,100,5

acel,,1.4
pres_surf=40*1.7          !ground surface uniform pressure
psf
point_cent=200000*1.7     !point load at center lb
pres_annulus=-20*1.4      !annulus pressure inches h2o
pres_int=-12*1.4          !annulus internal pressure inches
h2o
hwaste=35.17*12           !total waste height
height_waste1=hwaste/3    !height of waste 1 inches
gamma_waste1=1.83*1.4     !specific gravity of waste 1
height_waste2=hwaste/3    !height of waste 2 inches
gamma_waste2=1.83*1.4     !specific gravity of waste 2
height_waste3=hwaste/3    !height of waste 3 inches
gamma_waste3=1.83*1.4     !specific gravity of waste 3
```

```
/inp,apply_loads_slice,mac

!***
!***    mpch to change density of soils
!***
*do,i,1,16
esel,,mat,,100+i
mpch,150+i,all
*enddo
*do,i,1,8
esel,,mat,,120+i
mpch,170+i,all
*enddo
esel,all

save
solv
```

Input file: set_sliceh.inp

```
!***
!***    Year 60      10/19/06   1.4D+1.7L+1.05T
!***    Adjust mpch (new SS temps) & Day 48 Steady State
6/8/04
!***    Adjust substeps 6/7/04
!***    2 year thermal cycle  ****inp modified****5/19/04
!***   multiple heating and cooling load steps
!***

/fil,set_slice_0
resu
/sol
```

```
anty,,rest

!*** Thermal load - Initial ramp
!***
fhrt=7.5/24


time,3+fhrt+365*60+1
!***
!***  Fast heat to 125F
!***
/nopr
/inp,frh,temp
/inp,bkh,temp
/gopr
bfsc,temp,1.05,50
nsub,3,10,2
solv


time,3+2.125+fhrt*365*60+1
!***
!***  First of two steps to 210F
!***
/nopr
/inp,frh1,temp
/inp,bkh1,temp
/gopr
bfsc,temp,1.05,50
nsub,20,100,6
solv

time,3+4.25+fhrt+365*60+1
!***
!***  Second of two steps to 210F
!***
/nopr
/inp,frh2,temp
/inp,bkh2,temp
/gopr
bfsc,temp,1.05,50
nsub,20,100,6
solv


time,3+23+365*60+1
!***
!***  210F
!***
/nopr
/inp,frss,temp
/inp,bkss,temp
/gopr
bfsc,temp,1.05,50
nsub,180,2000,40
solv

time,3+38+365*60+1
!***
!***  Steady state @ 210F
!***
/nopr
/inp,frss1,temp
/inp,bkss1,temp
/gopr
bfsc,temp,1.05,50
```

```
nsub,150,1000,25
solv

!***  Hold for 1 Year

time,354+365*60+1
nsub,300,10000,6
solv

!***  Cool to ambient

time,3+351+2.125+365*60+1
!***
!***  First of two steps to 125F
!***
/nopr
/inp,frc1,temp
/inp,bkc1,temp
/gopr
bfsc,temp,1.05,50
nsub,15,200,5
solv

time,3+351+4.25+365*60+1
!***
!***  Second of two steps to 125F
!***
/nopr
/inp,frc2,temp
/inp,bkc2,temp
/gopr
bfsc,temp,1.05,50
nsub,15,200,5
solv

time,3+351+4.25+fhrt+365*60+1
!***
!***  Fast cool down to 50F
!***
/nopr
/inp,frc3,temp
/inp,bkc3,temp
/gopr
bfsc,temp,1.05,50
nsub,7,100,3
solv

time,3+351+4.25+fhrt+1+365*60+1
!***
!***  Tank cool down transient to 50F
!***
/nopr
/inp,frc4,temp
/inp,bkc4,temp
/gopr
bfsc,temp,1.05,50
nsub,5,100,2
solv

time,3+365+365*60+1
!***
!****  Uniform 50F
!***
nsub,47,150,20
bf,all,temp,50
save
```

```
solv
```

B.1 Lower Bound Soil Model Input Files

There is only one input file that is unique to the Lower Bound Soil analysis. It is listed below.

Input file: set_parms.mac

```
!***
!***  Low Bound soil properties  7/14/04
!***
!*** Run 2, Load Case 1 - 4
!***   (8.3' soil, 125 lb/ft3)
!***   (0.06" primary tank corrosion)
!*** 4/16/03
!***
!***
!***  JED mods 3/20/03
!***  add clr - concentrated load radius
!***  add backfill properties 3/24
!***  backfill properties f(depth)  4/1

finish
/clear
/fil,pnnla
/prep7
/titl,5% K; low soil E, high concrete E with no Creep"
!
! DST - AY

pi=acos(-1)

clr=10*12            !Concentrated load radius
or=12*41.5           !Outside radius concrete wall
ir=12*40             !Inside radius concrete wall
ir2=12*37.5          !Radius primary tank
icr=37*12+3          !Radius insulating concrete
h1=0
h2=-8.125
h3=381.5             !Height dome tangent  (31'9-1/2")
h4=h3+70.875         !Height exterior corner  (+ 5'10-7/8" =
37'8-3/8")
h5=h3+15*12          !Height interior center dome
h6=h5+15             !Height exterior center dome

covext=2             !Concrete cover - exterior dome
covint1=4            !Concrete cover - wall
covint2=1.5          !Concrete cover - interior dome

r1=105*12+.25        !Exterior dome radius - center
th1=7+(45+14/60)/60  !Angle at tangent of external radii
r2=74*12+4           !Exterior dome radius - outer
r3=3*12+8.375        !Radius primary tank to dome


! This file sets the values of all parameters that may be changed

! These were originally defined in define_soil_layers.mac:

overburden=8.3*12  !overburden height above dome apex (ft)
subdepth=168*12    !subgrade soil depth (ft)
totalwidth=240*12  !total soil width (radius) from tank
centerline to edge (ft)


! These were originally defined in dstay7.mac:
```

```
r50=1-.06      !shell thickness (in) (R1 of Figure 11 in RPP-
13990)
r51=3/8-.06    !shell thickness (in) (R2,R6,R7,R9 of Figure 11
in RPP-13990)
r52=7/8-.06    !shell thickness (in) (R3 of Figure 11 in RPP-
13990)
r53=3/4-.06    !shell thickness (in) (R4 of Figure 11 in RPP-
13990)
r54=1/2-.06    !shell thickness (in) (R5,R8 of Figure 11 in RPP-
13990)
r55=1/4    !shell thickness (in) (R10 of Figure 11 in RPP-
13990)


! This was originally defined in set_esys_3d.mac:

r56=3/8    !shell thickness (in) of secondary liner above 357.5 in


! These were originally defined in set_materials.mac:

![1]          steel (for liner, jbolts, studs, anchors, bearing plates)
steel_ex=27.7e6                !elastic modulus [psi]
steel_prxy=0.3                 !Poisson ratio
steel_alpx=6.38                !thermal expansion
coefficient [microstrain/degree F]
steel_gamma=490                !unit weight [lbf/ft^3]
steel_yield=36000              !yield strength [psi]
steel_tan=0.01                 !rebar tangent modulus [%
of elastic modulus]

![2]          structural concrete
conc_ex=3.8e6                  !elastic modulus [psi]
conc_prxy=0.15                 !Poisson ratio
conc_alpx=3.7                  !thermal expansion
coefficient [microstrain/degree F]
conc_gamma=145                 !unit weight [lbf/ft^3]

conc_open=0.1      !shear transfer coefficient for open crack
conc_closed=0.98           !shear transfer coefficient for closed
crack
conc_crush=3000                !uniaxial crushing stress
[psi]
conc_crack=0.1*conc_crush      !tensile cracking stress [psi]

![3]          rebar
rebar_ex=29.0e6                !elastic modulus [psi]
rebar_prxy=0.3                 !Poisson ratio
rebar_alpx=6.                  !thermal expansion
coefficient [microstrain/degree F]
rebar_gamma=490                !unit weight [lbf/ft^3]
rebar_yield=71000          !yield strength [psi]
rebar_tan=0                    !rebar tangent modulus [psi]

![4]          insulating concrete
insul_ex=165e3                 !elastic modulus [psi]
insul_prxy=0.15                !Poisson ratio
insul_alpx=3.7                 !thermal expansion
coefficient [me/F]
insul_gamma=50                 !unit weight [lbf/ft^3]

insul_open=0.1                 !shear transfer coefficient
for open crack
insul_closed=0.98          !shear transfer coefficient for closed
crack
```

```
insul_crush=200                 !uniaxial crushing stress
[psi]
insul_crack=20                  !tensile cracking stress [psi]

![6]        slab rebar
srebar_ex=29.0e6            !elastic modulus [psi]
srebar_prxy=0.3                 !Poisson ratio
srebar_alpx=6.                  !thermal expansion
coefficient [microstrain/degree F]
srebar_gamma=490                !unit weight [lbf/ft^3]
srebar_yield=49000              !yield strength [psi]
srebar_tan=0                    !rebar tangent modulus [psi]


!*** Backfill
! These were originally defined in define_loads.mac:
! [5]         backfill soil
backfill_phi=34.5           !soil friction angle deg
backfill_dil=34.5           !backfill dilatancy angle deg
backfill_cte=0              !thermal expansion coef me/f

!*** No waste, pressures or ext. load
pres_surf=0                 !ground surface uniform pressure
psf
point_cent=0                !point load at center lb
pres_annulus=0              !annulus pressure inches h2o
pres_int=0                  !annulus internal pressure inches
h2o
hwaste=35.17*12             !total waste height
height_waste1=hwaste/3      !height of waste 1 inches
gamma_waste1=0              !specific gravity of waste 1
height_waste2=hwaste/3      !height of waste 2 inches
gamma_waste2=0              !specific gravity of waste 2
height_waste3=hwaste/3      !height of waste 3 inches
gamma_waste3=0              !specific gravity of waste 3

!define soil layers
*dim,soil_emod,,16
*dim,soil_pr,,16
*dim,soil_z0,,16
*dim,soil_z1,,16
*dim,bf_emod,,8
!*dim,bf_pr,,8
*dim,bf_z0,,8
*dim,bf_z1,,8
bfdinc=(h6+overburden+18.5)/8
sdinc=(subdepth+60)/8

*do,i,1,8
soil_z0(i)=i*bfdinc !vertical distance from surface
soil_z1(i)=(i-1)*bfdinc
soil_z0(i+8)=i*sdinc+bfdinc*8
soil_z1(i+8)=(i-1)*sdinc+bfdinc*8
bf_z0(i)=i*bfdinc
bf_z1(i)=(i-1)*bfdinc
*enddo

!Elastic modulus
soil_emod(1)=44000,46000,48711,51423,53833,56544,59255,6
1665,66835,75000
soil_emod(11)=78900,82851,87169,91403,95000,99000
bf_emod(1)=8000,10000,12864,15727,18273,21136,24000,260
00

!Poisson's ratio
soil_pr(1)=.24,.24,.24,.24,.19,.19,.19,.19,.19,.19
```

```
soil_pr(11)=.19,.19,.28,.28,.28,.28
bf_pr=.27

!*** Soil 110 pcf - undisturbed
!*** Soil 125 pcf - backfill/overburden
s_gam=110                    !lbf/ft^3 density of soil layers
(excluding backfill)
b_gam=125                    !lbf/ft^3 density of soil layers
(excluding backfill)

save
```

B.2 Upper Bound Soil Model Input Files

There is only one input file that is unique to the Upper Bound Soil analysis. It is listed below.

Input file: set_parms.mac

```
!***
!***  Upper bound soil   11/21/05
!***  Best estimate soil properties  3/19/04
!***
!*** Run 2, Load Case 1 - 4
!***   (8.3' soil, 125 lb/ft3)
!***   (0.06" primary tank corrosion)
!*** 4/16/03
!***
!***
!***  JED mods 3/20/03
!***  add clr - concentrated load radius
!***  add backfill properties 3/24
!***  backfill properties f(depth)  4/1
finish
/clear
/fil,pnnla
/prep7
/titl,Baseline, Upper Bound Soil
!
! DST - AY

pi=acos(-1)

clr=10*12            !Concentrated load radius
or=12*41.5           !Outside radius concrete wall
ir=12*40             !Inside radius concrete wall
ir2=12*37.5          !Radius primary tank
icr=37*12+3                  !Radius insulating concrete
h1=0
h2=-8.125
h3=381.5             !Height dome tangent  (31'9-1/2")
h4=h3+70.875           !Height exterior corner  (+ 5'10-7/8" =
37'8-3/8")
h5=h3+15*12            !Height interior center dome
h6=h5+15             !Height exterior center dome

covext=2             !Concrete cover - exterior dome
covint1=4            !Concrete cover - wall
covint2=1.5          !Concrete cover - interior dome

r1=105*12+.25          !Exterior dome radius - center
th1=7+(45+14/60)/60      !Angle at tangent of external radii
r2=74*12+4           !Exterior dome radius - outer
r3=3*12+8.375          !Radius primary tank to dome
```

```
! This file sets the values of all parameters that may be changed

! These were originally defined in define_soil_layers.mac:

overburden=8.3*12  !overburden height above dome apex (ft)
subdepth=168*12    !subgrade soil depth (ft)
totalwidth=240*12  !total soil width (radius) from tank centerline
to edge (ft)


! These were originally defined in dstay7.mac:

r50=1-.06       !shell thickness (in) (R1 of Figure 11 in RPP-
13990)
r51=3/8-.06     !shell thickness (in) (R2,R6,R7,R9 of Figure 11 in
RPP-13990)
r52=7/8-.06     !shell thickness (in) (R3 of Figure 11 in RPP-
13990)
r53=3/4-.06     !shell thickness (in) (R4 of Figure 11 in RPP-
13990)
r54=1/2-.06     !shell thickness (in) (R5,R8 of Figure 11 in RPP-
13990)
r55=1/4     !shell thickness (in) (R10 of Figure 11 in RPP-13990)

! This was originally defined in set_esys_3d.mac:

r56=3/8    !shell thickness (in) of secondary liner above 357.5 in

! These were originally defined in set_materials.mac:

![1]            steel (for liner, jbolts, studs, anchors, bearing plates)
steel_ex=27.7e6                     !elastic modulus [psi]
steel_prxy=0.3                      !Poisson ratio
steel_alpx=6.38                     !thermal expansion
coefficient [microstrain/degree F]
steel_gamma=490                     !unit weight [lbf/ft^3]
steel_yield=36000             !yield strength [psi]
steel_tan=0.01                      !rebar tangent modulus [%
of elastic modulus]

![2]       structural concrete
conc_ex=3.8e6                       !elastic modulus [psi]
conc_prxy=0.15                      !Poisson ratio
conc_alpx=3.7                       !thermal expansion
coefficient [microstrain/degree F]
conc_gamma=145                      !unit weight [lbf/ft^3]

conc_open=0.1       !shear transfer coefficient for open crack
conc_closed=0.98              !shear transfer coefficient for closed
crack
conc_crush=3000                     !uniaxial crushing stress
[psi]
conc_crack=0.1*conc_crush !tensile cracking stress [psi]

![3]            rebar
rebar_ex=29.0e6                     !elastic modulus [psi]
rebar_prxy=0.3                      !Poisson ratio
rebar_alpx=6.                       !thermal expansion
coefficient [microstrain/degree F]
rebar_gamma=490                     !unit weight [lbf/ft^3]
rebar_yield=71000                   !yield strength [psi]
rebar_tan=0                         !rebar tangent modulus [psi]

![4]       insulating concrete
insul_ex=165e3                      !elastic modulus [psi]
insul_prxy=0.15                     !Poisson ratio
```

```
insul_alpx=3.7              !thermal expansion coefficient
[me/F]
insul_gamma=50              !unit weight [lbf/ft^3]

insul_open=0.1              !shear transfer coefficient for open
crack
insul_closed=0.98           !shear transfer coefficient for closed
crack
insul_crush=200             !uniaxial crushing stress [psi]
insul_crack=20              !tensile cracking stress [psi]

![6]          slab rebar
srebar_ex=29.0e6            !elastic modulus [psi]
srebar_prxy=0.3             !Poisson ratio
srebar_alpx=6.              !thermal expansion coefficient
[microstrain/degree F]
srebar_gamma=490            !unit weight [lbf/ft^3]
srebar_yield=49000          !yield strength [psi]
srebar_tan=0                !rebar tangent modulus [psi]


!*** Backfill
! These were originally defined in define_loads.mac:
! [5]          backfill soil
backfill_phi=34.5           !soil friction angle deg
backfill_dil=34.5           !backfill dilatancy angle deg
backfill_cte=0              !thermal expansion coef me/f

!*** No waste, pressures or ext. load
pres_surf=0                 !ground surface uniform pressure
psf
point_cent=0                !point load at center lb
pres_annulus=0              !annulus pressure inches h2o
pres_int=0                  !annulus internal pressure inches
h2o
hwaste=35.17*12             !total waste height
height_waste1=hwaste/3      !height of waste 1 inches
gamma_waste1=0              !specific gravity of waste 1
height_waste2=hwaste/3      !height of waste 2 inches
gamma_waste2=0              !specific gravity of waste 2
height_waste3=hwaste/3      !height of waste 3 inches
gamma_waste3=0              !specific gravity of waste 3


!define soil layers
*dim,soil_emod,,16
*dim,soil_pr,,16
*dim,soil_z0,,16
*dim,soil_z1,,16
*dim,bf_emod,,8
!*dim,bf_pr,,8
*dim,bf_z0,,8
*dim,bf_z1,,8
bfdinc=(h6+overburden+18.5)/8
sdinc=(subdepth+60)/8

*do,i,1,8
soil_z0(i)=i*bfdinc  !vertical distance from surface
soil_z1(i)=(i-1)*bfdinc
soil_z0(i+8)=i*sdinc+bfdinc*8
soil_z1(i+8)=(i-1)*sdinc+bfdinc*8
bf_z0(i)=i*bfdinc
bf_z1(i)=(i-1)*bfdinc
*enddo

!Elastic modulus
```

```
soil_emod(1)=75000,78000,80524,83049,85292,87817,90341,92
585,97398,105000
soil_emod(11)=140494,176448,215742,254268,287000,315000
bf_emod(1)=16000,20000,26136,32273,37727,43864,50000,540
00

!Poisson's ratio
soil_pr(1)=.24,.24,.24,.24,.19,.19,.19,.19,.19,.19
soil_pr(11)=.19,.19,.28,.28,.28,.28
bf_pr=.27

!*** Soil 110 pcf - undisturbed
!*** Soil 125 pcf - backfill/overburden
s_gam=110                    !lbf/ft^3 density of soil layers
(excluding backfill)
b_gam=125                    !lbf/ft^3 density of soil layers
(excluding backfill)

save
```

B.3 Postprocessing Files

There are five postprocessing files associated with the ACI evaluation, the ASME evaluation of the primary and secondary liner, and the J-bolts. They are listed below.

Input file: paci11.inp

```
!***
!*** ACI postprocessing
!***    9/2/04  Automate for year 61
!***    8/3/04  Delete section 64
!***    1/15/04 Revised
!***    9/8/03 Add 6 locations to foundation
!***    9/4/03 Use pcal,intg for hoop direction
!*******************************
!***    9/3/03 Add titles - change as necessary!!
!*******************************
!***    8/23/03 (FSUM)
!***

*dim,dox,,15
dox(1)=30,61,90,120,152,183,210,237.5,270,304.5
dox(11)=314,334,354,368.9,390.2
*dim,thx,,9
thx(1)=146.6,148.9,152.0,154.91,158.75,163.9,168.1,172.35,176
.177
*dim,wh,,23
wh(1)=382.1,361.5,346.1,335,321,306,300,281,260.5,236
wh(11)=212.7,200,186.8,171,151.6,145.5,120.5,100.5,80,60
wh(21)=39.9,21,-4.5
*dim,dsx,,16
dsx(1)=514,503,489,477,461.5,440,421.4,390,358,338
dsx(11)=277.7,218.5,180,129.9,95.7,54

*do,m,138,147
set,m

*cfo,ls%m%,aci
*afun,deg
!*** Titles
tt1='Baseline'
tt2='Year 61'
tt3='ls%m%'
tt4a='40 psf uniform,'
tt4b='100 ton concentrated,'
tt4c='-20 in. annulus,'
```

```
tt4d='-6 in. vapor space'
!tt4d='None'
!tt5='1.4(D + F) + 1.7(L + H)'
tt5='None'
!*** Column headings
ct1='Section'
ct2='  shear'
ct3='F-merid '
ct4='M-merid '
ct5='F-hoop  '
ct6='M-hoop  '
ct7='Tmin    '
ct8='Tmax    '
ct9='Tave    '
ct10='xbar   '
ct11='ybar   '
ct12='sect thk'
ttb='    '

*vwri,tt1
%c
*vwri,tt2
%c
*vwri,tt3
%c
*vwri,tt4a,tt4b,tt4c,tt4d
%c %c %c %c
*vwri,tt5
%c
*vwri,ttb
(a8)
*vwri,ttb
(a8)
*vwri,ttb
(a8)
*vwri,ct1,ct2,ct3,ct4,ct5,ct6,ct7,ct8,ct9,ct10,ct11,ct12
(12a8)
*vwri,ttb
(a8)

!***
!*** Dome

k=0
csys
esel,,type,,12,15
nsle

!***     Find center of outer arc
cdl=distkp(6,18)
cda=asin(cdl/(2*r2))
cthet=atan((ky(6)-ky(18))/(kx(6)-kx(18)))
cgam=90-cda-cthet
cdelx=r2*cos(cgam)
cdely=r2*sin(cgam)
orcirx=kx(18)+cdelx
orciry=ky(18)-cdely

*do,i,1,15
k=k+1
esel,,type,,12,15
nsle
csys
x1=dox(i)
thed1=acos(x1/480)
y1=h5-180+180*sin(thed1)
```

```
*if,i,le,5,then
thd1=asin(x1/(r1-15))
x2=r1*sin(thd1)
y2=h6-r1+r1*cos(thd1)
*else
thd1=atan((y1-orciry)/(x1+orcirx))
x2=r2*cos(thd1)-orcirx
y2=r2*sin(thd1)+orciry
thd1=90-thd1
*endif

path,sect %k%,2,,200
ppat,1,,-x1,y1
,2,,-x2,y2

nsel,r,loc,y,400,599
loca,45,,-x1,y1,,thd1-90
nsel,r,loc,y,-3,500
esln,,1
esel,r,type,,12,15
*if,i,eq,8,then
esel,a,,,8995
*elseif,i,eq,9,then
esel,a,,,9181
*elseif,i,eq,11,then
esel,a,,,9200
*elseif,i,eq,12,then
esel,a,,,8941
*elseif,i,eq,13,then
esel,a,,,8825
*elseif,i,eq,14,then
esel,a,,,8999
*endif
cm,upper,elem

pdef,temp,bfe,temp
pcalc,intg,itemp,temp,s
*get,delt,path,,last,s

nsel,r,loc,y,-3,0
,r,loc,z
*if,i,eq,10,then
nsel,u,,,2990
*endif
*get,ncount,node,,count
cm,sectn,node
slocxt=0
slocyt=0
secx=0
secy=0
csys
rsys
*do,j,1,ncount
ncur=ndnext(j)
slocxt=slocxt+nx(ncur)+ux(ncur)
slocyt=slocyt+ny(ncur)+uy(ncur)
secx=secx+nx(ncur)
secy=secy+ny(ncur)
nsel,u,,,ncur
*enddo
rsys,45
slocx=slocxt/ncount
slocy=slocyt/ncount
xbar=-secx/ncount
ybar=secy/ncount
```

```
secw=xbar*swp_th/2*pi/180
cmse,,sectn
rsys,45
spoi,,slocx,slocy
fsum,rsys
*get,smeru,fsum,,item,fx
*get,pmeru,fsum,,item,fy
*get,mmeru,fsum,,item,mz
*get,tmin,path,,min,temp
*get,tmax,path,,max,temp
*get,ttot,path,,last,itemp
esel,,type,,12,15
cmse,u,upper
fsum
*get,smerl,fsum,,item,fx
*get,pmerl,fsum,,item,fy
*get,mmerl,fsum,,item,mz
smer=(smeru-smerl)/2
pmer=(pmeru-pmerl)/2
mmer=(mmeru-mmerl)/2

!** Calculate hoop area
esln
esel,r,type,,12,15
*if,i,eq,8,then
esel,u,,,8996
*elseif,i,eq,9,then
esel,u,,,9182
*elseif,i,eq,10,then
esel,u,,,9203
*elseif,i,eq,11,then
esel,u,,,9199
*elseif,i,eq,12,then
esel,u,,,8942
*elseif,i,eq,13,then
esel,u,,,8824
*elseif,i,eq,14,then
esel,u,,,8998
*endif
nsle
nsel,r,loc,z
*get,ecount,elem,,count
hparea=0
*do,j,1,ecount
ecur=elnext(j)
hparea=hparea+arface(ecur)
esel,u,,,ecur
*enddo
hparea=hparea/2
hpw=hparea/delt

esel,,type,,12,15
cmse,,sectn
fsum,rsys
*get,php,fsum,,item,fz
*get,mhp,fsum,,item,my

tave=ttot/delt
smer=smer/secw*12/1000
pmer=pmer/secw*12/1000
mmer=-mmer/secw/1000
php=php/hpw*12/1000
mhp=mhp/hpw/1000

*vwri,k,smer,pmer,mmer,php,mhp,tmin,tmax,tave,xbar,ybar,delt
(11f8.1,f8.2)
```

```
*enddo

!*** Haunch

csys
esel,,type,,12,15
nsle

!***     Find center of outer arc
csys
cdl=distkp(6,18)
cda=asin(cdl/(2*r2))
cthet=atan((ky(6)-ky(18))/(kx(6)-kx(18)))
cgam=90-cda-cthet
cdelx=r2*cos(cgam)
cdely=r2*sin(cgam)
orcirx=kx(18)+cdelx
orciry=ky(18)-cdely

*do,i,1,9
k=k+1
esel,,type,,12,15
nsle
csys
x1=480*cos(thx(i))
y1=480*sin(thx(i))*.375+h3
*if,i,le,4,then
thd1=atan((y1-orciry)/(x1-orcirx))
x2=orcirx-r2*cos(thd1)
y2=orciry-r2*sin(thd1)
*elseif,i,eq,5,then
thd1=atan((y1-orciry)/(x1-orcirx))+5
x2=orcirx-r2*cos(thd1-4.85)
y2=orciry-r2*sin(thd1-4.85)
*elseif,i,eq,6,then
thd1=atan((y1-orciry)/(x1-orcirx))+11
x2=orcirx-r2*cos(thd1-10.5)
y2=orciry-r2*sin(thd1-10.5)
*elseif,i,eq,7,then
x2=-498
y2=427.6
thd1=atan((y2-y1)/(x2-x1))
*elseif,i,eq,8,then
x2=-498
y2=408.8
thd1=atan((y2-y1)/(x2-x1))
*else
x2=-498
y2=393.5
*endif

path,sect %k%,2,,200
ppat,1,,x1,y1
,2,,x2,y2

nsel,r,loc,y,380,599
loca,45,,x1,y1,,thd1
nsel,r,loc,y,-3,500
esln,,1
esel,r,type,,12,15
*if,i,eq,4,then
esel,u,,,8475
*elseif,i,eq,6,then
esel,a,,,9403,9434,31
,a,,,9480,9640,160
*elseif,i,eq,7,then
```

```
esel,u,,,9455
*endif
cm,upper,elem

rsys,45
pdef,temp,bfe,temp
pcalc,intg,itemp,temp,s
*get,delt,path,,last,s

nsel,r,loc,y,-3,0
,r,loc,z
*if,i,eq,4,then
nsel,u,,,2692,2694,2
*elseif,i,eq,6,then
nsel,a,,,3807,3820,13
*elseif,i,eq,7,then
nsel,u,,,3822,3824,2
,u,,,2707
*endif
*get,ncount,node,,count
cm,sectn,node
slocxt=0
slocyt=0
secx=0
secy=0
csys
rsys
*do,j,1,ncount
ncur=ndnext(j)
slocxt=slocxt+nx(ncur)+ux(ncur)
slocyt=slocyt+ny(ncur)+uy(ncur)
secx=secx+nx(ncur)
secy=secy+ny(ncur)
nsel,u,,,ncur
*enddo
rsys,45
slocx=slocxt/ncount
slocy=slocyt/ncount
xbar=-secx/ncount
ybar=secy/ncount
cmse,,sectn

spoi,,slocx,slocy
fsum,rsys
!*** Sum moments about neutral axis
*if,k,gt,18,and,k,lt,23,then
 *get,mzn,fsum,,item,mz
  flag=1
  *if,mzn,gt,0,then
   flag=-1
  *endif
   *if,k,eq,19,then
    slocx=slocx+flag*.85*cos(thd1)
    slocy=slocy+flag*.85*sin(thd1)
   *elseif,k,eq,20
    slocx=slocx+flag*.8*cos(thd1)
    slocy=slocy+flag*.8*sin(thd1)
   *elseif,k,eq,21
    slocx=slocx+flag*.82*cos(thd1)
    slocy=slocy+flag*.82*sin(thd1)
   *else
    slocx=slocx+flag*.77*cos(thd1)
    slocy=slocy+flag*.77*sin(thd1)
   *endif
*endif
spoi,,slocx,slocy
```

```
fsum,rsys

*get,smeru,fsum,,item,fx
*get,pmeru,fsum,,item,fy
*get,mmeru,fsum,,item,mz
*get,tmin,path,,min,temp
*get,tmax,path,,max,temp
*get,ttot,path,,last,itemp
esel,,type,,12,15
cmse,u,upper
fsum
*get,smerl,fsum,,item,fx
*get,pmerl,fsum,,item,fy
*get,mmerl,fsum,,item,mz
smer=(smeru-smerl)/2
pmer=(pmeru-pmerl)/2
mmer=(mmeru-mmerl)/2

!** Calculate hoop area
esln
esel,r,type,,12,15
*if,i,eq,4,then
esel,a,,,8478
*elseif,i,eq,6,then
esel,u,,,9378,9479,101
*endif
nsle
nsel,r,loc,z
*get,ecount,elem,,count
hparea=0
*do,j,1,ecount
ecur=elnext(j)
hparea=hparea+arface(ecur)
esel,u,,,ecur
*enddo
hparea=hparea/2
hpw=hparea/delt

esel,,type,,12,15
cmse,,sectn
fsum,rsys
*get,php,fsum,,item,fz
*get,mhp,fsum,,item,my

secw=xbar*swp_th/2*pi/180
tave=ttot/delt
smer=smer/secw*12/1000
pmer=pmer/secw*12/1000
mmer=-mmer/secw/1000
php=php/hpw*12/1000
mhp=mhp/hpw/1000

*vwri,k,smer,pmer,mmer,php,mhp,tmin,tmax,tave,xbar,ybar,delt
(11f8.1,f8.2)
*enddo

!***
!*** Wall

csys
esel,,type,,12,15
nsle

*do,i,1,23
k=k+1
esel,,type,,12,15
```

```
,u,type,,14
nsle
csys
x1=-480
y1=wh(i)
x2=-498
y2=wh(i)

path,sect %k%,2,,200
ppat,1,,x1,y1
,2,,x2,y2

nsel,r,loc,y,h2,599
nsel,r,loc,y,wh(i)-3,599
esln,,1
esel,r,type,,12,15
*if,i,eq,2,then
esel,a,,,11133
*elseif,i,eq,3,then
esel,a,,,8559,11138,2579
*elseif,i,eq,4,then
esel,a,,,10972
*elseif,i,eq,8,then
esel,a,,,8590
*elseif,i,eq,9,then
esel,a,,,11091,11257,166
*elseif,i,eq,10,then
esel,a,,,8604,11098,2494
*elseif,i,eq,11,then
esel,a,,,11242
*elseif,i,eq,12,then
esel,a,,,11238
*elseif,i,eq,14,then
esel,a,,,11087,11229,142
*elseif,i,eq,15,then
esel,a,,,11156,11223,67
*elseif,i,eq,16,then
esel,a,,,11158,11221,63
*elseif,i,eq,17,then
esel,a,,,11213
*elseif,i,eq,18,then
esel,a,,,11173
*elseif,i,eq,19,then
esel,a,,,10931,11048,117
*elseif,i,eq,20,then
esel,a,,,11194
*endif
cm,upper,elem

rsys
pdef,temp,bfe,temp
pcalc,intg,itemp,temp,s
*get,delt,path,,last,s

nsel,r,loc,y,wh(i)-3,wh(i)
,r,loc,z
,r,loc,x,-498,-480
*get,ncount,node,,count
cm,sectn,node
slocxt=0
slocyt=0
secx=0
secy=0
csys
rsys
*do,j,1,ncount
```

```
ncur=ndnext(j)
slocxt=slocxt+nx(ncur)+ux(ncur)
slocyt=slocyt+ny(ncur)+uy(ncur)
secx=secx+nx(ncur)
secy=secy+ny(ncur)
nsel,u,,,ncur
*enddo
slocx=slocxt/ncount
slocy=slocyt/ncount
xbar=-secx/ncount
ybar=secy/ncount
cmse,,sectn
secw=xbar*swp_th/2*pi/180

spoi,,slocx,slocy
fsum,rsys
*get,smeru,fsum,,item,fx
*get,pmeru,fsum,,item,fy
*get,mmeru,fsum,,item,mz
*get,tmin,path,,min,temp
*get,tmax,path,,max,temp
*get,ttot,path,,last,itemp
esel,,type,,12,15
cmse,u,upper
fsum
*get,smerl,fsum,,item,fx
*get,pmerl,fsum,,item,fy
*get,mmerl,fsum,,item,mz
smer=(smeru-smerl)/2
pmer=(pmeru-pmerl)/2
mmer=(mmeru-mmerl)/2

!** Calculate hoop area
esln
esel,r,type,,12,15
*if,i,eq,2,then
esel,u,,,11134
*elseif,i,eq,3,then
esel,u,,,8558,11139,2581
*elseif,i,eq,4,then
esel,u,,,10973
*elseif,i,eq,8,then
esel,u,,,8591
*elseif,i,eq,9,then
esel,u,,,11092,11256,164
*elseif,i,eq,10,then
esel,u,,,8605,11106,2501
*elseif,i,eq,11,then
esel,u,,,11241
*elseif,i,eq,12,then
esel,u,,,11237
*elseif,i,eq,14,then
esel,u,,,11086,11228,142
*elseif,i,eq,15,then
esel,u,,,11157,11222,65
*elseif,i,eq,16,then
esel,u,,,11159,11220,61
*elseif,i,eq,17,then
esel,u,,,11212
*elseif,i,eq,18,then
esel,u,,,11174
*elseif,i,eq,19,then
esel,u,,,10930,11049,119
*elseif,i,eq,20,then
esel,u,,,11193
*endif
```

```
nsle
nsel,r,loc,z
*get,ecount,elem,,count
hparea=0
*do,j,1,ecount
ecur=elnext(j)
hparea=hparea+arface(ecur)
esel,u,,,ecur
*enddo
hparea=hparea/2
hpw=hparea/delt

esel,,type,,12,15
cmse,,sectn
fsum,rsys
*get,php,fsum,,item,fz
*get,mhp,fsum,,item,my

secw=xbar*swp_th/2*pi/180
tave=ttot/delt
smer=smer/secw*12/1000
pmer=pmer/secw*12/1000
mmer=-mmer/secw/1000
php=php/hpw*12/1000
mhp=mhp/hpw/1000

*vwri,k,smer,pmer,mmer,php,mhp,tmin,tmax,tave,xbar,ybar,delt
(11f8.1,f8.2)
*enddo

!***
!*** Found
csys
esel,,type,,12,15
nsle
*do,i,1,16
k=k+1
esel,,type,,12,15
nsle
csys
x1=dsx(i)
*if,i,le,5,then
y1=-30.125
*elseif,i,le,9,then
y1=(ky(305)-ky(304))/(kx(305)-kx(304))*(-dsx(i)-
kx(304))+ky(304)
*elseif,i,le,15,then
y1=-18.625
*elseif,i,eq,16,then
y1=(ky(303)-ky(302))/(kx(303)-kx(302))*(-dsx(i)-
kx(302))+ky(302)
*endif
x2=dsx(i)
y2=h2
*if,i,le,2,then
y2=-6.625
*endif
path,sect %k%,2,,200
ppat,1,,-x1,y1
,2,,-x2,y2
nsel,r,loc,y,-40,y2
nsel,r,loc,x,-dsx(i)-3,1
esln,,1
esel,r,type,,12,15
*if,i,eq,7,then
```

```
esel,a,,,12008
*elseif,i,eq,13,then
esel,a,,,12088
*elseif,i,eq,16,then
esel,a,,,11793,12283,490
*endif
cm,lower,elem

pdef,temp,bfe,temp
pcalc,intg,itemp,temp,s
*get,delt,path,,last,s

nsle
nsel,r,loc,x,-dsx(i)-3,-dsx(i)
,r,loc,z
*if,i,eq,6,then
nsel,u,,,9483
*elseif,i,eq,7,then
nsel,u,,,9344
*elseif,i,eq,16,then
nsel,a,,,281
*endif
*get,ncount,node,,count
cm,sectn,node
slocxt=0
slocyt=0
secx=0
secy=0
csys
rsys
*do,j,1,ncount
ncur=ndnext(j-1)
slocxt=slocxt+nx(ncur)+ux(ncur)
slocyt=slocyt+ny(ncur)+uy(ncur)
secx=secx+nx(ncur)
secy=secy+ny(ncur)
nsel,u,,,ncur
*enddo
slocx=slocxt/ncount
slocy=slocyt/ncount
xbar=-secx/ncount
ybar=secy/ncount
cmse,,sectn
secw=xbar*swp_th/2*pi/180

spoi,,slocx,slocy
fsum
*get,smerl,fsum,,item,fy
*get,pmerl,fsum,,item,fx
*get,mmerl,fsum,,item,mz
*get,tmin,path,,min,temp
*get,tmax,path,,max,temp
*get,ttot,path,,last,itemp
esel,,type,,12,15
cmse,u,lower
fsum
*get,smeru,fsum,,item,fy
*get,pmeru,fsum,,item,fx
*get,mmeru,fsum,,item,mz
smer=(smerl-smeru)/2
pmer=(pmerl-pmeru)/2
mmer=(mmeru-mmerl)/2

!** Calculate hoop area
esln
esel,r,type,,12,15
```

```
*if,i,eq,6,then
esel,u,,,12148
*elseif,i,eq,7,then
esel,u,,,11797,12007,210
*elseif,i,eq,13,then
esel,u,,,12101
*endif
nsle
nsel,r,loc,z
*get,ecount,elem,,count
hparea=0
*do,j,1,ecount
ecur=elnext(j)
hparea=hparea+arface(ecur)
esel,u,,,ecur
*enddo
hparea=hparea/2
hpw=hparea/delt

esel,,type,,12,15
cmse,,sectn
fsum,rsys
*get,php,fsum,,item,fz
*get,mhp,fsum,,item,mx

tave=ttot/delt
smer=smer/secw*12/1000
pmer=pmer/secw*12/1000
mmer=-mmer/secw/1000
php=php/hpw*12/1000
mhp=mhp/hpw/1000

*vwri,k,smer,pmer,mmer,php,mhp,tmin,tmax,tave,xbar,ybar,delt
(11f8.1,f8.2)
*enddo

*cfc
*enddo
```

Input file: postprimcomb.inp

```
/post1
set,148
lcwr,1

loca,199,1,,280.75,,90
esel,,,,14927,14943,16
,a,,,14962,15000,19
,a,,,15018,15037,19
,a,,,15050,15056,6
,a,,,15061,15064,3
,a,,,15070,15076,6
,a,,,15081,15086,5
,a,,,15092,15097,5
,a,,,15103,15115,6
,a,,,15120,15168,6
,a,,,15172,15180,4
,a,,,15185,15197,12
,a,,,15211,15227,16
,a,,,15247,15258,11
,a,,,15264,15276,12
,a,,,15303,15324,21
rsys,solu

*do,k,138,147
set,k
lcop,sub,1
```

```
shel,top
ETAB,sintt,s,int
ETAB,locy,cent,y
shel,bot
ETAB,sintb,s,int
ETAB,locy,cent,y
esor,etab,locy,1
/out,primsec%k%,lis
PRET,locy,sintt,sintb
/out
*enddo
```

Input file: postprimcomb1.inp

```
/post1
set,148

loca,199,1,,280.75,,90
esel,,,,14927,14943,16
,a,,,14962,15000,19
,a,,,15018,15037,19
,a,,,15050,15056,6
,a,,,15061,15064,3
,a,,,15070,15076,6
,a,,,15081,15086,5
,a,,,15092,15097,5
,a,,,15103,15115,6
,a,,,15120,15168,6
,a,,,15172,15180,4
,a,,,15185,15197,12
,a,,,15211,15227,16
,a,,,15247,15258,11
,a,,,15264,15276,12
,a,,,15303,15324,21
rsys,solu
shel,mid
etab,sxm,s,x
ETAB,sym,s,y
ETAB,sxym,s,xy
ETAB,sintm,s,int
ETAB,locy,cent,y
shel,top
etab,sxt,s,x
ETAB,syt,s,y
ETAB,sxyt,s,xy
ETAB,sintt,s,int
ETAB,locy,cent,y
shel,bot
etab,sxb,s,x
ETAB,syb,s,y
ETAB,sxyb,s,xy
ETAB,sintb,s,int
ETAB,locy,cent,y
pret,locy,sxm,sym,sxym,sintm
PRET,locy,sxt,syt,sxyt,sintt
PRET,locy,sxb,syb,sxyb,sintb
```

Input file: postseccomb.inp

```
/post1
csys

esel,,,,15185,15211,26
,a,,,15227,15247,20
,a,,,15258,15264,6
,a,,,15276,15798,522
,a,,,15303,15324,21
,a,,,15804,15814,10
```

```
,a,,,15654,15666,12
,a,,,15687,15708,21
,a,,,15723,15737,14
,a,,,15750,15953,203
,a,,,15785,15788,3
,a,,,15819,15837,18
,a,,,15851,15866,15
,a,,,15877,15897,20
,a,,,15795,15912,117
,a,,,15764

loca,199,1,,280.75,,90

*do,k,138,148
set,k
etab,locy,cent,y
shel,mid
etab,epstm,epto,1
,epscm,epto,3
sadd,epscm,epscm,,-1
shel,top
etab,epstbt,epto,1
,epscbt,epto,3
sadd,epscbt,epscbt,,-1
shel,bot
etab,epstbb,epto,1
,epscbb,epto,3
sadd,epscbb,epscbb,,-1
esor,etab,locy,1
/out,combsl%k%,lis
pret,locy,epstm,epscm,epstbt,epscbt,epstbb,epscbb
/out
*enddo
```

Input file: jbolt2.inp

```
!*** J-bolts
!*** 6/1/04
!***

!***  writes data for all laod steps in a single file! modified
09/02/04 - Siva!
!***  NB!! 6/1/04
!***   This version uses (sfyi**2+sfzi**2)**1/2
!***   because beams on z <> 0 face are
!***   incorrectly oriented (should use nod1k in set_slicea.mac)
!***

/fil,set_slice_0
resu
/post1

*do,k,138,148

set,k
*cfo,lsteps,asme,,append
tt1='Load Step'
*vwri,tt1
%c

*vwri,k
(11f8.1,f8.1)

ct='J-bolt pos'
ct1='F-axial'
ct2='F-shear'
ct3='U-axial'
```

```
ct4='U-shear'

*vwri,ct,ct1,ct2,ct3,ct4
(12a12)

esel,,real,,50,56
nsle
esln
esel,r,type,,30
nsle
etab,fxi,smisc,1
,sfyi,smisc,6
,sfzi,smisc,5
,exi,smisc,7
,esyi,smis,12
,eszi,smis,11
csys,1
etab,jloc,cent,y
esor,etab,jloc,1
*dim,faxial,,13
,fshear,,13
,uaxial,,13
,ushear,,13
*do,i,1,13
*get,e1,sort,,imin
*get,fx1,elem,e1,etab,fxi
*get,fsheary1,elem,e1,etab,sfyi
*get,fshearz1,elem,e1,etab,sfzi
*get,ex1,elem,e1,etab,exi
*get,esheary1,elem,e1,etab,esyi
*get,eshearz1,elem,e1,etab,eszi
esel,u,,,e1
esor,etab,jloc,1
*get,e2,sort,,imin
*get,fx2,elem,e2,etab,fxi
*get,fsheary2,elem,e2,etab,sfyi
*get,fshearz2,elem,e2,etab,sfzi
*get,ex2,elem,e2,etab,exi
*get,esheary2,elem,e2,etab,esyi
*get,eshearz2,elem,e2,etab,eszi
faxial(i)=fx1+fx2
fsheary=(fsheary1**2+fshearz1**2)**0.5
fshearz=(fsheary2**2+fshearz2**2)**0.5
fshear(i)=fsheary+fshearz
uaxial(i)=(ex1*4+ex2*4)/2            !** 4" J-bolt length
usheary=(esheary1**2+eshearz1**2)**0.5
ushearz=(esheary2**2+eshearz2**2)**0.5
ushear(i)=(usheary*4+ushearz*4)/2
esel,u,,,e2
esor,etab,jloc,1

fax=faxial(i)
fsh=fshear(i)
uax=uaxial(i)
ush=ushear(i)

*vwri,i,fax,fsh,uax,ush
(12g12.5,g12.5)

*enddo
*cfc
*enddo
```