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2014 V&V Challenge: Problem Statement

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Abstract

This document describes the problem to be addressed for the 2014 Sandia Verification and Validation Challenge Workshop, as well as all the available information for participants. Visit the Challenge Workshop website: https://share.sandia.gov/vvcw/ to download the relevant data and code.

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Acknowledgments

This challenge problem and the resulting workshop were made possible with support from Sandia National Laboratories and ASME. We wish to thank several people for their contributions: George Orient, Brian Carnes, Vicente Romero, and Adam Hetzler at Sandia National Laboratories, Ryan Crane and the V&V20 committee at ASME, and many other colleagues and workshop participants.

Nomenclature

See ASME V&V 10 – Guide for Verification and Validation in Computational Solid Mechanics for standard definitions and introduction to Verification and Validation (V&V).

- σ Von Mises stress
- d Tank wall displacement, normal to the surface
- x Axial location
- φ Circumferential angle
- P Gauge Pressure
- γ Liquid specific weight
- χ Liquid Composition (mass fraction)
- H Liquid height
- E Young's Modulus
- ν Poisson's ratio
- L Length
- R Radius
- T Wall thickness
- m Mesh ID

1 SCENARIO

MysteryLiquid Co. maintains a large number of liquid-storage tanks. Standard operating procedures limit the liquid level to below a certain fraction of the tank's height, and the remaining space is filled with pressurized gas. The tanks are placed all over the world, and are used to store Mystery Liquid. The weight of the contents plus the pressurization causes deformation of the tank walls.

1.1 Tank Information

The Tanks are cylinders with two half-sphere end caps. They are supported by rings around the circumference, located at the junction of the cylinder and end caps. Locations on the tank surface are described by axial distance from centerline and circumferential angle, from straight down. This is shown in Figure 1.

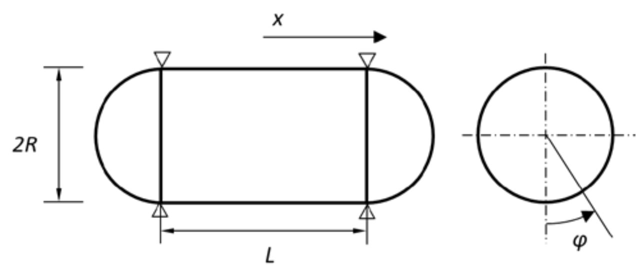

Figure 1: Side view and axial view of tanks

1.2 Tank Inspections

Each year, several tanks are inspected at random. This year, one tank failed to meet a required safety criterion when a large load was applied. This margin has been established from historical data, but is not a regulatory requirement. It has never before been violated during an inspection. The tank in question, Tank 0, did not physically fail, but the consequences of a failure would be significant. Given that the tank is out of spec, we wish to know if there is a real chance of physical failure. See Appendix 4.8 for more information about testing, the tanks, and Tank 0.

The out-of-spec tank and its two neighboring tanks were taken out of service and underwent testing. In addition, four tanks, in four different locations, each underwent multiple tests while still in service.

The company has commissioned a modeling study to complement these experimental tests. The assumption is that the historical safety margins are being violated, and we need to better understand the margin to failure. The goal is to determine whether the remaining tanks must be retired, or if they can be kept in service for a few years while replacements are ordered. The decision will be based on calculation of Probability of Failure.

2 CHALLENGE PROBLEM

The 2014 Verification and Validation Challenge Problem consists of three parts:

- Prediction: the ultimate product of this study will be prediction of Probability of Failure for two scenarios. In addition to a best estimate of Probability of Failure, we expect to produce uncertainty estimates.
- Credibility Assessment: In addition to the predictions, we need to know the credibility the predicted Probability of Failure.
- V&V Strategy: The key to providing a good credibility assessment is a logical and clearly defined strategy to gather evidence that the predictions are accurate.

All data and models will be provided. No model development will be necessary or accepted, and no additional data can be generated (this year).

2.1 Prediction

Modeling & Simulation will be used to make a decision on whether to remove all the tanks from service, or modify operating limits. The specific model predictions of interest will be Probability of Failure under two scenarios, listed below.

2.1.1 Simulation at the nominal conditions of the out-of-spec tank

- In this scenario, the environmental state is specified at the nominal test conditions:
  - $P = 73.5 psig$
  - $\chi = 1$
  - $H = 50 in$
- Participants should compute the Probability of Failure and uncertainty, with these input values fixed.

2.1.2 Understand the limits of the operating space

- Here, the Probability of Failure is set at a threshold, $P(Fail) < 10^{-3}$, and the participants must determine the loading levels which will violate the threshold.
- Standard operating procedures put limits on the pressure, composition, and liquid height.
  - Pressures must be within $P = [15, 75]\ psig$
  - Composition: $\chi = [0.1, 1]$
  - Liquid height should be $H < 55 in$
- These limits are strictly followed, but the measured operating conditions are not completely accurate – meaning that operators ensure that the measured values are within limits.

- What is the range of "safe" operating condition *measurements*, such that $P(Fail) < 10^{-3}$? Are current operating procedures enough to ensure safety?

These calculations will require both model predictions and some failure criterion. To simplify this exercise and ensure some level of consistency, "Failure" is strictly defined based on stress. More explicitly, failure occurs when the von Mises stress exceeds the yield stress at any point on the tank's surface. See Section 3.4 for more discussion about Quantities of Interest.

2.2 V&V Strategy

The V&V strategy is the overall approach to making predictions AND assessing the uncertainty and credibility of those predictions. The implemented approach takes the form of a series of tasks to incorporate the experimental and Modeling & Simulation results.

The requirement for this part of the Challenge Problem is:

> ***Develop and communicate a strategy for how data and models will be used to make the requested predictions AND assess both uncertainty and credibility of those predictions***

The specific predictions of interest were listed in Section 3.1. The data and models are described in Sections 4 and 4.3. In this section, we first give an overview of the available data and models, and then give a list of possible tasks that might make up a V&V strategy, and finally discuss a V&V hierarchy as a possible way of communicating the strategy.

2.2.1 Summary of available Data

The experimental study includes legacy data and five test series:

1. Legacy data from the manufacturer
   Documented nominal material properties and tank dimensions
2. Coupon tests in a controlled, lab environment
   Measure material properties and Tank wall thickness
3. Liquid characterization tests in a controlled, lab environment
   Specific weight & composition measurements on Mystery Liquid
4. Full Tank tests in a controlled, lab environment full tank indicates the complete system, not that the tank is filled w/ liquid
   No loading on the tank – measure dimensions (length and radius)
5. Full Tank tests in a controlled, lab environment
   Pressure loading, measure displacements at four locations
6. Full Tank tests in a production environment
   Measured loading – both pressure and liquid, measured displacement at 20 locations

2.2.2 Tank Model

In addition, a mathematical model has been created for an idealized Tank under pressure & liquid loading. The pressure only loading is a special case. Datasets 5) and 6) above are collected from experimental conditions that are subsets of the scenarios that this model can simulate. The final predictions of interest are an extrapolation from the experimental conditions of dataset 6). The participant must determine if the model is adequate to simulate these more extreme conditions.

Additional information about V&V Strategies is included in Section 4.1. This includes some potential V&V related tasks that might be beneficial in this project, and an introduction to the concept of a V&V hierarchy. The relationship between the datasets and the model can be visualized with the V&V hierarchy in Figure 2. This is, of course, an incomplete picture but it does help to identify uses for the data and models. Details about the data and models are available in the Appendix.

2.3 Credibility Assessment

At the end of the project, the ultimate goal would be to make a decision regarding viability of the tanks. Such a decision would require knowledge of many external factors, like company finances, economics, and consequences of tank failure. This is too broad a scope for the challenge problem. Instead, participants are asked to comment – qualitatively or quantitatively – on the credibility of their predictions. Some guiding questions include:

- How do you communicate the results, uncertainty, and credibility?
- How does each V&V task contribute to the credibility of the predictions of interest?
- Does the V&V strategy as a whole add credibility?
- What is the impact of extrapolation from the validation domain?
- Would you feel comfortable making decisions based on your analysis?
- How would you improve the analysis?

2.4 Quantities of Interest

We will use Quantities of Interest (QoIs) to refer to: model predictions of a specific quantity, quantities derived from model predictions, quantities measured experimentally, OR quantities derived from measurements.

The experimental and modeling studies must be coordinated, so that the experiments produce QoIs that will be useful for the modeling activity. In order to reduce the scope of this challenge, several QoI decisions have been made and cannot be modified.

1. The first type of QoI is displacement normal to the tank surface, at various, specified locations. This is the quantity that is directly measured during tests, and is simulated in the model. It is directly available from the Python code.
   Displacements were used because they are easy to understand, visualize, and compute.

This is not intended to be a completely realistic scenario.

2. The second type of QoI is the von Mises stress at arbitrary locations on the Tank walls. The material is observed to fail very quickly after reaching its yield stress. Therefore, the decision has been made to correlate tank failure to the event where von Mises stress exceeds yield stress. This is the only available failure criterion and must be used to estimate Probability of Failure.

Note that displacement data is available from the tanks, but no stresses are ever measured. This means that the prediction of interest is based on a quantity that is never really observed. However, there is a strong relationship between these two quantities of interest.

3 APPENDIX

3.1 Additional Information about V&V Strategies

A V&V Strategy is very problem dependent and is influenced by: the intended use of the predictions, the computational & experimental resources, schedule, etc. Most of these constraints are not applicable for this Challenge Problem.

As examples:

- The intended use is described, but lacks context and consequence
- The models are very inexpensive, so computational budget is not a factor

It is up to participants to self-impose constraints – realizing this is a learning experience, not a real project.

The primary concern here is function evaluations. Keep in mind the code provided is a proxy for an expensive finite element model, and so the number of function evaluations is quite important and should be tracked.

3.1.1 A list of potential tasks

To help focus the activities, we have created a list of potential tasks to include in a V&V strategy. This is not exhaustive or exclusive, but is meant as a starting point:

- Characterization of input uncertainties (material parameters, dimensions, etc.)
- Characterization of environmental variability/uncertainty (loading conditions / model inputs)
- Calibration of model parameters to match experimental data
- Elicitation and/or treatment of epistemic vs. aleatoric uncertainty
- Solution verification / estimate of numerical uncertainty
- Sensitivity analysis
- Uncertainty quantification
- Validation of models against experimental data
- Aggregation of uncertainty
- Assess relevancy of information
- Predictions plus uncertainty
- Qualitative credibility assessment

Note that some critical tasks are not listed because we have made assumptions and restrictions. The biggest example is the choice of quantities of interest. For more information see Section 3.4. Also, it is not required that all tasks be performed, and not all data must be taken into account.

3.1.2 The V&V Hierarchy Concept

While we hope not to influence the participant's thinking too strongly, we have to communicate the ideas here and to do so we will utilize a V&V Hierarchy. As shown in Figure 2, the experimental test and Modeling & Simulation analyses can be arranged by the complexity of the system/hardware and environment/loading. The purpose is to visualize what data and models are available, and match these resources to the various tasks listed above – crafting the V&V Strategy. The resulting evidence allows us to build the case that the final predictions are credible.

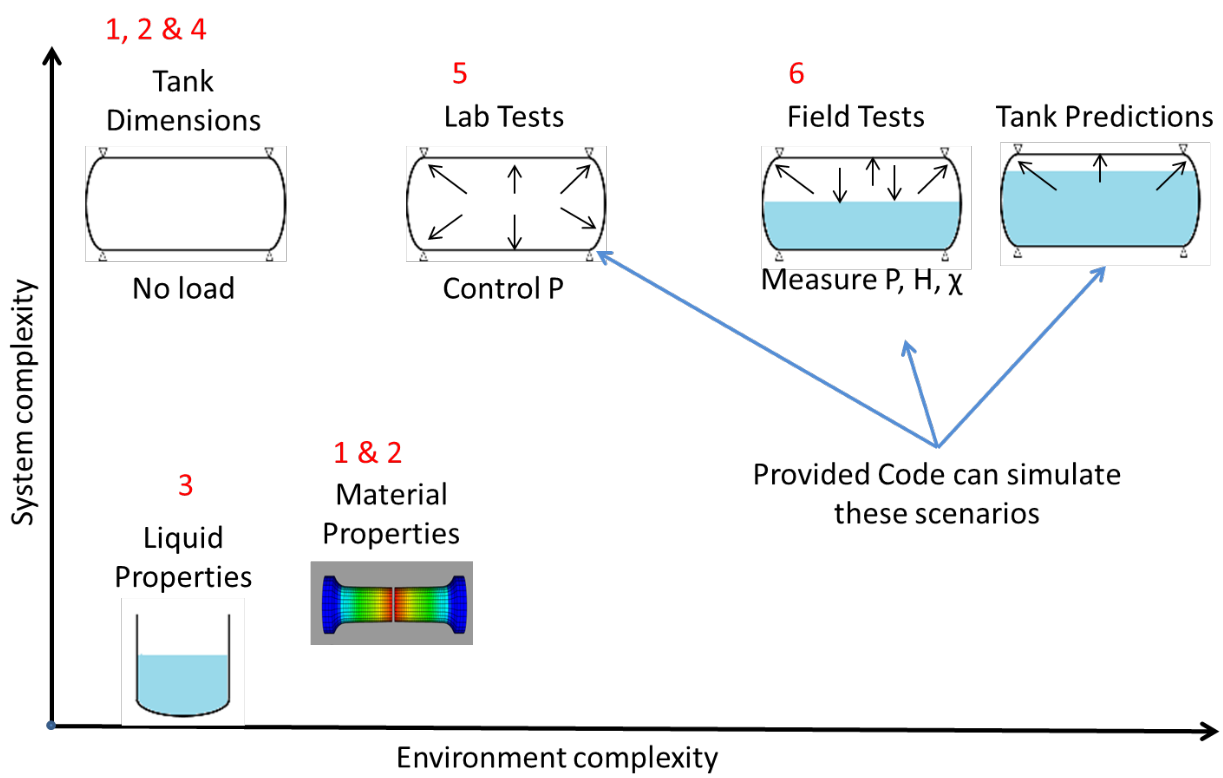

Figure 2: V&V Hierarchy for the Tank analysis

The six datasets mentioned in Section 3.2.1 are listed in Figure 2 in **RED**. The model/code are capable of simulating any of the Tank loading scenarios (of course the quality of these simulations is not yet known).

V&V Hierarchies are sometimes separated into different "levels" of complexity. In this case there are only two system complexity levels: material/physics-level and Tank (full system) level. On the environmental axis, there is a more gradual scale: no loading, uniaxial tension, pressure loading, combined pressure & liquid loading at "normal conditions", and finally pressure & liquid at "extreme conditions".

A second way to illustrate a V&V hierarchy is shown in Figure 3. This "pyramid view" shows how different aspects of the physical problem are combined.

Note that these are simply examples. It is not necessary to utilize the V&V hierarchy concept to communicate the V&V strategy. If the hierarchy is used, it does not need to match these examples.

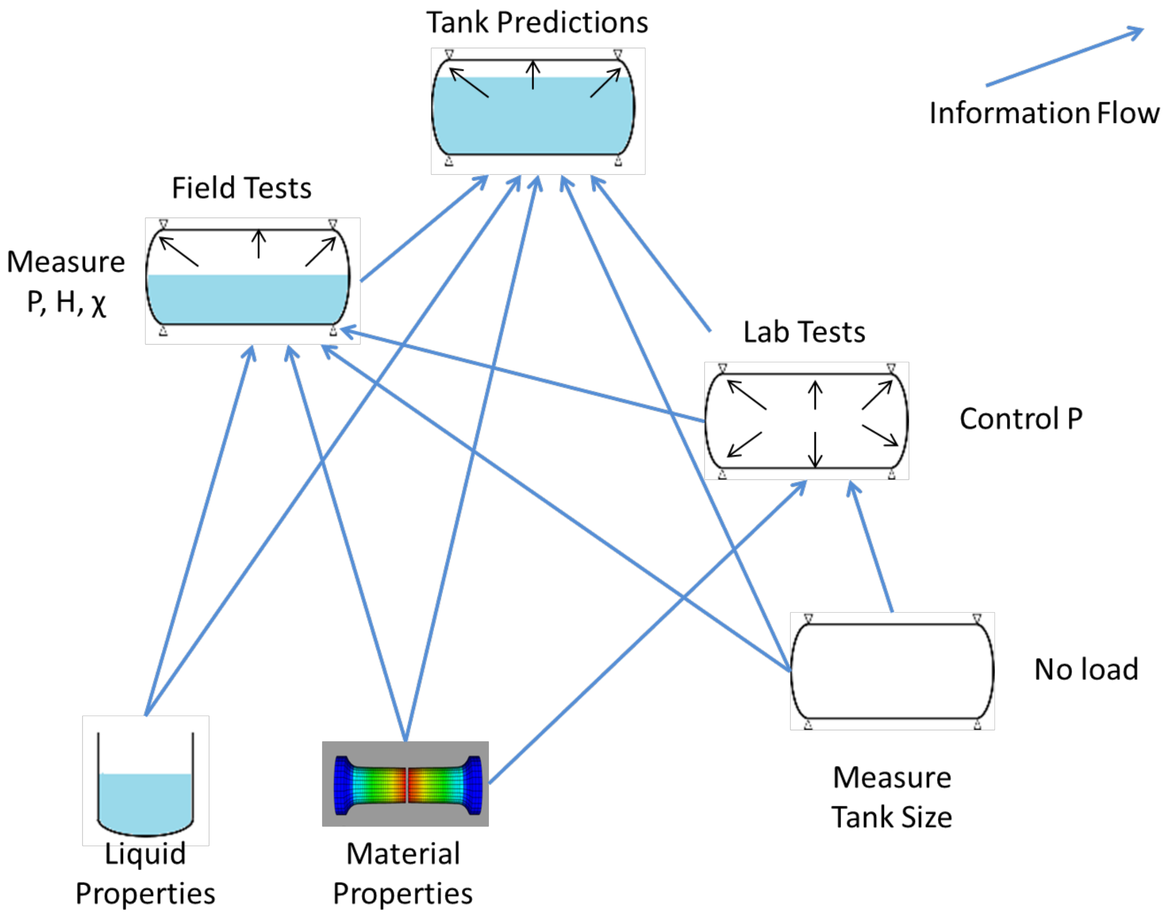

Figure 3: V&V Hierarchy – alternate view

3.1.3 Forming the strategy

The primary focus of this Challenge Workshop is to explore the diversity of V&V Strategies. Even with a simple problem, there are a huge number of variations and methods that can be used to estimate Probability of Failure.

Some particularly tricky choices include:

- Which model inputs to calibrate in order to match data
- What data to use and how to use it
- How to incorporate vague information into mathematical descriptions of uncertainty
- What validation comparisons are meaningful
- How to assess credibility for a QoI that has no corresponding experimental data
- The organizers realize that participants will bring a range of interests to the workshop. We hope to focus on the choices of V&V Strategies, and not on the mechanics of running the model or particular algorithms. We are interested in several questions:

- What is the current state of the art in validation
- What are the effects of assumptions and different V&V strategies
- What is the minimum information/V&V work that is required to answer the question?

3.2 Data

Data from the experimental study is available prior to the start of this project. No further data will be available before the conclusion of the project.

The experimental study includes legacy data and five test series:

1. Legacy data from the manufacturer
   Documented nominal material properties and tank dimensions
2. Coupon tests in a controlled, lab environment
   Measure material properties and Tank wall thickness
3. Liquid characterization tests in a controlled, lab environment
   Specific weight & composition measurements on Mystery Liquid
4. Full Tank tests in a controlled, lab environment
   No loading on the tank – measure dimensions (length and radius)
5. Full Tank tests in a controlled, lab environment
   Pressure loading, measure displacements at four locations
6. Full Tank tests in a production environment
   Measured loading – both pressure and liquid, measured displacement at 20 locations

These datasets can be associated with the V&V hierarchy in Figure 2.

Story for Tank experiments and data:

- A total of three tanks were removed from the field
- The failed tank (Tank 0) was cut up for testing → Dataset 2
- The two intact tanks (Tanks 1, 2) were used for full system testing
  → Datasets 4,5
- Additional tests were performed in the field on tanks (Tanks 3-6) that remained in service
  → Dataset 6

1) Legacy data from the manufacturer

The manufacturer gave specs when the tanks were delivered, however, there is no other data about manufacturing tolerances, evidence that the specs were met, or data on what changes may have occurred in the decade(s) since delivery.

- Young's Modulus $E_{legacy} = 3e7$ psi
- Poisson's Ratio $\nu_{legacy} = 0.27$
- Yield Stress $\sigma_{y,legacy} = 0.045e6$ psi
- Length $l_{legacy} = 60$ in
- Radius $r_{legacy} = 30$ in
- Wall thickness $t_{legacy} = 0.25$ in

2) Lab tests: material characterization

- The failed tank (Tank 0) was cut up and used for lab tests
- At ten locations around the tank, two test coupons were cut away. One sample was used in a uniaxial tension test to estimate Young's modulus and yield stress. The second sample had its thickness measured before being machined into the test article used to estimate Poisson's ratio.
- The raw data (measurements from the tests) are not available, only the processed material property estimates. The lab did not provide any uncertainty data or details about their measurements or procedure.
- The coupons were carefully marked, so we know that the ordering of the data in each file is consistent. For example: data point 1 in each file listed came from coupons taken from the same spot on Tank0.
- Unfortunately, the original tank locations of the coupons were not recorded. However, we can tell that the coupons came from a variety of locations.
- Files:
  - MaterialData_Tank0_E.txt
  - MaterialData_ Tank0_YS.txt
  - MaterialData_ Tank0_Nu.txt (Poisson's Ratio)
  - Dimensions_Tank0_Thickness.txt

3) Lab tests: Specific weight measurements on Mystery Liquid

- In addition to the material tests, we also have lab data about the Mystery Liquid's specific weight as a function of composition.
- Raw data is unavailable, but an equation of state (EoS) has been fitted – see Figure 6.
- This is discussed in the Models section.

4) Lab tests: Full Tank – no loading

- The two intact tanks (Tanks 1, 2) were used for full system testing
- The tank dimensions – length and radius, were measured very accurately
- The measurements are not repeats in the same locations. Each measurement is from a different location, and they are spread evenly over the tanks.
- Again, the locations were not recorded.
- There is variability in dimensions, w.r.t. location on the tank.
- Ten measurements each for length and radius; five on each tank
- Files
    - Dimensions_Tank1_Length.txt
    - Dimensions_Tank2_Length.txt
    - Dimensions_Tank1_ Radius.txt
    - Dimensions_Tank2_ Radius.txt

5) Lab test: Full Tank – pressure loading

- Tanks 1 and 2 are tested in the lab
- Pressure controlled: 3 pressures, two independent repeats → 6 tests on each tank
- Measurements
    - Displacement measurements are taken at four locations, see Figure 4
    - It is presumed that these are extremely accurate, within $\pm 3\%$ or $0.002 in$, whichever is greater.
    - Pressure is measured by a gauge on the tank, and should be within $\pm 5\%$ of the absolute pressure (gauge pressure + atmospheric pressure). This is gauge pressure. No additional documentation was available about the gauges, regarding the meaning of 5% or any confidence level.
- Measurement devices

- Each tank has its own pressure gauge. These gauges are made by the same supplier and have the same calibration process.
- The displacements were measured by 4 contact sensors. They are considered interchangeable – the data from each location is not associated with a specific sensor.

- Experimental information is indexed by test and measurement location: $[12 \times 4]$
  - Tests 1-6 are Tank 1, tests 7-12 are Tank2
- Files:
  - Ponly_X_meas.txt x Locations, same for all tests $[1 \times 4]$
  - Ponly_Phi_meas.txt φ Locations, same for all tests $[1 \times 4]$
  - Ponly_Tank1_DisplacementData.txt Four locations per test $[6 \times 4]$
  - Ponly_Tank2_DisplacementData.txt Four locations per test $[6 \times 4]$
  - Ponly_Tank1_NominalP.txt Measured Pressures for each test $[6 \times 1]$
  - Ponly_Tank2_NominalP.txt Measured Pressures for each test $[6 \times 1]$

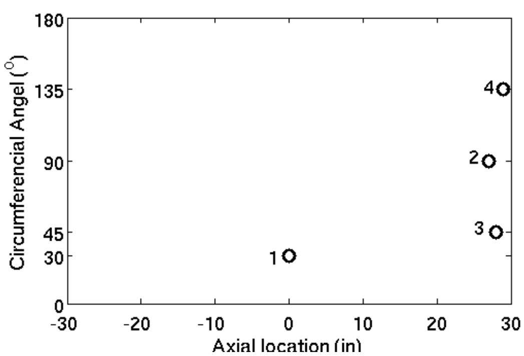

Figure 4: Dataset 5 measurement locations

6) Field test: Full Tank – pressure plus liquid loading

- Four tanks are tested in the field, Tanks 3-6
  - Each has different (unmeasured) material properties and dimensions
- Three tests done on each tank, each is considered independent
- Each test has different experimental conditions which are measured but not controlled
  - Pressure P

- Composition χ, and height H
- Liquid specific weight γ is inferred from composition, via Equation 1

- Measurements
  - Displacement measurements are taken at twenty locations
  - It is presumed that these are extremely accurate, within $\pm 3\%$ or $0.002 in$, whichever is greater.
  - Pressure is measured by a gauge on the tank, and should be within $\pm 5\%$ of the gauge. This is gauge pressure.
  - Liquid height can be measured, but due to orientation of the tank it varies slightly w/ axial position. Tanks are leveled so the height difference is $\leq 2in$ at the supports, $x = \pm 30$.
  - χ is measured but with significant uncertainty. The measurement devices are only rated to be within ± 0.05 mass fraction. For example, $\chi = 0.5$ measured → $\chi = [0.45 \sim 0.55]$ actual.
  - Specific weight is not measured, but can be inferred from χ. This is discussed in the Models section.
  - χ is measured by a probe located near the bottom of each tank. These are permanently attached, so the location does not change. There is a moderate amount of mixing while the tanks are in use, so χ measurements are believed to be representative of the tank contents.

- Measurement devices
  - The four tanks each had their own set of pressure and liquid height gauges, but all devices had the same supplier and calibration process.
  - The measurement of composition takes place offline, using liquid samples removed from the tank. Each test used a different machine, since the tanks were physically in different sites.
  - The displacements were measured by contact sensors, again the devices used in each test were different.

- Files:
  - PandL_X_meas.txt — x Locations, same for all tests $[1 \times 20]$
  - PandL_Phi_meas.txt — φ Locations, same for all tests $[1 \times 20]$
  - PandL_Tank3_DisplacementData.txt — 20 locations per test $[3 \times 20]$
  - PandL_Tank4_DisplacementData.txt
  - PandL_Tank5_DisplacementData.txt

- o PandL_Tank6_DisplacementData.txt
- o PandL_Tank3_NominalChi.txt — Measured χ for each test $[3\times1]$
- o PandL_Tank4_NominalChi.txt
- o PandL_Tank5_NominalChi.txt
- o PandL_Tank6_NominalChi.txt
- o PandL_Tank3_NominalGamma.txt — Computed γ, based on χ $[3\times1]$
- o PandL_Tank4_NominalGamma.txt
- o PandL_Tank5_NominalGamma.txt
- o PandL_Tank6_NominalGamma.txt
- o PandL_Tank3_NominalHeight.txt — Measured Heights for each test $[3\times1]$
- o PandL_Tank4_NominalHeight.txt
- o PandL_Tank5_NominalHeight.txt
- o PandL_Tank6_NominalHeight.txt
- o PandL_Tank3_NominalP.txt — Measured Pressures for each test $[3\times1]$
- o PandL_Tank4_NominalP.txt
- o PandL_Tank5_NominalP.txt
- o PandL_Tank6_NominalP.txt

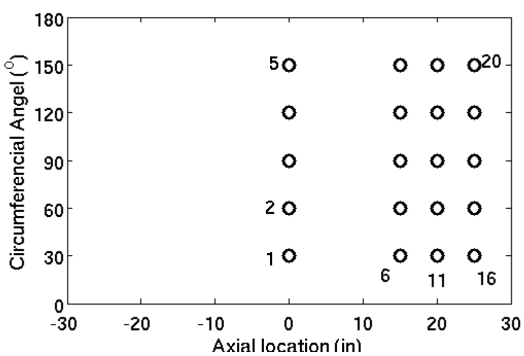

Figure 5: Dataset 6 Measurement Locations

3.3 Models

Separate from the experimental study, models have been developed to simulate the behavior of the materials and tanks.

3.3.1 Material models

It is up to the participants to use the given information to characterize the material properties. See Notes on the Quantities of Interest on Page 12 for how the yield stress will be used.

3.3.2 Liquid specific weight model

This empirical Equation of State was supplied from the lab:

Equation 1

$$\gamma = \frac{7\chi}{1+0.25(\chi-0.3)^2} - 8\sqrt{\chi} + 5$$

This is an excellent empirical fit for all χ, supported by many tests. The error is less than $\pm 2\%$ of the measured value over the entire range of χ.

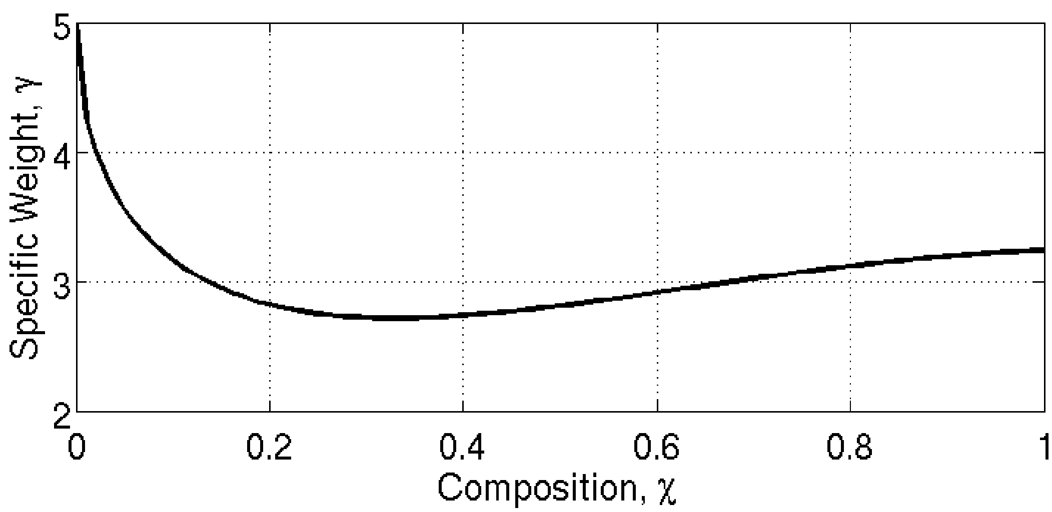

Figure 6: Relationship between composition and specific weight for Mystery Liquid

3.3.3 Tank model

The model for pressure and liquid loading on a tank is described in the context of the Challenge Problem. In reality, the provided Tank Model is a simple series solution which serves as a proxy for a large finite element model. For our purposes, we will treat it as if it were an actual finite element code and model, for which the numerical behavior and the complex physics are not completely understood. The actual equations and physics being modeled are revealed in Section 4.7.2.

3.3.3.1 Challenge workshop context

The supplied Tank model is a finite element model, built off a simplified geometry. The true system is a cylinder with two half-sphere end caps, and supports at the ends of the cylinder – see Figure 1. The Tank model geometry only includes the cylinder portion, with simple supports at the edges and flat, immovable end caps. Some features:

- All responses (displacements and stresses) vary smoothly w.r.t. parameters
- Four meshes were created from this geometry, with different characteristic “length scales” or “mesh sizes”.
- Participants can only use the four meshes that are supplied. The corresponding length scales/ mesh sizes are:
  - MeshID 1 – $2in$
  - MeshID 2 – $1in$
  - MeshID 3 – $0.5in$
  - MeshID 4 – $0.35in$
- Meshes are not necessarily within the ‘asymptotic regime’ for which Richardson Extrapolation is valid
- The meshes are uniform and use 4-noded shell elements.
- For the purpose of this challenge problem, the provided code is imagined as a finite element code. Prior verification testing has indicated that the code is correctly implemented and for this class of problems, should provide a theoretical first order convergence with mesh refinement. However, the current problem is more complicated than any prior verification tests.
- Each mesh has a different computational cost:
  - MeshID 1 – 12 CPU-hrs
  - MeshID 2 – 105 CPU-hrs
  - MeshID 3 – 1100 CPU-hrs
  - MeshID 4 – 10200 CPU-hrs
- The model can be treated as a black box

- Responses:
  - Displacement w and Stress σ
- $[w,\sigma] = M(x,\varphi,P,\gamma,H,E,\nu,L,R,T,m)$
- Arguments are:
  - x,φ Axial location and circumferential angle
  - P Gauge Pressure
  - γ Liquid specific weight (Zero will simplify to the pressure only scenario)
  - H Liquid height (zero in the pressure only scenario)
  - E Young's Modulus
  - ν Poisson's ratio
  - L Length
  - R Radius
  - T Wall thickness
  - m Mesh size (choose from 1,2,3,4)

3.4 Code

The Tank model has been implemented in Python, as a proxy for a finite-element code. The executable script and the source will be made available but should NOT be modified.

3.4.1 Model and Code Considerations

1. It is clear that these models and the code implementation have major problems. There are obvious model form errors:
    a. The "tank" has no hemispherical end caps
    b. There is no way to accommodate non-uniform tank dimensions (e.g.: inconsistent wall thickness and tank radius) or non-ideal tank orientation.
2. The series solution model has been modified to serve as a proxy for a finite-elements model. Only the finite elements model, implemented in the FEMTank.py code, should be used. The unmodified code is available and can be run without modifications, but that is not part of this challenge.
3. We have verified that the code does accurately compute the equations described in the Series Solution Model Section, however we are claiming that the code is in fact computing a finite elements solution.

3.4.2 Usage

The model described above is implemented in FEMTank.p. In addition to the "physics code", we also supply a helpful utilities: EvalTank.py and Matlab_Tank_Interface.m. The Matlab script is documented within the file.

3.4.3 FEMTank.py

Usage examples are given in the comments of the python file.

python FEMTank.py X_vec Phi_vec P (Gamma, -Chi) H E Nu L R T m summaryFile dataFile

Arguments are:

1. *X_vec* $1\times N_x$ vector, passed as comma delimited string, bounds $\left[0,\frac{L}{2}\right]$ (in)
2. *Phi_vec* $1\times N_\varphi$ vector, passed as comma delimited string, bounds $[0,180]$ (^{o})

   The code computes responses at all combinations of x,φ → $N_x \times N_\varphi$ locations
3. *P* Scalar, bounds $[0,\infty]$ (psig, gage pressure)
4. *Gamma, -Chi* Scalar – Liquid specific weight OR composition
   a. Positive numbers interpreted as specific weight, bounds $[0,\infty]$ (lbs/in^3)
   b. Negative numbers $[-1,0]$ interpreted as negative composition
      The code applies Equation 1 to compute specific weight
5. *H* Scalar (zero in the pressure only scenario) , bounds $[0,2R]$ (in)
6. *E* Scalar, bounds $[20e6,35e6]$ (psi)
7. *Nu* Scalar, bounds $[0.2,0.5]$
8. *L* Scalar, bounds $[0,\infty]$ (in)
9. *R* Scalar, bounds $[0,\infty]$ (in)
10. *T* Scalar, bounds $[0,\infty]$ (in)
11. *m* Mesh ID (choose from 1,2,3,4)
12. *summaryFile* Name of summary file, This writes out:
    a. Maximum von Mises Stress
    b. x position of maximum stress
    c. φ position of maximum stress
    d. Surface of maximum stress – inner (-1) or outer (1)
13. *dataFile* Name of data file – if empty string is passed, no dataFile is written. This writes out:
    a. All inputs

b. Locations (x and φ)

c. Comma separated matrices for normal displacement (in), and stresses (psi) on the outside and inside surface of the tank $\left[N_x \times N_\varphi\right]$

- IMPORTANT – the bounds are NOT checked by the code

3.4.4 EvalTank.py Usage

The major purpose of EvalTank.py is to set up the x and φ locations for four common usages of FEMTank.py and generally make life easier.

- resultStyle 1
  - Set up a fine grid of x and φ, suitable for visualizing the model responses. See
- resultStyle 2
  - Set up a nonuniform grid of x and φ, finest near the centerline and the support.
  - This is suitable for searching for the max von Mises stress
- resultStyle 3
  - Set x and φ to the nominal locations corresponding to Dataset 5 – Pressure only loading tests. See Figure 4.
  - Print only the four displacements to the summaryFile. No dataFile is written.
- resultStyle 4
  - Set x and φ to the nominal locations corresponding to Dataset 6 – Pressure and Liquid loading tests. See Figure 5.
  - Print only the 20 displacements to the summaryFile. No dataFile is written.
- If other locations are required, participants must utilize FEMTank.py directly.

Usage:

python EvalTank.py inputFile summaryFile [dataFile]

- *inputFile* text file listing all the necessary inputs
  - An example is shown in Figure 7.
  - Note that this is the same format that Dakota software uses (dprepro format)
  - See http://dakota.sandia.gov
- *summaryFile* and *dataFile* are passed to FEMTank.py and are described above in Section 0.

```
31.563      P  # Pressure (psi)
3.1631      Gamma_Chi #Gamma (>0) or chi (<0)
35.903      H # Liquid Height (in)
2.8618e7    E # Young's Modulus (psi)
0.2684      Nu # Poisson ratio
60.068      L # Tank length (in)
29.952      R # Tank radius (in)
0.2252      T # Tank wall thickness (in)
2           meshID
1           resultStyle
```

Figure 7: Format of inputFile to EvalTank.py

3.5 Dakota Examples

Dakota input files are also distributed with the problem. Each is in its own directory, and they all have instructions and notes. Unfortunately, these have only been tested on linux machines.

The examples show how a list_parameter_study, Latin Hypercube Sampling, and nonlinear least squares (parameter calibration) can be applied to the tank problem. See the input files and README files for usage information.

See the Dakota website for information about the software: http://dakota.sandia.gov , and contact us at vvcw@sandia.gov if you are interested in using the Dakota software.

3.6 Visualization of Simulation Results

The final utility is a Matlab script that plots the tank wall responses. This is set up to read from dataFiles output by FEMTank.py. Examples are shown in Figure 8**.** If using EvalTank.py to set up the simulations, this utility works great for resultStyle 1, however it should also work for any regular grid of X_vec and Phi_vec values.

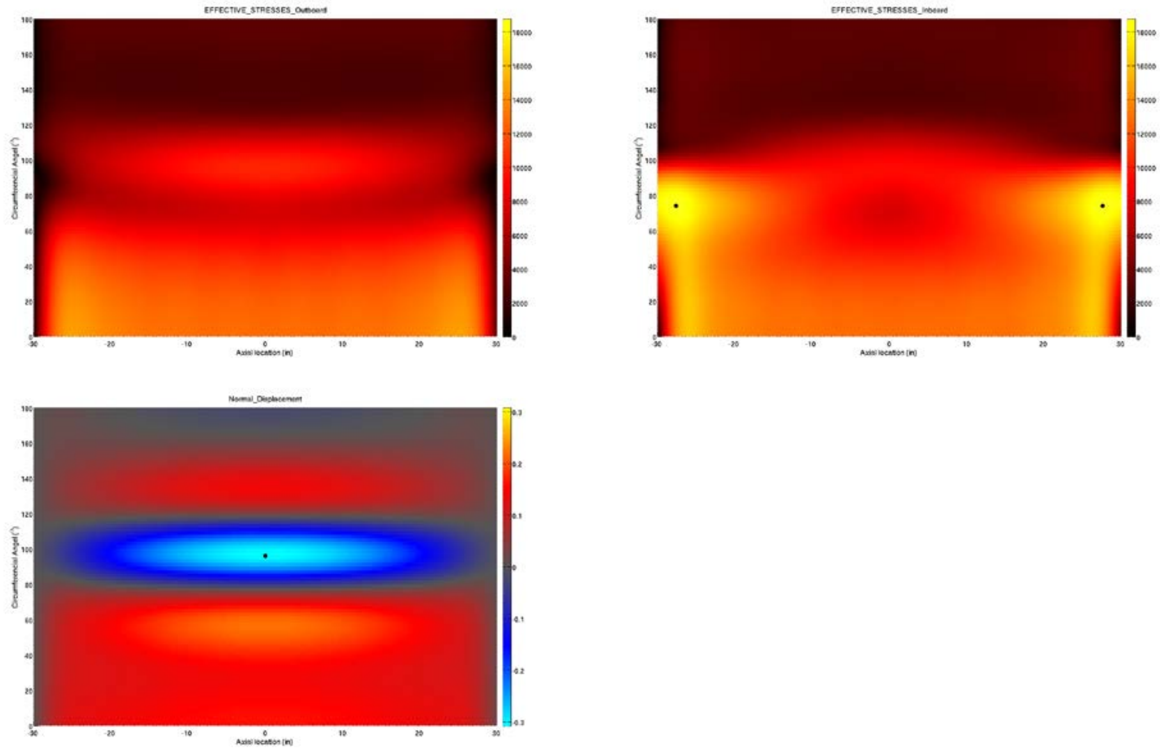

Figure 8: Examples of the visualization of FEMTank.py dataFiles, max values indicated with black dots

3.7 Behind the Scenes

3.7.1 Truth Model

The truth model is a finite element model. The mesh is created in Cubit, and the solution is found using Sierra SM – adagio. This is used to synthesize "experimental data" for datasets 5 & 6. The details of the truth model will not be revealed until after participants have presented their solutions.

- Uniform mesh with 4-noded shell elements
- Mesh size corresponds to the edge length of the shell elements, which have roughly 1:1 aspect ratio
- CAD model partitioned at the liquid surface
- Model responses on the cylinder section are translated from Cartesian to Cylindrical coordinates, displacements are "measured" relative to the un-loaded surface, in the normal direction

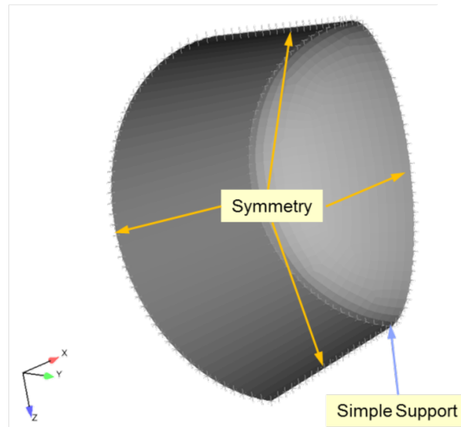

Figure 9: Finite Element Model

3.7.2 Series Solution Model

The series solution is adapted from: S. Timoshenko, S. Woinowsky-Krieger: Theory of Plates and Shells. McGraw-Hill (1987).

https://ia700807.us.archive.org/34/items/TheoryOfPlatesAndShells/TheoryOfPlatesAndShellsS.timoshenko2ndEdition.pdf

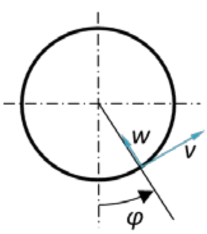

Figure 10: Tank Variables

3.7.2.1 Pressure Only Model

- Linear elastic, thin shell theory, small displacements (displacement -> displacement gradient -> strain -> stress + equilibrium equations)
- Edges are simply supported (no radial or circumferential displacement and no moment transfer at edges)

- Shell mid-surface displacements from displacement form of equilibrium PDE:

$u(x,\phi)$ is the displacement along the x axis (Not shown in Figure 10, instead see Figure 1)

$$w(x,\phi) = -\frac{PR^2}{ET} + C_1 \sin\beta x \sinh\beta x + C_2 \sin\beta x \cosh\beta x +$$
$$C_3 \cos\beta x \sinh\beta x + C_4 \cos\beta x \cosh T\beta x$$

$$\beta^4 = \frac{3\left(1-\nu^2\right)}{R^2 T^2}$$

The code solves for C_1, C_2, C_3, C_4, from boundary conditions

$$u(x,\phi) = v(x,\phi) = 0$$

$$w(\pm\frac{L}{2},\phi) = 0$$

3.7.2.2 Pressure and Liquid Loading

Same assumptions as pressure only model

$$u(x,\phi) = \sum_{m=1,3,5,\dots,M} \sum_{n=0,1,2,\dots,N} A_{mn} \cos(n\phi) \cos\left(\frac{m\pi x}{l}\right)$$

$$v(x,\phi) = \sum_{m=1,3,5,\dots,M} \sum_{n=0,1,2,\dots,N} B_{mn} \sin(n\phi) \sin\left(\frac{m\pi x}{l}\right)$$

$$w(x,\phi) = \sum_{m=1,3,5,\dots,M} \sum_{n=0,1,2,\dots,N} C_{mn} \cos(n\phi) \sin\left(\frac{m\pi x}{l}\right)$$

- Coefficients determined by B.C.'s and parameters

3.8 Tank 0 – Notes and Test Procedure

Tank 0 is part of a fleet of 450 nominally identical tanks, located all over the world. They operate in all climates, and have never experienced a physical failure. Tank 0 is also the first tank to fail a safety test. The fleet age ranges from 4 to 12 years old. Tank 0 has been in service for 6 years. There is nothing obvious about Tank 0 or the testing conditions to differentiate it from other tanks. The temperature was high, but not extreme – the tanks were designed for all weather conditions.

The safety tests measure displacement at various locations around the tank under controlled loading, as mentioned in Section 3.1.1. The location that was out of spec was at the bottom, centerline of the tank – X=0, phi = 0, as marked in Figure 11. Note that displacements are measured in the test for convenience, but it is believed that stress is the better predictor of physical failure. The location of max stress is not necessarily the same as max displacement.

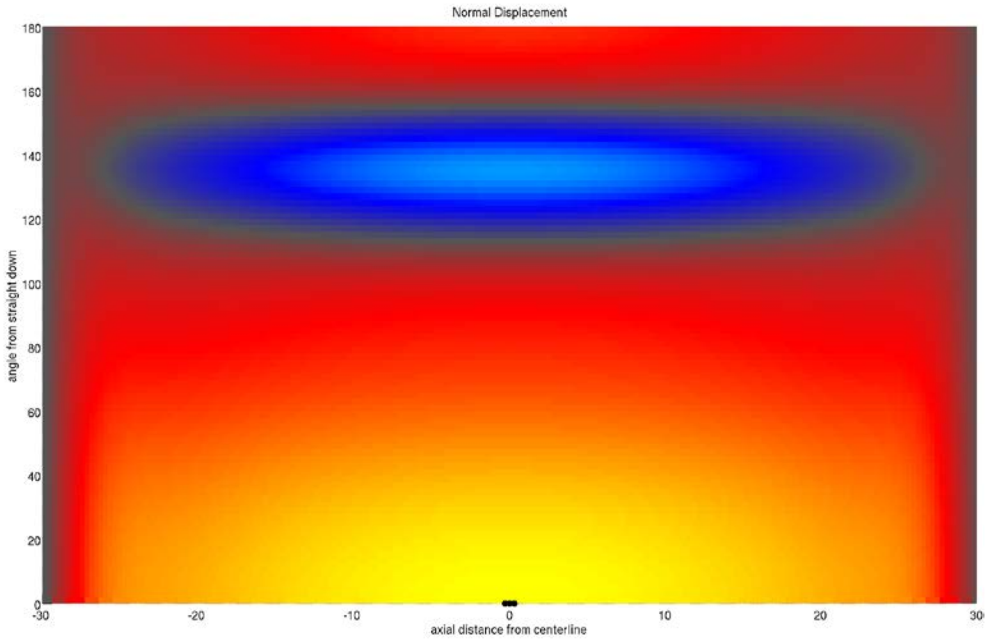

Figure 11: Tank 0 displacements during safety testing. Out of spec measurement indicated with black dots

4 DISTRIBUTION

1	MS0899	Technical Library	9536 (electronic copy)

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