Evaluation of Agency Non-code Layered Pressure Vessels (LPVs)

Appendices

William H. Prosser/NESC
Langley Research Center, Hampton, Virginia
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Volume II. Appendices

Evaluation of Agency Non-code Layered Pressure Vessels (LPVs)

June 26, 2014
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## Appendix A. Example LPV Procurement Specification

### HRL INVITATION, BID, AND AWARD

- **Supplement Contract**: Order No. (if any) 4-3510
- **Address**: Moffett Field, California

**Sealed bid in quadruplicate, subject to: (1) the Terms and Conditions of the Invitation for Bids, (2) the accompanying Schedule, (3) General Provisions (Standard Form 32, Oct. 1957 edition), which are incorporated herein by reference, and (4) such other contract provisions and specifications as are attached or incorporated by reference in the Schedule, will be received at the above office until 3:00, p.m., February 20, 1961, Time, Moffett Field, California.**

General information and instructions to bidders are contained in the terms and conditions on the reverse hereof.

### SCHEDULE

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>SUPPLIES OR SERVICES</th>
<th>QUANTITY (No. or Units)</th>
<th>UNIT</th>
<th>UNIT PRICE</th>
<th>AMOUNT</th>
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<tbody>
<tr>
<td>1.</td>
<td>PRESSURE VESSEL; Services and Materials</td>
<td>1</td>
<td>Ea.</td>
<td>necessary for the design, fabrication, testing and delivery, P.O.B. Moffett Field, California of a 15,000 PSI gas storage vessel in accordance with Specification A-3510, dated December 16, 1960. (Continued on page 27)</td>
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**In compliance with the above, the undersigned offers and agrees, if this bid is accepted within calendar days (30 calendar days unless a different period is inserted by the bidder) from the date of opening, to furnish any or all of the items upon which prices are quoted, at the prices set opposite each item, delivered at the designated point(s) within the time specified in the Schedule. Discounts will be allowed for prompt payment as follows:**

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<tr>
<th>Discount</th>
<th>Amount</th>
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<td>percent, 1% of contract;</td>
<td>percent, 2% of contract.</td>
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**HIGHER REPRESENTS:** (Check appropriate boxes)

1. That the bid contains a small business concern. (See definition on reverse hereof.)
2. That the bidder is not a small business concern, and the manufacturer of the supplies bid upon, he also represents that all supplies to be furnished hereunder will not be manufactured or produced by a small business concern in the United States, its Territories, its possessions, or the Commonwealth of Puerto Rico.
3. That he is a regular dealer in the manufacturer of the supplies bid upon.
4. That he is an individual, partnership, corporation, incorporated in the State of (Check appropriate boxes, including those "none bid on" the Code of Federal Regulations, Title 10, Title 21."

**PHONE:**

**AWARD**

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<th>AWARD</th>
<th>AMOUNT</th>
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<td>United States of America</td>
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**SUBMIT AVERAGE PAYMENT TO**

National Aeronautics and Space Administration
Moffett Field, Calif.

**PAYMENT WILL BE MADE BY**

[Signature]

Award will be made on this Form, or on Standard Form 26, or by other official written notice.
**CONTINUATION SHEET (SUPPLY CONTRACT)**

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<td>Telegraphic bids will be considered subject to confirmation on these forms. To be considered, confirmation must be received at the Ames Research Center, Moffett Field, California, on or before the close of business five (5) calendar days after the opening date. (MOUNTAIN VIEW, CA, 94043)</td>
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<td>The attached Form ARC 325 is hereby made a part of any contract resulting from this invitation.</td>
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<td>Material specified is needed by the NASA in connection with aeronautical research to promote the national defense. The NASA will extend priority and allocation assistance to the Contractor when applicable.</td>
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<td>Specific information as to articles, materials, and supplies excepted from the Buy American Act is available to prospective contractors upon request to this Research Center.</td>
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**BUY AMERICAN CERTIFICATE**

The bidder or offeror hereby certifies that each end product (as defined in the contract clause entitled Buy American Act); and that components of unknown origin have been considered to have been mined, produced, or manufactured outside the United States.

**EXCLUDED ITEMS:**
National Aeronautics and Space Administration
Moffett Field, California
Specification
For
High Pressure Storage Vessel
For the
Mass-Transfer Cooling and Aerodynamics Facility
Specification No. A-2023 January 29, 1960

Section 1.

1-1 General Description.................. 1
1-2 Scope................................. 1
1-3 Information Required with Bid........ 2
1-4 Time for Completion.................. 3
1-5 Design Conditions...................... 3
1-6 Accessories........................... 4
1-7 Materials............................. 5
1-8 Welding................................. 5
1-9 Radiographic Inspection............... 5
1-10 Stress Relieving....................... 6
1-11 Hydrostatic Testing................... 6
1-12 Cleaning and Painting............... 6
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MOFFETT FIELD, CALIFORNIA
SPECIFICATION
FOR
HIGH PRESSURE STORAGE VESSEL
FOR THE
MASS-TRANSFER COOLING AND AERODYNAMICS FACILITY

Specification No. A-2023 January 29, 1960

Section 1.

1-1 General Description:

(a) This Specification covers the fabrication, radiographic inspection, stress relieving, hydrostatic testing and delivery, F.O.B., Moffett Field, California, of one (1) High Pressure Storage Vessel of one hundred (100) cubic feet capacity (water volume).

(b) The vessel will be used as a receiver and storage vessel for two (2) reciprocating air compressors, compressing atmospheric air to a maximum pressure of 15,000 (fifteen thousand) pounds per square inch.

(c) The vessel will form a permanent component of the Mass Transfer Cooling and Aerodynamics Facility to be constructed at the Ames Research Center of the National Aeronautics and Space Administration.

1-2 Scope:

(a) The Contractor shall furnish all services and materials necessary for the fabrication and delivery of the vessel specified herein and all work incidental thereto, except such materials and services specified as not in contract, furnished by the Government or furnished by others.
Section 1 - Page 2

(b) The Contractor's work includes the following major items:

(1) Engineering and design of the vessel.

(2) Fabrication of the high pressure storage vessel, steel supports and the accessories specified.

(3) Radiographic examination and stress relieving.

(4) Hydrostatic testing at one and one-half (1-1/2) times the maximum operating pressure.

(5) Cleaning and painting of the vessel.

(6) The delivery of the vessel, F.O.B., Moffett Field, California.

(c) The following items will be furnished and installed by others and are not a part of this contract.

(1) All connecting piping and valving.

(2) Reinforced concrete foundations.

(3) Foundation anchor bolts, nuts and lockwashers. Anchor bolts will be set in the foundation concrete by others to the pattern indicated on the Contractor's drawings.

1-3 Information Required with Bid:

(a) The Bidder shall submit the following information with his bid:

(1) Proposed design procedure.

(2) Vessel material specifications.

(3) Estimated weight and physical dimensions.
1-4 **Time for Completion:**

All work specified herein must be completed and delivered within two hundred and fifty (250) days after award of contract.

1-5 **Design Conditions:**

(a) The total air storage capacity shall be a minimum of one hundred (100) actual cubic feet (water capacity) and the vessel shall be designed and constructed for a maximum working pressure of fifteen thousand (15,000) pounds per square inch.

(b) The vessel shall be cylindrical in shape with an internal diameter not less than twenty-four (24) inches.

(c) The temperature of the air in the vessel will vary between the limits of one hundred and twenty-five (125) degrees Fahrenheit maximum and twenty (20) degrees Fahrenheit minimum.

(d) Design and fabrication of the vessel shall conform to one of the following:

(1) The ASME Code for Unfired Pressure Vessels, 1956, with the following exceptions:

   (a) The pressure limitations stated therein shall not apply.

   (b) The provisions covered by Code Interpretations Case 1205-3, shall apply.

(2) A.O. Smith Corporation's specification MLS-30A and A.O. Smith Corporation's specification dated August 27, 1957 for multi-layer construction vessels above three thousand (3000) psi with the following additional provisions:
The shell thickness shall be determined by the Lame\'s formula using a longitudinal joint efficiency specified by the ASME Code.

(e) The maximum allowable stress value shall be determined from one of the following:

(1) The minimum tensile strength using a safety factor of three (3).

(2) The minimum yield strength using a safety factor of two (2); provided that the yield-strength ratio does not exceed sixty-five (65) percent.

(3) No corrosion allowance is required.

1-6 **Accessories:**

(a) The storage vessel shall be furnished with the following accessories:

(1) One 2-3/4 inch O.D., 3/4-inch I.D. welding nipple welded on center to one (1) head and extending twelve (12) inches.

(2) One 2-3/4 inch O.D., 3/4-inch I.D. welding nipple welded on center to the opposite head, and extending twelve (12) inches.

(3) One (1) 1-inch drain connection with removable plug.

(4) The vessel shall be supported by means of saddles or equivalent leg supports and such other reinforcement as may be necessary to prevent excessive stresses in the shell. The saddle supports or legs shall extend a minimum of twelve (12) inches from the outer diameter of the vessel.
Section 1 - Page 5

1-7 Materials:

(a) The steel selected for fabrication of the vessel does not necessarily have to be in strict accordance with the requirements of the ASME Code. However, the Bidder shall state, in his bid, the chemical composition, physical properties and suitability of the steel selected for fabrication. Suitability of the material used will be subject to approval by the Contracting Officer.

(b) All pipe welding nipples shall be Seamless AISI 1015-1020, mechanical steel tubing, or equal.

(c) All structural steel shapes and plates used for the supports shall be ASTM-A7, or equal, for general structural purposes.

1-8 Welding:

(a) All welding shall be done in conformance with the ASME Code. The appropriate sections pertaining to Welder Procedure Qualifications, Welder Qualifications and Test Plates shall apply.

(b) All welding shall be continually supervised by a competent welding supervisor fully qualified by experience and ability to oversee and direct all phases of the welding.

(c) The Contracting Officer reserves the right to have his observer present during any welding and to require proof of welder qualification and test plates.

1-9 Radiographic Inspection:

(a) A radiographic examination shall be made of all welds in accordance with the requirements and techniques of the ASME Code except for the laminated vessel in which only the longitudinal and circumferential welds of the inner shell and heads shall be radiographed.
Section 1 - Page 6

(b) In lieu of a radiographic examination of the circumferential head welds of the laminated vessel, a hydrostatic pressure test which will stress these welds circumferentially to a unit stress equal to a ninety percent (90%) of the specified minimum yield point of the inner shell material may be substituted.

1-10 Stress Relieving:

(a) Full stress relieving of the vessel shall be conducted in strict conformance with the ASME Code.

(b) Stress relieving of only the inner shell and head assemblies is required of the laminated vessel.

1-11 Hydrostatic Testing:

A hydrostatic pressure test shall be conducted on the completed vessel. Test pressure shall be 22,500-pounds (twenty-two thousand five hundred) per square inch for a period of time not less than 1.0 hours.

1-12 Cleaning and Painting:

After the hydrostatic test of the vessel is satisfactorily completed, the vessel shall be thoroughly cleaned and painted as described below:

(a) Interior Surfaces:

The interior surfaces of the vessel shall be cleaned by flushing with a twenty percent (20%) solution of Oskite No. 131 or equivalent. The water and chemical solution shall be circulated within the vessel for a minimum of four (4) hours at a temperature recommended by the manufacturer. The vessel shall then be purged with fresh water until the concentration has dropped to below one percent (1%); Oskite Number 98, or equivalent, will then be circulated within the vessel for a length
of time and at a temperature and concentration recommended by the manufacturer. The vessel will then be drained and hot air circulated to evaporate all remaining moisture. Undiluted Oakite Special Protective Oil, or equivalent, will then be circulated within the vessel and then drained and dried by circulating warm air. The vessel will then be sealed to prevent the entrance of dirt and moisture. Alternate cleaners and rust inhibitors are subject to approval by the Contracting Officer.

If the Contractor uses a stainless inner-liner or cladding, the above mentioned interior surface treatment may be deleted.

(b) Exterior Surfaces:

The vessel exterior surfaces shall be thoroughly cleaned of all rust, scale, dirt, grease, etc., by appropriate means and then given one (1) coat of paint. The paint shall be a first coat primer fully equal to Valdura 951 Metal Primer-Yellow, as manufactured by the American Marietta Company, Chicago, Illinois.
Appendix B. Center Request for Information (RFI) Summaries

Ames Research Center (ARC)

Layered, Non-Code Pressure Vessel Request for Information

Ames Research Center / D. Fraser

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

Sixteen large (1750 cf) AO Smith 5 ft ID x 2.65" t x 86'-8.75" shell L + solid hemispherical heads. Shell layers are 1146a nominal ¼"and solid heads are A-225B 2.5" thick. Nozzles are V5002 and 304 SS (6" discharge). Installed mid 1980s as surplus from Jackass Flats. Nameplate rating 3500 psi, ARC MAWP is 3150 psig which is an F.S. of 2.8 on specific minimum tensile strength of AOS 1146a shell plate. Dry compressed air only. Vessels are behind a 15 ft. earthen berm as risk mitigation.

One 15,000 psi AO Smith being used as instrument air reservoir at 135 psig, excluded as negligible risk.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

16 AO Smiths were previously assessed and are in service. We need to decide whether we should keep doing AE, or switch to some other viable alternative (perhaps phased array for the head to shell welds?) No known relevant or active growing defects.

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

Inactive Vessels: 1 large CB&I (2400 ft³ volume) + several Kaiser m/l vessels each about 50 ft³.

2. History of NDE or other inspections/analyses related to continued usage.

RT of both head-to-shell welds and two nozzles in mid-1980s, plus MT & PT of inner & outer surface of all welds. 31 repairs performed on 10 vessels. One shell to shell weld RT'ed later on each vessel with film laid lengthwise to achieve 1% coverage of long welds based on Mike Hudson recommendation. UT performed on nozzles and heads. Many indications from MT and new RT, some indications not repaired. Vessels were hydrotested to 4950 psig in September 1987. Internal coating made later 2/99 internal inspections of circ & long welds problematic and ineffective. Periodic external VT, MT & PT performed in 1998 on all vessels, no findings. 2/99 internal inspections of nozzles of 4 vessels, no findings. 7/02 internal inspections of remaining 12 vessels...
vessels, including coating removal for full weld inspections, no findings. Detailed inspection history and reports are available if needed and useful.

Monpac AE and DWC MAE performed on vessel #12 in 2001. MAE selected and performed on all vessels in 2002 and 2009, including an attempted Hal Dunnegan demonstration in 2002. Additional MAE calibrations were performed in the summer of 2011.

Fracture analyses indicate minimum 1200 cycles for crack propagation to critical size after 10% overpressure, but many assumptions are made in arriving at this, and better analyses are required. Previous Aptec fracture analysis indicated 12,000 or 22,000 full pressure safe cycles, depending on the material properties and initial crack assumptions made, based on the 1.5x hydrotest.

Complete diameter measurements were taken on all vessels at zero and 3000 psi this past December and January for the purpose of performing ASME gap effectiveness measurements per part ULW, although the analyses have not been performed yet.

2a. Description of inspection/analysis methods, schedule, etc.

See above. Also, we do not have any Charpy impact or any other actual material test data for the material in these specific vessels.

2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

All inspection records including RT film are available. All MAE raw data is available and can be run on DWC WaveExplorer software.

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

Same as above, reports available, but interpretation of layer wash on RT likely lead to significant overestimation of actual flaw conditions.

3. Any currently used additional risk mitigation approaches (e.g., special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)

Earth berm 15 ft high is primary protection for casual passers-by. Will protect for approximately 30 deg. Vessel liftoff due to head separation failure. MAE is scheduled for 6 – 7 year intervals (based on nominal 50 full pressure cycles per year) is the current approach. Frequent walk-throughs by operators for anything unusual, including leaks.
4. Any risk mitigation approaches used in the past, but no longer practiced

Monpac AE was considered and baselined, but rejected in 2001. MAWP pressure was lowered in 2001 from 3300 to 2000 briefly, but significant impact to UPWT operations lead to establishment of 3150 psi as the certified pressure based on MAE inspections and overpressure as documented by Waiver.

5. Any risk mitigation approaches under testing, development, or evaluation
(provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

SWRI material testing to establish high confidence material properties including fracture properties for 1146a and A225B is ongoing, scheduled for completion in July 2013. Phase 1 report issued, more extensive phase 2 testing is in progress.

Cyclic testing performed by DWC in 2011 – 2012 to validate MAE, but marginal results for the machined shell crack were not satisfactory for full validation. A more realistic pre-crack location and geometry are believed necessary to fully validate the approach.

SWRI was previously asked to develop a phased array demonstration/qualification proposal for head to shell welds, which was submitted several months ago. Not action has been taken.

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

Follow up full scale cyclic testing to validate AE methods on m/l vessels is needed. Lead breaks are not adequate due to energy content, and are not validation of any method.

If Phased array UT can be used to inspect circ welds, it must be demonstrated, qualified, calibration standards developed, and procedures developed for the benefit of all Centers.

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.

The thick heads of A225 have shown significant variability in properties in past testing, and what exists on each unique installation may need to be
tested, rather than using generic material properties. Calculated MDMT for 2.5" heads in 108 F per current UCS-66.

The past Charpy U-notch or keyhole impact test data has unknown relevance to ASME acceptance standards or current fracture toughness methodologies. It is used as the basis of qualification of many vessels today, but is of unknown value. Correlations must be developed between V-notch as these old methods if possible, which is not a certainty.

ASME Div. 2 is not a valid rating basis for any m/l vessel that pre-dates the Code and was not fabricated to ALL Div. 2 requirements. Showing that basic stresses meet Div. 2 limits is not sufficient risk mitigation in and of itself, and vessels so certified are likely being used under a false sense of safety.

There was an actual failure of a m/l vessel in 2010 where the head separated from the shell. Whatever we do needs to address this failure mode to the best of our abilities. Previous failures seemed to involve cold operating conditions, and this must also be adequately considered with our A225 thick heads and full thickness circ welds.

8. Communications route to Center management on perceived global and specific vessel risks. (Gentz to clarify?)

ARC approved a waiver in 2002 for continued operation of the AOS vessels for the conditions described above. The vessels are certified on the basis of that waiver, and there have been no incidents, so current Center awareness beyond the Owner directorate is not high. The Waiver process as per NASA STD 8719.17A is the specified and appropriate way of communicating elevated risk to the Center, but it has been 11 years since this was done for these vessels, although conditions have not fundamentally changed, and the current Director is not usually asked to review risk decisions made by his predecessors.

Doug Fraser
ARC PSM
4/21/13
Updated 5/13/13
# Evaluation of Agency Non-code LPVs

<table>
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<tr>
<th>Manufacturer</th>
<th>Location</th>
<th>Vessel ID</th>
<th>Service Media</th>
<th>Nameplate Rating (PSI)</th>
<th>Center's Design Pressure (PSI)</th>
<th>Operating Pressure (PSI)</th>
<th>Water Volume (ft³)</th>
<th>Age (yr)</th>
<th>Wall thickness (shell, total nominal, in.)</th>
<th>Number of Shell layers and thicknesses (nominal, in.)</th>
<th>Shell Materials of construction</th>
<th>Head thickness (total, in.)</th>
<th>Number of Head layers and thicknesses</th>
<th>Head Materials of construction</th>
<th>Comments (general condition, vessel history, known flaws, etc.)</th>
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<tbody>
<tr>
<td>AO Smith</td>
<td>ARC</td>
<td>MV-50527-1</td>
<td>Air</td>
<td>3500</td>
<td>3150</td>
<td>3000</td>
<td>1750</td>
<td>53</td>
<td>2.635</td>
<td>8 - 0.267, 1 - 0.500</td>
<td>AOS 1146a</td>
<td>2.5</td>
<td>1</td>
<td>A-225 Gr. B FBQ</td>
<td>No known relevant flaws remain. Installed at ARC mid 1980's, rehydrotested, inspected &amp; weld repairs made.</td>
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<td>53</td>
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<td>22 - 0.265, 12 - 265</td>
<td>AOS 1146a</td>
<td>6.5</td>
<td>1</td>
<td>A-225 Gr. B FBQ</td>
<td>In instrument air service, excluded as negligible assessed hazard.</td>
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<td>n/a</td>
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<td>54</td>
<td>3.125</td>
<td>12 - 25</td>
<td>AOS 1146a</td>
<td>2.5</td>
<td>1</td>
<td>A-225 Gr. B FBQ</td>
<td>Spare for cyclic tests at DWC in 2012, not in service.</td>
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<tr>
<td>CB&amp;I</td>
<td>ARC</td>
<td>M232</td>
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<td>n/a</td>
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<td>47</td>
<td>5.4</td>
<td>18 (est) - 25</td>
<td>CBI 1146 (1143 inner)</td>
<td>3.625</td>
<td>1</td>
<td>A-335 Gr. B FBX</td>
<td>Hydrotested 1986 at 4950-psig after NDE &amp; weld repairs.</td>
</tr>
</tbody>
</table>
Glenn Research Center (GRC)

**GRC Layered, Non-Code Pressure Vessel Information**

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

   M/L Vessel listing with detail information is included as Attachment A. In general, the inventory consists mostly of AO Smith vessels manufactured between 1958 – 1962, typically operated at pressures of 2200 – 3000 psig, and ranging in size from 50 to 830 cubic feet. Vessel materials are typically AO Smith material specifications (modified ASTM SA-225 or IB heads and a custom alloy 1164A shell). At present, GRC has 57 active vessels, 25 inactive vessels, an excluded vessel (functioning as an atmospheric tank), and three vessels currently undergoing recertification.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

   All operational M/L Vessels are covered by GRC certification program and are regularly recertified via inspection/assessment procedures specified NASA STD 8719.17A. Vessels are thus prioritized by their recertification due date.

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

   Any of the vessels listed as inactive in Attachment A could be utilized for alternative purposes subject to owner approval. Vessels are put in inactive status for a variety of reasons, but usually the original requirement expires and the vessel is waiting repurposing. In recent years, a concerted effort has been made to excess these unutilized vessels due to their age and non-code status.

2. History of NDE or other inspections/analyses related to continued usage.

   As detailed below, all vessels must pass rigorous certification NDE/Analysis to be put into service, and must continue to pass regular In-Service Inspections (ISI) to remain in service. An inspection/analysis history is retained for each vessel.

2a. Description of inspection/analysis methods, schedule, etc.

   To qualify for service, all vessels are subject to certification NDE/Analysis which includes Radiography (RT), Ultrasonic Thickness Testing (UTT), Ultrasonic Shear Wave testing (UT), Internal and External Visual Examinations (VE), Magnetic Particle Testing (MT), and Acoustic Emissions Testing (AE). Analysis requirements include: (1) a detailed Maximum Allowable Working Pressure (MAWP) calculation and stress analysis based on minimum UTT readings (typically with the aid of software such as PVElite), (2) a corrosion assessment in which actual UTT thickness measurements are compared with past readings and the required minimum design thickness with results used to determine a linear corrosion rate and remaining life (more detailed analysis in accordance with API RP-579 can be made for local thin areas if using the minimum UTT results in too conservative of a calculation), (3) a fatigue analysis utilizing the peak stresses from the MAWP calculations in which service history (estimated cycles) is used to estimate remaining life, (4) a fracture mechanics analysis to determine the certification intervals based on half of the cycles required for a postulated minimum detectable flaw (based on the various NDE methods used) to grow to critical size (with the aid of software such as NASGRO or VCE-Sage Fitness For Service Software). Other damage mechanisms are evaluated as appropriate for the commodity and service (e.g. hydrogen service has specific damage mechanisms) and additional NDE is selected as appropriate to detect any other damage due to the relevant mechanisms. Any other damage detected during inspection is analyzed in accordance with NUBC NB-23 and API RP-579. An estimated safe remaining life is determined from the results of the NDE performed to mitigate all of the relevant damage mechanisms. In turn, the remaining life assessment is used to establish certification interval and ISI schedule. To remain in service, the vessel must pass regular ISI which typically includes VE (and potentially UTT, if corrosion is a concern) on a regular schedule (typically every 5 – 10 years depending on vessel specifications). A graphic chart of GRC inspection/analysis methods is provided in Attachment B. Risk mitigation information associated with respective NDE inspection and analysis methods is provided in Attachment C.
2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

All vessel inspection and analysis records are retained. Historical records are paper based and have not yet been scanned into electronic form. A migration to all electronic files is under way, but may be years in fully coming to fruition. Most historical data remains in paper form.

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

A detailed list of typical flaws detected in GRC’s multilayer pressure vessel inventory is provided in Attachment D. The list contains the vessel recertification barcode ID numbers, the location of the defect/defect, type of defect, type of NDE used to detect the flaw, NDE report number, and final disposition of the flaw. Of 92 multilayer vessels examined by the NDE procedures noted in item 2a above, 45% (41/92 PVs) contained nozzle LOF detected by UT bore probe exam; of the 184 head nozzle welds examined, 33% (60/184 nozzle) failed due to LOF as detected by UT bore probe exam; 27% (25/92) of the vessels examined by RT and MT failed due to linear indications, of which 76% (19/25) were detected by RT and the remaining 24% (6/25) were discovered at the outer surface with MT. In 2004 Modal AE was added as a supplemental inspection technique to complement other NDE methods. Of 86 vessels screened, no active defects have been detected utilizing modal AE.

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)

Primary means of risk mitigation are derating vessel MAWP and/or limiting recertification interval.

4. Any risk mitigation approaches used in the past, but no longer practiced

Modal Acoustic Emissions testing has historically been used as a general screening tool for vessel health in addition to other NDE techniques. While not formally discontinued, the use of MAE in future M/L vessel recertification is under review in light of recent agency findings that question the effectiveness of this technique for detecting flaws in M/L vessels.

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

Customized UT Bore Probes have been used for nozzle and nozzle to head weld inspections and the hardware/technique continues to be refined. See separate UT Nozzle Bore Probe Presentation dated 18-APR-2013 for detail. Phased Array UT methods are being explored for head-to-shell and shell-to-shell full penetration welds. Ref Son Le presentation and SSC/MSFC updates for additional information. Optical Strain measurement is being investigated as a potential verification of layer gap code compliance, and as a potential gross screening tool for the multilayered shell. See separate presentation Preliminary Vessel Photogrammetry Presentation dated 28-FEB-2013.

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

Ongoing work in developing PAUT and photogrammetry should continue. A probability of detection study to find various crack-like flaws in head-to-shell and shell-to-shell full penetration welds using radiography should be explored. With some judgment, additional investment in Acoustic Emissions could have favorable payback.

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.
The issue of applicability of ASME Section VIII, Div 2 (versus Div 1) should be addressed in this effort. With establishment of appropriate conditions and prerequisites, we believe Div 2 criteria can safely be used to rate these vessels for service. Also, the overall industry safety record of multi-layer vessels should be investigated. Failure cases often cited for these vessels involve processes and conditions that are never a factor for vessels at our site (and, we suspect, most of the agency).

8. Communications route to Center management on perceived global and specific vessel risks.

Communication route to center management has been through issue briefing regarding general risks. There is no special communication to Center Management regarding individual vessels, other than perhaps issues with vessel de-rating or recommendations for replacement. These vessels have been in-use for decades and there is not much awareness of potential risks other than in S&MA and Facilities Directorate management chains.
Attachment A – M/L vessel listing

<table>
<thead>
<tr>
<th>no</th>
<th>material type</th>
<th>manufacturer</th>
<th>model</th>
<th>design temp</th>
<th>weld</th>
<th>p_max低压</th>
<th>p_min低压</th>
<th>service temp</th>
<th>length</th>
<th>sheet material</th>
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<td>150</td>
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Attachment B – Non-code vessel inspection/analysis process
Evaluation of Agency Non-code LPVs

**UTT – Ultrasonic Thickness Testing**
An examination technique in which beams of high frequency sound waves are introduced into materials for the purpose of measuring the thickness of the test object; determines extent of material loss associated with erosion/corrosion and establishes minimum material thickness for Code stress calculations. Mitigates one mode of catastrophic failure due to metal loss.

**UT – Ultrasonic Shearwave Examination**
A volumetric examination technique in which beams of high frequency sound waves are introduced into materials for the detection of flaws; used to detect flaws within the nozzle base materials and in the nozzle to head weld to mitigate failure in these highly stressed areas.

**MT – Magnetic Particle Testing**
A surface (and near sub-surface) examination technique used to detect surface and near surface flaws in ferromagnetic materials; used to mitigate failure due to surface cracking.

**MAE, Modal Acoustic Testing**
A volumetric and surface examination technique used to identify and locate defects whereby an elastic wave is generated by the rapid release of energy (as produced by crack growth) from the source within a material, such as crack. Used as an overall screening tool to detect active cracks within intermediate shell layers and within other areas of the vessel that may have been missed by other methods. The pneumatic pressure test at 110% of MAWP can also serve as a proof test which can be supplemented with a fracture mechanics analysis to extend the vessel fracture life by screening for critical sized flaws.

**RT – Radiographic Inspection**
A volumetric examination technique in which a test object is exposed to x-rays or gamma rays and the resulting image of the object is recorded on photographic film placed behind the test object. Internal discontinuities are detected by observing and interpreting variations in the image caused by differences in thickness, density or absorption within the test object. 100% Radiography is performed on all full penetration circumferential shell welds. Some special techniques are required to evaluate head to shell weld. This mitigates potential for catastrophic event due to failure of primary vessel weld.

**Fracture Mechanics Calculations**
Estimates remaining fatigue fracture life. The basis for vessel life extensions beyond the vessel calculated fatigue life and can also be used to evaluate existing characterized flaws. Mitigates against catastrophic fatigue failure of vessels heads and critical welds.

**Corrosion Remaining Life Calculations**
Establishes/maintains corrosion rate. Helps establish/maintain examination frequencies and updated MAWP.

**Fit-for-service Calculations (API 579 and related standards)**
Provides NCS approach for mitigating, monitoring, and documenting non-critical flaws.

**Establish Certification Period and In-Service-Inspection (ISI) Intervals**
Based on one half the shortest safe remaining life (fatigue, corrosion, etc.).
<table>
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<tr>
<th>Action</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documentation review</td>
<td>Performed in order to determine compliance of the PVs with current applicable Codes, standards, guides, regulations, and/or NASA safety standards and practices. Used to determine the extent of engineering analysis and NDE required for certification. Screens vessels for certification. Vessels without basic documentation are ineligible for certification under this procedure. Also establishes nominal anticipated operating criteria.</td>
</tr>
<tr>
<td>Service history review</td>
<td>Used to determine the extent of engineering analysis and NDE required. Identifies unique damage mechanisms which further screens some vessels for certification and may revise allowable operating criteria.</td>
</tr>
<tr>
<td>VE, VI – external and internal visual examinations</td>
<td>A surface inspection technique used to detect and examine a variety of surface flaws, such as corrosion, erosion, cracks, and surface discontinuities. Also detects unauthorized repairs and helps to identify premature or unexpected damage. Used to mitigate failure due to surface flaws.</td>
</tr>
<tr>
<td>UTT – ultrasonic thickness testing</td>
<td>An examination technique in which beams of high frequency sound waves are introduced into materials for the purpose of measuring the thickness of the test object; Determines extent of material loss associated with erosion/corrosion and establishes minimum material thickness for Code stress calculations. Mitigates one mode of catastrophic failure due to metal loss.</td>
</tr>
<tr>
<td>UT – ultrasonic shearwave examination</td>
<td>A volumetric examination technique in which beams of high frequency sound waves are introduced into materials for the detection of flaws; used to detect flaws within the nozzle base materials and in the nozzle to head weld to mitigate failure in these highly stressed areas.</td>
</tr>
<tr>
<td>RT – radiographic inspection</td>
<td>A volumetric examination technique in which a test object is exposed to x-rays or gamma rays and the resulting image of the object is recorded on photographic film placed behind the test object. Internal discontinuities are detected by observing and interpreting variations in the image caused by differences in thickness, density or absorption within the test object. 100% Radiography is performed on</td>
</tr>
<tr>
<td>Method</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>MT — magnetic particle testing</td>
<td>A surface (and near sub-surface) examination technique used to detect surface and near surface flaws in ferromagnetic materials; used to mitigate failure due to surface cracking.</td>
</tr>
<tr>
<td>MAE, modal acoustic testing</td>
<td>A volumetric and surface examination technique used to identify and locate defects whereby an elastic wave is generated by the rapid release of energy (as produced by crack growth) from the source within a material, such as crack. Used as an overall screening tool to detect active cracks within intermediate shell layers and within other areas of the vessel that may have been missed by other methods. The pneumatic pressure test at 110% of MAWP can also serve as a proof test which can be supplemented with a fracture mechanics analysis to extend the vessel fracture life by screening for critical sized flaws.</td>
</tr>
<tr>
<td>Fracture Mechanics calculations</td>
<td>Estimates remaining fatigue fracture life. The basis for vessel life extension beyond the vessels calculated fatigue life and can also be used to evaluate existing characterized flaws. Mitigates against catastrophic fatigue failure of vessels heads and critical welds.</td>
</tr>
<tr>
<td>Corrosion remaining life calculations</td>
<td>Establishes/updates corrosion rates. Helps establish/maintain examination frequencies and updated MAWP.</td>
</tr>
<tr>
<td>Fit-for-service calculations (API 579 and related standards)</td>
<td>Provides NCS approach to mitigating, monitoring, and documenting non-critical flaws.</td>
</tr>
<tr>
<td>Establish certification period and In-Service-Inspection (ISI) intervals</td>
<td>Based on one-half the shortest safe remaining life (fatigue, corrosion, etc.).</td>
</tr>
</tbody>
</table>
**Attachment C – Non-code Multilayer vessel original design deficiencies and risk reduction countermeasures**

<table>
<thead>
<tr>
<th>Potential Fabrication Deficiencies</th>
<th>Potential Failure Mode</th>
<th>Catastrophic Failure Potential (pre-mitigation)</th>
<th>Mitigation</th>
<th>Catastrophic Failure Potential (post-mitigation)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flawed Base Material:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base plate and forging materials not in conformance with ASME Code and/or Manufacturers Specifications</td>
<td>Brittle Fracture Failure / Ductile Rupture; potential fragmentation</td>
<td>High</td>
<td>Manufacturers’ Data Reports and material test reports (MTRs) are on file for a majority of the NASA Glenn AO Smith vessels. The MTRs specify the vessel serial numbers, steel manufacturers, melt/slab serial heat numbers, chemical composition, elastic limit, ultimate tensile strength, elongation, and bend test results in accordance with the manufacturer’s material specifications.</td>
<td>Low</td>
</tr>
<tr>
<td>- Insufficient Fracture Toughness at MDMT</td>
<td>Brittle Fracture Failure; potential fragmentation</td>
<td>High</td>
<td>Charpy keyhole notch toughness test results at the vessel MDMTs (down to (-40^\circ F)) in accordance with the ASME Code at the time of manufacture are on file for many AO Smith vessels at NASA Glenn. Additional fracture toughness and fatigue crack growth testing data is documented in NASA TM X-3316. Minimum fracture toughness values from NASA TM X-3316 (more conservative than API RP-579 default values) and API RP-579 Paris crack growth equation parameters (more conservative than NASA TM X-3316 actual test data) are used to perform fracture mechanics analysis in accordance with API RP-579 for all multilayer vessels.</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Flawed Welds:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- ASME Code Compliant WPS, PQR, &amp; WPQ not fully implemented and documented</td>
<td>Brittle Fracture Failure / Ductile Rupture; potential fragmentation</td>
<td>High</td>
<td>Manufacturer's fabrication specifications (AO Smith Spec MLS 30A) references that PQR and WPQ comply with ASME Section IX. Many vessel files</td>
<td>Low</td>
</tr>
</tbody>
</table>
### Evaluation of Agency Non-code LPVs

<table>
<thead>
<tr>
<th>Potential Fabrication Deficiencies</th>
<th>Potential Failure Mode</th>
<th>Catastrophic Failure Potential (pre-mitigation)</th>
<th>Mitigation</th>
<th>Catastrophic Failure Potential (post-mitigation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base plate and forging materials not in conformance with ASME Code and/or Manufacturers Specifications</td>
<td>Brittle Fracture Failure / Ductile Rupture; potential fragmentation</td>
<td>High</td>
<td>Manufacturers’ Data Reports and material test reports (MTRs) are on file for a majority of the NASA Glenn AO Smith vessels. The MTRs specify the vessel serial numbers, steel manufacturers, melt/Slab serial heat numbers, chemical composition, elastic limit, ultimate tensile strength, elongation, and bend test results in accordance with the manufacturer’s material specifications.</td>
<td>Low</td>
</tr>
<tr>
<td>Insufficient Fracture Toughness at MDMT</td>
<td>Brittle Fracture Failure; potential fragmentation</td>
<td>High</td>
<td>Charpy keyhole notch toughness test results at the vessel MDMTs (down to -40°F) in accordance with the ASME Code at the time of manufacture are on file for many AO Smith vessels at NASA Glenn. Additional fracture toughness and fatigue crack growth testing data is documented in NASA TMX-3316. Minimum fracture toughness values from NASA TMX-3316 (more conservative than API RP-579 default values) and API RP-579 Paris crack growth equation parameters (more conservative than NASA TMX-3316)</td>
<td>Low</td>
</tr>
<tr>
<td>Potential Fabrication Deficiencies</td>
<td>Potential Failure Mode</td>
<td>Catastrophic Failure Potential (pre-mitigation)</td>
<td>Mitigation</td>
<td>Catastrophic Failure Potential (post-mitigation)</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------</td>
<td>------------------------------------------------</td>
<td>------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Flawed Welds:</td>
<td></td>
<td>3316 actual test data are used to perform fracture mechanics analysis in accordance with API RP-579 for all multilayer vessels.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- ASME Code Compliant WPS, PQR, &amp; WPQ not fully implemented and documented</td>
<td>Brittle Fracture Failure / Ductile Rupture; potential fragmentation</td>
<td>High</td>
<td>Manufacturer’s fabrication specifications (AO Smith Spec MLS 30A) references that PQR and WPQ comply with ASME Section IX. Many vessel files contain weld test plate reports with weld tensile and bend test results, and a “Certification of Welders” signed by the AO Smith Chief Inspector certifying that all welders working on the specified vessels (listed by serial number) were qualified in accordance with ASME Section IX and all tests were witnessed by a National Board Inspector. A hydrostatic pressure test at 150% of MAWP was performed on all AO Smith multi-layer pressure vessels.</td>
<td>Low</td>
</tr>
<tr>
<td>- Insufficient Fracture Toughness at MDMT</td>
<td>Brittle Fracture Failure; potential fragmentation</td>
<td>High</td>
<td>Charpy keyhole notch toughness test results at the vessel MDMTs (down to -40°F) in accordance with the ASME Code at the time of manufacture are on file for some AO Smith vessels at NASA Glenn. Additional fracture toughness and fatigue crack growth testing data is documented in NASA TM X-3316. Minimum fracture toughness values from NASA TM X-3316 (more conservative than API RP-579 default values) and API RP-579 Paris crack growth equation parameters (more conservative than NASA TMX-3316 actual test data) are used to perform fracture mechanics analysis in accordance with API</td>
<td>Low</td>
</tr>
</tbody>
</table>
### Evaluation of Agency Non-code LPVs

<table>
<thead>
<tr>
<th>Potential Fabrication Deficiencies</th>
<th>Potential Failure Mode</th>
<th>Catastrophic Failure Potential (pre-mitigation)</th>
<th>Mitigation</th>
<th>Catastrophic Failure Potential (post-mitigation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Intermediate layer welds</td>
<td>Ductile failure with minimal fragmentation; Undetected crack likely to self-arrest (confined within a single layer)</td>
<td>Med/High</td>
<td>CB&amp;I multi-layer vessel specs require MT on all inner layer longitudinal weld seams at time of fabrication. AO Smith Bulletin V-52 and V-53 indicates that rigid in-process inspection and quality control are enforced during every stage of manufacture and assembly of the multi-layer vessels, and that the fabrication technique permits minute inspection of both sides of each individual layer in the vessel wall. During the recertification process, VE and VI are performed on the outer and inner-most layers, and 110% MAWP pneumatic pressure test with MAE is performed to screen for active cracks/flaws in intermediate layer welds.</td>
<td>Low</td>
</tr>
<tr>
<td>- Nozzle attachment welds</td>
<td>Brittle Fracture Failure / Ductile Rupture; potential fragmentation</td>
<td>High</td>
<td>Head to Nozzle subassemblies were stress relieved after fabrication (per AO Smith fabrication specification MLS-30A, fabrication drawings, and affidavit packages), AO Smith welding to relieve residual stresses. During the recertification process, VE, VI (with fiberscope), MT, 110% MAWP pneumatic pressure test with MAE, &amp; IIT bore probe examinations are performed to detect potential flaws. A fracture mechanics analysis is performed in accordance with API RP-579 to establish examination frequencies at no greater than ½ the safe</td>
<td>Low</td>
</tr>
<tr>
<td>Potential Fabrication Deficiencies</td>
<td>Potential Failure Mode</td>
<td>Catastrophic Failure Potential (pre-mitigation)</td>
<td>Mitigation</td>
<td>Catastrophic Failure Potential (post-mitigation)</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------</td>
<td>-----------------------------------------------</td>
<td>------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Head to Shell weld &amp; full penetration circumferential welds</td>
<td>Brittle Fracture Failure / Ductile Rupture; potential fragmentation</td>
<td>High</td>
<td>During fabrication AO Smith Spec MLS-30A calls for a VE on each layer of weld. All undercut, Lack Of Fusion, irregularities in weld deposit, slag inclusions, and porosity are to be corrected before the next weld layer is deposited. 100% RT was performed on the inner layer longitudinal weld seams, and 100% RT of the head to inner shell circumferential welds. During the recertification process, VE, VI (with fiberscope), 110% MAWP pneumatic pressure test with MAE, 100% MT &amp; 100% RT are performed to detect potential flaws. A fracture mechanics analysis is performed in accordance with API RP-579 to establish examination frequencies at no greater than ½ the safe remaining life based on a minimum detectable flaw.</td>
<td><strong>Low</strong></td>
</tr>
</tbody>
</table>
## Attachment D – Summary of vessel flaws, defects, and damage identified

<table>
<thead>
<tr>
<th>NESC Request No.</th>
<th>Identification</th>
<th>Type of Defect</th>
<th>Type of Vessel</th>
<th>NESC Request Number</th>
<th>Final Disposition</th>
<th>NESC Request No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI-13-00852</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### Evaluation of Agency Non-code LPVs

<table>
<thead>
<tr>
<th>NESC Request No.</th>
<th>Identification</th>
<th>Type of Defect</th>
<th>Type of Vessel</th>
<th>NESC Request Number</th>
<th>Final Disposition</th>
<th>NESC Request No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI-13-00852</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Goddard Space Flight Center (GSFC)/Wallops Flight Facility (WFF)

GSFC/WFF Layered, Non-Code Pressure Vessel Request for Information

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

See attached file for list of the vessels and their information.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

All 12 vessels were retested and recertified in 2012; therefore, there is no current prioritized of needing evaluation.

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

There are some surplus large vessels with pressure rating of 2700 psig.

2. History of NDE or other inspections/analyses related to continued usage.

2a. Description of inspection/analysis methods, schedule, etc.

During recertification in 2012 the following inspection and test were performed on all of the pressure vessels:

- External and Internal Visual examination
- Weep holes cleaning and measurement
- Magnetic particle examination on nozzle-to-head welds and attachment welds
- Ultrasonic thickness examination on vessel heads and nozzles
- Radiographic examination on head-to-shell welds and shell-to-shell welds with some indications notes: Processing marks, slag inclusion, layer wash, porosity, and film artifacts.
- Ultrasonic volumetric on nozzle-to-head welds
- Hydrostatic pressure test to 1.42 times certified MAWP
- Modal acoustic emission test during hydrostatic pressure test 1.42 times certified MAWP by Digital Wave
- PI Tape measurement
- Hardness Testing

Below analyses were performed to support recertification:

Design Analysis for vessel MAWP
Remaining life analysis (linear elastic fracture mechanics) using API 579-1/ASME FFS-1 for postulated flaws

ASME B&PV Code Section VIII, Div. 1, Gap Analysis for Layer Vessels

2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

Results of examination and test are available and well documented.

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

The vessels that have any rejectable indications were repaired per NB-23 and documented. Information is available upon request.

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)

Additional inspection and testing were performed to further understand and identify potential flaws in the vessels. Operational pressure cycles are limited and closely tracked. The remaining life and recertification interval is reduced to a maximum of 10 years even though calculated remaining pressure cycles allow the vessels to be in service for 20 years (40/2).

4. Any risk mitigation approaches used in the past, but no longer practiced

None

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

None

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

None

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.

None
Not at this point

8. Communications route to Center management on perceived global and specific vessel risks.

WFF management was informed on the risks of using these pressure vessels.
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Location</th>
<th>Vessel ID</th>
<th>Number</th>
<th>Service Media</th>
<th>Nameplate</th>
<th>Rating (PSI)</th>
<th>Center's Design</th>
<th>Pressure (PSI)</th>
<th>Wall Thickness (in, nominal)</th>
<th>Number of Head Flanges</th>
<th>Number of Head Layers</th>
<th>Head Material of Construction</th>
<th>Comments (general condition, vessel history, known flaws, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #20 MV-59866-5</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>73</td>
<td>1960</td>
<td>3.125</td>
<td>116-25</td>
<td>1-0.375</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Weep holes were cleaned and measured.</td>
</tr>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #21 MV-59867-7</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>378</td>
<td>1960</td>
<td>3.75</td>
<td>130-25</td>
<td>1-0.500</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Head layers were cleaned and measured.</td>
</tr>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #22 MV-59868-2</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>73</td>
<td>1960</td>
<td>3.125</td>
<td>116-25</td>
<td>1-0.375</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Head layers were cleaned and measured.</td>
</tr>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #23 MV-59869-9</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>378</td>
<td>1960</td>
<td>3.75</td>
<td>130-25</td>
<td>1-0.500</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Head layers were cleaned and measured.</td>
</tr>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #24 MV-59870-1</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>378</td>
<td>1960</td>
<td>3.75</td>
<td>130-25</td>
<td>1-0.500</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Head layers were cleaned and measured.</td>
</tr>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #25 MV-59871-3</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>378</td>
<td>1960</td>
<td>3.75</td>
<td>130-25</td>
<td>1-0.500</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Head layers were cleaned and measured.</td>
</tr>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #26 MV-59872-5</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>378</td>
<td>1960</td>
<td>3.75</td>
<td>130-25</td>
<td>1-0.500</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Head layers were cleaned and measured.</td>
</tr>
<tr>
<td>A.O. Smith</td>
<td>WWF/ Pad 0A</td>
<td>MARS #27 MV-59873-7</td>
<td>GNE2</td>
<td>6006</td>
<td>$170</td>
<td>8900</td>
<td>378</td>
<td>1960</td>
<td>3.75</td>
<td>130-25</td>
<td>1-0.500</td>
<td>AOS 1146</td>
<td>Installed at SLC-06, Cape Canaveral Air Force Station in 1969. Refurbished and put back in service in 2012 at WFF. Flange marked in September 2010. Vessel was operating in 1969. Head layers were cleaned and measured.</td>
</tr>
</tbody>
</table>

Flange marked in September 2010. Vessel was operating in 1969. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured. Incomplete Fusion nozzle N-2 by UTV early 2012. Weep holes were cleaned and measured.
Johnson Space Center (JSC)/White Sands Test Facility (WSTF)

Layered, Non-Code Pressure Vessel Request for Information

WSTF Input

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

Four Vessels, (3 AO Smith, 1 Struthers Wells) all built between 1958 and 1964. See Excel spreadsheet for other details. The vessels appear to have been at WSTF for at least 20 years. Beyond that, no information has been found indicating other details such as when they arrived at WSTF and previous service life.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

One vessel has been evaluated using Modal AE only. The other three are on the risk-based schedule to be evaluated in FYs 2015 and 2016. The systems are tracked as number 105 and number 126 on our prioritized list. We are currently evaluating systems near number 75. Lower priority was placed on the systems due to dry gas service (dew point monitored), use at a 65% or less of nameplate rating, and very low number of pressure cycles (on the order of 1 cycle per year (or less) with a magnitude more than half range).

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

One vessel currently used at only 600 psi might be available if a replacement vessel was provided. Last year, an AO Smith vessel stored at WSTF (but not owned by WSTF) was loaned to Blue Origin in Van Horn Texas (Contact Sean Gates, sgates@blueorigin.com).

2. History of NDE or other inspections/analyses related to continued usage.

2a. Description of inspection/analysis methods, schedule, etc.

Other than MAE on one vessel, no evidence of any NDE could be found for the other three vessels except for a mention of UTT testing on the heads.

In 1983, General Physics was contracted to perform an assessment of the layered vessels at WSTF. A "preliminary" analysis was performed based on Section VIII Div. 1 and Div. 2, and recommendations were made for various NDE and testing. A report was published. No data could be found indicating the General Physics recommended inspections/tests were ever performed.
In 1988, a WSTF internal study of one layered vessel (and one non-layered vessel) was conducted and a report filed. The study reviewed existing documentation, performed a fracture mechanics analysis of the heads only, and performed ultrasonic thickness testing of the heads. The analysis assumed leak before break in the shell, and reportedly calculated leak before break in the heads, although a calculation could not be found.

2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

The 1983 and 1988 reports are available (paper copy, but can easily be scanned). Raw data for any ultrasonic thickness evaluations were not found.

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

No flaws were detected on the one vessel for which Modal AE was performed. No evidence of other inspections that could have detected flaws was found.

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)

Operating pressures and cycles are such that the risk is mitigated to some degree. It is not clear whether the operating pressure and lack of cycles is intentional and a direct result of analysis or just that these vessels happened to be selected for this service and “normal” operation results in low cycles. The weep holes are regularly (annually) inspected for leaks.

4. Any risk mitigation approaches used in the past, but no longer practiced

Not aware of any past mitigation approaches no longer practiced.

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

No.

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

No.
7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.

    I agree with the goal others have expressed regarding a consistent approach to NDE, analysis, and evaluation is developed with enough flexibility to accommodate a variety of designs and use scenarios.

8. Communications route to Center management on perceived global and specific vessel risks. (*Gentz to clarify?)

    Center management (local) is aware WSTF is transitioning systems from our “old” process, which is not very robust and rarely performed proper analysis on vessels, to our “new” process which is intended to meet the NASA Standard and has critical engineering evaluation built-in to the process. Management is generally aware systems in the “old” process have some level of risk associated with the gaps in inspection, analysis, and testing that exist with our “old” process.
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Manufacturer's Model Number</th>
<th>Location</th>
<th>Vessel ID Number</th>
<th>PVS Package</th>
<th>Service Media</th>
<th>Nameplate Rating (PSI)</th>
<th>Center's Design Pressure (PSI)</th>
<th>Operating Pressure (PSI)</th>
<th>Water Volume (ft³)</th>
<th>Year Built</th>
<th>Age (yr)</th>
<th>Wall thickness (shell, total nominal, in.)</th>
<th>Number of Shell layers and thicknesses (nominal, in.)</th>
<th>Shell Materials of construction</th>
<th>Number of Head layers and thicknesses (nominal, in.)</th>
<th>Head Materials of construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AO Smith</td>
<td>MV50309-11</td>
<td>WSTF</td>
<td>TK-8GN-JA11</td>
<td>8061</td>
<td>Air</td>
<td>2800</td>
<td>600</td>
<td>600</td>
<td>312</td>
<td>1958</td>
<td>55.00</td>
<td>2.1875</td>
<td>8 layers - inner 0.5&quot;, plus 7 0.25&quot; layers</td>
<td>1146a</td>
<td>1</td>
<td>ASTM A225 Gr. B FBQ</td>
</tr>
<tr>
<td>AO Smith</td>
<td>MV50582-1</td>
<td>WSTF</td>
<td>TK-4GN-HN074</td>
<td>4005</td>
<td>Nitrogen</td>
<td>6600</td>
<td>4203</td>
<td>2300</td>
<td>398</td>
<td>1960</td>
<td>53</td>
<td>3.72</td>
<td>13 layers - inner 15/32 plus 12 0.271&quot; layers</td>
<td>1146a</td>
<td>1</td>
<td>ASTM A225 Gr. B FBQ</td>
</tr>
<tr>
<td>Struthers Wells</td>
<td>48-1872</td>
<td>WSTF</td>
<td>TK-4GN-FG006</td>
<td>4005</td>
<td>Nitrogen</td>
<td>5500</td>
<td>4425</td>
<td>2300</td>
<td>650</td>
<td>1964</td>
<td>49</td>
<td>6.5</td>
<td>5 layers - inner 0.5&quot;, then 1.75&quot;, 1.5&quot;, 1.5&quot;, 1.5&quot;</td>
<td>Proprietary SWC 100302, except inner layer is SA302 Gr. B with 1/8&quot; Type 304 Stainless Clad</td>
<td>1</td>
<td>SA302 Gr. B with 1/8&quot; Type 304 Stainless Clad</td>
</tr>
<tr>
<td>AO Smith</td>
<td>MV50309A27</td>
<td>WSTF</td>
<td>TK-5BA-AM169</td>
<td>5006</td>
<td>Air</td>
<td>2800</td>
<td>2100</td>
<td>1800</td>
<td>312</td>
<td>1958</td>
<td>55</td>
<td>2.1875</td>
<td>8 layers - inner 0.5&quot;, plus 7 0.25&quot; layers</td>
<td>1146a</td>
<td>1</td>
<td>ASTM A225 Gr. B FBQ</td>
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</tbody>
</table>
Kennedy Space Center (KSC)

KSC Response May 2013

Layered, Non-Code Pressure Vessel Request for Information

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

The KSC AO Smith vessel listing has been posted on the NSCKN site. 13 Vessels are currently out-of-service/in-active. KSC has 10 active multi-layered pressure vessels. These vessels are used primarily for nitrogen service, helium and breathing air service. These vessels were built in the 1957-1960.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g., particular application, known damage conditions, etc.)

We have no vessels with known flaws that are currently in service. The inspection prioritization will assess accordingly to the Risk Based Plan date.

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g., damaged, no longer needed, etc.)

KSC has 13 in-active AO. Smith vessels, these may be available for test or use. We just need to confirm with various programs at KSC.

2. History of NDE or other inspections/analyses related to continued usage.

Periodic inspections followed in subsequent years consisting primarily of VE, RT, MT and UT. RT performed around the head (head-to-shell), shell-to-shell, and accessible butt welds in the nozzle. UT-Shear of nozzle welds in the event RT cannot be performed. MT performed on nozzle configurations for which RT and/or UT-Shear are not accessible. UT-Thickness performed on the both heads.

2a. Description of inspection/analysis methods, schedule, etc.

Currently, we are performing VE, MT, RT and UT on all accessible welds according to the ISI in the certification report and inspecting the connection hubs for corrosion. Engineering analysis performed on those vessels per ASME Section VIII, Div. 2 and API 579.

2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

KSC used the Acceptance Data Package and hard copies. It has fairly extensive records on most of the multi-layered vessels including fabrication drawings, material test reports, manufacturer’s data report and previous inspection records. We also have weld procedures and weld qualification records for some vessels.
KSC Response May 2013

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

Detailed results for any flaws, defects, or damage identified are addressed in the certification report (if any).

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)

The active multi-layered pressure vessels are currently operating below their MAWP as shown in the KSC vessel listing based on ASME Code calculations and flanges rating by analysis.

4. Any risk mitigation approaches used in the past, but no longer practiced

No previous risk mitigation approaches are known beyond those already addressed.

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

No.

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

No.

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.

Inactive pressure vessels that haven’t had an ASME Section VIII, Div. 1 or Div. 2 calculation to show their actual MAWP should have a calculation performed.

8. Communications route to Center management on perceived global and specific vessel risks.

The PVS Program is currently reporting to the KSC Center Director on a quarterly basis in a formal KSC Management Council (KMC).
## Evaluation of Agency Non-code LPVs

<table>
<thead>
<tr>
<th>Vessel Manufacturer</th>
<th>Vessel Type</th>
<th>Number of Vessels</th>
<th>Vessel Serial Number</th>
<th>Design Pressure (psig)</th>
<th>Design Temperature (°F)</th>
<th>Head - Shell</th>
<th>Operating Pressure (psig)</th>
<th>Operating Temperature (°F)</th>
<th>Stabilization Method</th>
<th>Vessel Status</th>
<th>Certification No.</th>
<th>Certification Times</th>
<th>Certification Records Available</th>
<th>Certification Records Available Remarks/Approvals</th>
<th>Certification Records Available Remarks/Approvals</th>
</tr>
</thead>
</table>

### Description
- **Vessel Serial Number**: The unique identifier for each vessel.
- **Design Pressure**: The maximum pressure rating of the vessel.
- **Operating Pressure**: The pressure under which the vessel operates.
- **Operating Temperature**: The temperature under which the vessel operates.
- **Certification Times**: The dates when the certification was performed.
- **Certification Records Available**: Indicates whether records are available for the vessel.
- **Remarks/Approvals**: Notes on the current status or any additional information.
Langley Research Center (LaRC)

NESC Study of Layered, Non-Code Pressure Vessel Request for Information

Langley Research Center

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

- 4 A. O. Smith Vessels, purchased new in 1961
- See “LaRC - ML Vessel Listing - 6 May 2013.xlsx” for details

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

- 1st LaRC priority – methane vessels @ 8 Foot High Temperature Tunnel

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

- None

2. History of NDE or other inspections/analyses related to continued usage.

- Fracture Mechanics Analysis of 2 methane vessels
- UT of head to shell welds
- UT of nozzle welds
- VE of external surfaces

2a. Description of inspection/analysis methods, schedule, etc.

- VE of external surfaces every 2 years
- Original recertification per NHB 1700.6
- Recertification of vessels scheduled for 2013 and 2014

2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

- Some records are available in PDF format (low quality)

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

- None known in vessels in service
NESC Study of Layered, Non-Code Pressure Vessel
Request for Information
Langley Research Center

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)
   - None

4. Any risk mitigation approaches used in the past, but no longer practiced
   - None

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)
   - None

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.
   - Installation of 18” manways

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.
   - Internal surfaces are not accessible for inspection

8. Communications route to Center management on perceived global and specific vessel risks.
   - PSM -> LaRC Safety Manager -> Center Director
<table>
<thead>
<tr>
<th>Vessel Manufacturer</th>
<th>Location</th>
<th>Vessel ID Number</th>
<th>Service Media</th>
<th>Manuf. Nameplate Rating (PSI)</th>
<th>Center's Design Pressure (PSI)</th>
<th>Operating Pressure (PSI)</th>
<th>Water Volume (ft³)</th>
<th>Age (yr.)</th>
<th>Wall Thickness (shell total, nominal, in.)</th>
<th>Number of Shell Layers and Thk. (nominal, in.)</th>
<th>Head thickness (total, in.)</th>
<th>Number of Head Layers and Thkn (in.)</th>
<th>Materials of Construction (Shell)</th>
<th>Materials of Construction (Heads)</th>
<th>Comments (general condition, vessel history, known flaws, etc.)</th>
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</thead>
<tbody>
<tr>
<td>A. O. Smith</td>
<td>LaRC 8'HIT</td>
<td>MV 50563-1</td>
<td>Methane</td>
<td>6,000</td>
<td>6,000</td>
<td>5,375</td>
<td>832</td>
<td>52</td>
<td>5-1/4&quot; thk. 17 @ .250&quot; thk.</td>
<td>VMS 1146A 4-3/8&quot; thk. 1</td>
<td>1</td>
<td>ASTM A225 Grade B, FBO</td>
<td>External condition: good Internal condition: unknown No known flaws</td>
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<td>ASTM A225 Grade B, FBO</td>
<td>External condition: good Internal condition: unknown No known flaws</td>
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<tr>
<td>A. O. Smith</td>
<td>LaRC 1247B</td>
<td>MV50631-1</td>
<td>Vacuum</td>
<td>6,600</td>
<td>6,200</td>
<td>-15</td>
<td>1,015</td>
<td>52</td>
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<td>ASTM A225 Grade B, FBO</td>
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<td>A. O. Smith</td>
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<td>6,200</td>
<td>5,000</td>
<td>999</td>
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<td>VMS 1146A 4-3/4&quot; thk. 1</td>
<td>1</td>
<td>ASTM A225 Grade B, FBO</td>
<td>External condition: good Internal condition: unknown No known flaws</td>
<td></td>
<td></td>
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</table>
Evaluation of Agency Non-code LPVs

Michoud Assembly Facility (MAF)

Layered, Non-Code Pressure Vessel Request for Information

Michoud Assembly Facility

List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

Nine ASME non-code Vessels as listed in attached spreadsheet. Six are A.O. Smith 40 cu. ft. layered vessels. Two are T-1 Steel layered vessels of 1500 cu ft and 1375 cu ft capacity. One is a single layer shell 575 cu ft vessel constructed of 2.25% Chromium. All vessels are in 2000 psig operating pressure GN2 service.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

All vessels are periodically inspected by the AE Monopak method. The AO Smith vessels have weld buildup repairs from corrosion that were performed in 2007. All of these vessels are currently in service. The MAF plan is to continue AE inspection supplemented by UT Phased Array inspection of head to shell welds. No known relevant or active defects have growing have been noted. Some are to be watched on AO Smith vessels.

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

No vessels are unused on the MAF site. History of NDE or other inspections/analyses related to continued usage.

See attached spreadsheet for applicable NDE History.

2a. Description of inspection/analysis methods, schedule, etc.

The vessels are AE Monopak inspected every five to seven years.

2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

Charpy impact data at minus 40 F is available for only the AO Smith vessels. The vessel drawings and specifications describe 100% RT inspection of all welds during manufacture. However, films of the RT inspection test results
are not available. AE Monopak hard copy raw data is available for the 2001 and 2007 test periods.

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

All surface corrosion damage identified to date has been corrected. Reference attached spreadsheet for more specific data.

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)

All vessels are at remote locations within the facility. The system operating pressure has recently been reduced from 4400 psig to 2000 psig. MAE is scheduled for five to seven year intervals. PV Elite design stress calculations were performed on all vessels in accordance with Div 1 and 2 standards. MAWP's and estimated fatigue remaining lives were calculated. Variances were prepared and accepted by PSM for all the vessels.

4. Any risk mitigation approaches used in the past, but no longer practiced

MAWP pressure was lowered from 7000 to 5000 psig in the late 1970’s.

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

Operating pressures will remain at 2000 psig unless otherwise required for SLS production activities. Variances will be prepared and accepted for mitigation during SLS LH Tank proof test procedures and LH and LOX Tank leak test procedures. All personnel will be evacuated from potential blast radii. Temporary or permanent berms will be erected to mitigate equipment damage risk. At this time, it is anticipated that these critical test procedures will occur one to three times a year with each test lasting one to two days.

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

All SLS testing is to be accomplished at flight tank pressures below 80 psig. The high pressure system will be used to provide storage capacity for testing. A redesign to allow local Liquid N2 storage near point of use as a low
pressure high flow capacity feed system would significantly mitigate the risk associated with high pressure systems.

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.

No vessel failures have occurred with this system at this site. Based on previous history and continued periodic MAT and UT Sherography testing for risk mitigation, unforeseen future events should be minimized.

8. Communications route to Center management on perceived global and specific vessel risks. (Gentz to clarify?)

MSFC approved a waiver in CY-2011 for continued operation of non-ASME Coded multi-layered and single shell vessels in High Pressure GN2 service at MAF. The vessels continue to be certified on the basis of the waiver. No incidents have occurred. The Waiver process as per NASA STD 8719.17A is the specified and appropriate means of communicating elevated risk to the Center. Current Center awareness beyond the Owner directorate is not high. Since approval, additional PV Elite stress and fatigue analysis has been performed per Div 1 using Div 2 allowables. The operating pressure has recently been reduced to below these calculated MAWPs. Waivers will be developed and approved for programmatic pressure increases required to support SLS production.

Dale Heintzelman, P.E.
MAF Pressure Vessel Engineer
4/29/13
### Evaluation of Agency Non-code LPVs

<table>
<thead>
<tr>
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<tbody>
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<td>102682, Rev. 5</td>
<td>Forged Vessel (Random forgings), B404</td>
<td>Babcock &amp; Wilcox</td>
<td>1965</td>
<td>New No AFO for MAF HP Velcro to 1975, GN2 in 1975</td>
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<td>57</td>
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<td>A/Every 5 years</td>
<td>A/Concern for continued operation</td>
<td>SA-182-F20/19 M8 Copy 1.20&quot; 3.8395&quot;</td>
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<td>5123</td>
<td>2000</td>
<td>8.25 (heads)</td>
<td>8.75 (shells)</td>
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Marshall Space Flight Center (MSFC)

MSFC Response May 2013

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

The MSFC multilayer (ML) vessel listing has been posted on the NSCKN site. Vessels highlighted in yellow in the listing are currently out of service. MSFC has 173 in-service ML vessels from four different manufacturers with the majority of the vessels built by A.O. Smith and CB&I. These vessels are used primarily for air and nitrogen service although a limited number are also used for hydrogen and helium service. There is a wide variety of vessel sizes up to 1255 cft and these vessels were built in the 1950’s and 1960’s.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

We are in the process of developing a new ML vessel inspection priority list. We have no vessels with known flaws that are currently in service and we have one ML vessel with zero remaining fatigue life which is currently out of service. The inspection prioritization will assess the hazard level for each vessel based on original design pressure, current operating pressure, vessel capacity, service media, personnel exposure, remaining fatigue life, and current vessel condition. This priority list will continue to be updated as we learn more about the condition of these vessels through additional analysis and inspection.

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

MSFC has two A.O. Smith 35 cft 5500 psig vessels to be used for test purposes. The vessels have been out of service for ~20 years. We continue to look for additional vessels that may be available for testing purposes. (Reference item 5 for additional information on the two A.O. Smith test vessels)

2. History of NDE or other inspections/analyses related to continued usage.

Many, if not all, the ML vessels were inspected during the 1980’s by traditional methods as well as AE. A number of vessel repairs were made during that timeframe based on results of these inspections. Periodic inspections followed in subsequent years consisting primarily of VT, MT and UT.

2a. Description of inspection/analysis methods, schedule, etc.

Currently, we are performing VT, UT, and MT on all accessible welds prior to performing modal and parameter based AE. We are also considering other inspection techniques such as RT and phased array UT. We are currently performing material testing on a CB&I 35 cft 3500 psig vessel. These tests include or will include tensile, fracture toughness, fatigue crack growth rate, transition temperature, and Charpy Impact.
2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

MSFC has fairly extensive records on most of the ML vessels including fabrication drawings, material test reports, manufacturer's data report and previous inspection records. We also have weld procedures and weld qualification records for some vessels.

2b. Detailed results for any flaws, defects, or damage identified (e.g., method, date, vessel defect description, disposition, etc.)

We have only one known defect on a ML vessel and this vessel is currently out of service. The defect is a 2.5” readily visible crack in the outer shell and does not appear to be a service induced flaw. The crack is in the parent metal of the outer layer running longitudinally toward (and perpendicular to) the head to shell weld. We have x-ray film and phased array graphs of the defect. Additional phased array data will be available for this vessel in the coming weeks to compare with the RT results. We are performing damage tolerance analysis on this vessel and plan to perform an AE test with photogrammetry in the coming weeks (hydrostatic test).

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s)

Many of the ML vessels are currently operating below the original design pressure as shown in the MSFC vessel listing. Also, a number of the ML vessels are located in areas where personnel access is restricted to test crews only and/or the vessel is only pressurized during test operations. These considerations, among others, are being included in our ML vessel inspection priority list.

4. Any risk mitigation approaches used in the past, but no longer practiced

No previous risk mitigation approaches are known beyond those already addressed.

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

MSFC is collaborating with SSC and GRC to have a phased array UT procedure qualified by an outside contractor.

MSFC currently has two A.O. Smith 35 cft 5500 psig vessels to be used for test purposes. Both vessels have been out of service for ~20 years. We plan to perform an AE test and a photogrammetry test on the first vessel prior to cutting the vessel for test coupons. The second vessel is being considered for an AE test-bed at MSFC and a test plan will be developed in the coming weeks. The test plan can be provided to the NESC team for review. We have funds available for this testing in FY13 but may have limited funds in FY14 to continue this effort.
MSFC Response May 2013

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.

It has become obvious from our discussions with and visits to other centers that different operational factors drive the ML vessel inspection process or vessel hazard mitigation techniques. For example, de-rating ML vessels to increase factor of safety may have little or no impact at one center but may have significant impact at others. Another example is that intrusive vessel inspection techniques employed at one center may have serious drawbacks at another due to potential for vessel contamination. Tailored inspection or hazard mitigation approaches for different centers may be necessary to accommodate the different operational considerations.

8. Communications route to Center management on perceived global and specific vessel risks.

The Pressure System Program is currently reporting to the Associate Center Director (ACD) on a quarterly basis in a formal Program Management Review (PMR). Non-code vessel work activities are reported, among other items, during the PMR.
**Title:** Evaluation of Agency Non-code LPVs  

**Document #:** NESC-RP-13-00852  

**Version:** 1.0  

<table>
<thead>
<tr>
<th>Vessel ID</th>
<th>Media</th>
<th>Location</th>
<th>Head Thickness</th>
<th>Inner Shell Material</th>
<th>Nozzle Material</th>
<th>Shell Material</th>
<th>Number of Layers &amp; Thickness (T1)</th>
<th>Number of Layers &amp; Thickness (T2)</th>
<th>Total Shell Thickness</th>
<th>Manufacturer</th>
<th>Year Built</th>
<th>Vessel Type</th>
<th>Vessel Volume</th>
<th>Operating Pressure</th>
<th>Design Pressure</th>
<th>Max All Working Pressure</th>
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<th>Length</th>
<th>Comments</th>
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<tbody>
<tr>
<td>V0362</td>
<td>Germano Hydrogen</td>
<td>453SA - TEST STAND 115</td>
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<td>SA-212 B</td>
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### Evaluation of Agency Non-code LPVs

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<th>Inner Shell Material</th>
<th>Inner Shell Thickness</th>
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<th>Shell Material</th>
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<th>Number of Layers &amp; Thickness (T2)</th>
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<th>Manufacturer</th>
<th>Year Built</th>
<th>Vessel Type</th>
<th>Operating Pressure</th>
<th>Design Pressure</th>
<th>Max All Working Pressure</th>
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**Title:** Evaluation of Agency Non-code LPVs

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<td>AOS 1146A</td>
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<td>Multilaminar</td>
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<td>AO Smith Spec 1146A</td>
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<td>5 (\geq) 250</td>
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<td>1.750&quot;</td>
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### Evaluation of Agency Non-code LPVs

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<th>Inner Shell Thickness</th>
<th>Noodles Material</th>
<th>Shell Material</th>
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<th>Total Shell Thickness</th>
<th>Manufacturer</th>
<th>Year Built</th>
<th>Vessel Type</th>
<th>Vessel Volume</th>
<th>Operating Pressure</th>
<th>Design Pressure</th>
<th>Max All Working Pressure</th>
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<td>Multilaminar</td>
<td>35 Cu. Ft</td>
<td>3,275</td>
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<td>AOS 1146 a</td>
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<td>A. O. Smith</td>
<td>1978</td>
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<td>Number of Layers &amp; Thickness (T2)</td>
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<td>Year Built</td>
<td>Vessel Type</td>
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<td>Operating Pressure</td>
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<td>Max All Working Pressure</td>
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<td>3.275</td>
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<td>1.750&quot;</td>
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<td>2.188&quot;</td>
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<td>35 Cu Ft</td>
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<td>MLP 1146</td>
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<td>Chicago Bridge &amp; Iron</td>
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<td>B FBX MOD</td>
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<td>CH &amp;I 1146</td>
<td>4 @ 1/4&quot;</td>
<td>7 @ 9/32&quot;</td>
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<td>0.500&quot;</td>
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<td>CH &amp;I 1146</td>
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<td>7 @ 9/32&quot;</td>
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<td>0.500&quot;</td>
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<td>AIS 1103 GRB</td>
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<td>Vessel Volume</td>
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<td>Design Pressure</td>
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<td>Diameter</td>
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<td>A. O. Smith</td>
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**Struthers Wells**

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- 300 Series 316 Stainless Steel 80/20 Piping and Valves
- 316 Stainless Steel 80/20 Piping and Valves
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**Gaseous Hydrogen - Facility AOS 212-G**

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**Gaseous Hydrogen - Facility AOS 212-B**

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<td>ASTM A105 CL 2</td>
<td>AOS</td>
<td>1140a</td>
<td>10 @ 0.277&quot;</td>
<td>N/A</td>
<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
<td>625 Cu. Ft.</td>
<td>3.100</td>
<td>4.400</td>
<td>3.142</td>
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<td>N/A</td>
<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
<td>625 Cu. Ft.</td>
<td>3.100</td>
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<td>A. O. Smith</td>
<td>1960</td>
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<td>625 Cu. Ft.</td>
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<td>ASTM A105 CL 2</td>
<td>AOS</td>
<td>1140a</td>
<td>10 @ 0.277&quot;</td>
<td>N/A</td>
<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
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<td>AOS</td>
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<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
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<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
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<td>AOS</td>
<td>0.46785&quot;</td>
<td>ASTM A105 CL 2</td>
<td>AOS</td>
<td>1140a</td>
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<td>N/A</td>
<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
<td>625 Cu. Ft.</td>
<td>3.100</td>
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<td>AOS</td>
<td>0.46785&quot;</td>
<td>ASTM A105 CL 2</td>
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<td>1140a</td>
<td>10 @ 0.277&quot;</td>
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<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
<td>625 Cu. Ft.</td>
<td>3.100</td>
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<td>N/A</td>
<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
<td>625 Cu. Ft.</td>
<td>3.100</td>
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<td>AOS</td>
<td>0.46785&quot;</td>
<td>ASTM A105 CL 2</td>
<td>AOS</td>
<td>1140a</td>
<td>10 @ 0.277&quot;</td>
<td>N/A</td>
<td>3.305&quot;</td>
<td>A. O. Smith</td>
<td>1960</td>
<td>Multilaminar</td>
<td>625 Cu. Ft.</td>
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<td>4.400</td>
<td>3.142</td>
<td>58&quot; ID</td>
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<td>Head Material</td>
<td>Head Thickness</td>
<td>Inner Shell Material</td>
<td>Inner Shell Thickness</td>
<td>Nozzle Material</td>
<td>Shell Material</td>
<td>Number of Layers &amp; Thickness (T1)</td>
<td>Number of Layers &amp; Thickness (T2)</td>
<td>Total Shell Thickness</td>
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<td>Year Built</td>
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<td>Vessel Volume</td>
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<td>Design Pressure</td>
<td>Max All Working Pressure</td>
<td>Diameter</td>
<td>Length</td>
<td>Comments</td>
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<td>A350-LF3</td>
<td>7&quot;</td>
<td>CH&amp;I</td>
<td>1/2&quot;</td>
<td>A350-LF3</td>
<td>CH&amp;I</td>
<td>10 @ 1/4&quot;</td>
<td>20 @ 9/32&quot;</td>
<td>8.830&quot;</td>
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<td>1965</td>
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<td>1/2&quot;</td>
<td>A350-LF3</td>
<td>CH&amp;I</td>
<td>10 @ 1/4&quot;</td>
<td>20 @ 9/32&quot;</td>
<td>8.830&quot;</td>
<td>Chicago Bridge &amp; Iron</td>
<td>1965</td>
<td>Multilaminar</td>
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<td>CH&amp;I</td>
<td>1/2&quot;</td>
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<td>CH&amp;I</td>
<td>10 @ 1/4&quot;</td>
<td>20 @ 9/32&quot;</td>
<td>8.830&quot;</td>
<td>Chicago Bridge &amp; Iron</td>
<td>1965</td>
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<td>9,400</td>
<td>15,000</td>
<td>10,000</td>
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<td>18' 9&quot;</td>
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<tr>
<td>V0001</td>
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<td>7&quot;</td>
<td>CH&amp;I</td>
<td>1/2&quot;</td>
<td>A350-LF3</td>
<td>CH&amp;I</td>
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<td>20 @ 9/32&quot;</td>
<td>8.830&quot;</td>
<td>Chicago Bridge &amp; Iron</td>
<td>1965</td>
<td>Multilaminar</td>
<td>100 Cu. Ft.</td>
<td>9,400</td>
<td>15,000</td>
<td>10,000</td>
<td>30&quot; I.D.</td>
<td>18' 9&quot;</td>
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</table>
Stennis Space Center (SSC)

SSC RFI Results for Non-Code Multilayered Vessels

1. List of vessels, manufacturer, age, general condition, rated pressure, operating pressure, application/contents, design details (materials of construction, wall and layer thicknesses, weld and nozzle locations, etc.), vessel history (purchased new or used, was it moved during service life, and if so, provide details).

See Chart. Material used in accordance with ASME Code Case 1204-9 for Struthers-Wells vessels.

1a. Prioritized list of vessels needing evaluation and basis for prioritization (e.g. particular application, known damage conditions, etc.)

Prioritization is based on Certification dates.

1b. Listing of unused vessels that might be available as testing resources and reasons not in use (e.g. damaged, no longer needed, etc.)

Railcar (V-072-GH): Cracks in the inner shell found during interval inspection. Leaks were noted at the weepholes.

Vessel (V-071-GH): Hydrogen leaks detected at three weepholes. Vessel has no manway so internal inspection could not be accommodated. Vessel removed from service in 1990.


2. History of NDE or other inspections/analyses related to continued usage.

Detailed NDE and in-service repair records archived for all Struthers Wells vessels since arriving in the mid-1960s. All vessels have recertification interval of 10 years. Vessel certification documents starts from the 1980’s.

2a. Description of inspection/analysis methods, schedule, etc.

All vessels have undergone at least one cycle of acoustic emission testing by various vendors since the 1980’s.

All welds are ground flush for inspection. Inspection of welds included projection scans, time of flight diffraction and manual shearwave were used on some vessels in 2004.

Projection scan is a projection of comprehensive B-scan data, which gives the side view of the inspected component. It is used for weld inspection with specialized probes, where the scan results is shown in projection of top, side and end view, providing a three dimensional visualization of the defect or corrosion. Different color codes are used to indicate the origin of each signal, together with its amplitude to facilitate analysis of the scans.

Time of flight diffraction is based upon diffraction and reflection of ultrasound. This increases the probability of detection since it is less affected by the angle of incident with respect to the orientation of
SSC RFI Results for Non-Code Multilayered Vessels

- The discontinuity. Discontinuities orientated perpendicular to the surface is also detectable as well as discontinuities in the weld fusion faces.

- TOFD was performed by Mistras. The contractor was aware of the multi-layered nature of the vessel.

2b. Information on the availability of inspection records (written or digital, summary presentations or detailed engineering reports, raw data available, etc.)

Inspection reports are kept in Central Engineering Files (CEF) and archived in digital and original formats.

3. Any currently used additional risk mitigation approaches (e.g. special inspections, limited operating pressures/cycles, additional materials testing or structural analyses, etc.) in general for these vessels, or specific to particular vessel(s).

All vessels are de-rated to a 4:1 design safety factor.

Although there are physical barriers, the locations of the vessels are somewhat isolated from inhabited building.

4. Any risk mitigation approaches used in the past, but no longer practiced

None.

5. Any risk mitigation approaches under testing, development, or evaluation (provide as much information as possible to include reports, presentations, proposals, reviews, etc.)

SSC is collaborating with MSFC and GRC to have a phased array UT procedure qualified by an outside contractor.

SSC is in the process of establishing a dual use technology transfer project with LSU to promote entropy as a material property used as a predictor of cyclic fatigue life. Awaiting funding approval from Office of the Chief Technologist. White paper submitted to you for review.

SSC is in the process of establishing a dual use technology with IRISNDT Matrix to develop technology that can use guided wave as a flaw detector in addition to wall loss. SSC hope this technology can be used to target non-intrusive inspection of nozzle penetrations. Funding secured through NASA NDE Working Group.

6. Any recommendations for risk mitigation approaches that should be considered, but have not been addressed due to limited opportunity, funding, expertise, manpower, equipment, etc.

None

7. Any special concerns that you have about the continued safe operations of these vessels that you think need to be addressed in this assessment and any follow-on efforts.
SSC RFI Results for Non-Code Multilayered Vessels

None for continued safe operation, but similar to MSFC in terms of intrusive inspection and its impact on contamination of these vessels.

8. Communications route to Center management on perceived global and specific vessel risks.

Multi-Layered vessel risks documented in IRMA, and is reviewed by SSC Management on a quarterly basis in a formal Program Management Review (PMR).
<table>
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<tr>
<th>Nameplate Rating (PSI)</th>
<th>Center's Design Pressure (PSI)</th>
<th>Operating Pressure (PSI)</th>
<th>Water Volume (ft³)</th>
<th>Age (yr)</th>
<th>Wall thickness (shell, total nominal, in.)</th>
<th>Number of Shell layers and thicknesses (nominal, in.)</th>
<th>Shell Materials of construction</th>
<th>Head thickness (in.)</th>
<th>Number of Head layers and thicknesses</th>
<th>Head Materials of construction</th>
<th>Comments (general condition, vessel history, known flaws, etc.)</th>
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<tr>
<td>3.750 (SF=4)</td>
<td>2,750</td>
<td>950</td>
<td>49</td>
<td>3.125</td>
<td>1 - 1.8125, 1 - 1.3125</td>
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<td>1.6875</td>
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<td>Vessel built for SSC, all inspection records and repair history maintained.</td>
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<td>49</td>
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<td>3.062</td>
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<td>49</td>
<td>49</td>
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<td>6,300</td>
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<td>SA-517F 'T-1 Steel'</td>
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</table>

Vessels built for KSC's Auxiliary GN Supply System and moved to SSC ~2010. Historical inspection data not currently on record.
Appendix C. MSFC Sacrificed Vessel General Information

General Vessel Information

The following tables and figures provide general information on V0032, V0125 and V0256. Vessels V0032 and V0125 are surplus vessels that were used for materials testing. The V0256 vessel is currently in service, and its configuration was used for analytical evaluation using finite element analysis and fitness-for-service evaluation. This information was collected from several sources, primarily from the packages available in MSFC’s PSRT (Pressure System Reporting Tool).

References: (work orders, reports, etc.)

Work order references: none
Reports: TI-13-00852 Evaluation of Agency Non-Code Layered Pressure Vessels
Evaluation of Agency Non-code LPVs

General Information

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<thead>
<tr>
<th>Vessel ID #</th>
<th>Vessel Serial Number</th>
<th>Media</th>
<th>Vessel Drawing Number</th>
<th>Manufacturer</th>
<th>Year Built</th>
<th>Cert Status</th>
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<td>M117</td>
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<td>1963</td>
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<td>M108</td>
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<td>Aug. 86</td>
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Size and Environment

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<th>Design Temp</th>
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<td>16 7 1/2&quot; overall</td>
<td>Ambient</td>
<td>5,500</td>
<td>3,933</td>
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<td>V0125</td>
<td>24&quot;</td>
<td>9' 10&quot; tangent-to-tangent</td>
<td>10 to 110 F</td>
<td>3,275</td>
<td>3,500</td>
<td>4,750 LBS</td>
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<tr>
<td>V0256</td>
<td>60' 1/4&quot;</td>
<td>60' 0&quot; tangent-to-tangent</td>
<td>120 F</td>
<td>4,280</td>
<td>5,000</td>
<td>199,000 LBS</td>
<td>1,250 Cu. Ft.</td>
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Head and Shell Information

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<th>Inner Shell Thickness</th>
<th>Nozzle Material</th>
<th>Nozzle Size</th>
<th>Number Of Nozzles</th>
<th>Shell Material</th>
<th>No. of Shells</th>
<th>Individual Outer Shell Thickness</th>
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<td>1.438&quot;</td>
<td>AOS 1146 x</td>
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<td>ASTM A105 GR.11</td>
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<td>2</td>
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<td>5</td>
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V0032

MSFC Vessel V0032

Vessel V0031 was manufactured by A.O. Smith Corporation. It is a vertical vessel (No. MV-50288-34) built on September 1962.

Surplus Vessels V0030's Series
Evaluation of Agency Non-code LPVs

V0125

NESC Request No.: TI-13-00852
Vessel V0125 in service

Vessel V0125 pre- and post-dissection.
V0256

MSFC Vessel V0256

Vessel V0256 was manufactured by CB&I in 1963 (serial No. M 108), and currently in service at MSFC, Building 4572 at the Propulsion and Structural Test Facility.
Evaluation of Agency Non-code LPVs
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Title: General Information on Layered Pressure Vessels
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Summary and Future Reporting Observations:

This report contains general information on three of the LPVs under evaluation. This information was obtained from the MSFC Pressure System Reporting (PSRT) and other databases. Vessels V0032 and V0125 are surplus vessels that were sacrificed to conduct materials testing. V0256 is a vessel in service, the configuration of which is being modeled for use in the analytical evaluation using finite element analysis and fitness-for-service evaluation.
Appendix D. Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment Presentation, February 28, 2014

The purpose of this investigation was to identify the approaches, material systems, and testing that will be required to evaluate MSFC Non-Code pressure vessel materials. A sacrificial vessel was identified for dissection, and preliminary testing has been conducted on various regions. This preliminary assessment is to aid in laying the groundwork and planning in the understanding of material properties of LPVs.

References: (work orders, reports, etc.)
Work order references:
Reports: TI-13-00852 Evaluation of Agency Non-Code Layered Pressure Vessels
The goal is to integrate build-history materials data with new evaluations of sacrificial vessels to build a modern materials database representing each of the materials of concern in the non-code layered vessels within the Agency.

Evaluate required fundamentals for each material system:
- Tensile
- Fracture toughness
- Fatigue crack growth rate
- Charpy impact (mainly for tie to historic data and comparison with modern code evaluations)

Material systems under current consideration:
- A.O. Smith class layered vessel materials
- 1143 inner liner, 1143/1143 weld, 1143/A225 weld
- 1146 outer liner, 1146/1146 weld, 1146/A225 weld
- A225 head material, A225/5002 weld
- 5002 nozzle forging

Weld microstructures
- Tests currently performed at weld centerline
- Need to evaluate fusion line and HAZ for each combination

Temperatures
- Each material system evaluation needs to be performed to understand the stochastic nature of the upper transition region of the Master Curve.
Test Methods

- **Tensile**
  - Standard ASTM E8 tensile evaluations
  - Assume base metals are isotropic; evaluate axial vessel direction
  - Test welds transverse [base/HAZ/Weld] and axially (Weld)

- **Fracture Toughness**
  - Standard $J_R$ per ASTM E1820, elastic-plastic $J$-R curve
  - Follow ASTM E1921 for effects of transition temperature
  - Review suitability regarding homogeneity and thickness scaling
  - Weld testing to consider new standards ASTM E2818/ISO15653

- **Fatigue Crack Growth Rate**
  - Standard $da/dN$ tests per ASTM E647

- **Charpy**
  - Standard Charpy per ASTM E23
  - Re-Evaluation of build-history data enabling key-hole to V-notch comparisons

Current Testing

- **MSFC Vessel V125**
  - CB&I, Liner plus 3 wraps
  - Typical construction

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Strain gage installation on Ring #3 prior to cutting and removing the 3 wrap cylinders around internal cylinder.
Strain measurements as layers sequentially cut

Cross-section micrograph of multi-pass axial shell weld

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment

Shell (Wrap #2)
Outer Shell (Wrap #3)

CP344-3-54
2012-0443
Approximate plane location of cracks for fracture testing.

In each weld, the centerline crack location was chosen due to the pronounced, coarse grain structure. HAZ or fusion line testing was not pursued due to limited material and resources.

Cross-section micrograph of multi-pass axial shell weld

Shell (Wrap #1)

Cross-section micrograph of multi-pass axial shell weld

Shell (Wrap #1)
Approximate plane location of cracks for fracture testing. In each weld, the centerline crack location was chosen due to the pronounced, coarse grain structure. HAZ or fusion line testing was not pursued due to limited material and resources.
Shell
Head
Approximate plane location of cracks for fracture testing.
In each weld, the centerline crack location was chosen due to the pronounced, coarse grain structure. HAZ or fusion line testing was not pursued due to limited material and resources.

![Graph showing Alloy MLP 1143 Mod Ultimate Strength](image)

![Graph showing Alloy MLP 1146 Yield Strength](image)
Approximate plane location of cracks for fracture testing. In each weld, the centerline crack location was chosen due to the pronounced, coarse grain structure. HAZ or fusion line testing was not pursued due to limited material and resources.
In each weld, the centerline crack location was chosen due to the pronounced, coarse grain structure. HAZ or fusion line testing was not pursued due to limited material and resources.
Approximate plane location of cracks for fracture testing. In each weld, the centerline crack location was chosen due to the pronounced, coarse grain structure. HAZ or fusion line testing was not pursued due to limited material and resources.

Fracture Toughness, The JIC Test

File: CP344-3-19T1   WO: 2012-0443   Matl: 1146   Specimen: CP344-3-19   Temp: 70F

Kq = 33781
Pm/Pq = 1.75

K analysis is not informative. Plasticity obscures crack extension.

Fracture Toughness, The JIC Test

File: CP344-3-19T1   WO: 2012-0443   Matl: 1146   Specimen: CP344-3-19   Temp: 70F

Jq = 169
Kjq = 73.4

All J-Δa data
Valid J-Δa data
J @ Pimax
JIc curve fit

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Fracture Toughness, JIC Test Summary (Preliminary)

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Fatigue Crack Growth Rate (Preliminary)

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment

Not Ready for Engineering Use

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment

Not Ready for Engineering Use
Fatigue Crack Growth Rate (Preliminary)

Charpy Impact Tests, 1143 Base Metal (Preliminary)
Summary and Future Reporting Observations:

Next Steps for Materials

- MSFC Vessel V32
  - A.O. Smith Vessel, similar size and construction to V125
  - Executing careful cut-up by saw

- Test Objectives
  - Evaluate temperature transition effects on toughness
  - Refine weld JIC test methods in welds, as possible
  - Utilize repeated tests to exercise E1921 methodology
  - Evaluate toughness in local microstructures in welds: HAZ, fusion line, centerline
  - Continue da/dN survey, [reduced emphasis versus toughness]
  - Re-focus on A225 head material and 5002 nozzle toughness
  - Expand Charpy testing to welds, U-notch/V-notch

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment

NESC Request No.: TI-13-00852

This report provides an update of the materials testing being conducted at MSFC in support of LPV assessments as well as the testing planned in support of this effort. Transition temperature evaluation based on ASTM E1921 is introduced as the method to be used in the ongoing materials evaluation. This material was presented at the LPV Technical Interchange (TIM) held MSFC on September 2013.
Material Testing

- Develop an understanding of Layered Pressure Vessel (LPV) materials' performance
- Develop needed data to understand the inherent variability in structurally significant material properties, including tensile and fracture mechanics behavior
- Collect data from all qualified sources to develop a diverse database across as many lots as feasible
- Determine if there are any meaningful differences between materials at vendor change (A.O.Smith to CB&I)
- Confirm tensile properties of base metal and welds to evaluate the integrity of design assumptions, e.g., base metal UTS and YS and 100% weld efficiency
- Investigate fracture mechanics data, primarily toughness, as a function of temperature due to brittle transition effects
- Utilize the "Master Curve" approach for toughness evaluation to maximize the information gained from testing.

Fundamental Properties

- Tensile properties collected at MSFC to date do not show expected margin over reported design strengths
  - Only reflects one CB&I vessel
  - Additional data becoming available from Ames/SwRI work and the "V32" A.O. Smith vessel cut-up
- Charpy Impact data remains of interest
  - Additional testing to be performed in addition to fracture mechanics tests
  - Develop understanding of historical data for U and V notches
  - Correlate to new transition data based on toughness
  - Relatively inexpensive
  - Considering move to instrumented hammer testing
Fracture Toughness

- Fracture toughness as a function of temperature is the most influential material property for vessel assessment.
- Testing in the size-limited materials provided by surplus vessels requires the use of elastic-plastic fracture mechanics.
- The fully ductile fracture toughness (upper shelf) and the transition to cleavage fracture (transition range) is of interest to our assessments.
- Some vessel materials may be in the transition range at our standard operating conditions (A225).
- Scatter in measured fracture toughness is expected in the transition range.
- Use of the Master Curve methodology from ASTM E1921 should facilitate the assessment of transition range test data.
- When welds are included, there are a significant number of materials to be evaluated – E1921 can assist in this.

Master Curve Background

- The master curve concept is used to describe the transition in fracture toughness due to cleavage mechanisms as temperature decreases to the lower shelf.

\[
K_{\text{c,med}}(T_{\text{m}}) = 30 + 70 \exp\left[0.019(T - T_{\text{m}})\right]
\]

For 1 inch thick specimens.

\[
T_{\text{m}} = 100 \text{ MPa} \sqrt{\text{m}}
\]
Master Curve Background

- A physics-based model to handle the data scatter problem

- Local stress and strain produces a dislocation pile-up which impinges on a grain boundary or carbide.

- Cracking of the carbide or the grain boundary introduces a microcrack which propagates into the matrix.

- The advancing microcrack encounters the first large angle boundary.

References:
Master Curve Background

- A physics-based model to handle the data scatter problem
- Weakest link statistics, two-parameter Weibull model

\[ P[J_c \leq J_i] = 1 - \exp \left( \frac{J_i}{J_c} \right) \]

Scaling parameter for 63.2% failure probability

Weibull slope (empirical)

Power of the model:
- Model fits most all ferritic/BCC steels with \( b = 4 \) and \( K_{max} = 20 \text{ MPa}\sqrt{m} \)
- This pre-establishes scatter expectation via the model’s Weibull slope
- Only need to test for the scaling factor, \( K_o \)
Master Curve Background

- Round robin data illustrating model independence of temperature for Weibull slope = 4 and $K_{\min} = 20$ MPa√m

![Graph illustrating data taken from the MPCI59S round robin activity, plotted in Weibull coordinates showing constant Weibull slopes independent of test temperature.](image)

Ref 2.

- Statistical size effect (length of crack front)
- Weakest length stats indicate that $P_f$ will be a function of the volume of material tested, therefore the length of the crack front is important.
- Thickness of specimen in testing
- Assumed or identified length of crack in structure

Test data must be normalized using the statistical model to an equivalent 25.4mm (1 inch) crack length to evaluate the Master Curve parameter, $K_o$ (and thus $T_o$)

$$K_{IC(x)} = K_{\min} + \left( K_{IC(1)} - K_{\min} \right) \left( \frac{B_1}{B_x} \right)^{1/4}$$
Master Curve Background

- How do we use the MC model? Fairly Simple...
- Test replicate specimens near estimated $T_0$.
- Size adjust data, then evaluate the scale parameter, $K_o$.

$$K_o = \left( \sum_{i=1}^{N} \left( \frac{K_{Jc(i)} - K_{min}}{N} \right) \right)^{1/4} + K_{min}$$

- Convert $K_o$, [63% CP] to $K_{Jc(med)}$, [50% CP]

$$K_{Jc(med)} = K_{min} + \left( K_o - K_{min} \right) \left[ \ln(2) \right]^{1/4}$$

- Calculate the $T_o$ for use in the Master Curve Equation

$$T_o = T_{ref} - \left( \frac{1}{0.019} \ln \left[ \frac{K_{Jc(med)} - 30}{70} \right] \right)$$
## Planned Testing Tasks

- The LPV team has agreed on three testing tasks for this initial assessment period.
- Head material fracture mechanics assessment.
- Shell base metals fracture mechanics assessment.
- Weld microstructural regions assessment.
- Each of these tasks will involve using the MC methodology.
- Existing data from previous assessments will play a role.
  - SwRI data on material orientation and impact energy versus temperature data provides significant background.
- Material sources currently available at MSFC include the CB&I vessel (V125) and A.O. Smith vessel (V32).

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Planned Testing Tasks

- Fracture testing will utilize two specimen types to accommodate material orientation limitations
  - Compact Tension
  - Charpy-sized 3-pt Bend

Planned Testing – Base Metal

- Fracture testing for the base metal tasks is now getting started on pathfinder specimens from V32
- Test matrices and cut plans are in development
- Final plans (accommodating the funded scope) will be determined after review of all available data
  - MSFC data – new pathfinder and prior
  - SwRI data – phase I and II
- Will establish clear plans by early October to share with team for concurrence
- Dr. Joyce will assist in planning scope for E1921 testing
Planned Testing – Base Metal

- Orientation more important than expected
- Test data from SwRI Phase II indicates strong dependence

A225 Head Material - Metallurgy

Looking into Radial Face

Looking into Meridional Face

Looking into Circumferential Face

Planned Testing – Weld Metal

- Fracture testing for the weld metal tasks is still in the planning phase
- Tests are planned to follow ASTM E2818 and ISO15653
- Scope involves investigating the varied microstructure around the various welds
- First step will be to evaluate the various welds of interest with metallography and microhardness traverses
  - Shell seam (1143, 1146, 1146a)
  - Head to shell (A225 to shell materials)
  - Nozzle to head (5002 to A225)
- Must decide/determine if screening weld locations for worst actor can be done at 70F or if low temperature tests are required
Examples of potential fracture planes to investigate

A225 Head

Inner Wrap

Multi-layer Wraps
Planned Testing – Weld Metal

- Weld metal metallography sections to be in work by early October
- Pathfinder testing of seam weld regions by mid-October

Questions?
Appendix F. MSFC Layered Pressure Vessel Analysis Activities/LPV Analysis Tool (LAPVAT) Presentation, March 17, 2014

MSFC's approach to the analysis of layered pressure vessels (LPV) has taken a multi-faceted approach. First, MSFC used finite element modeling to develop a big picture view of the mechanics of LPV's and understand the sensitivities of these structures. Next, MSFC has been actively developing approaches to take the core principals and philosophies of API 579 and apply them to layered vessel. This includes developing methods to adapt commercially available API 579 code analysis tools for use with LPVs. Finally, MSFC has been developing a software tool (LAPVAT) to quickly create finite element models of layered pressure vessels to support both the increase of understanding of LPV's and provide input to the existing API 579 code analysis tools.

Executive Summary: (Purpose and Result)

References: [work orders, reports, etc.]

Work order references:

Title: MSFC Layered Pressure Vessel Analysis Activities/ LAPVAT

NESC Request No.: TI-13-00852
Foundational Work

- The first step taken by MSFC in the analysis of the LPV was to take a simplified, conceptual vessel and create finite element models of several scenarios.
- Layer gaping, cracked layers, various finite element model boundary conditions, and thick-walled verses layered construction were all examined.
- The results of this work allowed MSFC to gain a better understanding of the mechanics of LPVs and begin understanding the relationship between layered vessels and closed form solutions for thick walled vessels such as the Lamé equations.

Examples of 2D models

Gaining Experience with API-579

At this point, the next step was to begin to use and understand the industry standard for fitness-for-service evaluations of monolithic pressure vessels, API 579. To do this, the first vessel examined was a monolithic tank located at MSFC. This tank was, for the most part, in line with what the authors of API 579 had designed the document for. An existing flaw was found in one of the welds and was evaluated using the Failure Assessment Diagram (FAD) approach, the residual stress policies, flaw re-categorization, and material property assumptions detailed by the specification. Now, with the experience in using API 579 (as well as the ancillary software tools), MSFC was ready to begin formulating an approach to adapting the API 579 ideas to apply to LPVs. The general process that was beginning to crystallize was:

1. Use the best quantifiable NDE (e.g. PAUT, circumferential expansion, etc.) to determine a rough estimate for flaw sizes and layer gaping estimates.
2. Estimate vessel stress state, by layer, based on NDE observations, vessel build records, vessel use history, etc.
3. Evaluate the fitness-for-service state for any known defects, defects below the estimated NDE inspection limit, and a representative bounding defect size distribution for un-inspectable welds.
Finite Element Modeling - LAPVAT

- Combined with what we learned through the initial finite element modeling phase and the first use of API 579 on a vessel, it became clear that each vessel would require a custom built finite element model. Building a finite element model of a layered pressure vessel is a time consuming task. Given the large number of LPVs at MSFC, it became clear that a tool to automate the creation of models based on parametric inputs would be a great time saver. Additionally, it would speed up the ability to investigate "what if" scenarios allowing MSFC to gain a better understanding of LPV mechanics. This spawned the creation of LAPVAT (Layered Pressure Vessel Analysis Tool). LAPVAT, developed internally at MSFC, is a Python script that interfaces with ABAQUS to create 3D layered pressure vessel models based on a number of user definable parameters.

- The model has contact surfaces between each of the layers and can be modeled with or without the longitudinal welds that form bridges between adjacent layers. Post processing of the model can be handled via the ABAQUS GUI or LAPVAT can generate an html report of model results from defined key locations. Using either method, the model results can then be broken down into layer-by-layer stress state and fed into the API 579 code evaluation software, with assumptions and adaptations for LPVs, to produce limiting flaw sizes for each layer.

Layered Pressure Vessel Analysis Tool (LAPVAT)

- Automated creation and post-processing of layered pressure vessel finite element models using the ABAQUS python interface.

- Developed and built in-house by MSFC/EM20

- LAPVAT allows the user to input the dimensions of the vessel, the number of layers, the layer gaps, the material properties, meshing parameters, internal pressures, temperatures, angular section size, and other parameters.

- LAPVAT uses these parameters to build a 3D model in its entirety complete with contact between layers. The user has the ability to modify some of the parameters via ABAQUS CAE.

- Greatly reduces the time required for detailed vessel analysis.

- Allows more time to examine parameters and develop a better understanding of the system.
LAPVAT Inputs

- Geometry
  - Head Thickness
  - Head Internal Radius
  - Shell length
  - Number of layers
  - Thickness of each layer
  - Gap between each layer on head-to-shell side and the shell-to-shell side
  - Weld width on top and bottom
  - Weld transition aspect ratio (for vessels with a larger shell OD then head OD)

- Load Parameters
  - Internal Pressure
  - Temperature

- Model Parameters
  - Materials
  - Job names
  - Mesh seeding parameters

LAPVAT Post Processing

- Automatically extracts stress profiles through predetermined locations for Hoop, axial, and radial stresses.
  Locations:
  - Head-to-shell weld
  - Shell-to-shell weld
  - Layers at the middle of segment

- Creates an html summary report of the data that can easily be imported in Excel or other software packages.
Example Results: 14 layer vessel with thicker inner liner layer, 60" ID, 4000 psi
Appendix G. ARC Modal Acoustic Emission Validation Effort Summary

Validation of AE for use on Layered Vessel Inspections

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1. Background

Since 2001, Digital Wave Corporation (DWC) has worked with NASA's Ames Research Center (ARC) to validate the use of their method of Acoustic Emission testing, which they call Modal AE (MAE) for volumetric examination of ARC's 16 large A.O. Smith multilayer pressure vessels which are used in high pressure (3000 psi), dry air service. Modal AE is based on complete waveform capture and analysis using broadband sensors as opposed to assessment of AE features and parameters as captured by resonant sensors, usually referred to as MONPAC AE. DWC's MAE work is documented in their inspection and test reports provided to ARC [Refs. 1 – 3], and their recent cyclic test report [Ref. 4] and in the raw data files retained at ARC for every test. DWC has also performed MAE examination of layered vessels for other NASA Centers since that time and other validation work may have been performed, but this appendix focuses on the work performed and documented for ARC. ARC's layered vessels are the among the largest known to exist in NASA's active inventory (1750 cubic feet, 90 feet long, 5 foot inner diameter), potentially making them the most difficult to test. These vessels have 16 inch manways, thus enabling test engineers to access their interiors, and relatively large diameter gas piping (6 inches) which minimizes flow noise during pressurization. Also, their remote sitting inside an earthen berm isolates the vessels from most environmental background noise. These factors afforded an ideal opportunity to perform in-situ validation testing of most aspects of AE testing in general and MAE in particular on these large layered vessels, the details of which are discussed in the following sections. However, the vessels are so large that performing cyclic pressure testing to achieve verifiable growth of an induced crack was not feasible. Thus, as proposed to NASA OSMA in 2011, when a much smaller vessel became available for such cyclic crack growth testing, DWC was tasked to perform what was intended to be the final validation test [Ref 4], but was only partly successful mostly due to incomplete knowledge (at the time of the test) of the higher toughness of the material used in the vessels and the resulting likelihood of lower than expected AE intensity (see discussion below), and
limited funding that precluded continuation of the cycling to obtain a crack closer to critical size with
(presumed) greater intensity acoustic emissions.

Other proprietary validation testing of the MAE method has been separately performed by DWC in
support of retesting DOT cylinders and submarine flasks, including that done as the basis for the award
of DOT Special Permit 15322 (in 2012) for periodic MAE retesting of DOT 3AX, 3AAX, 3T, 3AA, and 3A
cylinders [Ref. 5]. The original publicly available validation testing for generalized acoustic emission
testing for DOT cylinder requalification was performed by Blackburn and Rana as documented in their
1986 ASME paper [Ref. 6], and for submarine flasks by SwRI in their 1995 work [Ref. 7]. Both of these
efforts demonstrated the ability to use AE to identify and locate structural flaws and sub-critical and
critical size cracks in solid wall vessels composed of high strength material with only one or two
pressurization cycles. The SwRI work also demonstrated the ability to do so during cyclic pressurization
tests when run to leakage failure (with 12,000 + cycles). However, both [6] and [7] used the parametric
method that was available at the time, although the waveform analysis method was recommended by
SwRI in [7, page 96] to improve source location accuracy, which DWC has, of course, implemented in its
MAE method with waveform analysis. MAE is well suited for cylinder requalification and for this work
on layered vessels based on its ability to capture, analyze and time waveforms (for location analysis),
particularly with its use of low threshold sensitivity (32 dBae) for triggering acoustic event capture in the
frequency ranges of interest. The MAE method is also accepted by the DOT as evidenced by their award
of SP 15322 to DWC [Ref. 5] as discussed above, as well as the Navy as evidenced by their ongoing use of
DWC MAE technology for flask requalification, which is stated by DWC to be documented in proprietary
DWC reports.

The ASTM has also published many AE related standards that DWC follows as they apply to Modal AE.
These standards generally specify the underlying requirements for instrument calibration and system
performance testing, and are cited when the DOT and other customers specify AE tests. Several such AE
standards are discussed in the following sections, and are listed at the end of this Appendix [Refs 8 – 11].
ASTM E-1419-02b [9] is specifically cited in DWC’s special permit for cylinder requalification. ASME has
also incorporated many of these into the Boiler and Pressure Vessel Code, Section V, Nondestructive
Examination, including ASTM E-1419 [Ref. 9], which is included as Appendix 29 of Section V.

Plate wave AE has its theoretical basis in the physics of wave motion in elastic media as has been
documented by many including, but not limited to, Graff in 1976, Pao in 1978, and Goreman in 1991
[Refs. 12 – 14]. The basis for its implementation as the Modal AE (MAE) method is documented in
technical papers including that by Goreman in 1991 [14], but the details of its application to these much
larger layered vessels with different materials having generally lower strength and higher toughness
(e.g., AO Smith 114G6 shell vs. DOT spec material similar to SAE 4130, and MIL spec flask material; see
SwRI phase 1 and 2 reports in [15] and [16] vs. data in [6] and [7]) had not been previously documented.
Therefore, ARC requested that DWC perform as much validation testing as feasible within time and
budget constraints, and that work is summarized in this section and documented in the cited test
reports. As a result, the only primary aspect of MAE application to these vessels that had not been
validated was the detection of an actual growing crack in an in-service vessel, or the correlation of the
MAE signals received to the crack size or nearness to criticality. This could not be done on the in-service
AO Smith layered vessels due to their size and the first such known validation test for cyclic crack growth detection in a layered vessel was by conducted by DWC in 2011 – 2012 on the much smaller layered vessel (44 cubic feet) obtained from KSC as documented in the body of the 2012 DWC report [4].

Since the four validation tests described below were successful and established the viability of plate wave AE transmission, data capture and waveform analysis in these noisy vessels, and since the fundamental ability to detect sub-critical cracks in metallic vessels had already been demonstrated by others on solid wall vessels, the engineering judgment of both DWC and the ARC pressure systems manager was that the MAE method could be used as a periodic inspection tool to determine whether any relevant, growing cracks existed in the vessels. It was understood from the beginning that “relevant” meant significant, and if any such crack indications had been found, the vessel(s) would likely have been removed from service since there is very little ability to perform any other NDE to fully and reliably characterize anything other than outer layer surface-connected cracks. However, none of the vessels tested by at ARC exhibited relevant crack growth characteristics, which also meant that none could be further examined or extracted to validate the AE indications. ARC therefore concluded that a test with a known, fully characterized growing crack was required, which lead to the work discussed in the 2012 DWC report [4].

The previous validation testing for layered vessels focused on the following issues.

1. Pencil lead break system performance tests
2. Validation of Acoustic Emission propagation through layers
3. AE plate wave velocity dispersion characteristics on layered vessels
4. Validity of background noise discrimination capability and threshold sensitivity

Each is discussed in the following sections.

2. Pencil lead break system performance tests

ASTM Standards for acoustic emission testing require system performance verification, with the standard Hsu pencil lead break (0.3 mm, 2H hardness, 3 mm long lead) common among them. In addition, DOT Special Permits for AE requalification of gas cylinders, including DWC’s SP-15322 [4], require that ASTM E-1419 [9], Examination of Seamless, Gas-Filled, Pressure Vessels Using Acoustic Emission, be followed. The pencil lead break (PLB) test ensures that a sensor is properly coupled to the vessel, demonstrates a predetermined level of response to the induced stress wave, and provides the opportunity to demonstrate that the AE system source location algorithm is working properly. The test inherently assumes that the AE resulting from PLBs is representative of the AE from an actual flaw or crack growth, and hence demonstrates that the AE systems can receive and locate growing cracks. This is documented in section 9.3 and 9.4 of ASTM E-1419 [9] and was explicitly stated in section 9.3 of ASTM E-569 – 1997 [6] in the past, although the stated comparison to flaw signals has been removed from the
current 2013 edition. E-1419 also requires that there be no background noise above the “signal processor threshold setting”, which should be 32 dBV as shown in Table X1.2 of the E-1419 Standard. The threshold sensitivity setting is discussed further in section 4 below concerning noise discrimination.

The E-1419 PLB test is also to be performed within 4 inches of each sensor. A PLB so close to a sensor does not, by itself, verify much more than sensor coupling to the vessel because this actually results in a relatively large (loud) acoustic event. The amplitude of these lead breaks usually exceeds the range of the nearest sensor with a 32 dBV threshold. Thus, a more meaningful test for performance and sensitivity on these vessels is how far away the E-1419 lead break can be detected and accurately located by the AE system. On small diameter tubes such as DOT cylinders, location analysis can be achieved using only two sensors as prescribed by E-1419 since only the linear position along the tube is required (further UT examination of the full circumference is subsequently required), but for larger diameter cylinders such as these vessels, wave capture by three or more sensors is required to perform triangulation for source location determination. SwRI also concluded in [7] that at least 8 sensors were required even on DOT cylinders and Navy flasks to achieve reasonable accuracy in flaw source location. Indeed, since crack identification depends partially on identifying clusters of emissions during repeated pressure cycling, the ability to locate emission sources accurately and quickly around the entire circumference is essential.

Therefore, the distance over which we were able to capture and accurately locate the pencil lead breaks was documented on the layered vessels at ARC. It was shown in the referenced reports [1 - 3] that DWC’s system will typically record and locate the outer surface lead breaks over 15 ft. from the break source using the typical 5 - 7 foot sensor spacing. When the PLB is performed on the sidewall of a part-through core-drilled hole in the vessel wall (as was provided by ARC on vessel #32 [Ref. [2], which was later renumbered vessel 12], the extensional mode is much stronger and can be captured and located more than 40 ft. from the PLB. This is documented in each of the ARC test reports and can be reproduced by running the raw data through DWC’s WaveExplorer® software (for which ARC maintains a licensed copy). Lead breaks were also performed as standard practice inside the 3½ inch vent holes that are present throughout the vessel to demonstrate location algorithm accuracy since the vent holes are at known coordinates in each vessel. The demonstrated accuracy for sensor and vent hole locations is usually +/- 3 to 6 inches on the shell and heads, and rarely as high as +/- 12 inches, as is documented in the test reports. If the threshold sensitivity were increased to 40 – 45 dBV for this system (as was done in done in the 2001 MONPAC test at ARC, Ref [17], the ability to detect PLBs at remote distances would decrease significantly, but this was not specifically documented.

Finally, lead breaks were performed from the interior surface of vessel 32 in the 2002 test series [2] to demonstrate that sound transmission would carry completely through the 9 layers of ARC’s vessels (2.635 inches total thickness) and still be captured and located by the exterior surface mounted sensors. This was successfully demonstrated, as documented in Figure 4 of Reference [2], which shows slightly greater attenuation than for the outer surface breaks, but still with 14.4 foot detection capability.

It was concluded that the ASTM E-1419 PLB is an equally valid system performance test for layered vessels similar to those at ARC, and that it is also a valid test of source location capability at remote
sensors. It is also noted that, as shown in the current cyclic crack growth tests, that flaw-induced and crack growth emissions are much smaller in energy content than PLBs, and the ability to record and locate PLBs does not in itself prove that an AE system will detect flaws.

3. Validation of Acoustic Emission propagation through layers

As discussed above for pencil lead break tests, captured AE waveforms for PLBs on the inner vs. outer surfaces of these 2.635 inch thick layered vessels showed only slightly greater attenuation for inner surface breaks due either to the greater distance they travel through the thickness, or as a result of the internal surface corrosion coating, or both. Otherwise, they were virtually indistinguishable from outer surface PLBs. When lead breaks are performed on the side walls of the cored hole in vessel 32 or in a vent hole [2 and 3], or in the cored hole in the cyclic test vessel [4, Fig. 5], the elongation mode is much stronger due the in-plane excitation, and there is virtually no dependence on how deep (which layer) the lead break is performed in terms of how far away it can be captured and located by the AE system. One typical core-response lead break plot is shown in Figure 3 of Ref. [2], and complete data is contained in the binary data files that were saved from the tests, which ARC has for use with their licensed installation of DWC’s WaveExplorer® software.

From these tests, it was concluded that the layers, at least on vessel 32 and the cyclic test vessel, were in sufficiently tight contact that they have no apparent effect on the ability of the vessel shells to transmit acoustic energy released by a lead break. Since there were no other core-holes on any other vessels, and no other internal surface PLBs were performed, it could not be conclusively stated that all layered vessels would exhibit the same AE transmission behavior, although ARC has performed other circumferential expansion tests in accordance with ASME Section VIII, Part ULW that indicate that the layers are, in fact, tight on all vessels measured. Thus, it is concluded that the vessel layers are generally identical to solid wall vessels in terms of AE propagation, and the expectation is that crack growth emissions would similarly be transmitted. While crack growth AE transmission through layers was not explicitly demonstrated on the cyclic test vessel since both the crack and sensors were on the outer surface, it is a reasonable conclusion to draw.

4. AE plate wave velocity dispersion characteristics on layered vessels

Acoustic wave velocity must be accurately known in order to be able to locate AE sources in vessels being tested. However, there are two principal modes of propagation (in-plane and out of plane), and each has a significantly different velocity. Only waveform analysis is able to distinguish which mode is being measured and determine the correct velocity for use in source location algorithms. As discussed previously, plate wave theory has been extensively documented in the technical literature. As opposed to bulk waves in essentially infinite elastic media, such as seismic waves in the Earth, when a plate wave’s wavelength is less than the thickness of the plate it is propagating in, two primary modes of propagation are developed, in-plane (elongation) and out of plane (flexure). The velocity of propagation in a plate is dependent on plate thickness and the wave frequency, and the two plate modes have
different frequency dependence, and thus there are separate dispersion curves for each. These are shown in Ref. 1, Fig. 3, and are reproduced below for 0.25 inch steel plate.

Dispersion curves for 0.25 inch thick steel plate. The extensional mode curve is on the left; the flexural mode curve is on the right [Ref. 1]

Therefore, in 2001 and during every test since, DWC determined which wave mode was being timed during the PLB tests (elongation, since it is faster and arrives first), and calculated it’s velocity based on the time of flight from the break location to a remote sensor that captured the acoustic wave. They then determined the frequency of the waveform that was captured. The first arriving elongation mode velocity was measured to be about 4600 m/s (Ref 1, page 4), and this was verified in the subsequent tests at ARC with some variation up to about 5200 m/s. As stated in the 2001 test report, Section III, it was initially unknown whether a plate wave resulting from a surface lead break would travel only in the outer layer or through the entire thickness of the vessel. The first arrival wave was measured to have a frequency of 23 kHz. From the dispersion curve for a ¼ inch plate (shown above on the left), the theoretical extension mode frequency is 5400 m/s and flexure mode is 2100 m/s, vs. the 4800 m/s velocity actually measured. However, the dispersion curve for a 2.75 inch thick plate (see below) shows the extensional mode velocity to be 4800 m/s, very close to the measured 4600 m/s, and a flexure mode velocity of 2500 m/s.

In the 2002 test, the measured velocity was reported to be 5156 m/s [Ref. 2, page D-2, reported as 203,000 inches per second]. At this vessel thickness in the 20 kHz range, the frequency dependence is becoming flat, and there is some level of inherent error involved in taking these measurements. The measurements were also taken at different locations, and it is possible that a small layer gap may have locally changed the propagation characteristics. What is clear is that the appropriate velocity to use for location analysis is that of the elongation mode rather than the flexure mode, and that if crack emission characteristics are seen, additional velocity measurements should be made to ensure that the correct location analysis is being performed.
Dispersion curves for a 2.75 inch thick steel plate. The extensional mode curve is on the left, flexural mode curve is on the right [Ref 1, Fig 4]

As an additional check on validity, the wavelength can be calculated based on the propagation frequency and velocity. For this case, wavelength = velocity / frequency = 4600 m/s / 23,000 Hz = 0.2 meters, or 7.9 inches. Thus, since the wavelength is much larger than the plate thickness, plate modes rather than bulk wave propagation should occur.

Thus, it was concluded that the first arriving wave, which is an extensional mode based on the measured waveform characteristics, was propagating at an appropriate velocity for a solid wall vessel, and that the thinner layers did not significantly affect the propagation characteristics of the plate waves.

5. Validity of background noise discrimination and threshold sensitivity

A common problem in testing layered vessels is that they generate a significant amount of nonrelevant noise as compared to solid wall vessels. This causes particular problems for parameter based MONPAC systems since the severity classification scheme by itself cannot discriminate between noise and relevant events, and in the reports reviewed by the ARC Pressure Systems Manager (PSM), the requirement to perform follow up NDE is usually stated as necessary to confirm whether the apparent severe findings in fact represent significant defects. Modal AE attempts to deals with this through waveform analysis since relevant in-plane crack growth will exhibit elongation mode waves that travel faster than nonrelevant flexure waves from corrosion particle cracking, etc. However, the quantity of noise captured in a particular system is directly related to the system threshold setting as discussed elsewhere, and a significant amount of attention was paid to whether relevant signals could be distinguished, if they existed, using the E-1419 32 dBV setting, rather than increasing the threshold to screen out noise, and also, possibly, low amplitude relevant signals.
The threshold setting for triggering AE data capture is set by instrumentation gains for the sensor, preamplifier, signal and trigger. Higher threshold settings = lower sensitivity = fewer AE events captured. ASTM E-1419 requires that there be no background noise above the "signal processor threshold setting" [Ref 9, para. 10.6], which should be 32 dBV as shown in para. X.1.2 and Table X.1.2 of the E-1419 Standard (see note on dBV vs. dBAe below). Although X.1.2 is in a non-mandatory appendix, it is stated in para. X.1.2 that the settings in Table X.1.2 are based on "criteria for determining the need for secondary examination" "while working with the equipment and setup conditions listed in Table X.1.2", and it is thus effectively a requirement. The standard for continuous AE monitoring, ASTM E-1139 [Ref. 8], states that "As a guideline, acoustic emission system response to continuous process background noise should not exceed 35 dBAe." In either case, the concept is that a signal that is 32 dBV (or dBAe, see below) greater in amplitude than the reference voltage (1 microvolt) at the sensor attached to the vessel must trigger the system for data capture, and any acoustic energy below that threshold will not. The ASTM E-1419 threshold of 32 dBV was used for all DWC MAE tests for ARC as well as in their submittals for their DOT special permit [5].

**Note:** In AE Testing, dBAe as defined in ASTM E-1316 is a logarithmic measure of acoustic emission signal amplitude, referenced to 1 µV at the sensor, before amplification. Unlike electrical dB, it is a 20log₁₀ base from the reference signal, rather than 10 log₁₀. Hence, a 20 dBAe gain is a signal amplification of 10x. It is not known why ASTM E-1419 retains the notation dBV rather than dBAe, but they appear to be equivalent based on the examples of usage provided in the Standard.

As stated above based on testing experience, a significant amount of non-relevant noise is generated by a layered vessel during pressure testing, and much of it exceeds the 32 dB threshold for the DWC system. This noise is usually attributable to breaking or crushing of brittle corrosion particles, weld layer wash slag breaking, shell layers sliding, sliding plates on un-anchored supports, fluid flow noise, or other external events such as dust particles striking the vessel in windy environments, as referenced in many technical papers including [7] and from the ARC PSM's personal experience. Discrimination of non-relevant noise from relevant crack growth emissions is accomplished through modal wave analysis in DWC’s MAE method, along with assessment of event clustering and recurrence after first pressurization cycle (which could be caused by crack face contact or rubbing). Since stable, ductile crack growth is known to have low energy AE emission as evidenced by the DWC tests and documented by others including Ref. 7, the lowest threshold setting achievable without overwhelming the AE recording and analysis system is essential since large amplitude emissions apparently only occur for large cracks that are near critical size [Ref 7, page 63]. Based on the ASTM E-1419 requirement and the DWC experience with layered vessels, 32 dBAe is the lowest achievable threshold setting. If a higher threshold are used, more background noise will be eliminated from the data capture, but it is less likely that low amplitude stable crack growth emissions would be captured, and only near-critical crack emissions would potentially be received, although the correlation between crack size or its nearness to criticality has not yet been established.
It can be seen in the test reports and raw data for the ARC tests [Refs 1 - 3] as well as the most recent cyclic test report and data [Ref 4] that DWC may capture more than 10,000 events on a standard vessel test, although most ARC vessels recorded in the range of 3000 – 4500 events. Each of these events is accessed and evaluated for elongation mode content that could be indicative of in-plane crack extension, and the location plots are evaluated for event clustering and recurrence during the second pressure cycle when corrosion breakage events are significantly less common. While elongation modes are evident in the surface and side wall PLBs, very few elongation mode waveforms were seen in any of the vessel pressure test data. In the 2002 tests, vessels 22 and 29 did emit some small amplitude elongation mode waves, and they were investigated by forming dense arrays of sensors around suspect areas. One was at a shell drain nozzle, and one was in the mid-region of a shell plate. Upon retest, the emissions became flexural, and the initial findings could not be reproduced. Therefore, if the initial emissions were due to crack growth, it was certainly in the stable growth region, and not an immediate cause for concern. When the vessels were retested in 2009, no similar crack-like emissions were recorded.

When compared directly to a typical parametric AE test (MONPAC), as was done in 2001 at ARC, DWC’s threshold at 32 dBV typically records about 10 times the number of AE events as does a MONPAC system using a 45 dBV threshold setting as was done at ARC in 2001 [Ref 17], although additional filtering in the MONPAC system may also account for some of the reduced event count. This lower threshold setting also appears to be why DWC’s system will capture and record PLB signals over a much greater distance than a MONPAC system, although controlled tests of this have not been specifically documented.

From their 2011 – 2012, cyclic test work, DWC also demonstrated the ability to discriminate a very low energy acoustic emissions from the active crack induced to grow in the vessel outer shell [Ref. 4]. It is therefore concluded that DWC’s MAE method has the inherent ability to capture and evaluate meaningful data at the 32 dBV threshold setting with their current instruments and sensors, although the level of effort expended in doing so in [4] for a stable, noncritical crack, means that more validation testing is required to establish the actual correlation between crack size or criticality vs. captured AE waveform.

6. References

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Appendix H. Southwest Research Institute Testing Summary

Summary of Crack Growth Cyclic Testing with Waveform AE Monitoring, and Southwest Research Institute (SwRI) Materials Testing on AO Smith Vessel MV/50466-8

D. R. Fraser, Ames Research Center Pressure Systems Manager

A. Summary

NASA’s Office of Safety and Mission Assurance (OSMA) funded two research programs between 2011 and 2013 for validating the ability of waveform acoustic emission (AE) testing to detect growing cracks of a non-code layered vessel subjected to cyclic pressure loading, for determining the fracture toughness and fatigue crack growth properties of the principal material components in NASA’s fleet of such active pressure vessels, and for demonstrating the ability to perform linear elastic fracture mechanics calculations of the initial flaw in the test vessel to accurately predict the number of cycles to failure, consistent with actual crack growth results observed in the field testing.

In summary, waveform AE was shown to be able to detect the actual growing crack under field test conditions, although the crack exhibited lower acoustic energy release than expected and was essentially at the threshold of detectability for the AE system being used, and would likely have been missed in a standard production field test [Ref. 4, Executive Summary and Section 7]. The test vessel crack was later determined to be no more than about 25% of critical size (as through crack) [Ref 16, Section 4.7], and it is clear that a larger crack (closer to critical size) is needed to firmly establish the AE detection vs. remaining safe life validation that had been sought [Ref. 4, Section 7 and Ref. 7 page 63].

With regard to material properties testing, a significant although not all-encompassing suite of fracture data was obtained, which was shown to be sufficient to accurately predict crack growth a shell layer. However, these tests were only done on one vessel and only one head of that vessel and no nozzles, thus a significantly more diverse sampling is necessary to ensure the material properties obtained encompass those in NASA’s fleet of vessels. In addition, there was, surprisingly, some very low energy absorption and zero or very low lateral expansion observed in many of the Charpy impact tests at low temperatures (0 to -20 F) indicating the potential for brittle fracture at low operating temperatures. However, the nil-ductility temperature was not established with this test series, and additional testing to establish the nil-ductility and transition temperatures, which is currently being undertaken by MSFC for at least one sample of material from a different vessel. Also, inspection of etched shell sections determined that the directionality of the mill rolling direction varied, which was unexpected. In some cases the shell circumferential direction was determined to be the plate longitudinal direction, while in others, and particularly the outer shell of this vessel, the vessel longitudinal direction was also the plate longitudinal direction. The effect of this, because of the extremely low CVN and ductility in the transverse direction, may explain the cracks most commonly seen in layered vessels of this vintage, which are located within the shell material, longitudinal to the vessel, and are generally in the vicinity of the head to shell weld. Nonetheless, fracture mechanics calculations using NASA’s NASGRO program were successful in replicating the field test results using the new material properties at the higher ambient conditions.
The following describes each aspect of the research and testing program, with references to the contractor reports that document the work in detail.

B. Project Overview

In 2011 and 2012, NASA’s Office of Safety and Mission Assurance (OSMA) funded proposals from Ames Research Center (ARC) to perform cyclic crack growth and waveform acoustic emission (AE) validation testing on an A.O. Smith layered pressure vessel. Two surplus vessels were obtained from Kennedy Space Center (KSC) for this purpose (one a backup). The vessel selected for testing, serial number MV50466-8, was 7 ft. long, 36 inch outside diameter, with 12 total shell layers and 2.5 inch thick monolithic hemispherical heads. Following the cyclic pressure and AE testing by Digital Wave Corp. using their Modal AE method (which is their terminology for waveform based AE), the vessel was transported to Southwest Research Institute (SwRI) for material fracture toughness and fatigue crack growth testing using modern ASTM-standard methods and protocols. The only previous toughness and fatigue crack growth data available was obtained at LaRC in 1975, and while excellent for the time, due to data scatter, narrow load range, and undocumented ASTM protocol validity, was not considered adequate for high confidence remaining life analyses. Using the new SwRI data, the objective was to validate the ability to perform accurate fracture mechanics (FM) analyses on the outer shell layer of this type of vessel. This was achieved, with good correlation between the field test and predicted crack extension, as discussed later.

Digital Wave Corporation (DWC) performed the cyclic crack growth and waveform AE tasks at their facility in Centennial, CO. Their report, entitled, “Cyclic Crack Growth Testing of an A.O. Smith Multilayer Pressure Vessel With Modal Acoustic Emission Monitoring and Data Assessment”, Digital Wave Corp., 11/13/2012 [Ref 4]. Briefly, a total of 4,688 pressure cycles were applied at stress levels ranging from 1/2 yield to yield on the outer layer. The acoustic crack extension signal exhibited lower energy with minimal or no elongation mode characteristics proved to be difficult, but not impossible, to extract from the background noise inherent in these vessels using the ASTM E-1419 standard 32 db signal threshold [Ref 9, Appendix X]. Previous work, such as that discussed in Ref. 7 (page 63) has shown that the crack would have to have been closer to critical size (it only used about ¾ of the available life cycles) to obtain the originally expected level of AE signals and to provide the hoped-for AE vs. remaining life correlation. The crack signal likely would have been missed in a standard production field test, although improved filtering based on frequency content from this work will improve the probability of detection in future AE tests [Ref 4, Sections 6 and 7]. The NASA test manager originally judged that the induced crack would be close to critical based on the then-existing test data produced by Langley in 1975, but it was later determined that the material was tougher than previously documented [at the test temperature] and the crack did not approach critical size. Unfortunately, the cyclic test had to be terminated due to funding limitations, and further work is needed to correlate the Modal AE signal strength to crack size and relevance to structural integrity. Nonetheless, the fact that waveform AE could detect the growing crack is, in itself, significant since it establishes the validity of using the waveform AE method in general for these vessels, and the potential of the method to detect growing cracks in covered layers and in other vessel regions that are not currently accessible with high
confidence to any other form of nondestructive examination. This had not been previously accomplished for any layered vessel. Full details of the AE testing are provided in the cited DWC report.

Following the AE testing, the vessel was shipped to SwRI in San Antonio, TX in April, 2012 for sectioning and destructive testing of material specimens. This work is documented in the SwRI report dated November 6, 2012, “Revised Final report, Southwest Research Institute® (SwRI®) Project No. 17408, Multilayer Pressure Vessel Materials testing and Analysis (Phase 1), Ref. 15. The extent of SwRI’s Phase 1 work was substantially limited by the budget remaining from the cyclic testing at DWC, and was narrowly focused only on the outer shell and one head at ambient temperature. The principal objective was to obtain sufficient toughness (Kc) and fatigue crack growth (FCG) data to facilitate performing accurate fracture mechanics (FM) analysis of the shell crack, with chemical analysis, tension testing, and Charpy V-notch (CVN) impact testing also performed for completeness and for reference comparison with ASME Code requirements. In addition, in order to establish the accuracy of the FM analysis, SwRI was also tasked to perform fractographic analysis of the notch and cracked section for comparison to the calculated FM results. Since SwRI is the Space Act Agreement program manager for NASGRO development, they were tasked with the engineering work to both perform an FM analysis using available NASGRO models, and to determine what additional NASGRO development work would be required to facilitate routine FM analysis of these vessels, once sufficient material data is available.

Following the Phase 1 work, NASA OSMA funded a follow on Phase 2 materials testing effort at SwRI using material remaining from the same vessel. This work is documented in their report “Multilayer Pressure Vessel Materials Testing and Analysis (Phase 2), Final Report (Revision 01)”, September 2013, [Ref. 16]. Informed by the Phase 1 results, NASA and SwRI developed a test matrix for obtaining CVN, elastic and elastic-plastic Toughness (K, J), and FCG data on the highest priority parent material (PM), weld metal (WM), and heat affected zone (HAZ) material for the head, shell, and one head-to-shell weld (there were no shell-to-shell welds in the test vessel). In addition, testing at reduced temperatures was specified, the intent being to help identify transition temperature and / or lower shelf properties, which is critical for thick sections of low toughness material, and material operating in cold environments. However, limited funding precluded SwRI from obtaining the transition temperature or API 579 reference temperature under this task, although that is now being pursued by MSFC. Tensile and yield properties were also obtained at the colder temperatures. In addition, hardness properties were obtained since there is some basis for correlations between hardness and tensile properties and possibly toughness, and hardness is easy to obtain in the field, but further exploration of the data was not funded in this work.

The test matrices are shown in detail in the SwRI Phase 2 report, along with detailed results. The appendices of that report contain all of the detailed test records. Note that no testing was performed on VMS 5002 nozzle material.

A) Summary of results: Phase 1 Testing at SwRI (see report dated 11/6/2012)

1) Chemical Analysis:
   The shell plate met the material compositional requirements for the AO Smith 1146a
specification at the time of construction (1959) other than Vanadium, which was not measured. Since 1146a was a proprietary specification never incorporated into the ASME Code or listed by ASTM, the AO Smith specification is the applicable standard. The head met the ASTM A-225 Grade B specification in effect at the time of construction, although it contains less nickel than required in the current ASTM specification.

2) Crack Fractography:
As stated above, the initial test on this vessel involved pressure cycling to grow a crack from a radiused starter notch. The initial notch was 2.01 inches long and 0.172 inches deep, which was about 70% through the thickness of the shell layer. The resulting final fatigue crack was 1.78 inches long. A stereomicroscopic image of one surface of the crack is shown below.

![Crack Fractography Image]

The initial surface crack (SC) growth exhibited typical non-critical fatigue crack extension which was followed by rapid crack extension and ductile fracture through the remaining small ligament. This coincided with the yield-level stress at the end of the test series, and although the crack transitioned to a through-crack (TC) at this point, there was no further crack growth since the test was terminated. A suite of scanning electron microscope and stereomicrographs are available in the Phase 1 report.

3) Tensile testing (ASTM E8):
1146a shell and A-225 Gr. B head material were pull tested to obtain yield strength, ultimate tensile strength, ductility, and area reduction, and these results were compared to the 1975 Langley data. There were no significant surprises, and the test data were in reasonable agreement given that there is significant uncertainty in the actual source of the Langley material. Both materials were also within the ranges called for by their respective specifications.

4) Charpy V-Notch (CVN) impact tests (ASTM E23):
CVN tests were conducted at room temperature (RT) and -20 F for both 1146a and A225-B. Although this is insufficient to determine the ductile to brittle transition temperature, all tests showed significant impact energy loss at -20 F. The current tests also show significantly lower values at -20 F than reported by Langley, and in fact, are indicative of brittle fracture in both materials. Examination of the fracture surfaces also indicates that they experienced brittle fracture at -20 F. The large discrepancy with Langley data is unexplained due to insufficient...
knowledge of the details of the 1975 tests.

5) Plane strain fracture toughness (K1c) tests (ASTM E399):
The shell layer material is too thin to support K1c testing, and plane strain toughness testing was only attempted on the thick A-225B head material. However, this was not successful due to apparent relatively low yield strength and apparent toughness, and it was concluded that plane stress, elastic-plastic J-R toughness testing was required. See Phase 2 results below for more information.

6) Plane stress (K-R) fracture toughness testing (ASTM E561):
K-R plane stress toughness testing was performed at RT and -20 F for the thin shell material to obtain Kc toughness values. Developing the crack growth resistance curve and plotting the tangent curve at critical load establishes the plane stress fracture toughness, Kc, which is specific to the thickness tested. The values of Kc (in units of ksi\(\sqrt{in}\)) were very close (90 at RT vs. 86 at -20 F), and also similar to the values reported by Langley. However, the Langley values were reported to have been obtained from ASTM E399 testing (which was unsuccessful now, see above) and were identified as K1E elastic fracture toughness, which is not consistent with current practice. Hence, the favorable comparison to LaRC data is questionable.

7) Fatigue Crack Growth (FCG) testing (ASTM E647):
FCG testing, which results in crack growth per cycle (da/dN) plotted against delta-stress intensity (\(\Delta K\)) for that cycle was performed on outer shell layer 1146a material and A-225 Grade B material from one of the vessel heads. The load ratio “R” for all FCG tests in Phase 1 was 0.15, and temperature was ambient RT. R = 0.15 was chosen for Phase 1 because matched the large majority of the pressure cycles applied to the vessel. Both constant amplitude and K-decreasing testing was performed to characterize both the larger crack and the near threshold regimes. The results for 1146a and A225-B are very similar. In the large crack growth region near failure, test data became invalid for the specimens used, and further testing is required to adequately characterize this region. The SwRI data was also compared to the 1975 Langley data, and while they were generally consistent, the SwRI data does demonstrate that the recommended Barsom equation from the LaRC report is unconservative in that virtually all SwRI data points lie above the LaRC data and Barsom curve line.

8) Fracture Mechanics Analysis of Flaw in Outer Shell using NASGRO
A primary objective of the Phase 1 cyclic testing and materials characterization work was to determine whether linear elastic fracture mechanics (FM) as developed in the NASGRO program could accurately predict the crack growth that was seen in the test vessel as a result of pressure cycling.  NASGRO is owned by NASA but is developed under a Space Act Agreement by SwRI, and its licensed use is free to NASA. However, NASGRO has not been extensively developed for pressure system applications since its primary outside funding community is in the aerospace field, and some approximations and non-optimal stress models must be used in pressure system calculations. Since SwRI is the developer, their engineering assessment was desired.
SwRI used the flat plate surface crack model SC02 to perform the FM analysis, with the assumption that the effects of curvature of the 3 ft. OD vessel would be minimal. It was determined that the applied stress intensity during the cyclic testing varied from 61 to 85 ksi√inch, which is in the near failure regime based on the aforementioned apparent plane stress fracture toughness of 90 ksi√inch found in these tests. This is consistent with the as-found crack that had traveled through the thickness of the shell, although there was insignificant crack extension as a through-crack (TC) thereafter. The analysis calculated that the surface crack (SC) would penetrate the shell after 3674 cycles (using the exact pressure load history from the cyclic test) and then transition to a through crack (TC) before experiencing brittle fracture at about 100 fewer cycles than were actually applied. This prediction was not what actually happened in that there was very little actual crack growth after the transition to a TC, and it was apparent from the fractographic assessment of the split specimen that was removed from the vessel that it was not on the verge of catastrophic failure as a TC. So while the prediction of number of cycles to transition from SC to TC was reasonable, the prediction of catastrophic failure was wrong. As became apparent in Phase 2, the principal reason was that the fracture toughness was too low when compared to more appropriate elastic-plastic J-R data. This is discussed in the Phase 2 results below.

In summary, the maximum amount of data and analyses were obtained from the available funds for the Phase 1 work, but it was clear that elastic-plastic (J-R) fracture toughness testing was needed for the thin shell material that is available from the test vessel, and that a greater range of data and test samples was required in order to be assured of having a valid approach to fatigue life estimation based on fracture mechanics. As can also be seen, there was no attempt to characterize weld or heat affected zone (HAZ) material in Phase 1.

B) Summary of results: Phase 2 Testing at SwRI (see report dated 9/13/2013)

To fill in as many important information gaps as possible after Phase 1, a test matrix was developed for comprehensive 1146a inner and outer layer shell, seam weld, and HAZ material characterization. This included hardness, Charpy V-Notch (CVN), fracture toughness and fatigue crack growth (FCG) testing. However, due to funding limitations, much testing was deferred for future programs, and the most critical matrix elements were the focus of Phase 2. One surprise was that, for this vessel, the material rolling direction was different for the inner and outer layers, showing that assumptions about rolling direction must always be confirmed through metallurgical polish and etching.

1) Shell Layer Testing:

The phase 2 SwRI report discusses shell and head tests in separate chapters, and that format is followed in the discussion below.

a. Tensile and hardness tests of outer shell at -20 F (ASTM E8):

In order to build on the data obtained in phase 1, tensile testing was performed at -20 F
on outer shell material in the vessel circumferential direction, which corresponds to the rolling direction of that plate. Tensile tests were not performed on the inner layer material. The average tensile properties increased slightly at -20 F, with average measured yield stress (YS) of 90.9 ksi at -20 F vs. 82.8 ksi at room temperature (RT), and average tensile stress (TS) of 121.9 ksi at -20 F vs. 119.1 ksi at RT. The two results meet the OEM specification requirements of 77 ksi YS and 105 – 135 ksi TS and both RT and -20 F.

Vickers hardness (HV) tests were performed on both the inner and outer shell in the vessel C-L direction, and show that the inner shell is significantly less hard than the outer (172 inner vs. 265 outer HV average), which corresponds to high Rockwell B or low Rockwell C. These indicate that the inner shell material has lower tensile properties than the outer, which was a surprise since they are close in thickness (3/8 inner vs. 1/4 inch outer). This was not anticipated, and further inner shell testing should be performed in future work.

b. Charpy V-notch (CVN) testing (ASTM E23):
Significant emphasis was placed on understanding the plate rolling directions and flaw growth directions in the material test results, and the following graphic is provided for reference when reviewing the following summaries.
i. Inner layer:
CVN tests were performed on the inner layer 1146a at RT, 0 F and -20 F in both material L-T (primary loading) and T-L (weak material orientation). Impact energy and lateral expansion were measured as per ASTM E23. Confirmatory testing for Phase 1 results was performed on the outer shell in the T-L direction at RT and -20, which was primary loading for that layer, to verify the low Phase 1 CVN data obtained (it was confirmed), see below.

Due to the thin shell layers, half-size specimens were used for CVN testing, with actual results scaled by the thickness ratio per ASTM and ASME, although this is not necessarily conservative due to reduced notch top constraint on the subsize specimens. Hence, the scaled full size results may be an overestimation, although they are what would be compared to ASME criteria (where applicable) and used in various CVN – Toughness correlations.

The test temperatures were selected to envelope the ambient conditions seen by NASA’s vessels, and were known to be insufficient (due to funding limitations) to determine the nil-ductility temperature, transition temperature or reference temperature (Tt) for ASME FFS-1 / API-579 evaluations. In fact, nil-ductility behavior was seen, as discussed below. The selected conditions do not encompass temperatures that may be induced by adiabatic cooling effects from rapid depressurization or flow in nozzle regions.

The Phase 2 results for the inner layer show that CVN is highly dependent on material orientation, ranging from 60 – 72 ft-lb for the material L-T orientation (primary loading) to 28 – 30 ft-lb for the material T-L direction (weak material orientation). The 1975 LaRC work did not report material direction, but their results were generally consistent with the inner layer primary L-T results above, which are much greater than, and not representative of, the outer layer (see next paragraph). In general, the inner layer material behaved as expected with impact energy exceeding ASME requirements, which is indicative of good toughness. Lateral expansion, which is the actual basis of ASME acceptance for materials having tensile strength above 95 ksi (ref: ASME B&PV VIII-1, UG-84(c)(4)), as is the case for 1146a, also exceeded the ASME standard of 15 mils for all inner layer tests at all temperatures and orientations. It is clear that this inner layer material is not on the lower energy shelf at -20 F.

ii. Outer Layer
The outer layer material is far less tough, with results that are indicative of brittle fracture behavior. Tests were performed in the T-L (vessel C-L) orientation (for primary hoop stress loading) at RT and -20 F, with 12 and 9 ft-lb
(full size scaled values) reported, respectively, confirming the 15 and 7 ft-lb results from phase 1. This is below ASME minimum criteria of 15 ft-lb at both temperatures for lower strength material. In addition, there was zero measured lateral expansion which is also clearly indicative of brittle fracture and in violation of ASME requirements for high strength steel such as this.

iii. Outer Shell HAZ

CVN testing was performed on specimens of outer shell seam weld heat affected zone (HAZ) material in the primary loading / weak material orientations. Results for HAZ were similar to and slightly better than the base outer shell 1146a material, with 20, 16 and 12 ft-lb at RT, 0 and -20 F, and 15, 8 and 8 mils LE, respectively. Thus the HAZ also indicated brittle fracture and failed ASME criteria at 0 and -20 F, but passed at RT.

iv. Outer Shell Weld Metal

The outer shell weld metal exhibited much better toughness and LE at all three temperature points, with absorbed energy of 50 or more ft-lb and LE never less than 20 mils. The weld metal was clearly in the upper shell region even at -20 F.

c. Elastic-Plastic (J1c) Toughness Testing (ASTM E1820):

J1c elastic plastic toughness test series were performed for both the outer and inner shell material, both in the material L-T orientation. This was unexpectedly the vessel L-C direction (secondary loading) in the outer shell rather than the desired T-L (vessel C-L) weak material / primary loading orientation which was tested in Phase 1 with limited success using the K-R method (results were technically invalid, but were reported as likely representative). Results for both tests, which are reported as K values using the K - J correlation equation, are almost double (at 149 to 171 ksi/inch) those reported in Phase 1 (86 - 90 ksi/inch) and in the LaRC 1975 report, and are nearly identical at RT and -20 F. Of course, through-thickness crack growth in the cyclic test was actually in the vessel L-R / material T-ST (short transverse), but J1c tests could not be conducted in the T-ST direction due to the ½ inch thickness of the shell. Also, since there was very little, if any, crack growth after its transition to a through crack in the vessel C-L direction, missing this data does not change the assumptions required to perform FM analyses; assumptions about material characteristics must still be made until a more complete suite of tests can be performed.

d. Fatigue Crack Growth (FCG) Testing, inner & outer shell layers (ASTM E647):

FCG testing was performed on the inner layer at RT and -20 F, in the material L-T / vessel C-L orientation (primary loading / strong material orientation on the inner shell). The intent was to obtain da/dN data across the entire range of delta-K, but due to the high toughness it was only possible to obtain data up to 50 ksiInch for R = 0.15. There was minimal R (load ratio) or temperature dependence, or differences from the outer
shell phase 1 data, although the lack of data at higher delta-K values limits the ability to perform fully validated remaining life assessments that include near-failure crack growth.

2) Vessel Head ASTM A-225 Grade B Testing
In order to have consistent results with Phase 1, and due to limited funding, all Phase 2 head testing was performed on material from that same head as was used in Phase 1. The 2nd head of this vessel has not been tested thus far. Metallurgical polishing and light etching were used to determine rolling direction. Since the angle between the rolling direction and girth weld varies around the circumference, specimens were taken from a region where the rolling direction was parallel to the girth weld for testing the HAZ, which should be the weak material direction, although additional testing would be required to verify this.

The test matrix included in the report shows the testing that was performed on this one head, what was not done due to resource limitations, and what would be very difficult to do even with adequate resources. As with the shell material, the tests focused on tensile, CVN, toughness, and FCG, and results are summarized below.

a. Head Tensile tests:
Tests at -20 F were performed to complement the RT data from Phase 1, and because no low temperature tests were reported in the previous LaRC data. There was little temperature dependence noted, and the results also met the A-225 B specification at the time of construction.

b. CVN tests:
With the thicker head material, A-225 B parent material specimens were tested in the primary loading – weak material orientations, in both the T-L and T-ST directions. As with the shell material, there was a significant decrease in CVN from RT to -20 F, although further work is required to determine the actual transition reference temperature (T_{50}) per API-579. However, the data clearly indicate for all tests that -20 is in the lower shelf region with both energy and lateral expansion data indicating brittle fracture and failing ASME criteria.

Comparisons with the LaRC data are provided, although LaRC did not report material rolling directions and the value of the comparison is unknown. What is clear is that the nil-ductility temperature (NDT) of -25 F in the LaRC report is too low, and the actual NDT will be higher when T_{50} is obtained in future tests.

Head inner HAZ CVN results were similar to the parent material, and are clearly in the lower shelf region at -20 F. HAZ tests near the outer surface were not obtained due to the beveled transition between the shell and head outer diameters. Weld metal
exhibited better toughness, with a minimum of 29 ft-lb at -20 F, although there was a significant drop from RT (58 ft-lb).

c. Head Fracture Toughness Testing (JIC per ASTM E1820):
Elastic-plastic JIC toughness testing was performed on head parent material and inner region HAZ in material T-L orientation, and on weld metal in the vessel L-C orientation, at RT and -20 F. Not all testing resulted in valid JIC data per ASTM E-1820, but all results are reported with appropriate annotations. As with CVN, toughness drops significantly between RT and -20 F for all tests, but when reported as K values using the traditional J - K correlation equation \((121 - 217) \text{ ksi} \text{in} \) at RT, \(93 - 140 \text { ksi} \text {in} \) at -20 F results are generally consistent with K1e values previously reported by LaRC \((76 - 122) \text{ ksi} \text {in} \). However, direct comparison with LaRC data is not possible since that work was performed per ASTM E-399 plane strain toughness testing with stress intensity factors from a reported “boundary collocation analysis” and no information on material orientation is provided. Much more work is needed to obtain unequivocally valid toughness data for all of the needed orientations and temperatures, and for more than one head.

d. Head FCG Testing (ASTM E-647)
FCG testing on head parent material in the T-L orientation was performed at room temperature (RT) for \(R = 0.1\) and \(0.7\) (0.15 was obtained in Phase 1), and at -20 F for \(R = 0.1, 0.15\) and \(0.7\). FCG testing was also performed at RT for \(R = 0.15\) and \(0.7\) on inner HAZ and weld metal (there were insufficient funds for -20 F testing). As with shell FCG testing, while the intent was to target the upper range of crack growth da/dN behavior, this was not adequately achieved and valid results were only obtained up to 40 ksi\text{in} for \(R = 0.15\) and 20 ksi\text{in} for \(R = 0.7\). This is reported as being a result of low yield, high toughness characteristics of the material tested. Producing adequate FCG specimens for weld and HAZ was also problematic due to vessel geometry, and a detailed discussion is provided in the Phase 2 report including the limiting factors for the valid data range. The detail results in the report show minimal temperature or load ratio dependence, which is stated to be consistent with most steels.

Also, while the Phase 2 report does not directly compare test data with that from the 1975 LaRC report, when they are plotted together, it is shown that these data points are almost entirely above the LaRC data, indicating greater da/dN per delta-K than reported in the past.

3) Fatigue Crack Growth Modeling in NASGRO
Section 4 of the Phase 2 report provides SwRI’s engineering assessment of how to use the test data to develop appropriate curve fits and determine the constants needed for fracture mechanics analysis in the NASGRO software. Since SwRI is the NASGRO developer, obtaining their recommendations in this regard was considered essential in the Phase 2 work.
SwRI's recommended NASGRO equation curve fit parameters are provided for shell, head, head-to-shell HAZ and weld material in the figures that are direct outputs from NASGRO. The values are clearly different from, and will result in faster crack growth for parent metal than the Barsom equation \((da/dN = 3.6E-10 (\Delta K)^{1.9})\) which has been assumed adequate for many years. While the NASGRO equation has many more parameters than Barsom's (which is the original Paris law equation, \(da/dN = C(\Delta K)^{n}\) in the stable crack growth region) in order to also model the near-threshold and near-failure regimes, the directly comparable constants and exponents for the stable crack growth region are as follows:

- Barsom / LaRC 1975: \(C = 3.6E-10, n = 3.0\)
- SwRI 1146a PM at RT: \(C = 2.0E-9, n = 2.75\)
- SwRI 1146a PM at -20 F: \(C = 2.0E-9, n = 2.57\)
- SwRI A-225B PM at RT: \(C = 1.5E-9, n = 2.75\)
- SwRI A-225B PM at RT: \(C = 9.00E-10, n = 2.756\)
- SwRI A-225B WM at RT: \(C = 2.38E-10, n = 3.173\)
- SwRI A-225B HAZ at RT: \(C = 1.61E-10, n = 3.461\)

A detailed explanation of all parameters is provided in Table 4.1 of the report.

4) Re-evaluation of FCG analysis of the notch in the outer shell test vessel:

The NASGRO analysis of the cyclic test crack growth reported in Phase 1 was reconsidered in light of the updated phase 2 data, with the principal change being the appropriate critical fracture toughness to apply. In phase 1, \(K_{IC}\) was considered to be 90 ksi\(\sqrt{in}\), while based on the phase 2 data for the inner shell, the more appropriate value of 170 ksi\(\sqrt{in}\) was used. As discussed above, in hindsight, it would have been best to retest the vessel outer shell in the material T-L orientation using the ASTM E-1820 protocol to match the loading and crack growth direction, but that will have to be left for future work. The data available from the outer shell L-T and inner shell L-T are reasonably consistent and judged appropriate for this reconsideration analysis, although future verification is needed.

The results of the reanalysis are much closer to the actual crack growth experienced in the test vessel. Recalling that Phase 1 predicted no remaining life after the crack broke through the inner surface of the outer layer (i.e., immediate brittle fracture), when 170 ksi\(\sqrt{in}\) is used as the toughness the analysis indicates that many more cycles of stable crack growth remained as a through-crack (TC), which is consistent with the field results (i.e., little actual TC growth, and AE emissions remained at low amplitude throughout the test). While 4688 cycles is the actual number of pressure cycles applied to the test vessel, NASGRO now predicts 13,948 are required before critical fracture toughness is reached as a through-crack, at a total crack length of 8.386 inches vs. 1.78 inches actual final length.
5) SwRI Phase 2 Recommendations

The Phase 2 report lists many recommendations for additional material testing to overcome data validity problems, important but missing test matrix data, 2nd head testing and material sample size, intermediate shell layer testing, obtaining a broader range of da/dN FCG curves particularly in the threshold and large ΔK regions, testing a broader sample of HAZ and weld materials, etc. The reader is referred to the section 6 of the Phase 2 report for the complete set of recommendations.

SwRI Recommendations for NASGRO Development

As previously stated, SwRI is the developer of the fracture mechanics program NASGRO under a Space Act agreement. NASGRO was originally written and developed by NASA, but has been under the control of SwRI for more than a decade. It is and will remain free for use by NASA personnel and projects. However, NASA does generally not pay directly for SwRI’s development work. Instead, it is funded by a membership community organized by SwRI that focuses on issues important to the members. They are mostly in aerospace, and that is where NASGRO development has focused (e.g., thin skin aluminum panels for aircraft). Consequently, even when material characterization of these vessels is adequately addressed in future testing, when the residual stress states at welds are better understood, and when appropriate examination techniques have been developed to allow for reliable defect determination, or when proof-test logic is employed, it will still be difficult to perform reasonably accurate fracture mechanics analyses for remaining safe life determination of layered vessels using NASGRO since it does not currently contain most of the stress intensity factor (SIF) models needed for fracture toughness (K) solutions for pressure vessels. Recall that for the simple shell surface crack, SwRI used the flat plate K-solution model and ignored curvature—an assumption with unknown validity, although apparently reasonable based on results. But for more complicated features, such as at nozzles, head to shell transitions or welds with complex residual stress states, corner cracks, or even for spherical heads, the analytical options are less clear and more difficult to justify. In addition, the need to enhance NASGRO for consistency with the ASME FFS-1 / API-579 standard is clear now that FFS-1 has been incorporated into the ASME Code and OSHA expects it to be used to establish the safety of operating vessels.

Therefore, based on SwRI’s Phase 1 and 2 materials testing work and their detailed knowledge of these vessels, they were asked to provide engineering recommendations for NASGRO software development to enhance the suitability of the program for ground based pressure vessels for the benefit of all NASA Centers. There are other commercial programs that are currently better developed for vessels than NASGRO (although none for layered vessels), but they are all expensive, and every Center would need to purchase one or more licenses for its own use (Center IT and security policies and firewalls effectively preclude sharing licensed engineering software on an inter-Center basis). Their nine specific recommendations for software development were included in an email to Doug Wells and Doug Fraser on August 20, 2013, which is attached as an addendum to this report. Eight of the nine recommendations were provided with ROM cost estimates for near term actions. The ninth, for new SIF models and K-solutions for specific vessel geometries, is listed as TBD, and is expected to entail
significant cost. But the value to the PVS program and enhanced safety would also be significant, and their recommendations should be part of future efforts as regards the layered vessels.

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Addendum

Fraser, Douglas R. (ARC-QS)

From: Cardinal, Joseph W. <joseph.cardinal@swri.org>
Sent: Tuesday, August 20, 2013 9:13 AM
To: Wells, Douglas N. (MSFC-EM20), Fraser, Douglas R. (ARC-QS)
Cc: McClung, Craig
Subject: NASGRO Development Tasks for Pressure Vessel Analyses and Failure Assessment Diagrams
Attachments: NASGRO FAD & PV Task List.pdf
Importance: High

Doug & Doug –

Attached for your consideration is a list of NASGRO development tasks that we feel would improve the capability of NASGRO to analyze fatigue crack growth and fracture in pressure vessels using both the FITNET and ASME/FFS procedures and the Failure Assessment Diagram (FAD).

This list complies tasks and needs from a number of sources including my previous list of items sent to Doug in April 2012, our recent telephone discussion on July 25th, ongoing items that have been on our NASGRO development list for some time, and items that SwRI has deemed were needed based on our ASME PV design and FFS projects for a number of non-aerospace clients.

Each task is listed with a brief scope/objective and some comments on timing/dependence on the other tasks followed by a rough-order-of-magnitude (ROM) cost. We have had a number of discussions internally on these tasks since our call on July 25, so please let me know if you have any questions or wish to discuss them further. Of course, if you have additional ideas/tasks that you would like to suggest and/or discuss, please feel free to bring them up as you wish.

If we were to begin work on any of these tasks, the new developments would be planned for incorporation into NASGRO v8.0 since our development cycle for v7.1 is now complete (with alpha and beta testing to begin soon). A number of these tasks have a “GUI-intensive” effort associated with them and this work would be performed by our NASGRO team members at Jacobs in Houston. We will also have to integrate/schedule these PV-related tasks with our other ongoing NASGRO development efforts.

Once you review this list, let’s discuss what you feel your priorities are, what is possible to get funded in the short term and what can be planned on for a bit down the road. If we need to act quickly to get things moving before the end of FY13, please let me know ASAP and we can start working/discussing that process. If you need to forward this to others within NASA, please go ahead and do so.

Thanks again,

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NASCRO FAD & Pressure Vessel Analysis Development Tasks:

TASK 1: Provide GUI Capability to Plot FAD Results

Scope: Add a FAD “post-processing” menu choice to the NASFLA “Select details to plot” menu. Enable plotting of results in terms of applied or limit stress and plot crack growth loci in FAD space for each crack tip.

Timing: Could begin at any time.

TASK 2: Proper Handling of Secondary Stresses

Scope: NASGRO currently has no means to distinguish between primary and secondary cyclic loads and all cyclic loads are assumed to be primary loads. A separate treatment of primary and secondary stresses is needed for both FITNET and ASME/FFS approaches, especially to account for residual stresses. Accomplishment of this task will involve considerable attention to planning the layout and structure of the changes to the NASFLA GUI in addition to developing an approach to handling the new data structures that will accommodate the separate treatment of secondary stresses.

Timing: Could begin at any time. This is a high priority task that needs to precede a number of the others.

TASK 3: Implement ASME FFS/API-579 FAD Approach as a Parallel Option to Existing FITNET FAD Capability

Scope: Calculation of the toughness ratio (Kr) needs to include a plasticity correction (interaction) term due to interactions between primary and secondary stresses. The basic approach between FITNET and ASME appears to be conceptually identical; however, it remains to be determined if there are any numerical implementation differences between the two. NASGRO currently contains FITNET options 1 (simple material model) and 3 (full stress-strain curve) to compute the FAD. In addition to implementing the plasticity interaction factors for both FITNET and ASME FFS, this task would implement the following three FAD options per ASME FFS:

- FAD in ASME FFS Figure 9.20 (Level 3, Method A)
- Material-specific FAD using actual material properties (Level 3, Method B)
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- FAD for actual material, geometry and loading (Level 3, Method C)
  This task will also involve a significant amount of GUI planning and development work.

Timing: Substantial progress on Task 2 (particularly the GUI planning) should be made before
this task begins although there could be some overlap.

TASK 4: Implement FAD Capabilities for Existing NASGRO Pressure Vessel Models that
have Limit Load Solutions Already Available

Scope:
4(a) First Priority:
- SC04 - axial surface crack (internal or external) in cylinder – univariant WF
- SC05 - circumferential surface crack (internal or external) in cylinder – tension/bending

4(b) Next Priority:
- SC06 - constant depth circumferential (internal or external) crack in cylinder
- TC06 - through crack in a sphere
- TC07 - axial through crack in a cylinder
- TC08 - circumferential through crack in a cylinder

Timing: This task is independent of the others.

TASK 5: Add Residual Stress Capability to Two Key Pressure Vessel Models

Scope: The following models would be much more useful if they had the capability to account
for residual stresses in a similar way to other NASGRO weight function models:
- SC04 - axial surface crack (internal or external) in cylinder – univariant WF
- SC06 - constant depth circumferential (internal or external) crack in cylinder

Timing: This task is independent of the others but would logically be paired with Task 4.
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TASK 6: Implement FAD Capabilities for Existing NASGRO Pressure Vessel Models that DO NOT have Limit Load Solutions Already Available

Scope: The following models need to have limit load solutions developed in order for them to be used in a FAD analyses:
- SC03 - surface crack (internal or external) in pressurized sphere
- CC09 - corner crack in plate – bivariant WF
- SC19 - surface crack (offset) in plate – bivariant WF
- ECO4 – embedded elliptical crack (offset) in plate – bivariant WF

Timing: This task is independent of the others but would logically follow after Task 4.

TASK 7: Develop a New FAD “Assessment/Screening” Module for NASGRO

Scope: The objective of this module would be to compute and plot assessment points (Kr, Lt) for known (detected or assumed) crack sizes and graphically compare them to the FAD line. It would be implemented for both FITNET and API-579/ASME FFS-1 procedures. There would be no crack growth analysis performed in this module. This module would be analogous to NASSIF and NASCCS but in “FAD Space”. Options would include:
- Plot (Kr, Lt) assessment point(s) vs FAD line
- Compute failure load (for a given crack size and toughness)
- Compute critical crack size (for a given load and toughness)

This task would involve a heavy graphics and GUI effort, but could build on or utilize much of the code to develop the plotting capability listed in Task 1.

Timing: This task would need to follow the completion of Tasks 1, 2 and 3.

TASK 8: Demonstrate Compatibility of NASGRO SIF models with ASME/FFS solutions

Scope: The objective of this task would be to verify the compatibility of the existing NASGRO SIF models with those recommended for use by ASME/FFS procedures. The following items would be investigated:
- SIF models and solutions
- Reference stress solutions
- Identify significant differences, potential resolutions and gaps
- Identify ASME/FFS SIF solutions that could be added to NASGRO
- Investigate the ability of the existing NASGRO weight function plate solutions (univariate/bivariate) to adequately compute SIFs for more complicated PV geometries (e.g., see Task 9 list).
This task would provide a good deal of direction and information in scoping out the details and need for the development of the new K solutions listed in Task 9.

Timing: This task is independent of the others and could begin at any time.

TASK 9: New K Solutions for Specific Pressure Vessel Geometries

Scope: The objective of this module would be to develop completely new stress intensity factor solutions for selected pressure vessel geometries. It could also include expansion or modification of existing models to accommodate more representative geometries.

- Identify existing SIF solutions that need expansion of geometry ranges to be more applicable to pressure vessels, e.g., thicker walls (D/t < 4).
- WF solution for circumferential surface crack in cylinder with residual stress (expansion of existing SC05)
- WF solution for circumferential surface crack in sphere with residual stress (expansion of existing SC03)
- Corner Crack (axial) at hole (nozzle penetration) in pressurized cylinder
  - See Figure C.27 from API-579/ASME FFS-1; however, that model is for quarter-circular cracks only
- Corner Crack at Nozzle penetration in pressurized thick-walled sphere
- Thick wall pressurized sphere model for both surface cracks and corner cracks at nozzles
  - Need a description of how/where these surface cracks are located
- Through Crack (axial) at hole (nozzle penetration) in hollow thick-walled sphere
  - What does “axial” mean in this context? Is the crack in the nozzle or in the sphere?
- Surface Crack (circumferential) at head-to-shell weld in pressurized cylinder, with S2 etc. through thickness variable stress due to head constraint and residual weld stress
  - A first cut at this would be a SC17/SC19 analogue for a pressurized cylinder with interior or exterior surface cracks and multiple gradients and residual stress capability.
- Corner crack at side penetrations (pressure ports) in thick wall vessels

Timing: The results of Task 8 would provide key information for scoping out the details of what solutions this task should develop. Depending on which solutions from the list above are chosen for development, they would each involve a numerical development effort as well as GUI efforts. Development of any of these models listed above is deemed a lower priority than Tasks 1-5 and 8.
In coordination with the Office of Safety and Mission Assurance and the respective Center Pressure System Managers (PSMs), the NASA Engineering and Safety Center (NESC) was requested to formulate a consensus draft proposal for the development of additional testing and analysis methods to establish the technical validity, and any limitation thereof, for the continued safe operation of facility non-code layered pressure vessels. The PSMs from each NASA Center were asked to participate as part of the assessment team by providing, collecting, and reviewing data regarding current operations of these vessels. This document contains the appendices to the main report.