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API 579 FFS Assessments of Storage Tanks with Uneven Support

Alex Tatarov, *Principal Engineer at Acuren*
Arash Ilbagi, *GM-Engineering at Acuren*

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Introduction

Storage tanks play a crucial role in supply chain management in industries such as oil and gas, chemicals, and water storage. However, in permafrost areas, the design and maintenance of these tanks become more challenging due to the uneven and unstable foundation caused by the thawing and freezing of the permafrost. Permafrost is a permanently frozen layer of soil or rock which acts as the natural foundation for many infrastructures in northern Canada and Alaska. The gradual thawing of permafrost can result in uneven settlement, leading to foundation instability, which can cause significant challenges for storage tanks built in these regions.

Fitness-for-service (FFS) is a method to evaluate the structural integrity and fitness of various types of equipment, such as storage tanks, to continue to operate safely and effectively. In the context of storage tanks in permafrost areas, FFS assessments can be crucial to ensure the safe and reliable operation of these tanks. In this article, a real-world scenario of a storage tank built in a permafrost area will be described, highlighting the challenges of foundation instability and how API 579/ASME FFS-1 assessment and finite element analysis were used to address the challenges.

Description of the Problem

In a tank farm located in a permafrost area in Northern Canada, eleven atmospheric storage tanks were installed on rig mats. Visual inspection revealed gaps between the mats and floors of several tanks, as shown in **Figures 1-3**. The following is the design information for the tanks in the subject tank farm.

- The floors, shells, and roofs were made of CSA G40.21-44W material.
- The nozzles, flanges, and repads were made of ASTM A106B, ASTM A105N, and ASTM A36 carbon steel.
- The tanks were constructed in accordance with API 650 modified.
- The tanks were designed for hydrostatic pressure, 16 oz internal pressure, and a 0.4 oz vacuum.

Laser scan inspection of the tanks during the operation showed that changes in tank liquid levels resulted in tank movement/inclination. This movement can be described by the displacement of the roof tip, as shown in **Figure 4**. The displacement of the roof tip was characterized as follows:

- Based on the laser scans, midpoints of the tank floor and tank rooftop were established.
- For each tank, the floor midpoint was projected vertically to the same level at the roof tip and served as a reference point for vertical position.
- The difference in positions between the roof tip and the reference point formed a displacement vector, which started at the reference point and ended at the roof tip.
- In polar coordinates, the deflection vector was characterized by the deflection magnitude (distance between the reference point/vertical position of the roof tip) and its direction.
- The direction was measured by a vector angle with respect to the North direction.

Figures 5 and **6** show the results of the measured deflection for five of those tanks as a function of the liquid fill level in each tank. Similar results were observed for all tanks. These results showed that the foundation supports of these tanks are not solid.

The detailed inspection of the positioning of the tanks on the rig mats showed the following:

- Tanks can be sitting on up to eight rig mats, depending on the position of the tank and the rig mats.
- Each tank contained several gaps along its circumference.
- **Figure 7** shows the locations of potential gaps.

Fitness-for-Service Assessment

The FFS assessment was performed using the following codes and specifications:

1. API Standard 650, Welded Tanks for Oil Storage (2014)
2. ASME Boiler and Pressure Vessel Code, Section II, Part D (2017)
3. API 579 / ASME FFS-1 Fitness-For-Service Assessment (2016)
4. ASME Boiler and Pressure Vessel Code, Section VIII, Div. 2 (2017)
5. ABSA AB 520 Finite Element Analysis (FEA) Requirements Regarding the Use of FEA to Support Pressure Equipment Design Submission (2009)

Assumptions

To perform the fitness-for-service assessment, several assumptions were made that were supported by the inspection documentation. The major assumptions were:

- The tanks were built in accordance with the available drawings.
- The material properties of the tank corresponded to the

Figure 1. Overview of the tank farm.

Figure 2. Gap between tank floor and supporting mat.

Figure 3. Same as Figure 2: closer view.

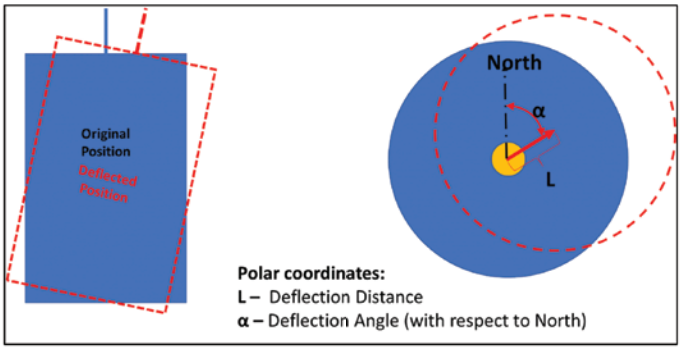


Figure 4. Tank deflections determined using laser scan

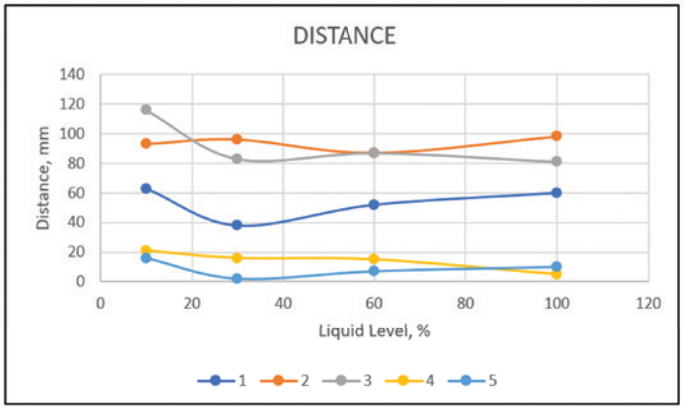


Figure 5. Deflection Distance vs. Liquid Level. (Deflection Distance: Length of the Deflection Vector Between the Reference Point [Vertical Position] and Roof Tip)

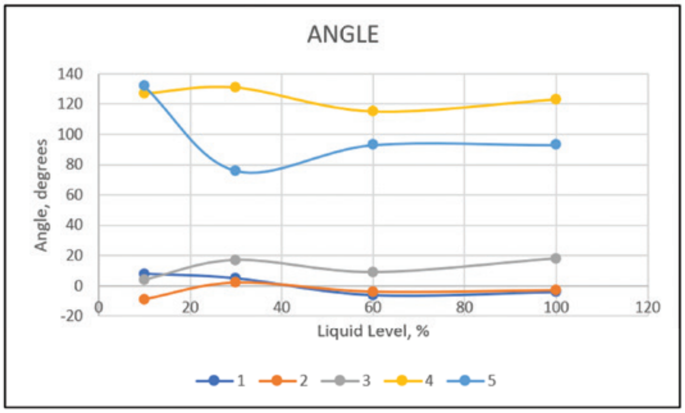


Figure 6. Deflection Angle vs. Liquid Level. (Deflection Angle: Angle of the Deflection Vector with Respect to the North Direction)

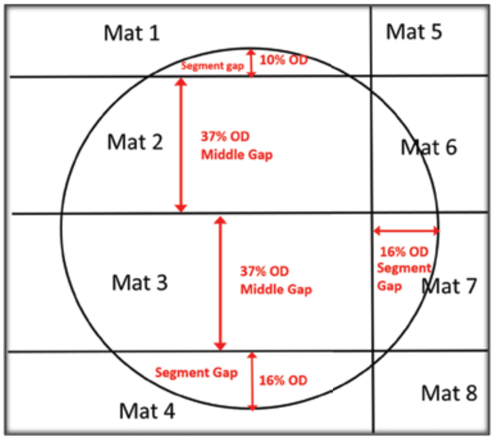


Figure 7. Positioning of One Tank on Rig Mats. Locations of Possible Support Gaps are Identified.

Table 1. Applied Loads and Constraints

Parameter	Load/Constraint	Applied To
Internal Pressure	Load	Shell, roof, floor, nozzles, blind flanges
Gravity Load	Load	All parts
Hydrostatic Head	Load	Floor, shell, shell nozzles, and blind flanges below liquid level
External Pressure (Internal Vacuum)	Load	Shell, roof, floor, nozzles, blind flanges
Fixed Points	Load	Tanks floors

Table 2. Properties of Tank and Nozzle Materials

Parameter Material	Yield Stress, SMYS, MPa	Tensile Stress, SMUT, MPa	Maximum Allowable Membrane Stress Sm away from Discontinuities, ksi		API 579 Maximum Allowable Combined Stress close to Discontinuities 0.8*3Sm, ksi
			ASME BPVC.II.D Microbial Favorable	API 650	
Nozzles: ASTM A106 Gr. B	35 min	60 min	17.1	N/A	17.1*3*0.8=41.0
Shell/Floor: CSA G40.21-44W	44 min	65 min	18.6	25.6	18.6*3*0.8=44.6

Table 3. Comparison of Load Cases (100% Support)

Load Case	Internal Pressure	Vacuum	Liquid level	Gravity	Result
LC1	16 oz	N/A	0	Applied	Acceptable
LC2	0	0	100%	Applied	Acceptable
LC3 (Worst Case)	16 oz	N/A	100%	Applied	Acceptable
LC4A - Stress	N/A	0.4 oz	0	Applied	Acceptable
LC4B - Buckling	N/A	0.4 oz	0	Applied	Acceptable

minimum specified properties of the materials used for construction.

- Tank materials did not experience environmental degradation. The tanks were in sweet service and not exposed to H_2S.
- Tanks contained no crack-like flaws or other unacceptable defects and were not affected by localized corrosion.
- As tanks were assumed to be crack-free, with limited numbers of fill cycles, fatigue mode of failure was not considered.
- Tank welds were introduced using appropriate welding procedures and were adequate.
- Tank welds were not radiographed, and their weld efficiency was taken as 0.8.
- Tanks were filled with produced water (relative density=1.2).
- Several support conditions were addressed (see **Figure 7**):
  - Full uniform support
  - Uniform support, except for one 16% segment
  - Uniform support, except for the 10% segment
  - Uniform support, except for peripheral gaps for each individual tank.
- Tank gaps were modeled as unsupported areas. It was assumed that except for gaps, the remaining part of the tank floor is flat and fully supported.

Loads and Constraints

Table 1 shows an overview of loads and constraints used in the assessment.

Materials Properties and Acceptance Criteria

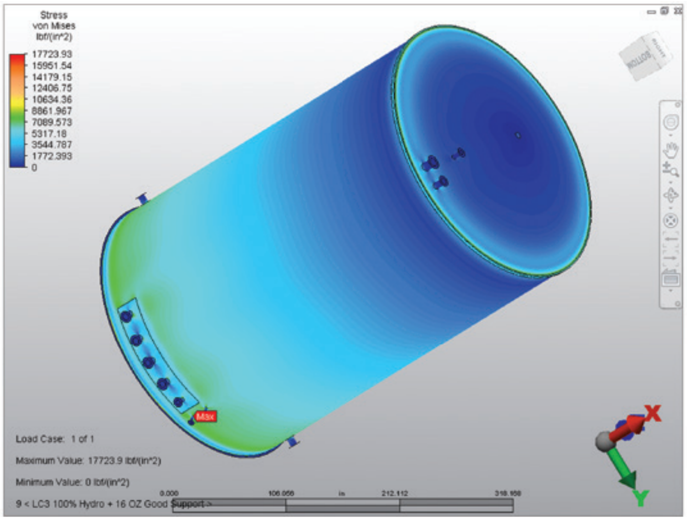
The following tank components were addressed in this assessment: the shell, the roof, the floor, and the major nozzles. **Table 2** shows the mechanical properties of the tank construction material and allowable stresses.

The following acceptance criteria were considered applicable to the shells/floors of tanks in question:

1. Shell, roof, and floor away from nozzles, discontinuities, and changes in support conditions: Pm ≤ 25.6*0.8 = 20.5 ksi (API 650).
2. Shell, roof, and floor close to discontinuities and changes in support conditions: PL+PB+Q ≤ 2.4 S = 18.6*2.4=44.6 ksi (API 579, not addressed by API 650).

Finite Element Analysis

The tank was modeled using a linear elastic finite element analysis (FEA) approach, and a 3D model of the tank was created using shell elements. Step 1 in the FEA calculations to confirm the model validity was a design check when the floor was fully supported. Four load cases that were combinations of different loads were considered. The load combinations are shown in **Table 3**.



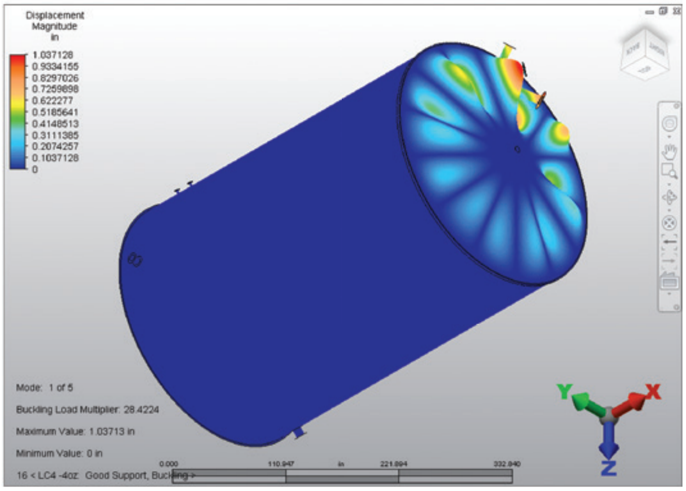
Load Case: 1 of 1

Maximum Value: 17723.9 lbf/(in^2)

Minimum Value: 0 lbf/(in^2)

9 < LC3 100% Hydro + 16 OZ Good Support >

Figure 8. Stress Distribution for LC3: Acceptable



Mode: 1 of 5

Buckling Load Multiplier: 28.4224

Maximum Value: 1.03713 in

Minimum Value: 0 in

16 < LC4 -4oz Good Support, Buckling >

Figure 9. Buckling Load for LC4B: Acceptable

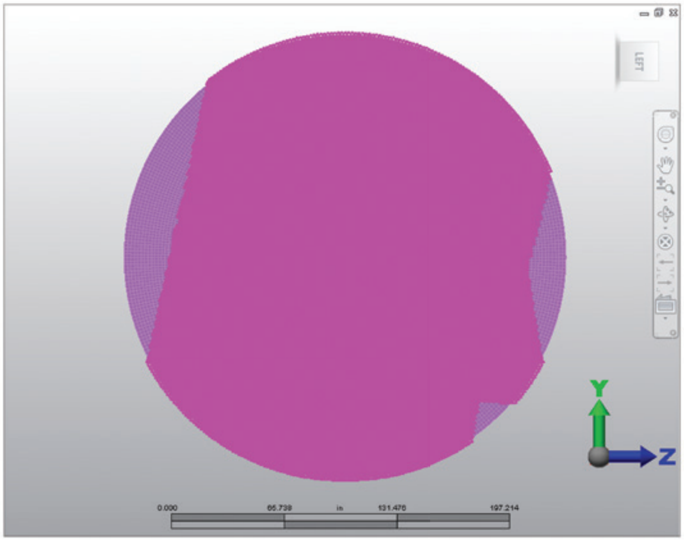
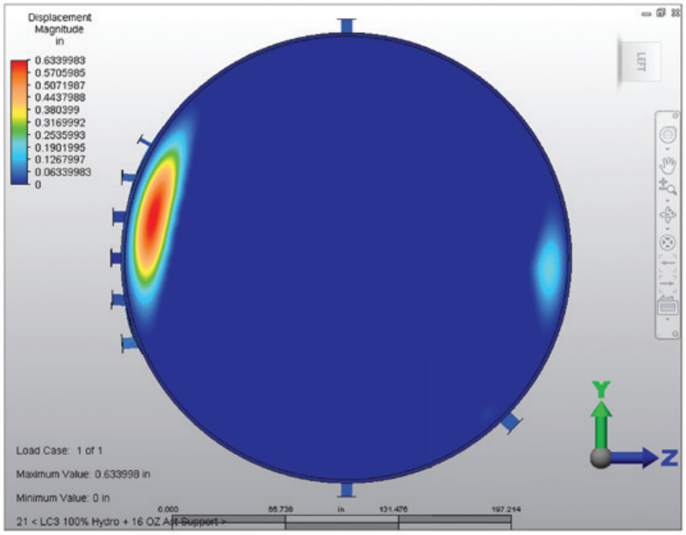


Figure 10. Support Condition for Tank 1 at 100% Liquid Level



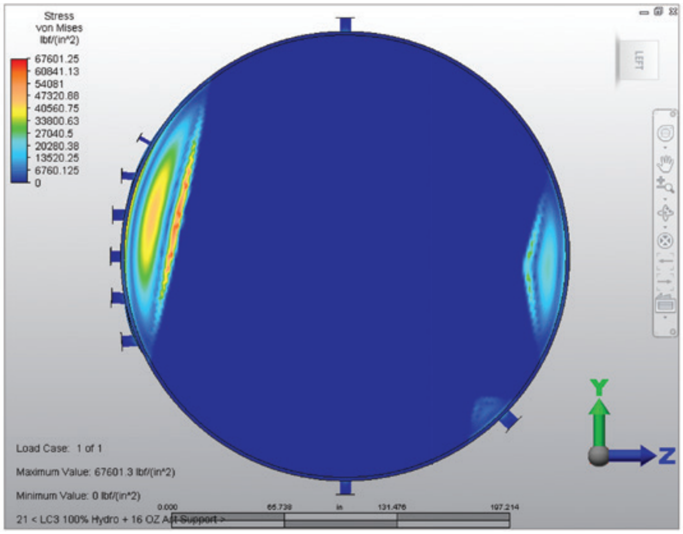
Load Case: 1 of 1

Maximum Value: 0.633998 in

Minimum Value: 0 in

21 < LC3 100% Hydro + 16 OZ Act Support >

Figure 11. Displacement Distribution in Tank 1 at 100% Liquid Level



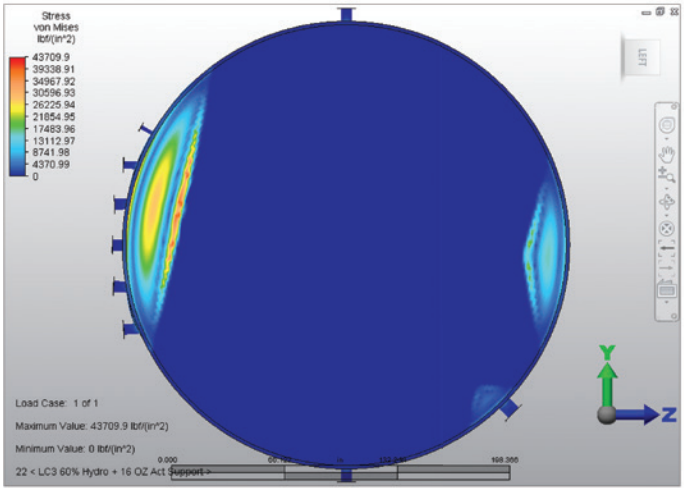
Load Case: 1 of 1

Maximum Value: 67601.3 lbf/(in^2)

Minimum Value: 0 lbf/(in^2)

21 < LC3 100% Hydro + 16 OZ Act Support >

Figure 12. Stress Distribution in Tank 1 at 100% Liquid Level: Not Acceptable



Load Case: 1 of 1

Maximum Value: 43709.9 lbf/(in^2)

Minimum Value: 0 lbf/(in^2)

22 < LC3 60% Hydro + 16 OZ Act Support >

Figure 13. Stress Distribution in Tank 1 at 100% Liquid Level: Not Acceptable

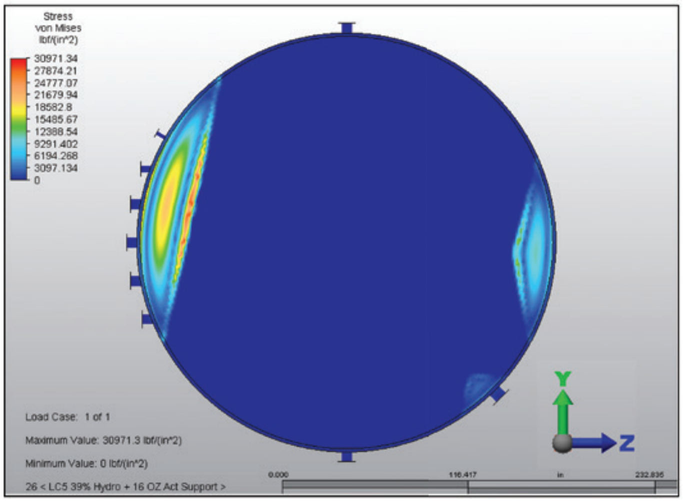


Figure 14. Stress Distribution in Tank 1 at 39% Liquid Level: Acceptable

Figures 8 and **9** show two examples of the results of FEA calculation (stress distribution) for LC3 and LC4B.

The maximum stresses and the acceptance criteria are shown in **Table 4**.

Table 4. Maximum Stress and Acceptance Criteria: Linear Material Model (100% Support)

Load Case	Max. Stress Away From Discontinuities (API 650), ksi			Max. Stress Close To Discontinuities (API 579), ksi		
	P_m+P_b	S_{All} API 650	Note	P_L+P_b+Q	2.4 S_m	Note
LC1	<11.6	25.6	PASS	11.7	44.6	PASS
LC2	<17.4	25.6	PASS	17.4	44.6	PASS
LC3	<17.7	25.6	PASS	17.7	44.6	PASS
LC4A - Stress	<1.7	25.6	PASS	1.7	44.6	PASS

The examination of the results of FEA calculations and **Table 4** show that:

- The highest stress was observed at the roof-to-shell connection and around nozzles.
- Accounting for hydrostatic pressure increases the stress at the bottom part of the shell; the highest stress at the roof-to-shell connection is still practically unchanged.
- Stresses were acceptable for all considered load cases.
- LC3 was the most critical load case, where the maximum stress was observed (i.e., when both the hydrostatic pressure (100% liquid level tank) and the internal pressure of 16 oz were applied).

LC3 was selected as the most critical load case for FEA calculations of stress in tanks that are not fully supported.

Each tank was then modeled using the actual tank gap geometries as found during the inspections. It was found that each tank contained several peripheral gaps. The gaps were modeled as unsupported areas. Each tank was modeled under different liquid fill levels, namely, 30%, 60%, and 100%. An example of the modeling for one of the tanks (Tank 1) is provided in this section.

Figure 10 shows support conditions of Tank 1 with 100% liquid level. **Figures 11** and **12** show the floor displacement and stress distribution at 100% liquid level. **Figures 13** and **14** show the stress distribution at 60% and 39% liquid levels.

Table 5 compares the results of FEA calculations for Tank 1. The calculations showed that for the gaps shown in **Figure 11**, stresses in static conditions for Tank 1 are acceptable at the liquid level of 39%.

Table 5. Tank 1 Maximum Stress in Different Areas vs Liquid Level

Location	100% Liquid Level	60% Liquid Level	39% Liquid Level	$S_{ALLOWABLE,}$ ksi
Shell-to-Floor	67.6	43.7	31.0	44.6
Support End	61.9	39.8	28.4	44.6
Mid-Gap	43.9	28.4	20.1	20.5

Note: Not acceptable stress values are shown in red.

A similar approach was used to assess all tanks with different geometry of supported area, and the acceptable liquid levels were calculated for each tank.

Table 6 shows the allowable fill level of tanks in static condition, that was calculated within assumptions of this report and based on the shape of peripheral gaps determined by visual inspection. It was also recommended to reduce the number of liquid level variations and internal pressure variations to reduce the likelihood of dynamic failure mechanisms until the owner can remediate the foundation instability.

Table 6. Allowable Fill Level of Tanks in Static Condition

Tank	Allowable Liquid Level %	Tank	Allowable Liquid Level %
0	68%	6	57%
1	39%	7	71%
2	60%	8	100%
3	100%	9	39%
4	56%	0	100%

Conclusion

Tanks with imperfect foundations were modeled using finite element analysis and assessed for continued service using API 579/ASME FFS-1. The maximum liquid fill level allowed for each tank was calculated to ensure the owner-operator can safely operate these tanks until the next shutdown when the foundation issues can be resolved. ■

For more information on this subject or the author, please email us at inquiries@inspectioneering.com.

CONTRIBUTING AUTHORS

Arash Ilbagi

Arash has a doctorate in Materials Science and Engineering and has assisted many organizations in the development of their pipeline and pressure equipment integrity management programs. Arash has extensive experience in the assessment of suitability of pipelines for their intended service.

Alex Tatarov

As a former university professor of physics, Alex has a solid background in materials and physics which assures successful solving of various technical problems. His area of expertise includes Failure Analysis, X-ray Diffraction, Mechanical Testing, Corrosion Testing and Evaluation, Fracture Mechanics, Finite Element Analysis, Fitness-for-Service Assessment, and Expert Witnessing for litigation. Alex has over 30 years of experience in failure analysis of oilfield equipment.