Application of VVUQ Concepts to ASME Codes and Standards for Pressure Vessels
VVS2023-108506

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“Program managers need assurance that computational models of engineered systems are sufficiently accurate to support programmatic decisions. This Standard provides the technical community — engineers, scientists, and program managers — with guidelines for assessing the credibility of computational solid mechanics (CSM) models.

Verification and Validation (V&V) are the processes by which evidence is gathered to determine the accuracy of the computer model for specified conditions. These accuracy results, along with uncertainty quantification (UQ), contribute to the determination of the credibility of the model for the conditions of its intended use.” (VVUQ10, EXSUM)

How does this not apply to all engineering uses of CSM models?
If engineering work is on a spectrum from the unknown of “theoretical research” to the well established “traditional engineering” using codified design, then Verification, Validation, and Uncertainty Quantification (VVUQ) goes from a detailed problem-solving explicit effort to a shortened codified implicit series of design checks.

**VVUQ efforts increase with uncertainty and consequence.**

This paper establishes the basis for pressure vessel designer, working outwards from well-established deterministic codes, for requiring adding VVUQ measures based on uncertainty and risk.
Introduction

Design By Analysis Framework using PVHO-1, BPVC, V&V10

**START:** User Design Specification (UDS), Risk Assessment with FMEA

**SIMULATION** → "Section VIII"
- Based on UDS, select methods, initial design, literature values for materials, conduct initial FMEA
- Analyze initial design, including implicit nonlinear Finite Element Analysis for stochastic range of variables. Diagnose critical areas.
- Update analysis using experimental material data. Inputs for Design of Experiment (DoE) for prototype.

**EXPERIMENT** → "Section II"
- Based on UDS, select initial materials and test methods. Establish QA and tolerances.
- Analyze materials stochastically for use in implicit nonlinear FEA. Develop DoE for prototype test
- Update testing based on analysis results, implement for key variables, locations, conditions.

**END:** Self-contained, fully documented design with calculations, validation tests, and data. Suitable for Authorized Inspector review.

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Traditional VVUQ

- Requires methodical use of experiments, theory, and simulation
- ID’s irreducible (aleatory) v reducible (epistemic) uncertainty
- Intended to inform managers of risks in project to assess time/resources
- Often for high consequence or extraordinary novelty
- Detailed, time consuming, and therefore expensive
It’s a spectrum

- In experimental work, VVUQ quantifies equipment uncertainty.
- Cutting-edge engineering needs to examine materials, structures, joints, loads, restraints because the solution is not codified.
- Engineering requirements become codified as the field matures, reducing explicit VVUQ requirements (consequences permitting).
Pressure Vessel Code

- Progressive improvements through distributed research and testing, findings added to code over years
- Thin wall (membrane) assumptions
- Established material properties, joining procedures, limits on geometry – results all within “design limits”
- Materials require mill testing to verify properties, hydrotesting, nondestructive testing goes to design margin for joints – “experiments” are now quality verification following specific standards
- Welders, facilities, inspectors must have certificates, design review by Professional Engineer
Pressure Vessel Code

ASME BPVC Section VIII, Div. 2, Part 5, “Design By Analysis” (also API 579/ASME FFS1)

Complete system (white oval)

Specifies:

- Types of FEM analyses permitted
- Material properties, curves at temp
- Service condition (corrosion, fatigue, etc.)
- Load combinations for different analyses
- NDT, system testing requirements

Within limits of Part 5, solution verification is still highly prudent, but not currently required.
Acrylics in PVHOs

Example of design info in ASME “Safety Standard for Pressure Vessels for Human Occupancy” (PVHO1). Shapes, design tables established in late 1960’s through US Navy testing.
BPVC design margins v. PVHO

<table>
<thead>
<tr>
<th>ASME BPVC, Section VIII</th>
<th>Tensile Margin</th>
<th>Yield Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Division 1</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Division 2, Class 1</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Division 2, Class 2</td>
<td>2.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Barkley, N., "A General Comparison of the Design Margins and Design Rules for ASME Section VIII, Divisions 1 and 2"

Assumptions for design margins:
- Thin wall pressure vessel
- Internal Pressure
- Failure mode is tensile
- Design based on material minimums
- Materials are tested to designated alloy and grade specification
- Has specified “elongation at break” which is in plastic range

PVHO-1 design process:
- Set design pressure (P) and temperature (T)
- Look up Conversion Factor (CF) for temp, shape
- CF*P = Short Term Crit. Pressure (STCP)
- Look up design charge for geometry to get ratio of window thickness (t) to inner diameter (D_i)
- DOES NOT USE MECHANICAL PROPERTIES

Assumptions for PVHO-1
- **STCP = failure of window at temperature**
- Pressure is internal or external
- Thin and thick wall pressure vessel design = same
- Single set of material specifications (no grades)
- Material specifications are not used in design
- No use of FEM or other calculations considered
- Minimum “elongation at break” is less than strain at yield – perfectly brittle, no toughness
- No consideration for service (offshore v hospital)
Is the CF the design margin?

\[ P = 27.6 \text{ MPa psi} @ 10^\circ C, 24^\circ C \ (50F, 75F) \text{ for a conical frustum} \]

@10°C STCP 5= \( P \times CF = 27.6 \text{ MPa} \times 5 = 110.4 \text{ MPa} \)
@24°C STCP 6= \( P \times CF = 27.6 \text{ MPa} \times 6 = 138.0 \text{ MPa} \)

<table>
<thead>
<tr>
<th>CF</th>
<th>Difference</th>
<th>( P ) (MPa)</th>
<th>( t/D_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Difference 1 to 5</td>
<td>27.6</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>Difference 1 to 6</td>
<td>110.4</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>Increase 5 to 6</td>
<td>138.0</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Increase in \( t/D_i \) is not proportional to increase in pressure, nor constant due to being on curve.

Design margin to failure does not follow conventional pressure vessel relationships.

Not a tensile failure. Original developers rejected FEM due to experimental failure.
Need for Design by Analysis

First order effects
Expands window design for PVHOs
Reduces the need for window-specific code cases, speeding innovation
Method for conventional pressure vessels to innovate in other industries
Potential to optimize for risk, uncertainty

Second order effects
Potential for expanding “fitness for service” methods to windows (PVHO-2)
Provides a comprehensive structural design methods for glassy polymers
Can be adapted for ROV/AUS optics to aquaria to aerospace windows (NASA) to protective structures

System will be written “for glassy polymers”, not restricted to PVHO. Given there are no engineering code calculations based on properties, it’s either “PVHO-1” or DBA with VVUQ. Dashed white oval illustrates the concept DBA encompassing the PVHO1 design code, but limits are still in development.
Need for new code (innovation)

Developments in medical hyperbarics and submarine

Crewed space systems are switching glass to acrylics

Non-PVHO pressure vessels for liquid chromatography
Need for new code (safety)

Store front signage failure, falling to ground and missing shoppers. OEM specifications did not extend to hurricane winds. (2022)

Aquarium failure in Berlin, Germany (Dec. 2022)
Design by Analysis

Starting point
User’s Design Specification (UDS). This will require detailed guidelines in order to frame the process correctly. Originates with system designer, includes full viewport design. Not limited to PVHO. Risk drives design margins, tolerances.

End point
PVHO Form GR-1 or variant. It will document explicitly how the window meets the UDS. Lead document for the full engineering package.

CHALLENGE: Developing the “punchlist” for UDS. Assess what must be delivered vs. confidential and still avoid need for code case.
Simulation Prong  
Replaces “Section VIII, Div. 2”  

- Based on UDS, select methods, initial design, literature values for materials, conduct initial Failure Means & Effects Analysis (FMEA).
- Analyze initial design, including implicit nonlinear FEA for range of variables. Diagnose critical areas.
- Update analysis using experimental material data. Inputs for Design of Experiment (DoE) for prototype.

CHALLENGE: Design margin criteria, dimensional tolerances, variables for stochastic analysis, analysis methods.

V&V guides the process. Use verified tools, validate the results. “Stochastic” addresses “uncertainty management”, where a range of variables is solved to ensure the design parameter set is reliable. Labs can have smaller range than working arctic-to-tropic ocean environments.
Polymer and window manufacturers should be held to the same due diligence as alloy manufacturers & fabricators, which allows for a degree of “trade secrets.” The key aspect is sufficient data to support the engineering report. Must advise regarding maintenance, installation hazards.

Experiment Prong
Replaces “Section II”

- Based on UDS, select initial materials and test methods. Ensure testing range satisfies UDS. Establish QA, tolerances, incl. stochastic methods
- Analyze materials for use in implicit nonlinear FEA. Develop specs for DoE for prototype for analysis.
- Update testing based on analysis results, implement DoE for prototype for key variables, locations, conditions.

CHALLENGE: Literature vs experiment criteria, requirements for: QA, statistical data, reporting, install & maintainance
Summary

- The need for VVUQ increases with uncertainty, novelty, and consequence, “cutting edge engineering”
- “Traditional engineering” areas has been codified over time, making the VVUQ aspects implicit requirements
- Traditional or “full VVUQ” is costly and time intensive
- ASME Pressure Vessel Code provides a full solution set for using Finite Element Analysis for Design By Analysis
- As uncertainty, novelty, or consequences increases, some form of VVUQ is needed to mitigate risk.
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References


[12] Sudret, B., and Der Kiureghian, A., 2000, Stochastic finite element methods and reliability: a state-of-the-art report, Department of Civil and Environmental Engineering, University of California


References


Conical Frustums: Testing

Two types of viewports, axisymmetric cross section. Blue is the acrylic conical frustrum window. Acrylic deforms under pressure and seals gaps with metal seat as pressure increases. This is the only PVHO viewport without a bearing gasket.

Testing above 69 MPa (10 ksi) using a naval gun shell casing. The “high pressure” side is downwards, a follower measures deflection upwards on the “low pressure” (ambient) side. Silicone lubricant paste held window in place during installation, also reduced friction.
Conical Frustums: FEA Models

A 90 degree, 25.4mm (1.0 inch) diameter low pressure face, 12.2mm (0.5 inch) thick. All models are using the same material curve (Snoey, 1970) for acrylic window. The newer “window only” model has the same loads and restraints as the original analysis range as well as the physical testing its compared to.

A window seat is modeled as alloy steel. Contact elements allows the face to deform against the seat as well as lift off. A positive angle is a gap at the bottom, as shown. Angles and friction varied.
Conical Frustums: Results

• Per previous slides, the variance in measured deflection is consistent with likely minute misalignments and imperfections. Future testing will use modern measurement methods.
• The error was in the comparing perfectly aligned models constrained to a perfect surface to imprecisely installed small test items.
• Like many nonlinear results, strain is more indicative than stress.
• Analyzing reported test items failing in a less than 200 cycles shows that a single implicit nonlinear FEA analyses that loads and unloads the test item will have residual strains consistent with crack initiation.
• The images to the left shows strain patterns at 50% loading to failure with different angular differences. The variance in strain patterns helps explains the variance in observed failure patterns.
• Implicit nonlinear FEA with contact elements reasonably approximates observed and historical failures.