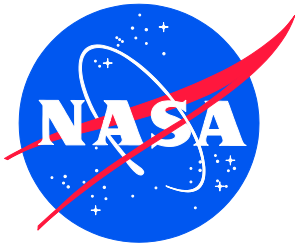
NASA/TM–2014-218505/Volume II
NESC-RP-13-00852



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

Appendices

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

July 2014

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  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

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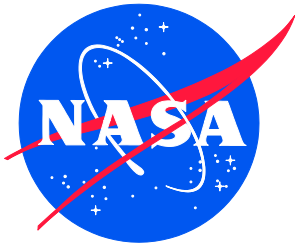

Evaluation of Agency Non-code Layered Pressure Vessels (LPVs)

Appendices

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Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

July 2014

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

Volume II. Appendices

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

June 26, 2014

Appendices

Appendix A. Example LPV Procurement Specification

HRL GIOVANNETTI - MO

Standard Form 33 (Oct. 1957 Edition)
Prescribed by General Services Administration
Regulation 1-II-209.00

INVITATION, BID, AND AWARD
(SUPPLY CONTRACT)

CONTRACT NO. | ORDER NO. (If any) | PAGE NO. 1 | NUMBER OF PAGES

ISSUED BY
National Aeronautics and Space Administration
A. S. Hertzog, Procurement Officer

ADDRESS
MOFFETT FIELD, CALIFORNIA
YORKSHIRE 7-5581 TWX: MOUNTAIN VIEW CAL 843

Buyer:

INVITATION FOR BIDS

DATE ISSUED: February 6, 1961 | INVITATION NO.: A-3510

Sealed bids 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 o'clock P. m., P. S. Time, February 20, 1961 (date) and at that time publicly opened, for furnishing the supplies or services described in the accompanying Schedule, for delivery f. o. b. Moffett Field, California

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

SCHEDULE

ITEM NO.	SUPPLIES OR SERVICES	QUANTITY (No. of units)	UNIT	UNIT PRICE	AMOUNT
	NASA Form 250 shall become a part of any resulting contract.				
	DELIVERY: Within days.				
1.	PRESSURE VESSEL; Services and Materials necessary for the design, fabrication, testing and delivery , F.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 2)	1	Ea.		

BID → DATE OF BID

In compliance with the above, the undersigned offers and agrees, if this Bid be accepted within _____ calendar days (*60 calendar days unless a different period be inserted by the bidder*) from the date of opening, to furnish any or all of the items upon which prices are quoted, at the price 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:

_____ percent, 10 calendar days; _____ percent, 20 calendar days; _____ percent, 30 calendar days.

BIDDER REPRESENTS: (*Check appropriate boxes*)

(1) That he ☐ is, ☐ is not, a small business concern. (*See definition on reverse hereof.*) If bidder is a small business concern and is not the manufacturer of the supplies bid upon, he also represents that all supplies to be furnished hereunder ☐ will, ☐ 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.

(2) That he is a ☐ regular dealer in, ☐ manufacturer of, the supplies bid upon.

(3) (a) [illegible] or agreed to pay any company or person (other than a full-time bona fide employee working solely for the bidder) any fee, commission, percentage or brokerage fee, contingent upon or resulting from the award of this contract; and agrees to furnish information relating to (a) and (b) above as requested by the Contracting Officer. (*For interpretation of representation, including definition of term "bona fide employee," see Code of Federal Regulations, Title 41, Part 150.*)

(4) He operates as an ☐ individual, ☐ partnership, ☐ corporation, incorporated in the State of _____

NAME AND ADDRESS OF BIDDER (*Street, city, zone, and State. Type or print*)

PHONE:

SIGNATURE OF PERSON AUTHORIZED TO SIGN BID →

TYPE OR PRINT SIGNER'S NAME AND TITLE

AWARD | DATE OF AWARD

ACCEPTED AS TO ITEMS NUMBERED | AMOUNT $

UNITED STATES OF AMERICA
BY _____
Contracting Officer.

SUBMIT INVOICE FOR PAYMENT TO
National Aeronautics and Space Administration
Moffett Field, Calif.

ACCOUNTING AND APPROPRIATION DATA
C&E-5701-B. Proj. 1993-B-3
C&E-5401 FB:enf

PAYMENT WILL BE MADE BY

Award will be made on this Form, or on Standard Form 26, or by other official written notice.

Standard Form 36
Prescribed by General Services
Administration, Nov. 1949 Edition

CONTINUATION SHEET
(SUPPLY CONTRACT)

CONTRACT, ORDER, OR INVITATION NO. (As applicable): A-3510

PAGE NO. 2

ITEM NO.	SUPPLIES OR SERVICES	QUANTITY (Number of units)	UNIT	UNIT PRICE	AMOUNT

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, no later than the close of business five (5) calendar days after the opening date. (TWX MOUNTAIN VIEW CAL. 845)

The attached Form ARC 325 is hereby made a part of any contract resulting from this invitation.

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.

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.

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:

NAME OF BIDDER OR CONTRACTOR

Standard Form 36
Rev. 1949 Edition

U.S. GOVERNMENT PRINTING OFFICE: 1952—O—206193

TIONAL 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.

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.

(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 lock-washers. 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' 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.

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.

(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 hydroatatic 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 Oakite 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%); Oakite Number 98, or equivalent, will then be circulated within the vessel for a length

Section 1 - Page 7

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 inhibiters 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 pig, 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 ft^3 volume) + several Kaiser m/l vessels each about 50 ft^3.

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, 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

Manufacturer	Location	Vessel ID Number	Service Media	Nameplate Rating (PSI)	Center's Design Pressure (PSI)	Operating Pressure (PSI)	Water Volume (ft^3)	Age (yr)	Wall thickness (shell, total nominal, in.)	Number of Shell layers and thicknesses (nominal, in.)	Shell Materials of construction	Head thickness (total, in.)	Number of Head layers and thicknesses	Head Materials of construction	Comments (general condition, vessel history, known flaws, etc.)
AO Smith	ARC	MV-50527-1	Air	3500	3150	3000	1750	53	2.635	8 - 0.267, 1 - 0.500	AOS 1146a	2.5	1	A-225 Gr. B FBQ	No known relevant flaws remain. Installed at ARC mid 1980's. rehydrotested, inspected & weld repairs made.
		MV-50527-2													
		MV-50527-3													
		MV-50527-4													
		MV-50527-5													
		MV-50527-6													
		MV-50527-7													
		MV-50527-8													
		MV-50527-9													
		MV-50527-10													
		MV-50527-11													
		MV-50527-12													
		MV-50527-13													
		MV-50527-14													
		MV-50527-15													
		MV-50527-16													
AO Smith	ARC	MV-50573	Air	15,000	135	120	100	53	6.56	22 - .265	AOS 1146a	6.5	1	A-225 Gr. B	In instrument air servuce, excluded as negligible assessed hazard
AO Smith	DWC - CO	MV-504656	n/a	6,600	n/a	n/a	70	54	3.125	12 - .25	AOS 1146a	2.5	1	A-225 Gr. B FBQ	Spare for cyclic tests at DWC in 2012, not in service
CB&I	ARC	M232	n/a	3,000	n/a	n/a	2,615	47	5.4	18 (est) - .25	CBI 1146 (1143 inner)	3.625	1	A-335 Gr. B FBX	Hydrotested 1986 at 4950- psig after NDE & weld rep[airs

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 Gr B heads and a custom alloy 1146A 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 VCESage 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 NBIC 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 specifics). 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/flaw, 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 nozzles) 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).

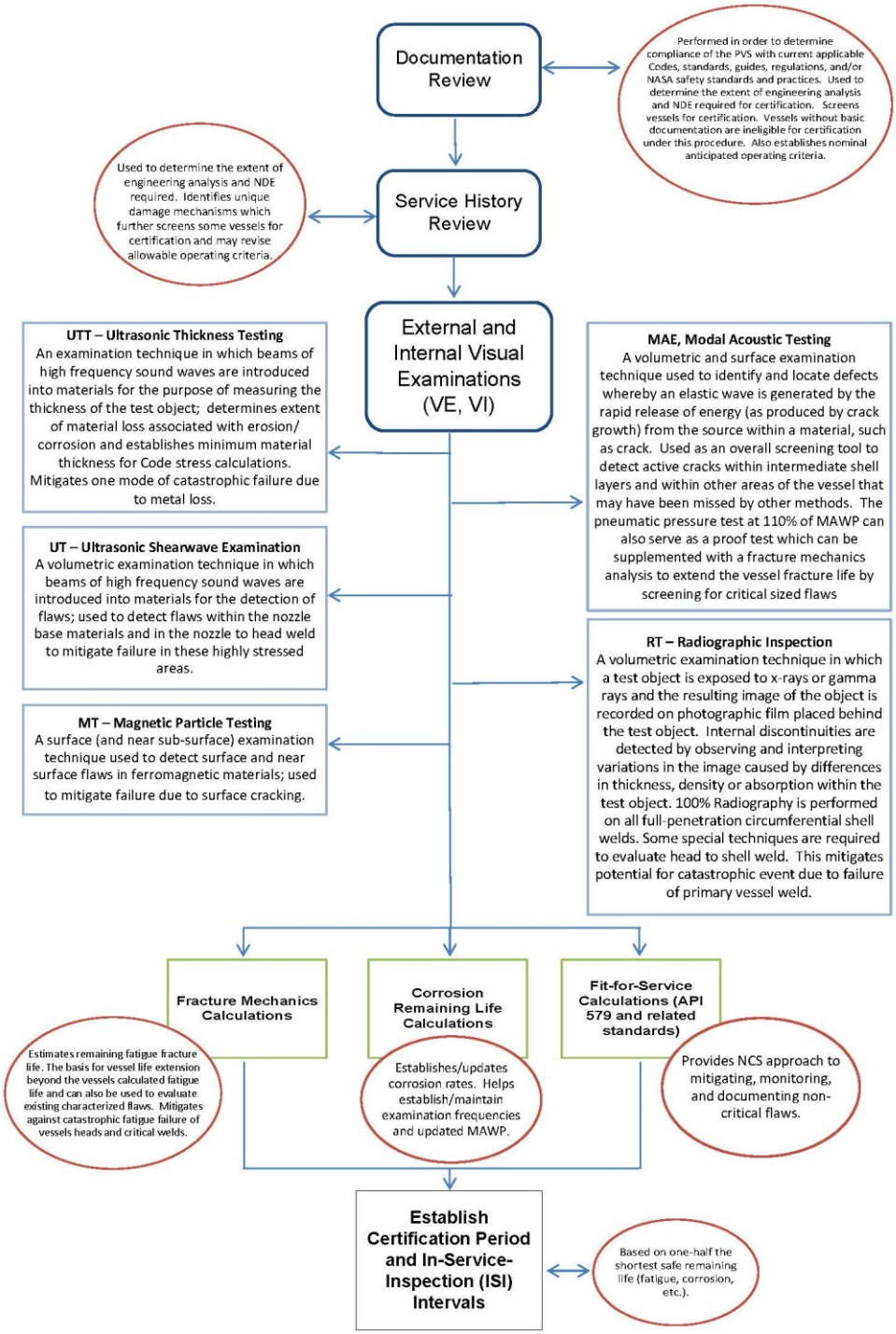
8. Communications route to Center management on perceived global and specific vessel risks.

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

recert_no	grc_no	manufacturer	model_no	cert mawp	capacity	design press	comp status	mfg year	pv_seam length	pv_shell_nom thickness	head material	shell material
PV0084	N0970	A.O. SMITH	MV50458	2640	52.7	2800	A	1959	186.625	1	SA-225 GR. B	A.O.SMITH 1146A
PV0085	N0913	A.O. SMITH	MV50405	2640	309.5	2800	A	1959	289	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0086	N0901	A.O. SMITH	MV50455	2727	105.2	2800	A	1960	209	1.5	SA-225 GR. B	A.O.SMITH 1146A
PV0088	N0122	A.O. SMITH	MV50405A	2640	306.5	2800	A	1959	219	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0089	N0123	A.O. SMITH	MV50405	2640	311.25	2800	A	1959	218	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0181	AH5010-08	A.O. SMITH	MV50454	2800	425	2800	A	1959	300	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0182	AH5010-06	A.O. SMITH	MV50454	2795	425	2800	A	1959	300	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0183	AH5010-04	A.O. SMITH	MV50454	2795	425	2800	A	1959	300	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0185	AH5010-02	A.O. SMITH	MV50407	2800	425	2800	A	1958	300	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0186	AH5010-07	A.O. SMITH	MV50454	2795	425	2800	A	1959	300.5	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0187	AH5010-05	A.O. SMITH	MV50454	2800	425	2800	A	1959	300	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0188	AH5010-03	A.O. SMITH	MV50454	2795	425	2800	A	1959	300	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0189	AH5010-01	A.O. SMITH	MV50407	2800	425	2800	A	1958	300	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0190	AH6060-1	A.O. SMITH	MV50411	2800	160	4400	A	1958	248.5	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0191	AH6060-2	A.O. SMITH	MV50411	2800	160	4400	A	1958	303	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0192	AH6060-3	A.O. SMITH	MV50411	2800	148	4400	A	1958	303	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0193	AH6060-4	A.O. SMITH	MV50411	2800	160	4400	A	1958	248.5	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0194	AH6060-5	A.O. SMITH	MV50410	2800	148	4400	A	1958	282.5	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0195	AH6060-6	A.O. SMITH	MV50410	2800	148	4400	A	1958	248.4	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0196	AH6060-7	A.O. SMITH	MV50410	2800	148	4400	A	1958	248.4	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0197	AH6060-8	A.O. SMITH	MV50410	2800	148	4400	A	1958	282.5	2.4375	SA-225 GR. B	A.O.SMITH 1146A
PV0198	N0470	A.O. SMITH	MV50406B	2650	53.3	2800	A	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0200	H0341	A.O. SMITH	MV50406B	2650	53.1	2800	A	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0201	H0342	A.O. SMITH	MV50406A	2650	52	2800	A	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0207	N0300	A.O. SMITH	MV50405	2800	311.25	2800	A	1959	219	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0208	N0136	A.O. SMITH	MV50406	2640	53	2800	A	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0209	N0135	A.O. SMITH	MV50406B	2640	53.2	2800	A	1958	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0211	N0106	A.O. SMITH	MV50484	2400	53	2800	A	1959	186.625	0.942	SA-225 GR. B	A.O.SMITH 1146A
PV0216	N0228	A.O. SMITH	MV50751	3500	325	5000	A	1962	435	2.99	SA-225 GR. B	A.O.SMITH 1146A
PV0217	N0229	A.O. SMITH	MV50751	3500	325	5000	A	1962	435	2.99	SA-225 GR. B	A.O.SMITH 1146A
PV0232	N0800	A.O. SMITH	MV50409	2700	108	2800	A	1959	241	1.25	SA-225 GR. B	A.O.SMITH 1146A
PV0233	N0755	A.O. SMITH	MV50532	2600	208	2800	A	1960	216	2.04	SA-225 GR. B	A.O.SMITH 1146A
PV0234	N0224	A.O. SMITH	MV50532	2350	208	2800	A	1960	136.5	2.04	SA-225 GR. B	A.O.SMITH 1146A
PV0235	H0321	A.O. SMITH	MV50533	1900	280.5	2800	A	1960	133	2.35	SA-225 GR. B	A.O.SMITH 1146A
PV0237	N0090	A.O. SMITH	MV50535	2640	107.7	6600	A	1960	225	3.55	SA-225 GR. B	A.O.SMITH 1146A
PV0239	N0601	A.O. SMITH	MV50406B	2400	53	2800	A	1958	228	1	SA-225 GR. B	A.O.SMITH 1146A
PV0240	N0600	A.O. SMITH	MV50406A	2400	52.5	2800	A	1958	228	1	SA-225 GR. B	A.O.SMITH 1146A
PV0243	N0300	A.O. SMITH	MV50405	2640	311.25	2800	A	1959	219	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0253	AC081	A.O. SMITH	MV50455	2700	106	2800	A	1959	209	1.5	SA-225 GR. B	A.O.SMITH 1146A
PV0291	N0117	A.O. SMITH	MV50458	2650	52	2800	A	1959	227	1	SA-225 GR. B	A.O.SMITH 1146A
PV0292	N0111	A.O. SMITH	MV50459	2650	52.6	2800	A	1959	227	1	SA-225 GR. B	A.O.SMITH 1146A
PV0293	N0112	A.O. SMITH	MV50458	2650	52.6	2800	A	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0295	G0050	A.O. SMITH	MV50405A	2640	307	2800	A	1959	289	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0297	N0113	A.O. SMITH	MV50458	2650	52	2800	A	1959	186.625	1	SA-225 GR. B	A.O.SMITH 1146A
PV0307	N0001	A.O. SMITH	MV50455	2639	105	2800	A	1959	209	1.5	SA-225 GR. B	A.O.SMITH 1146A
PV0355	N0106	A.O. SMITH	MV50406	2800	53	2800	A	1959	288	1	SA-225 GR. B	A.O.SMITH 1146A
PV0406	N5003	A.O. SMITH	MV-50548	2769	825.8	2800	A	1960	468	2.476	SA-225 GR. B FBQ	A.O.SMITH 1146A
PV0408	N5002	A.O. SMITH	MV-50548	2769	825.8	2800	A	1960	468	2.476	SA-225 GR. B FBQ	A.O.SMITH 1146A
PV1764	N0300	A.O. SMITH	MV50405A	2800	307	2800	A	1959	219	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0213	HE-1-B	A.O. SMITH	MV50566A	3700	500	4400	A	1961	342	3.08	SA-225 GR. B	A.O.SMITH 1146A
PV0214	HE-3-B	A.O. SMITH	MV50566A	3700	500	4400	A	1961	342	3.08	SA-225 GR. B	A.O.SMITH 1146A
PV0218	FH0003	A.O. SMITH	MV50554	6170	248.5	6600	A	1960	283.875	4.14	SA-225 GR. B	A.O.SMITH 1146A
PV0226	FH0005	A.O. SMITH	MV50554	6170	248.5	6600	A	1960	283.875	4.14	SA-225 GR. B	A.O.SMITH 1146A
PV0407	V-13-01	A.O. SMITH	MV-50548	2750	830	2800	A	1960	468	2.476	SA-225 GR. B	A.O.SMITH 1146A
PV0409	V-3301A	A.O. SMITH	MV50486A	2593	330	2800	A	1961	234	2	SA-225 GR. B	A.O.SMITH 1146A
PV1723	401-A	A.O. SMITH	MV50407	2700	425.6	2800	A	1958	221.5	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV1726	400-A	A.O. SMITH	MV50407	2700	425.6	2800	A	1958	221.5	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0435	RP1ST	A.O. SMITH	MV50492B	0	8.7	2800	E	1960	N/A	(sphere)	A-212 GR. B	N/A (sphere)
PV0176	N0553	A.O. SMITH	MV50405	2640	307.1	2800	G	1959	219	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0301	N0440	A.O. SMITH	MV50406A	2650	53.3	2800	G	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0302	N0441	A.O. SMITH	MV50458	2650	52.8	2800	G	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0177	LS0001	A.O. SMITH	MV50520	3960	101	3960	I	1960	228	4.4375	A-212 GR. B	A.O.SMITH 1135G GR. A
PV0199	UC0218	A.O. SMITH	MV50406A	0	53	2800	I	1959	228	1	SA-225 GR. B	A.O.SMITH 1146A
PV0210	UC0219	A.O. SMITH	MV50405	0	306.4	2800	I	1959	289	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0212	N2122	A.O. SMITH	MV50484	0	52	2800	I	1959	226	0.942	SA-225 GR. B	A.O.SMITH 1146A
PV0236	UC0220	A.O. SMITH	MV50405A	0	306.8	2800	I	1959	289	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0238	UC0221	A.O. SMITH	MV50488B	6600	39.9	6600	I	1960	180	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0241	UC0224	A.O. SMITH	MV50405	0	311.25	2800	I	1959	289	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0254		A.O. SMITH	MV50407	0	427.8	350	I	1958	221	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0289	UC0230	A.O. SMITH	MV50459	0	52	0	I	1959	226	1	SA-225 GR. B	A.O.SMITH 1146A
PV0296	G0001	A.O. SMITH	MV50405A	0	308	2800	I	1959	289	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0299	UC0231	A.O. SMITH	MV50458	0	52.6	2800	I	1959	228	1	SA-225 GR. B	A.O.SMITH 1146A
PV0300	UC0232	A.O. SMITH	MV50406A	0	52	2800	I	1958	228	1	SA-225 GR. B	A.O.SMITH 1146A
PV0003	N0001	A.O. SMITH	MV50406B	2650	53.2	2800	I	1959	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0004	N0002	A.O. SMITH	MV50406B	2650	53.2	2800	I	1958	188	1	SA-225 GR. B	A.O.SMITH 1146A
PV0005	N0004	A.O. SMITH	MV50405	2650	306.8	2800	I	1959	219	2.1875	SA-225 GR. B	A.O.SMITH 1146A
PV0090	UC0217	A.O. SMITH	MV50456	2400	32.2	8800	I	1959	141	3.5	SA-225 GR. B	A.O.SMITH 1146A
PV0283	N001	A.O. SMITH	MV50406	2800	53	2800	I	1958	228	1	SA-225 GR. B	A.O.SMITH 1146A
PV0284	UC0229	A.O. SMITH	MV50459	300	54	2800	I	1959	226	1	SA-225 GR. B	A.O.SMITH 1146A
PV0288	N8093	A.O. SMITH	MV50407	2800	425.6	2800	I	1958	221.5	2.5	SA-225 GR. B	A.O.SMITH 1146A
PV0309	UC0235	A.O. SMITH	MV50406	0	53	2800	I	1959	228	1	SA-225 GR. B	A.O.SMITH 1146A
PV0436	UC0245	A.O. SMITH	MV50492B	0	8.7	2800	I	1960	N/A	(sphere)	A-212 GR. B	N/A (sphere)
PV0228	FD0001	HAHN AND CLAY	HC-1	8739	78	6000	I	1960	158	7.625	A-212 GR. B	SA-299 (ASME CASE 1056-A)
PV0229	FD0100	HAHN AND CLAY	HC-2	8739	78	6000	I	1960	158	7.625	A-212 GR. B	SA-299 (ASME CASE 1056-A)
PV1664	WN0101	A.O. SMITH	MV50514	2800	17.16	2800	I	1960	143.125	1.52	SA-225 GR. B	A.O.SMITH 1146A
PV1667	N2201	CHICAGO BRIDGE & IRON	M-155	4778	2530	5000	I	1964	938	5.88	SA-225 GR. B FBQ	A.O.SMITH 1146A

Attachment B – Non-code vessel inspection/analysis process


Documentation Review
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.
Service History Review
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.
External and Internal Visual Examinations (VE, VI)
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.
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
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.
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.
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.
Fracture Mechanics Calculations
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.
Corrosion Remaining Life Calculations
Establishes/updates corrosion rates. Helps establish/maintain examination frequencies and updated MAWP.
Fit-for-Service Calculations (API 579 and related standards)
Provides NCS approach to 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.).

Action		Comment
Documentation review		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.
Service history review		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.
VE, VI – external and internal visual examinations		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.
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.
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.
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.
Fracture Mechanics calculations		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.
Corrosion remaining life calculations		Establishes/updates corrosion rates. Helps establish/maintain examination frequencies and updated MAWP.
Fit-for-service calculations (API 579 and related standards)		Provides NCS approach to 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.).

Attachment C – Non-code Multilayer vessel original design deficiencies and risk reduction countermeasures

Potential Fabrication Deficiencies	Potential Failure Mode	Catastrophic Failure Potential (pre-mitigation)	Mitigation	Catastrophic Failure Potential (post-mitigation)
Flawed Base Material:				
Base plate and forging materials not in conformance with ASME Code and/or Manufacturers Specifications	Brittle Fracture Failure / Ductile Rupture; potential fragmentation	High	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.	Low
- Insufficient Fracture Toughness at MDMT	Brittle Fracture Failure; potential fragmentation	High	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 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.	Low
Flawed Welds:				
- ASME Code Compliant WPS, PQR, & WPQ not fully implemented and documented	Brittle Fracture Failure / Ductile Rupture; potential fragmentation	High	Manufacturer's fabrication specifications (AO Smith Spec MLS 30A) references that PQR and WPQ comply with ASME Section IX. Many vessel files	Low

Potential Fabrication Deficiencies	Potential Failure Mode	Catastrophic Failure Potential (pre-mitigation)	Mitigation	Catastrophic Failure Potential (post-mitigation)
			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.	
Base plate and forging materials not in conformance with ASME Code and/or Manufacturers Specifications	Brittle Fracture Failure / Ductile Rupture; potential fragmentation	High	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.	Low
- Insufficient Fracture Toughness at MDMT	Brittle Fracture Failure; potential fragmentation	High	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 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-	Low

Potential Fabrication Deficiencies	Potential Failure Mode	Catastrophic Failure Potential (pre-mitigation)	Mitigation	Catastrophic Failure Potential (post-mitigation)
			3316 actual test data) are used to perform fracture mechanics analysis in accordance with API RP-579 for all multilayer vessels.	
Flawed Welds:				
- ASME Code Compliant WPS, PQR, & WPQ not fully implemented and documented	Brittle Fracture Failure / Ductile Rupture; potential fragmentation	High	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.	Low
- Insufficient Fracture Toughness at MDMT	Brittle Fracture Failure; potential fragmentation	High	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 TM X-3316 actual test data) are used to perform fracture mechanics analysis in accordance with API	Low

Potential Fabrication Deficiencies	Potential Failure Mode	Catastrophic Failure Potential (pre-mitigation)	Mitigation	Catastrophic Failure Potential (post-mitigation)
			RP-579 for all multilayer vessels.	
- Intermediate layer welds	Ductile failure with minimal fragmentation; Undetected crack likely to self-arrest (confined within a single layer)	Med/High	CB&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.	Low
- Nozzle attachment welds	Brittle Fracture Failure / Ductile Rupture; potential fragmentation	High	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, & UT 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	Low

Potential Fabrication Deficiencies	Potential Failure Mode	Catastrophic Failure Potential (pre-mitigation)	Mitigation	Catastrophic Failure Potential (post-mitigation)
			remaining life based on a minimum detectable flaw.	
- Head to Shell weld & full penetration circumferential welds	Brittle Fracture Failure / Ductile Rupture; potential fragmentation	High	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 & 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.	Low

Attachment D – Summary of vessel flaws, defects, and damage identified

Recert No	Location	Type of Defect	Type of NDE Used	NDE Report Number	Final Disposition	NOTES
PV0003						No Rejectable Indications
PV0004						No Rejectable Indications
PV0005	(2) 2" Nozzles	LOF	UT	153-05	FFS Analysis Performed	
PV0084	2" Nozzle	LOF	UT	091-06	REPAIR	
PV0085	(2) 2" Nozzles	LOF	UT	092-06	REPAIR	
PV0085	LONG	35" LINEAR	MT	1986	GROUND OUT	
PV0086						No Rejectable Indications
PV0088	(2) 2" Nozzles	LOF	UT	314-06	REPAIR	
PV0088	LONG	1/4" LINEAR	MT		GROUND OUT	
PV0089	(2) 2" Nozzles	LOF	UT	315-06	REPAIR	
PV0090						No Rejectable Indications
PV0176	(2) 2" Nozzles	LOF	UT	061-06	REPAIR	
pv0176	LONG	1/4" LINEAR	RT	2006	REPAIR	
PV0177						No Rejectable Indications
PV0181	CIR	SLAG	RT	364-05	REPAIR	
PV0182	2" Nozzle	LOF	UT	365-05	REPAIR	
pv0182	LONG	LINEAR	RT	2006	REPAIR	
PV0183	2" Nozzle	LOF	UT	366-05	REPAIR	
pv0183	LONG	LINEAR	RT	1996	REPAIR	
PV0185	2" Nozzle	LOF	UT	367-05	REPAIR	
PV0186	2" Nozzle	LOF	UT	368-05	REPAIR	
pv0186	CIR	SLAG	RT	1996	FFS Analysis Performed	
PV0187						No Rejectable Indications
PV0188	(2) 2" Nozzles	LOF	UT	370-05	REPAIR	
pv0188	LONG	LINEAR	RT	192-96	REPAIR	
PV0189	LONG	LINEAR	RT	152-96	REPAIR	
pv0189		LINEAR	MT	1985	GROUND OUT	
PV0190	(2) 2" Nozzles	LOF	UT	553-06	FFS Analysis Performed	
pv0190		LINEAR	MT	1985	REPAIR	
PV0191	(2) 2" Nozzles	LOF	UT	441-04	FFS Analysis Performed	
pv0191		LINEAR	RT	441-04	REPAIR	
PV0192	(2) 2" Nozzles	LOF	UT	442-04	FFS Analysis Performed	
PV0193	LONG	LINEAR	RT	443-04	REPAIR	
PV0193	(2) 2" Nozzles	LOF	UT	443-04	FFS Analysis Performed	
PV0194						No Rejectable Indications
PV0195	2" Nozzle	LOF	UT	448-04	REPAIR	
PV0196						No Rejectable Indications
PV0197				450-04		No Rejectable Indications
PV0198						No Rejectable Indications
PV0199						SCRAP
PV0200						No Rejectable Indications
PV0201	CIR	LINEAR	MT	SPEC.	REPAIR	Dec-86
PV0201		LINEAR	MT	1986	GROUND OUT	
PV0207	(2) 2" Nozzles	LOF	UT	130-04	FFS Analysis Performed	
PV0208	2" Nozzle	LOF	UT	431-04	REPAIR	
PV0209	2" Nozzle	LOF	UT	432-04	FFS Analysis Performed	
PV0210	Head to Shell Weld	LINEAR	RT	294-96	REMOVED FROM SERVICE	
PV0210	2" Nozzle	LOF	UT	294-06	REMOVED FROM SERVICE	
PV0211	2" Nozzle	LOF	UT	98-06	REPAIR	
PV0212						SCRAP
PV0213	C-1 / C-2	LINEAR	RT	393-06	REPAIR	
PV0214						No Rejectable Indications
PV0216	2" Nozzle	LOF	UT	299-04	REPAIR	
PV0217				458-07		No Rejectable Indications
PV0218	2" Nozzle	LOF	UT	388-06	REPAIR	
PV0226	(2) 2" Nozzles	LOF	UT	387-06	REPAIR	
PV0228						No Rejectable Indications
PV0229						No Rejectable Indications
PV0232	LONG	LINEAR	RT	446-04	REPAIR	
PV0233						No Rejectable Indications
PV0234						No Rejectable Indications
PV0235						No Rejectable Indications
PV0236	Head to Shell Weld	LINEAR	RT	100-95	REMOVED FROM SERVICE	
PV0236	(2) 2" Nozzles	LOF	UT		REMOVED FROM SERVICE	
PV0237	(2) 1-1/2 Nozzles	LOF	UT	121-93		INACTIVE
PV0238						INACTIVE
PV0239	LONG	LINEAR	RT	423-07	REPAIR	
PV0240						No Rejectable Indications
PV0241	(2) 2" Nozzles	LOF	UT	250-96		INACTIVE
PV0241	LONG	LINEAR	RT	250-96		INACTIVE
PV0243	LONG	3/16" LINEAR	RT	131-04	FFS Analysis Performed	ISI
PV0253				456-04		No Rejectable Indications
PV0254						SCRAP
PV0283	(2) 2" Nozzles	LOF	UT	079-092	FFS Analysis Performed	
PV0284	LONG		RT			SCRAP
PV0288	(2) 2" Nozzles	LOF	UT	165-10	FFS Analysis Performed	
PV0289						SCRAP
PV0291				324-06		No Rejectable Indications
PV0292	G-1 and G-3	SLAG	RT	325-06	FFS Analysis Performed	
PV0292	2" Nozzle	LOF	UT	325-06	REPAIR	
PV0293	2" Nozzle	LOF	UT	326-06	REPAIR	
PV0293	LONG	LINEAR	RT	326-06	REPAIR	
PV0295	2" Nozzle	LOF	UT	258-10	REPAIR	
PV0296	2" Nozzle	LOF	UT	256-10	REPAIR	
PV0297	2" Nozzle	LOF	UT	257-10	REPAIR	
PV0299						SCRAP
PV0300						SCRAP
PV0301	2" Nozzle	LOF	UT	196-06	REPAIR	
PV0302	2" Nozzle	LOF	UT	197-06	REPAIR	
PV0307						No Rejectable Indications
PV0309	LONG	LINEAR	RT	065-95		SCRAP
PV0355						No Rejectable Indications
PV0406	C-5	LINEAR	RT	069-03	REPAIR	
PV0407						No Rejectable Indications
PV0408	C-5	LINEAR	RT	024-03	REPAIR	
PV0409	2" Nozzle	LOF	UT	384-06	REPAIR	
PV1664	2" Nozzle	LOF	UT		REMOVED FROM SERVICE	FILE NOT IN CABINET
PV1667	(2) 6" Nozzles	LOF	UT	SPEC.	FFS Analysis Performed	
PV1667	Head to Shell Weld	High-Low mismatch	VI	SPEC.	REPAIR	
PV1723	2" Nozzle	LOF	UT	382-06	REPAIR	
PV1726	(2) 2" Nozzles	LOF	UT	383-06	REPAIR	
PV1726	Head to Shell Weld	LINEAR	RT	383-06	REPAIR	
PV1764						No Rejectable Indications

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 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.

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.

Manufacturer	Location	Vessel ID Number	Service Media	Nameplate Rating (PSI)	Center's Design Pressure (PSI)	Operating Pressure (PSI)	Water Volume (ft^3)	Year Built (yr)	Wall thickness (shell, total nominal, in.)	Number of Shell layers and thicknesses (nominal, in.)	Shell Materials of construction	Head thickness (total, in.)	Number of Head layers and thicknesses	Head Materials of construction	Comments (general condition, vessel history, known flaws, etc.)	Repair/Maintenance History
A.O. Smith	WWF/ Pad 0A	MARS #20 MV-50465-5	GN2	6600	6170	6000	70	1959	3.125	11-0.25, 1 - 0.375	AOS 1146a	2.5	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #21 MV-50457-1	GN2	6600	6170	6000	270	1959	3.75	13-0.25, 1 - 0.500	AOS 1146a	3.0625	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #22 MV-50465-2	GN2	6600	6170	6000	70	1959	3.125	11-0.25, 1 - 0.375	AOS 1146a	2.5	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured. Incomplete Fusion was found on the nozzle N-2 by UTV and was repaired in Dec. 2010 per NB-23.
A.O. Smith	WWF/ Pad 0A	MARS #23 MV-50457-2	GN2	6600	6170	6000	270	1959	3.75	13-0.25, 1 - 0.500	AOS 1146a	3.0625	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #24 MV-50465-1	GN2	6600	6170	6000	70	1959	3.125	11-0.25, 1 - 0.375	AOS 1146a	2.5	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #25 MV-50457-5	GN2	6600	6170	6000	270	1959	3.75	13-0.25, 1 - 0.500	AOS 1146a	3.0625	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured. Incomplete Fusion was found on the nozzle N-1 by UTV and was repaired in Dec. 2010 per NB-23.
A.O. Smith	WWF/ Pad 0A	MARS #26 MV-50464-2	GN2	6600	6170	6000	125	1959	3.125	11-0.25, 1 - 0.375	AOS 1146a	2.5	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #27 MV-50457A-15	GN2	6600	6170	6000	270	1959	3.75	13-0.25, 1 - 0.500	AOS 1146a	3.0625	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured. Incomplete Fusion was found on the nozzle N-2 by UTV and was repaired in Dec. 2010 per NB-23.
A.O. Smith	WWF/ Pad 0A	MARS #28 MV-50464-5	Ghe	6600	6170	6000	125	1959	3.125	11-0.25, 1 - 0.375	AOS 1146a	2.5	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #29 MV-50457A-11	Ghe	6600	6170	6000	270	1959	3.75	13-0.25, 1 - 0.500	AOS 1146a	3.0625	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #30 MV-50464-1	Ghe	6600	6170	6000	125	1959	3.125	11-0.25, 1 - 0.375	AOS 1146a	2.5	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in early 2012. Weep holes were cleaned and measured.
A.O. Smith	WWF/ Pad 0A	MARS #31 MV-50457A-10	Ghe	6600	6170	6000	270	1959	3.75	13-0.25, 1 - 0.500	AOS 1146a	3.0625	1	A-225 Gr. B FBQ	Installed at SLC-36, Cape Canaveral Air Force Station in 1960's. Relocated and refurbished and put back in service in 2012 at WFF.	Flange resurfaced to remove corrosion in 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.

Manufacturer	Manufacturer's Model Number	Location	Vessel ID Number	PVS Package	Service Media	Nameplate Rating (PSI)	Center's Design Pressure (PSI)	Operating Pressure (PSI)	Water Volume (ft^3)	Year Built	Age (yr)	Wall thickness (shell, total nominal, in.)	Number of Shell layers and thicknesses (nominal, in.)	Shell Materials of construction	Head thickness (total, in.)	Number of Head layers and thicknesses	Head Materials of construction
AO Smith	MV50309-11	WSTF	TK-8GN-JA11	8061	Air	2800	600	600	312	1958	55.00	2.1875	8 layers - inner 0.5" plus 7 0.25" layers	1146a	1.375	1	ASTM A225 Gr. B FBQ
AO Smith	MV 50582-1	WSTF	TK-4GN-HN074	4005	Nitrogen	6600	4203	2300	398	1960	53	3.72	13 layers - inner 15/32 plus 12 0.271" layers	1146a	3.33	1	ASTM A225 Gr. B FBQ
Struthers Wells	48-1872	WSTF	TK-4GN-FG006	4005	Nitrogen	5500	4425	2300	650	1964	49	6.5	5 layers - inner 0.5", then 1.75", 1.5", 1.5", 1.5"	Proprietary SWC 100302, except inner layer is SA302 Gr. B with 1/8" Type 304 Stainless Clad	3.5625	1	SA302 Gr. B with 1/8" Type 304 Stainless Clad
AO Smith	MV50309A27	WSTF	TK-5BA-AM169	5006	Air	2800	2100	1800	312	1958	55	2.1875	8 layers - inner 0.5" plus 7 0.25" layers	1146a	1.375	1	ASTM A225 Gr. B FBQ

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 A.O. 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 these 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).

Cert Report Number	Vessel Manufacturer	Vessel Type	Number of Vessels	Vessel Serial number	Design Pressure (PSIG)	Operating pressure (psig)	Material	Head thickness (in)	Shell Layer thicknesses (in)	Dimensions (Dia. x L) inch	weight (lbs)	Circumferential weld location	Nozzle location	Volume (cu.ft.)	Year Built	System Description	Commodity	Active/Inactive	Location	RBP Recert Date	General Condition	NDE performed	Analysis method	ISI plan	Inspection records available (summary reports/film/etc.)?	Identified damage/flaws/defects	Current Risk mitigation approaches (de-rate/clear zones/etc.)	Past risk mitigation	recommendations for risk mitigation approaches	Special concerns regarding safe operations of this vessel?	Communications to CD and management on perceived global and specific vessel risk	Notes
KSCE-8244-0140(1 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50226-1	4,944	4,450	AO Smith Spec 1146a similar to ASTM A225 Gr. C	2	inner layer 1/2" 10 layers 1/4" each	42 x 624	63,995	Head to Shell (2) Girth welds	1 Head 2 Shell	300	1957	GN2 Storge & Distribution System Facility	GN2	Active	Fuel Storage Area #1	Feb-17	Good	UTT, VE	ASME Division 2	VE-1 years UTT-10 years RT-10 years	UTT, VE reports available	None	Re-certify before use. Previously de-rated	More frequent Inspection intervals & vessel de-rate	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Active
KSCE-8244-0140(2 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50226-2	4,944	4,450	AO Smith Spec 1146a similar to ASTM A225 Gr. C	2	inner layer 1/2" 10 layers 1/4" each	42 x 624	63,995	Head to Shell (2) Girth welds	1 Head 2 Shell	300	1957	GN2 Storge & Distribution System Facility	GN2	Active	Fuel Storage Area #1 (80541)	Feb-17	Good	UTT, RT, VE	ASME Division 2	VE-1 years UTT-10 years RT-10 years	UTT, VE reports available	None	Re-certify before use. Previously de-rated	More frequent Inspection intervals & vessel de-rate	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Active
KSCE-8244-0139 (1 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50114-1	3,800* Derated from 6,000	3,450	AO Smith Spec 1146a similar to ASTM A225 Gr. C	2.125	Inner Layer 1/2" 15 layers 1/4" each	38.5 x 78	9,370	Head to Shell	Both ends 2 on shell	25	1957	GN2 Distribution System	GN2	Inactive	Hangar AF	*Due upon system activation	Good	UTT, MT, VE	ASME Division 1	VE-2 years UTT-20 years R-20 years	VE, MT & UTT Records available	None	Re-certify before use. Previously de-rated	Vessel de-rate	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Inactive. Cert Report KSCE-8244-0139.
KSCE-8244-0139 (2 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50114-4	3,800* Derated from 6,000	3,450	AO Smith Spec 1146a similar to ASTM A225 Gr. C	2.125	Inner Layer 1/2" 15 layers 1/4" each	38.5 x 78	9,370	Head to Shell	Both ends 2 on shell	25	1957	GN2 Distribution System	GN2	Inactive	Hangar AF	*Due upon system activation	Good	UTT, MT, VE	ASME Division 1	VE-2 years UTT-20 years R-20 years	VE, MT & UTT Records available	None	Re-certify before use. Previously de-rated	Vessel de-rate	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Inactive. Cert Report KSCE-8244-0139.
KSCE-8244-0139 (3 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50114-5	3,800* Derated from 6,000	3,450	AO Smith Spec 1146a similar to ASTM A225 Gr. C	2.125	Inner Layer 1/2" 15 layers 1/4" each	38.5 x 78	9,370	Head to Shell	Both ends 2 on shell	25	1957	GN2 Distribution System	GN2	Inactive	Hangar AF	*Due upon system activation	Good	UTT, MT, VE	ASME Division 1	VE-2 years UTT-20 years R-20 years	VE, MT & UTT Records available	None	Re-certify before use. Previously de-rated	Vessel de-rate	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Inactive. Cert Report KSCE-8244-0139.
KSCE-8244-0139 (4 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50114-6	3,800* Derated from 6,000	3,450	AO Smith Spec 1146a similar to ASTM A225 Gr. C	2.125	Inner Layer 1/2" 15 layers 1/4" each	38.5 x 78	9,370	Head to Shell	Both ends 2 on shell	25	1957	GN2 Distribution System	GN2	Inactive	Hangar AF	*Due upon system activation	Good	UTT, MT, VE	ASME Division 1	VE-2 years UTT-20 years R-20 years	VE, MT & UTT Records available	None	Re-certify before use. Previously de-rated	Vessel de-rate	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Inactive. Cert Report KSCE-8244-0139.
KSCE-8244-0146 (1 of 3)	A.O. Smith Corp.	Multi-Layer	1	MV-90414-5	6,250	6,000	AO Smith Spec 1146a similar to ASTM A225 Gr. C							100	1959	CIF GN2 Storage & Distribution System	GN2	Active	CIF (M6-0342)	*Scheduled to be abandoned, due upon system re-activation	Good	VE - 9/9/98 UTT - 8/22/85 UT Shear - Dec 86 MT - 10/30/85 RT - 11/19/86	Section VIII Div 2 analysis performed in 1986.	VE-2 years UTT-20 years RT-20 years MT - 20 years	VE, MT, UTS, UTT, RT Records available	0.75" slag indication found in weld C1	To be mothballed, then re-certify before future use.	None	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	
KSCE-8244-0146 (2 of 3)	A.O. Smith Corp.	Multi-Layer	1	MV-90414-2	6,250	6,000	AO Smith Spec 1146a similar to ASTM A225 Gr. C							100	1959	CIF GN2 Storage & Distribution System	GN2	Active	CIF (M6-0342)	*Scheduled to be abandoned, due upon system re-activation	Good	VE - 9/9/98 UTT - 8/22/85 MT - 10/30/85 RT - 8/29/86	Section VIII Div 2 analysis performed in 1986.	VE-2 years UTT-20 years RT-20 years MT - 20 years	VE, MT, UTS, UTT, RT Records available	None	To be mothballed, then re-certify before future use.	None	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	
KSCE-8244-0146 (3 of 3)	A.O. Smith Corp.	Multi-Layer	1	MV-90414-6	6,250	6,000	AO Smith Spec 1146a similar to ASTM A225 Gr. C							100	1959	CIF GN2 Storage & Distribution System	GN2	Active	CIF (M6-0342)	*Scheduled to be abandoned, due upon system re-activation	Good	VE - 9/9/98 UTT - 8/22/85 MT - 10/30/85 RT - 8/29/86	Section VIII Div 2 analysis performed in 1986.	VE-2 years UTT-20 years RT-20 years MT - 20 years	VE, MT, UTS, UTT, RT Records available	None	To be mothballed, then re-certify before future use.	None	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	
KSCE-8244-0203 (1 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50415-5	5,500	5,000	AO Smith Spec 1146a layers, ASTM A225 Gr. C heads, nozzles Forged low alloy steel spec. No. 5002 Modified.			42 x 300				155	1959	CRCA 5K GHe System	GHe	Active	CRCA (K6-1696)	May-18	No identified flaws	UTT - Vessels & Nozzles 5/12/98 VE 3/26/98	Section VIII Div 2 analysis performed in 1986.	VE every 2 years UTT every 20 years	VE & UTT Records available	No identified flaws	Currently certified. Due for re-certification FY18	None	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Active
KSCE-8244-0203 (2 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50415-2	5,500	5,000	AO Smith Spec 1146a layers, ASTM A225 Gr. C heads, nozzles Forged low alloy steel spec. No. 5002 Modified.			42 x 300				155	1959	CRCA 5K GHe System	GHe	Active	CRCA (K6-1696)	May-18	No identified flaws	UTT - Vessels & Nozzles 5/12/98 VE 3/26/98	Section VIII Div 2 analysis performed in 1986.	VE every 2 years UTT every 20 years	VE & UTT Records available	No identified flaws	Currently certified. Due for re-certification FY18	None	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Active
KSC-9553 (1 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50414-4	5,800	5,220	AO Smith Spec 1146a similar to ASTM A225 Gr. B	3	1/2" Inner layer 13 layers 1/4" each	36 x 203		Head to shell	Both ends	155	1959	Gaseous Hydrogen Dispensing System	GH2	Inactive	LH2 Storage Shed Area	TBD	Fair											Inactive. These could be from the original BAIR system KSCE-8244-0131.
KSC-9553 (2 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50414-1	5,800	5,220	AO Smith Spec 1146a similar to ASTM A225 Gr. B	3	1/2" Inner layer 13 layers 1/4" each	36 x 203		Head to shell	Both ends	155	1959	Gaseous Hydrogen Dispensing System	GH2	Inactive	LH2 Storage Shed Area	TBD	Fair											Inactive. These could be from the original BAIR system KSCE-8244-0131.
KSCE-8244-0211	A.O. Smith Corp.	Multi-Layer	1	MV-50415-6	5,500	5,000	AO Smith Spec 1146a layers, ASTM A225 Gr. C heads, nozzles Forged low alloy steel spec. No. 5002 Modified.	3	1/2" Inner layer 13 layers 1/4" each	42 x 300		Head to shell 1 girth weld	both ends 1 in shell	155	1959	SK BAIR System	BAIR	Active	CRCA (K6-1696)	Sep-18	No identified flaws	UTT - Vessel & Nozzles 10/19/98 VE 10/19/98 MT 11/19/86	Section VIII Div 2 analysis performed in 1986.	VE every 2 years UTT every 20 years	VE & UTT Records available	No identified flaws	Currently certified.	Previously under DOT inspection schedule	NDE including RT, Hydrostatic test, Risk Assessment	None	Released certification package with Calculations/NDE Records/ISI schedule	Active
KSC-6405	A.O. Smith Corp.	Multi-Layer	1	MV-50454-9	2,800	2,400	Shell - AO Smith Spec 1146a Head - ASTM A-225	2.125	inner layer 1/2" 8 layers 1/4" each	60 x 300	43,000	Head to shell 1 girth weld	Both ends & 1 in shell	425	1959	Mobile Service Unit #501	GN2	Active	CCAFS PSL 1724	Mar-14	Good	None	DOT	None	None	N/A	In RBP for evaluation		NDE including RT, Hydrostatic test, Risk Assessment	None	Part of RBP	Active
KSCE-8244-0142 (1 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50409-4	2,300	2,100	Shell - AO Smith Spec 1146a; Head - ASTM A225 Gr. B	1.0625	3 - 0.25 1 - 0.5	30 X 241.625	11,100	Head to shell 1 girth weld	Both ends	106	1958	The vessels and system were deactivated under WON E1028531 on 2/11/2009.	GN2	Inactive	M6-0688	none	Under 25 psig pad pressure. Deactivated.	N/A	N/A	initial two-year periodic external visual inspection to ensure all storage conditions have		N/A	N/A	N/A	N/A	N/A	N/A	None	Inactive. Vessels moved from GN2 system @ Central Heat Plant (M6-0595) to storage @ M6-0688 and excessed. Normal operating temperature between 10 - 120 degree F. Total 1034 pressure cycles. 3 layered + 1 inner. Documentation showed the vessel was scrap in 2010.
KSCE-8244-0142 (2 of 2)	A.O. Smith Corp.	Multi-Layer	1	MV-50409-3	2,300	2,100	Shell - AO Smith Spec 1146a; Head - ASTM A225 Gr. B	1.0625	3 - 0.25 1 - 0.5	30 X 241.625	11,100	Head to shell 1 girth weld	Both ends	106	1958	The vessels and system were deactivated under WON E1028531 on 2/11/2009.	GN2	Inactive	M6-0688	none	Under 25 psig pad pressure. Deactivated.	N/A	N/A	periodic external visual inspection to ensure all storage conditions have been met.		N/A	N/A	N/A	N/A	N/A	N/A	None	Inactive. Vessels moved from GN2 system @ Central Heat Plant (M6-0595) to storage @ M6-0688 and excessed. Normal operating temperature between 10 - 120 degree F. Total 1034 pressure cycles. 3 layered + 1 inner. Documentation showed the vessel was scrap in 2010.
BPVS 1041 (1 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50412-4	8,330	0	Shell - AO Smith Spec 1146a similar to ASTM A225 Gr. C Head - SA 275 Gr B	2.6875	3.5" total 1/2" inner layer 12 - 1/4" outer layers	24.125 x 168			Both ends	38	1959	Deactivated	GHe	Inactive	M7-0355	Not part of RBP	Under blanket pressure.		MT, UTT, VE								Inactive. Certification # BPVS 1041. Leaking at both of the Aminco end fittings. VE, UTT, MT performed in 1986. Vessels were analyzed and reviewed with current ASME, VIII, Div. 1 & 2 codes. Fatigue analysis was also conducted per code requirements. Head, shell, nozzle connections, flanges and other areas of design were analyzed per applicable paragraph of ASME code in 1986. Drawing is not
BPVS 1041 (2 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50463-8	8,024	5,000	Shell - AO Smith Spec 1146a similar to ASTM A225 Gr. C Head - SA 275 Gr B	2.75	3.5" total 1/2" inner layer 12 - 1/4" outer layers	24.125 x 168			Both ends 1 in shell	40	1959	Deactivated	GHe	Inactive	M7-0355	Not part of RBP	Under blanket pressure.		MT, UTT, VE, PT								Inactive. Certification # BPVS 1041. VE, UTT, MT, PT performed in 1986. Vessels were analyzed and reviewed with current ASME, VIII, Div. 1 & 2 codes. Fatigue analysis was also conducted per code requirements. Head, shell, nozzle connections, flanges and other areas of design were analyzed per applicable paragraph of ASME code in 1986. Drawing is not available.
BPVS 1041 (3 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50463-3	8,559	5,000	Shell - AO Smith Spec 1146a similar to ASTM A225 Gr. C Head - SA 275 Gr B	2.75	3.5" total 1/2" inner layer 12 - 1/4" outer layers	24.125 x 168			Both ends	40	1959	Deactivated	GHe	Inactive	M7-0355	Not part of RBP	Under blanket pressure.		MT, UTT, VE, PT								Inactive. Certification # BPVS 1041. VE, UTT, MT, PT performed in 1986. Vessels were analyzed and reviewed with current ASME, VIII, Div. 1 & 2 codes. Fatigue analysis was also conducted per code requirements. Head, shell, nozzle connections, flanges and other areas of design were analyzed per applicable paragraph of ASME code in 1986. Drawing is not available.
BPVS 1041 (4 of 4)	A.O. Smith Corp.	Multi-Layer	1	MV-50463-1	8,559	5,000	Shell - AO Smith Spec 1146a similar to ASTM A225 Gr. C Head - SA 275 Gr B	2.75	3.5" total 1/2" inner layer 12 - 1/4" outer layers	24.125 x 168			Both ends	40	1959	Deactivated	GHe	Inactive	M7-0355	Not part of RBP	Under blanket pressure.		MT, UTT, VE, PT								Inactive. Certification # BPVS 1041. VE, UTT, MT, PT performed in 1986. Vessels were analyzed and reviewed with current ASME, VIII, Div. 1 & 2 codes. Fatigue analysis was also conducted per code requirements. Head, shell, nozzle connections, flanges and other areas of design were analyzed per applicable paragraph of ASME code in 1986. Drawing is not available.
BPVS 1064 (*Not found in KEDS*) (1 of 3)	A.O. Smith Corp.	Multi-Layer	1		4,000		AO Smith Spec 1146a similar to ASTM A225 Gr. C							68.8 132	1960 1959	Deactivated			O&C Storage Battery	Not part of RBP	Under blanket pressure.										Inactive. Vessels currently under blanket purge. Formerly part of GO2 system @ O&C.
BPVS 1064 (*Not found in KEDS*)(2 of 3)	A.O. Smith Corp.	Multi-Layer	1		4,000		AO Smith Spec 1146a similar to ASTM A225 Gr. C							68.8 132	1960 1959	Deactivated			O&C Storage Battery	Not part of RBP	Under blanket pressure.										Inactive. Vessels currently under blanket purge. Formerly part of GO2 system @ O&C.
BPVS 1064 (*Not found in KEDS*) (3 of 3)	A.O. Smith Corp.	Multi-Layer	1		4,000		AO Smith Spec 1146a similar to ASTM A225 Gr. C							68.8 132	1960 1959	Deactivated			O&C Storage Battery	Not part of RBP	Under blanket pressure.										Inactive. Vessels currently under blanket purge. Formerly part of GO2 system @ O&C.
KSC-11163PVSC (KSCL-1792D-0162)	A.O. Smith Corp.	Multi-Layer	1	MV-50455-5	2,800	1,500	Inner shell, 4 layers, and Head in accordance with US Corps of Engineers spec DA-25-066 ENG 59.49 Vol. III Sec. 56 Par 56.09b(3)	1.25	4 - 0.25 1 - 0.5	36 x 192	12,820	3 total (2 heads + center)	Both ends	106	1959	Facility Water GN2 Controls, LC-39B	GN2	Active	LC-39B	May-13	Good	None	None	VE - 2yrs R - 20yrs	None	None	None	None	Re-certify Vessel	None	Previously release certification package, currently on RBP and scheduled for FY13 to be re-certified before use.	Active but under pad pressure. Built for Corps of Engineers & Insurance Inspection. New ISC cert report will be release as KSC-1163PVSC before use.

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

Vessel Manufacturer	Location	Vessel ID Number	Service Media	Manuf. Nameplate Rating (PSI)	Center's Design Pressure (PSI)	Operating Pressure (PSI)	Water Volume (ft^3)	Age (yr.)	Wall Thickness (shell total, nominal, in.)	Number of Shell Layers and Thkn. (nominal, in.)	Materials of Construction (Shell)	Head thickness (total, in.)	Number of Head Layers and Thkn (in.)	Materials of Construction (Heads)	Comments (general condition, vessel history, known flaws, etc.)
A. O. Smith	LaRC 8'HTT	MV 50563-1	Methane	6,000	6,000	5,375	832	52	5-1/4" thk.	1 @ 1" thk. 17 @ .250" thk.	VMS 1146A	4-3/8" thk.	1	ASTM A225 Grade B, FBQ	External condition: good Internal condition: unknown No known flaws
A. O. Smith	LaRC 8'HTT	MV 50563-B2	Methane	6,000	6,000	5,375	1,602	52	5-1/4" thk.	1 @ 1" thk. 17 @ .250" thk.	VMS 1146A	4-3/8" thk.	1	ASTM A225 Grade B, FBQ	External condition: good Internal condition: unknown No known flaws
A. O. Smith	LaRC 1247B	MV50631-1	Vacuum	6,600	6,200	-15	1,015	52	5-7/8" thk.	1 @ 1/2" thk. 17 @ 0.272" thk. 3 @ .250" thk.	VMS 1146A	4-3/4" thk.	1	ASTM A225 Grade B, FBQ	External condition: good Internal condition: unknown No known flaws
A. O. Smith	LaRC 1247B	MV50631-2	Nitrogen	6,600	6,200	5,000	999	52	5-7/8" thk.	1 @ 1/2" thk. 17 @ 0.272" thk. 3 @ .250" thk.	VMS 1146A	4-3/4" thk.	1	ASTM A225 Grade B, FBQ	External condition: good Internal condition: unknown No known flaws

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. MAWPs 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 radiuses. 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

MV50488-9	Multilaminar Vessel, B175	A.O. Smith	12/14/1959	Used	From Fairchild AFB, Spokane WA	GN2	40	AE-1984, 1991, 1994, 2001, 2007, RT&Hydrostatic (9900 psi)-1959, MT-2007	AE Paper Copy, 2001, 2007	AE noted some activity in 2007 for future study	AE Every 5 years	No Concern for continued operation	SA-225B FBX, 2"	AOS MLP1146-A, 2.366"	AOS MPP 5002-mod. 1.5" ID/0.831" 2" ID/0.875"	6600	5398	2000	8.1	4049	40
103282, Rev. 5	Forged Vessel (8 random forgings), B404	Babcock & Wilcox	1965	New	No, APCI for MAF HP Helium to 1970, GN2 in 1975	GN2	573	AE-1984, 1991, 1994, 2001, 2007, RT&Hydrostatic (9188 psi)-1965, UT &UT Shear Heads 2001, MT-2007, UT Shear at Head Welds-2007	AE Paper Copy, 2001, 2007	None	AE Every 5 years	No Concern for continued operation	SA-182-F22HT (B&W Croyloy 2.25) 3.8125"	SA-182-F22HT (B&W Croyloy 2.25) 3.8125"	SA-182-F22HT (B&W Croyloy 2.25) 2.5" ID and 2" ID head nozzles, integral	7350	5125	2000	7.7	3933	40
71-622/48-1971	Multilaminar Vessel, B404	Struthers-Wells	1964	New	APCI for Stennis, USAF Titan Missile Program, GN2, est. ship to MAF in 1980	GN2	1500	AE-1984, 1991, 1994, 2001, 2007, RT&Hydrostatic (11025 psi)-1964, MT-1981, UT &UT Shear Heads 2001, PT, UT Heads 2007, UT interior-1980	AE Paper Copy, 2001, 2007	None	AE Every 5 years	Field Installed Manway, 1981, Cosmetic interior defects repaired 1980, No Concern for continued operation	T1 Steel (SA-517E) 3.25"	T1 Steel (SA-517F) 6.5"	T1 Steel (SA-517E) 2" ID/1.75" 4" ID/2" 20" ID/7.5"	7350, SF-2 1/3	6170 (flanges)	2000	9.5 (heads) 10.25 (shells)	4860	32
71-612/481939-3	Multilaminar Vessel, B404	Struthers-Wells	1964	New	Scott Co. for Stennis as HP H2 Tank shipped to MAF in 1976	GN2	1375	AE-1984, 1991, 1994, 2001, 2007, RT&Hydrostatic (10080 psi)-1964, Hydrostatic(7550 psi)-1976, MT interior-1968, UT &UT Shear Heads 2001, PT, UT Heads-2007	AE Paper Copy, 2001, 2007	None	AE Every 5 years	Field Installed Manway, 1968, Inner vessel repairs 1968, No Concern for continued operation	T1 Steel (SA-517E) 2.749"	T1 Steel (SA-517F) 5.5"	T1 Steel (SA-517E) 3" ID/1.25" 10" ID/2.75" 20" ID/7.5"	6300	5523	2000	8.25 (heads) 8.75 (shells)	4142	40

Marshall Space Flight Center (MSFC)

MSFC 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 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.

MSFC Response May 2013

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.

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0362	Gaseous Hydrogen	4583A - TEST STAND 115	A212B FBX	3.61"	SA- 212 B FBX	3.75	A105-II	A212B FBX	12 @ .250	N/A	6 3/4"	Consolidated Western Steel	1963	Multilaminar	3520 GAL.	4000	5000	4119	48"	349	California Special No. 002
V0361	Gaseous Hydrogen	4583A - TEST STAND 115	A212B FBX	3.61"	SA- 212 B FBX	3.75	A105-II	A212B FBX	12 @ .250	N/A	6 3/4"	Consolidated Western Steel	1963	Multilaminar	3520 GAL.	4000	5000	4119	48"	349	California Special No. 003
V0349	High Purity Air	4752 - CENTER ACTIVITIES BUILDING	A225-B FBX	1.300"	CB&I 1143	0.375	A105-II	CB&I 1146	4 2 9/32"	N/A	1.470"	Chicago Bridge & Iron	1964	Multilaminar	35 Cu. Ft.	3275	5,500	4,880	20.00" ID	14" 11-1/2"	Scuba Club.Filled by trailer
V0348	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	0	5,500	3,867	20.00" ID	19.5'	Out of Service -- reduced mawp for GH2 service -- repaired 1991
V0347	Gaseous Nitrogen	4660 - Boiler House	A225 GR B FBQ	2.750"	AOS 1146A	0.500"	VMS 5002 Mod	AOS 1146A	12 @ .250	N/A	3.500"	A. O. Smith	1958	Multilaminar	28 Cu. Ft.	0	8,800	8,760	24" ID	7' 8-13/16"	Certification Required - Out of Service
V0346	Gaseous Helium	4648 - High Pressure Test Facility	AOS 1146A	1.125"	AOS 1146A	0.500"	SA212 GR B FB	AOS 1146A	5 @ 1/4"	N/A	1.750"	A. O. Smith	1957	Multilaminar	19 Cu. Ft.	380	5,000	4,939	22" ID	5' 9-1/4"	Out of Service
V0345	Gaseous Helium	4522 - TEST FACILITY 500 (TF500)	ASTM A-302 GR. B FBX MOD.	2.177"	CB&I 1143	0.500"	A350 LF3	CB&I 1146a	7 @ 1/4"	4 @ 9/32"	3.375"	Chicago Bridge & Iron	1965	Multilaminar	352 Cu. Ft.	4,000	5,000	5,402	40" ID	38' 1"	Repaired in 1988 GHe-RECERT-01-RR
V0344	Gaseous Helium	4676 - HELIUM COMPRESSOR BLDG.	ASTM A-225 GR. B FBX	3.640"	MLP 1143	0.469"	MLF 5002 MOD	MLP 1146	6 @ .250	8 @ .28125	4.293"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	4,050	5,000	4,667	60.250 ID	60'	Repaired in 1994
V0343	Gaseous Nitrogen	4522 - TEST FACILITY 500 (TF500)	ASTM A-225 GR. B FBX	3.640"	MLP 1143	0.469"	MLF 5002 MOD	MLP 1146	6 @ .250	8 @ .28125	4.293"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	4,050	5,000	4,667	60.250 ID	60'	Repaired in 1994 GHe-RECERT-01-RR
V0342	Gaseous Helium	4676 - HELIUM COMPRESSOR BLDG.	ASTM A-225 GR. B FBX	3.640"	MLP 1143	0.469"	MLF 5002 MOD	MLP 1143	6 @ .250	8 @ .28125	4.293"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	2,500	5,000	4,667	60-1/4" ID	60'	Repaired in 1994
V0339	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991
V0338	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991
V0337	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	
V0336	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991
V0335	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991
V0334	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0333	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991
V0332	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991
V0331	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1991
V0330	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0329	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0328	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0327	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0326	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0325	High Purity Air	4581 - NITROGEN GAS STORAGE FAC.	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1954	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0284	Gaseous Nitrogen	4467 - LIDAR FACILITY	A225 Gr B FBX	2.750"	AOS 1146A	0.500"	A5002 Mod	AOS 1146A	12 @ .250	N/A	3.500"	A. O. Smith	1959	Multilaminar	36 Cu. Ft.	0	8,800	8,760	24" ID	10' 1-1/4"	Has Known Defect - Out of Service
V0283	Gaseous Nitrogen	4643 - Propellants & Reactive Fluid Compatibility Test Facility	A-225-B FBX	1.510"	MPL 1143	0.375"	A-105 GR. II	MPL-1143	8 @ 1/4"	N/A	0.063"	Chicago Bridge & Iron	1964	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	14' 11-1/2"	OUT OF SERVICE
V0282	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,275	5,500	3,867	20.00" ID	19.5'	Out of Service -- reduced mawp for GH2 service -- repaired 1991
V0281	Gaseous Nitrogen	4530 - TEST FACILITY 300 (TF300)	A302 GR. B FBX MOD.	4.680"	CB&I 1143	0.500"	A-350-LF2	CBI 1143	17 @ .250	N/A	4.680"	Chicago Bridge & Iron	1965	Multilaminar	700 Cu. Ft.	4,280	5,000	5,476	48" ID	53'-1"	
V0280	Gaseous Nitrogen	4530 - TEST FACILITY 300 (TF300)	A302 GR. B FBX MOD.	4.680"	CB&I 1143	0.500"	A-350-LF2	CBI 1143	17 @ .250	N/A	4.680"	Chicago Bridge and Iron	1965	Multilaminar	700 Cu. Ft.	4,280	5,000	5,476	48" ID	53'-1"	GN2-RECERT-04-RR 08/83
V0279	Gaseous Nitrogen	4540 - TEST FACILITY 116 (TF116)	A302 GR. B FBX MOD.	3.980"	CB&I 1143	0.500"	A-350-LF2	CBI 1143	30 @ .250	N/A	8.300"	Chicago Bridge & Iron	1965	Multilaminar	700 Cu. Ft.	8000	8,000	8,176	48" ID	57'- 10"	Repaired 1990. Additional Drawing -

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
																					90M01376
V0278	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0277	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0276	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0275	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0274	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0273	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0272	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0271	Gaseous Nitrogen	4696 - Hydrogen Test Facility (95%)	A225 GR. B	3.062"	AOS 1146A	0.500"	A0S 5002 MOD	AOS 1146A	4 @ .500	2 @ .500	3.750"	A. O. Smith	1959	Multilaminar	260 Cu. Ft.	4,280	6,600	6,544	36"	41'-0"	
V0270	High Purity Air	4588 - COLD CALIBRATION TEST STAND	ASTM A-225 GR. B FBX	3.640"	MLP 1143	0.469"	MLF 5002 MOD	MLP 1146	6 @ .250	8 @ .28125	4.293"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	4,050	5,000	4,667	60.250 ID	60'	Repaired 1994, moved from B4676 and converted from GN2 Fall 1999.
V0269	High Purity Air	4751 - High Pressure Air Storage	ASTM A-225 GR. B FBX	3.640"	MLP 1143	0.469"	MLF 5002 MOD	MLP 1146	6 @ .250	8 @ .28125	4.293"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	4,050	5,000	4,667	60.250 ID	60'	Repaired 1994, moved from B4676 and converted from GN2 Fall 1999.
V0268	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225 GR. B FBX	3.640"	MLP 1143	0.469"	MLF 5002 MOD	MLP 1146	6 @ .250	8 @ .28125	4.293"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	4,050	5,000	4,667	60.250 ID	60'	Repaired 1994, moved from B4676 and converted from GN2 2/2000.
V0267	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225 GR. B FBX	3.640"	MLP 1143	0.469"	MLF 5002 MOD	MLP 1146	6 @ .250	8 @ .28125	4.293"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	4,050	5,000	4,667	60.250 ID	60'	Repaired 1994, moved from B4676 and converted from GN2 2/2000.
V0266	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0265	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0264	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0263	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0262	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0261	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0260	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0259	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0258	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0257	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,500	5,500	4,331	20.00" ID	19.5'	Repaired 1989, moved from B4598 and converted from GN2 Fall 1999.
V0256	Gaseous Nitrogen	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A225 GR. B FBX	3.690"		0.469"	A 105 GR II AND MLF 5002 MOD.	CBI 1143			4.180"	Chicago Bridge & Iron	1963	Multilaminar	1,250 Cu. Ft.	4,280	5,000	5,000			Repaired 1990
V0239	High Purity Air	4745 - SANDBLAST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0238	High Purity Air	4745 - SANDBLAST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0237	High Purity Air	4745 - SANDBLAST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX		ASTM A-105 GR. 11	ASTM A225 B FBX MOD			1.750"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1988
V0236	High Purity Air	4745 - SANDBLAST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0235	High Purity Air	4745 - SANDBLAST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0234	High Purity Air	4745 - SANDBLAST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0233	High Purity Air	4752 - CENTER ACTIVITIES BUILDING	A 225 GR. B FBX	1.300"	CB&I 1143	0.375"	A 105 GR. II	CBI 1146	4 @ 0.28125	N/A	1.470"	Chicago Bridge & Iron	1964	Multilaminar	35 Cu. Ft.	3275	5,500	4,885	20.00" ID	14',11.5"	Scuba Club,Filled by trailer
V0232	High Purity Air	4207 - Communications Facility	A 225 GR. B FBX	1.300"	CB&I 1143	0.375"	A 105 GR. II	CBI 1146	4 @ 0.28125	N/A	1.470"	Chicago Bridge & Iron	1964	Multilaminar	35 Cu. Ft.	3275	5,500	4,885	20.00" ID	14',11.5"	Moved from B4656 and converted from GN2 Fall 1999.
V0231	High Purity Air	4207 - Communications Facility	A 225 GR. B FBX	1.300"	CB&I 1143	0.375"	A 105 GR. II	CBI 1146	4 @ 0.28125	N/A	1.470"	Chicago Bridge & Iron	1964	Multilaminar	35 Cu. Ft.	3275	5,500	4,885	20.00" ID	14',11.5"	Moved from B4656 and converted from GN2 Fall 1999.
V0230	Gaseous Nitrogen	4660 - Boiler House	A105 GR. II	2.125"	AOS 1135G Gr B	0.500"	A105 GR. II	AOS 1135G Gr B	11 @ .250"	N/A	3.250"	A. O. Smith	1950	Multilaminar	30 Cu. Ft.	0	5,000	0	24" ID	8' 4"	Out of Service
V0229	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A 225 GR. II	1.173"	MLP-1143	0.375"	A 105 GR. II	MLP-1146	4 @ 0.250	N/A	1.363"	Chicago Bridge & Iron	1956	Multilaminar	35 Cu. Ft.	3275	5,500	4,468	20.00" ID	14',11.5"	Moved from B4650 and converted from GN2 Fall 1999.
V0228	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A 225 GR. II	1.173"	MLP-1143	0.375"	A 105 GR. II	MLP-1146	4 @ 0.250	N/A	1.363"	Chicago Bridge & Iron	1956	Multilaminar	35 Cu. Ft.	3275	5,500	4,468	20.00" ID	14',11.5"	Moved from B4650 and converted from GN2 Fall 1999.
V0227	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A 225 GR. II	1.173"	MLP-1143	0.375"	A 105 GR. II	MLP-1146	4 @ 0.250	N/A	1.363"	Chicago Bridge & Iron	1956	Multilaminar	35 Cu. Ft.	3275	5,500	4,468	20.00" ID	14',11.5"	Moved from B4650 and converted from GN2 Fall 1999.
V0226	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A 225 GR. II	1.173"	MLP-1143	0.375"	A 105 GR. II	MLP-1146	4 @ 0.250	N/A	1.363"	Chicago Bridge & Iron	1956	Multilaminar	35 Cu. Ft.	3275	5,500	4,468	20.00" ID	14',11.5"	Moved from B4650 and converted from GN2 Fall 1999.
V0186	High Purity Air	4777 - Engine Dynamic Fluid Flow Facility	ASTM A225 GRADE B	2.125”	AOS 1146A	0.500"	VMS-500S MODIFIED	AOS 1146A	7 @ 0.282"	N/A	2.474”	A. O. Smith	1959	Multilaminar	826.8 Cu. Ft.	1,920	2,800	2,630	60" ID	45' 8"	
V0185	High Purity Air	4777 - Engine Dynamic Fluid Flow Facility	ASTM A225 GRADE B	2.125”	AOS 1146A	0.500"	VMS-500S MODIFIED	AOS 1146A	7 @ 0.282"	N/A	2.474”	A. O. Smith	1959	Multilaminar	826.8 Cu. Ft.	1,920	2,800	2,630	60" ID	45' 8"	
V0174	High Purity Air	4207 - Communications Facility	A-225-B FBX	1.510"	MPL 1143	0.375"	A-105 GR. II	MPL-1143	8 @ 1/4"	N/A	0.063"	Chicago Bridge & Iron	1964	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	14' 11-1/2"	
V0161	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1952	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1988
V0160	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1988
V0159	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
								MOD													
V0158	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1957	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0157	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1989
V0156	Gaseous Nitrogen	4650 SOUTH - Calibration Facility	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted to HP Air Fall 1999.
V0155	Gaseous Nitrogen	4650 SOUTH - Calibration Facility	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted to HP Air Fall 1999.
V0154	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0153	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0152	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0151	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0150	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0149	Gaseous Nitrogen	4650 SOUTH - Calibration Facility	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0148	Gaseous Nitrogen	4650 SOUTH - Calibration Facility	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0147	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"		0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1957	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1989
V0146	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0145	High Purity Air	4572 - PROPUL. & STRUCTURAL	A-225-B FBQ	1.438"	AO Smith Spec	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
		TEST FACILITY			1146A																
V0144	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0143	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0142	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted to HP Air Fall 1999.
V0141	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0140	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Repaired in 1987
V0139	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0138	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0137	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0136	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0135	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Moved from B4572 and converted from HP Air Fall 1999.
V0134	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	Repaired in 1989, moved from B4572 and converted from HP Air Fall 1999.
V0133	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0132	High Purity Air	4572 - PROPUL. & STRUCTURAL	ASTM A212B	1.625"	A 225 GR. B	0.4375	ASTM A-105 GR. 11	ASTM A225 B	7 @ .250	N/A	2.188"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331			Repaired in 1990

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
		TEST FACILITY	FBX		FBX			FBX MOD													
V0131	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0130	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0129	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1955	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1990
V0128	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	A-225-B FBQ	1.438"	AO Smith Spec 1146A	0.5	A-105 GR. II	AOS 1146 a	5 @ .250	N/A	1.750"	A. O. Smith	1958	Multilaminar	35 Cu. Ft.	3,275	5,500	5,500	20" ID	16'	
V0127	High Purity Air	4572 - PROPUL. & STRUCTURAL TEST FACILITY	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1955	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1987
V0126	High Purity Air	4670 - ADVANCED ENGINE TEST FACILITY	A225 GR. B FBX	1.056"	MLP 1143 Mod	0.500"	MLF 5002 MOD	MLP 1146	3 @ 1/4"	N/A	1.217"	Chicago Bridge & Iron	1963	Multilaminar	35 Cu. Ft.	3,275	3,500	3,146	24" ID	9' 10"	Out of Service
V0125	High Purity Air	4670 - ADVANCED ENGINE TEST FACILITY	A225 GR. B FBX	1.056"	MLP 1143 Mod	0.500"	MLF 5002 MOD	MLP 1146	3 @ 1/4"	N/A	1.217"	Chicago Bridge & Iron	1963	Multilaminar	35 Cu. Ft.	3,275	3,500	3,146	24" ID	9' 10"	Out of Service
V0124	Gaseous Nitrogen	4598 - NITROGEN GAS STORAGE FACILITY	A-302 GR. B FBX MOD.	3.270"	CB&I 1143	0.500"	A-305-LF3	CB&I 1146	16 @ 9/32"	N/A	5.075"	Chicago Bridge & Iron	1963	Multilaminar	1255 Cu. Ft.	4230	5,000	5,402	60.25" ID	60"	Transfered from HP AIr serivce to GN2 Service in 2011. Replaced V256.
V0122	High Purity Air	4530 - TEST FACILITY 300 (TF300)	A-302 GR. B FBX MOD.	1.690"	CB&I 1143	0.500"	A-305-LF2	CBI 1143	11 @ 1/4"	N/A	3.180"	Chicago Bridge & Iron	1965	Multilaminar	700 Cu. Ft.	3,275	3,500	3,792	48" ID	53' 1"	
V0121	High Purity Air	4588 - COLD CALIBRATION TEST STAND	A-302 GR. B FBX MOD.	2.270"	CB&I 1143	0.500"	A-305-LF3	CB&I 1146	4 @ 1/4"	7 @ 9/32"	3.480"	Chicago Bridge & Iron	1965	Multilaminar	1255 Cu. Ft.	3,275	3,500	3,803	60.25" ID	60'	
V0120	High Purity Air	4648 - High Pressure Test Facility	A-302 GR. B FBX MOD.	2.270"	CB&I 1143	0.500"	A-305-LF3	CB&I 1146	4 @ 1/4"	7 @ 9/32"	3.480"	Chicago Bridge & Iron	1965	Multilaminar	1255 Cu. Ft.	3,275	3,500	3,803	60.25" ID	60'	Vessel at Building 4647, this location is not in our Location listing.
V0119	High Purity Air	4660 - Boiler House	A-212- GR B FBX	1.375	AOS 1135-G GRB	0.500"	ASTM A-105 GR. 11	AOS 1135-G GRB	7 @ .250"	N/A	2.250"	A. O. Smith	1953	Multilaminar	19 Cu. Ft.	0	3,500	0	24" ID	55"	Surplussed
V0117	High Purity Air	4650 SOUTH - Calibration Facility	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1987
V0116	High Purity Air	4650 SOUTH - Calibration Facility	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1956	Multilaminar	35 Cu. Ft.	3,275	5,500	4,331	20.00" ID	19.5'	Repaired in 1987 (nozzles), 11/95 (shell)

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0115	Gaseous Nitrogen	4619 - STR. DYNAMICS & THERMAL VAC LAB	A-302 GR. B FBX MOD.	3.270"	MLP 1143	0.46875	A-305-LF3	CBI 1143	6 @ .250	8 @ .281	5.075"	Chicago Bridge & Iron	1965	Multilaminar	1255 Cu. Ft.	4280	5,000	5,402	60.25" ID	60"	Converted 2/2000
V0114	Gaseous Nitrogen	4619 - STR. DYNAMICS & THERMAL VAC LAB	A-302 GR. B FBX MOD.	3.270"	MLP 1143	0.46875	A-305-LF3	CBI 1143	6 @ .250	8 @ .281	5.075"	Chicago Bridge & Iron	1963	Multilaminar	1255 Cu. Ft.	4280	5,000	5,402	60.25" ID	60"	Converted 2/2000
V0113	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225-B	1.187"	AOS 1148-b	0.500"	A-105 GR. II	AOS 1148-b	7 @ 1/4"	N/A	2.187"	A. O. Smith	1957	Multilaminar	120 Cu. Ft.	3,275	3,500	3,278	33" ID	24' 6-11/16"	
V0112	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225-B	1.187"	AOS 1148-b	0.500"	A-105 GR. II	AOS 1148-b	7 @ 1/4"	N/A	2.187"	A. O. Smith	1957	Multilaminar	120 Cu. Ft.	3,275	3,500	3,278	33" ID	24' 6-11/16"	
V0111	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225-B	1.187"	AOS 1148-b	0.500"	A-105 GR. II	AOS 1148-b	7 @ 1/4"	N/A	2.187"	A. O. Smith	1957	Multilaminar	120 Cu. Ft.	3,275	3,500	3,278	33" ID	24' 6-11/16"	
V0110	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225-B	1.187"	AOS 1148-b	0.500"	A-105 GR. II	AOS 1148-b	7 @ 1/4"	N/A	2.187"	A. O. Smith	1957	Multilaminar	120 Cu. Ft.	3,275	3,500	3,278	33" ID	24' 6-11/16"	
V0109	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225-B	1.187"	AOS 1148-b	0.500"	A-105 GR. II	AOS 1148-b	7 @ 1/4"	N/A	2.187"	A. O. Smith	1957	Multilaminar	120 Cu. Ft.	3,275	3,500	3,278	33" ID	24' 6-11/16"	
V0108	High Purity Air	4619 - STR. DYNAMICS & THERMAL VAC LAB	ASTM A-225-B	1.187"	AOS 1148-b	0.500"	A-105 GR. II	AOS 1148-b	7 @ 1/4"	N/A	2.187"	A. O. Smith	1957	Multilaminar	120 Cu. Ft.	3,275	3,500	3,278	33" ID	24' 6-11/16"	
V0107	High Purity Air	4751 - High Pressure Air Storage	SWC 100302	2.312"	SWC 100302	1.625"	SWC 90336	SWC 100302	1 @ 1.625"	1 @ 1.750"	5.000"	Struthers Wells Corp	1966	3-Layer	600 Cu. Ft.	3,275	5,000	3,412	60-1/4" ID	34' 7-7/8"	
V0106	High Purity Air	4751 - High Pressure Air Storage	SWC 100302	2.312"	SWC 100302	1.625"	SWC 90336	SWC 100302	1 @ 1.625"	1 @ 1.750"	5.000"	Struthers Wells Corp	1966	3-Layer	600 Cu. Ft.	3,275	5,000	3,412	60-1/4" ID	34' 7-7/8"	
V0105	High Purity Air	4751 - High Pressure Air Storage	A-212 BR. B FBX	1.375"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	7 @ 0.25"	N/A	2.250"	A. O. Smith	1953	Multilaminar	70 Cu. Ft.	3,275	3,500	3,955	24" ID	21' 0"	
V0104	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBX	1.375"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	7 @ 0.25"	N/A	2.250"	A. O. Smith	1953	Multilaminar	70 Cu. Ft.	3,275	3,500	3,955	24" ID	21' 0"	
V0103	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0102	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0101	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0100	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0099	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0098	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0097	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0096	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0095	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0094	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0093	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0092	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0091	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0090	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBX	1.375"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	7 @ 0.25"	N/A	2.250"	A. O. Smith	1953	Multilaminar	70 Cu. Ft.	3,275	3,500	3,955	24" ID	21' 0"	
V0089	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBX	1.375"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	7 @ 0.25"	N/A	2.250"	A. O. Smith	1953	Multilaminar	70 Cu. Ft.	3,275	3,500	3,955	24" ID	21' 0"	
V0088	High Purity Air	4751 - High Pressure Air Storage	A-212 GR.B.FBX	1.375"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	7 @ 0.25"	N/A	2.250"	A. O. Smith	1953	Multilaminar	70 Cu. Ft.	3,275	3,500	3,955	24" ID	21' 0"	Repaired in 1987
V0087	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0086	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0085	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0084	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0083	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0082	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0081	High Purity Air	4751 - High Pressure Air	A-212 GR. B FBQ	2"	AOS 1135G	0.500"	A-105 GR. II	A0S 1135-G	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
		Storage			GR B			GR. B													
V0080	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0079	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0078	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0077	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0076	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0075	High Purity Air	4751 - High Pressure Air Storage	A-212 GR. B FBQ	2"	AOS 1135G GR B	0.500"	A-105 GR. II	A0S 1135-G GR. B	10 @ 0.250"	N/A	3.000"	A. O. Smith	1953	Multilaminar	120 Cu. Ft.	3,275	3,500	3,862	33" ID	24' 7-1/2"	
V0065	Gaseous Hydrogen	4628 - Hydrogen Test Facility	AOS 1146A	1.125"	AOS 1146A	0.500"	SA212 GR B FB	AOS 1146A	5 @ 1/4"	N/A	1.750"	A. O. Smith	1957	Multilaminar	19 Cu. Ft.	380	5,000	4,939	22" ID	5' 9-1/4"	Out of Service
V0064	Gaseous Hydrogen	4628 - Hydrogen Test Facility	AOS 1146A	1.125"	AOS 1146A	0.500"	SA212 GR B FB	AOS 1146A	5 @ 1/4"	N/A	1.750"	A. O. Smith	1957	Multilaminar	19 Cu. Ft.	380	5,000	4,939	22" ID	5' 9-1/4"	Out of Service
V0063	Gaseous Hydrogen	4628 - Hydrogen Test Facility	A-212 Gr B	2"	AOS 1135G GR B	0.500"	A-105 GR. II	AOS 1135G GR B	6 @ 1/4"	N/A	3.250"	A. O. Smith	1960	Multilaminar	19 Cu. Ft.	0	5,000	5,565	24" ID	55"	Out of Service
V0040	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	0.438"	AOS 1146A	0.500"	ASTM A105 GR II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service - repaired 1991
V0039	Gaseous Hydrogen	4648 - High Pressure Test Facility	ASTM A212B FBX	1.438"	AOS 1146A	0.500"	ASTM A105 GR II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service. Repaired 3/99.
V0038	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1957	Multilaminar	35 Cu. Ft.	0	5,500	3,867	20.00" ID	19.5'	Out of Service -- reduced mawp for GH2 service -- repaired 1991
V0037	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A-105 GR. 11	ASTM A225 B FBX MOD	7 @ .250	N/A	2.188"	A. O. Smith	1957	Multilaminar	35 Cu. Ft.	0	5,500	3,867	20.00" ID	19.5'	Out of Service -- reduced mawp for GH2 service -- repaired 1991
V0036	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service - repaired 1991
V0035	Gaseous Hydrogen	4648 - High Pressure Test Facility	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR. II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service.
V0034	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service - repaired 1991

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0033	Gaseous Hydrogen	4583A - TEST STAND 115	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service - repaired 1991
V0032	Gaseous Hydrogen	4648 - High Pressure Test Facility	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR.11	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service. Repaired 3/99.
V0031	Gaseous Hydrogen	4648 - High Pressure Test Facility	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR.11	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service. Repaired 3/99.
V0030	Gaseous Hydrogen	4648 - High Pressure Test Facility	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR. II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service - repaired 1996
V0029	Gaseous Hydrogen	4648 - High Pressure Test Facility	ASTM A212B FBX	1.625"	A 225 GR. B FBX	0.4375	ASTM A105 GR. II	AOS 1146A	5 @ .250	N/A	1.750"	A. O. Smith	1962	Multilaminar	35 Cu. Ft.	0	5,500	3,933	20" ID	16'	Out of Service -- reduced mawp for GH2 service - repaired 1993
V0028	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0027	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0026	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0025	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0024	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0023	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	Out of Service
V0022	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0021	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0020	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0019	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0018	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0017	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0016	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0015	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0014	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0013	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0012	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0011	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0010	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0009	Gaseous Hydrogen	4699 - CRYOGENIC STRUCTURAL TEST FACILITY	ASTM A225 Gr B FBQ	3.030"	AOS 1146a	0.46785"	ASTM A105 CL 2	AOS 1146a	10 @ 0.277"	N/A	3.305"	A. O. Smith	1960	Multilaminar	625 Cu. Ft.	3,100	4,400	3,142	58" ID	36.25'	
V0008	Gaseous Hydrogen	4522 - TEST FACILITY 500 (TF500)	A-302 GR B FBX	2.610"	CB&I 1143	1/2"	A350-LF2	CB&I-1143	17 @ 1/4"	N/A	4.68"	Chicago Bridge & Iron	1965	Multilaminar	700 Cu. Ft.	4,000	5,000	4,400	48"	53' 1"	GH2-RECERT-02-PR2007
V0007	Gaseous Hydrogen	4522 - TEST FACILITY 500 (TF500)	A-302 GR B FBX	2.610"	CB&I 1143	1/2"	A350-LF2	CB&I-1143	17 @ 1/4"	N/A	4.68"	Chicago Bridge & Iron	1965	Multilaminar	700 Cu. Ft.	4,000	5,000	4,400	48"	53' 1"	GH2-RECERT-02-PR2007
V0006	Gaseous Hydrogen	4540 - TEST FACILITY 116 (TF116)	A350-LF3	7"	CB&I 1143	1/2"	A350-LF3	CB&I-1146	10 @ 1/4"	20 @ 9/32"	8.830"	Chicago Bridge & Iron	1965	Multilaminar	100 Cu. Ft.	9,400	15,000	10,000	30" I.D.	18' 9"	
V0005	Gaseous Hydrogen	4540 - TEST FACILITY 116 (TF116)	A350-LF3	7"	CB&I 1143	1/2"	A350-LF3	CB&I-1146	10 @ 1/4"	20 @ 9/32"	8.830"	Chicago Bridge & Iron	1965	Multilaminar	100 Cu. Ft.	9,400	15,000	10,000	30" I.D.	18' 9"	

Vessel ID #	Media	Location	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Shell Material	Number of Layers & Thickness (T1)	Number of Layers & Thickness (T2)	Total Shell Thickness	Manufacturer	Year Built	Vessel Type	Vessel Volume	Operating Pressure	Design Pressure	Max All Working Pressure	Diameter	Length	Comments
V0004	Gaseous Hydrogen	4540 - TEST FACILITY 116 (TF116)	A350-LF3	7"	CB&I 1143	1/2"	A350-LF3	CB&I-1146	10 @ 1/4"	20 @ 9/32"	8.830"	Chicago Bridge & Iron	1965	Multilaminar	100 Cu. Ft.	9,400	15,000	10,000	30" I.D.	18' 9"	
V0003	Gaseous Hydrogen	4540 - TEST FACILITY 116 (TF116)	A350-LF3	7"	CB&I 1143	1/2"	A350-LF3	CB&I-1146	10 @ 1/4"	20 @ 9/32"	8.830"	Chicago Bridge & Iron	1965	Multilaminar	100 Cu. Ft.	9,400	15,000	10,000	30" I.D.	18' 9"	
V0002	Gaseous Hydrogen	4540 - TEST FACILITY 116 (TF116)	A350-LF3	7"	CB&I 1143	1/2"	A350-LF3	CB&I-1146	10 @ 1/4"	20 @ 9/32"	8.830"	Chicago Bridge & Iron	1965	Multilaminar	100 Cu. Ft.	9,400	15,000	10,000	30" I.D.	18' 9"	
V0001	Gaseous Hydrogen	4540 - TEST FACILITY 116 (TF116)	A350-LF3	7"	CB&I 1143	1/2"	A350-LF3	CB&I-1146	10 @ 1/4"	20 @ 9/32"	8.830"	Chicago Bridge & Iron	1965	Multilaminar	100 Cu. Ft.	9,400	15,000	10,000	30" I.D.	18' 9"	

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.

   Vessel (V-066-GH): Crack propagation detection by acoustic emission. Vessel removed from service in 1980.

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).

Nameplate Rating (PSI)	Center's Design Pressure (PSI)	Operating Pressure (PSI)	Water Volume (ft^3)	Age (yr)	Wall thickness (shell, total nominal, in.)	Number of Shell layers and thicknesses (nominal, in.)	Shell Materials of construction	Head thickness (in.)	Number of Head layers and thicknesses	Head Materials of construction	Comments (general condition, vessel history, known flaws, etc.)
6,300 (SF=3)	4,500 (SF=4)	4,500	1,375	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,500 (SF=4)	4,100	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (FS=3)	4,576 (SF=4)	4,100	1,375	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
3,750 (SF=3)	2,800 (SF=4)	2,750	950	49	3.125	1 - 1.8125, 1 - 1.3125	SA-517F 'T-1 Steel'	1.6875	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,678 (SF=4)	4,100	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,647 (SF=4)	4,300	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,647 (SF=4)	4,100	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,678 (SF=4)	4,100	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,753 (SF=4)	4,300	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,814 (SF=4)	4,300	1,065	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,784 (SF=4)	4,100	1,375	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,693 (SF=4)	4,300	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,814 (SF=4)	4,300	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
6,300 (SF=3)	4,663 (SF=4)	4,100	1,500	49	5.5	4 - 1.375	SA-517F 'T-1 Steel'	3.062	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
3,750 (SF=3)	2,800 (SF=4)	2,750	950	48	3.125	1 - 1.8125, 1 - 1.3125	SA-517F 'T-1 Steel'	1.6875	1	SA-517F 'T-1 Steel'	Vessel built for SSC, all inspection records and repair history maintained.
2,756	2,000 (SF=4)	TBD	830	54	2.474	7 - 0.269, 1 - 0.5	AOS 1146a	2.125	1	A-225 Gr. B FBQ	Vessels built for KSC's Auxiliary GN Supply System and moved to SSC ~2010. Historical inspection data not currently on record.
2,756	2,000 (SF=4)	TBD	830	54	2.474	7 - 0.269, 1 - 0.5	AOS 1146a	2.125	1	A-225 Gr. B FBQ	

Appendix C. MSFC Sacrificed Vessel General Information

MSFC **M**aterials and **P**rocesses Laboratory
Flash **R**eport
MSFC Engineering Directorate
Materials and Processes Laboratory

Title: General Information on Layered Pressure Vessels			
Author: Gilda Ham-Battista	Org: EM20	Phone: 256-544-6328	email: Gilda.L.Battista@nasa.gov
Date: February 25, 2014	Supported Element/System: Pressure Systems: Layered Pressure Vessel Evaluation		
Keywords: Layered pressure vessels (LPVs)			

Executive Summary: (Purpose and Result)

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

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 1

MSFC Materials and Processes Laboratory
Flash Report

MSFC Engineering Directorate
Materials and Processes Laboratory

General Information

Vessel ID #	Vessel Serial Number	Media	Vessel Drawing Number	Manufacturer	Year Built	Cert Status
V0032	MV-50288-34	Gaseous Hydrogen	MV-50288	A. O. Smith	1962	Uncertified
V0125	M117	High Purity Air	Aug-95	Chicago Bridge & Iron	1963	Uncertified
V0256	M108	Gaseous Nitrogen	Aug-86	Chicago Bridge & Iron	1963	Uncertified

Size and Environment

Vessel ID #	Inside Diameter	Length	Design Temp	Operating Pressure	Design Pressure	Max Allowable Working Pressure	Weight	Vessel Volume
V0032	20"	16' 7 1/2" overall	Ambient		5,500	3,933	7,605 LBS	35 Cu. Ft.
V0125	24"	9' 10" tangent-to-tangent	10 to 110 F	3,275	3,500	3,146	4,750 LBS	35 Cu. Ft.
V0256	60' 1/4"	60' 0" tangent-to-tangent	120 F	4,280	5,000	5,000	199,000 LBS	1,250 Cu. Ft.

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 2

MSFC Materials and Processes Laboratory
Flash Report

MSFC Engineering Directorate
Materials and Processes Laboratory

Head and Shell Information

Vessel ID #	Head Material	Head Thickness	Inner Shell Material	Inner Shell Thickness	Nozzle Material	Nozzle Size	Number Of Nozzles	Shell Material	No. of Shells	Individual Outer Shell Thickness
V0032	ASTM A225 Gr. B Fire Box	1.438"	AOS 1146 a	1/2 "	ASTM A105 GR.11	1"	2	AOS 1146 a	5	1/4 "
V0125	A225 GR. B FBX	1.056"	MLP 1143 Mod.	1/2 "	MLF 5002 MOD	2"	2	MLP 1146	3	1/4 "
V0256	A225 GR. B FBX	3.699"	MLP 1143 Mod.	15/32 "	A 105 GR II AND MLF 5002 MOD.	1 1/2", 3", 5"	4	MLP 1146	13	9/32 "

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 3

MSFC Materials and Processes Laboratory
Flash Report
MSFC Engineering Directorate
Materials and Processes Laboratory

V0032

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 4

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Flash Report
MSFC Engineering Directorate
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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

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 5

MSFC Materials and Processes Laboratory
Flash Report

MSFC Engineering Directorate
Materials and Processes Laboratory

A. O. SMITH CORP.

MATERIAL RECORD

FOR PLATES, HEADS AND FORGINGS

CUSTOMER Geo. C. Marshall, Space Flight Center (NAS-8-3594)

ADDRESS Huntsville, Alabama

EQUIPMENT TYPE Gas Receivers

DESTINATION Huntsville, Alabama

DRAWING NO. MV 50288

A. O. S. SERIAL NO. MV 50288-33 thru 42

SHIPPING ORDER NO. 62-300-1449

DATE November 5, 1962

1. Hemispherical Heads
2. 1" Nozzles
3 thru 5 Inner Shells
6 and 7 Shell Layers

A. O. SMITH CORPORATION
PROCESS EQUIPMENT DIVISION
MILWAUKEE, WISCONSIN

BY John L. Iverson

MILL TEST REPORT

NO.	MANUFACTURER OF STEEL	MELT, SLAB AND SERIAL NO.	CHEMICAL C	MN	P	S	Si	Ni	V	PHYSICAL EL. LIMIT	ULT. STRENGTH	ELONG. 8"	BEND	NICK
1	U.S.Steel	672031-4-2	.18	1.32	.027	.022	.21	-	.10	59,920	87,870	29.0*	OK	OK
2	Lenape	A25	.26	.67	.015	.021	.20	-	-	48200	70,200	31.0*	RofA	56.0
3	U.S.Steel	199958	.22	1.26	.013	.024	.28	.54	.16	88,360	114,350	36.0*	OK	-
4	U.S.Steel	200291	.24	1.44	.016	.016	.25	.52	.14	91,830	124,800	29.0*	OK	-
5	U.S.Steel	401385	.25	1.38	.015	.025	.33	.55	.16	90,670	117,000	28.0*	OK	-
6	U.S.Steel	401385								89,990	116,400	25.0*	OK	-
7	U.S.Steel	332226	.23	1.40	.015	.021	.29	.53	.14	93,420	118,700	28.0*	OK	-

* Elongation in 2 inches

NOTE: Physical values reported on lines 3 thru 7 represent a composit minimum of all plate tests of the reported heat for material used in these units.

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 6

MSFC Materials and Processes Laboratory
Flash Report

MSFC Engineering Directorate
Materials and Processes Laboratory

V0125

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 7

MSFC Materials and Processes Laboratory
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MSFC Engineering Directorate
Materials and Processes Laboratory

Vessel V0125 in service

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MSFC Materials and Processes Laboratory
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MSFC Engineering Directorate
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Vessel V0125 pre- and post- dissection.

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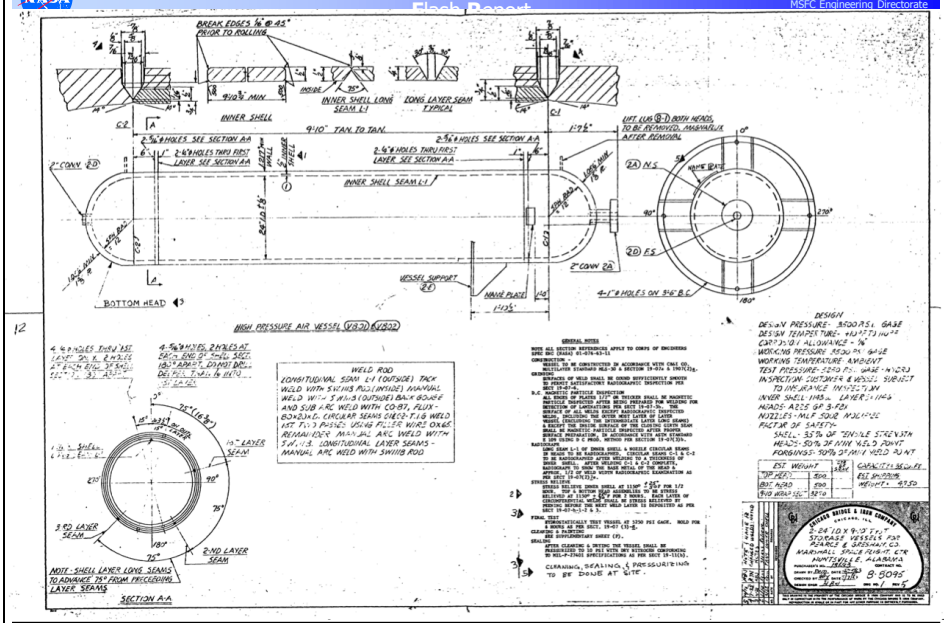
MSFC Materials and Processes Laboratory Flash Report

MSFC Engineering Directorate



Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 10

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MSFC Engineering Directorate Materials and Processes Laboratory

MATERIAL RECORD

FOR PLATES, HEADS, FORGINGS AND BOLTS

CUSTOMER Pearce & Gresham Co.
CONTRACT NO. 8-8095
CB&I SERIAL NO.
DATE 1-17-64

	SPECIFICATIONS
1. Hemispherical Heads	ASTM A225-B FBX
2. Inner Shell	1143
3. Thru 5, Shell Layers	1146
6. 2" Connection (Bottom Head)	MLF 5002 MOD. Chicago Bridge & Iron Co. Central Operations Chicago, Illinois
7. 2" Connection (Top Head)	MLF 5002 MOD. BY

MILL TEST REPORT

No.	Steel Produced by	Melt, Slab & Serial No.	CHEMICAL C	MN	P	S	SI	VA	NI	CR	PHYSICAL El.Limit	Ult.Str.	Elong*	Bend
1	U.S.Steel	622618-5-2	.17	1.27	.01	.016	.21	.10	-	-	58,890	81,400	33.5	OK
2	U.S.Steel	292646-15-1	.22	1.26	.016	.022	.30	.16	.50	.07	71,220	91,860	24.5	-
2	U.S.Steel	292646-15-2	"	"	"	"	"	"	"	"	70,650	92,140	23.5	-
2	U.S.Steel	292646-16-1	"	"	"	"	"	"	"	"	70,720	91,640	24.0	-
2	U.S.Steel	292646-16-2	"	"	"	"	"	"	"	"	70,240	91,500	23.0	-
3	U.S.Steel	199958-4-2	.22	1.26	.013	.024	.28	.16	.51	-	92,040	120,900	28.0	OK
4	U.S.Steel	372016-3-2	.24	1.30	.012	.024	.31	.15	.53	-	94,500	118,600	29.0	OK
5	U.S.Steel	372016-7-2	"	"	"	"	"	"	"	-	96,260	117,800	27.0	OK
6	Indust.Forge & Steel, Inc.	21068-2	.22 MO = .04	1.47	.015	.024	.30 CU = .11	.15	.59	.06	62,500	87,500	25.0	-
7	Indust.Forge & Steel, Inc.	22017-3	.21 MO = .04	1.46	.019	.027	.27 CU = .07	.16	.53	.07	62,000	95,000	27.0	-

* Percent in 2"

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 11

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Materials and Processes Laboratory

V0256

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 12

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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.

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 13

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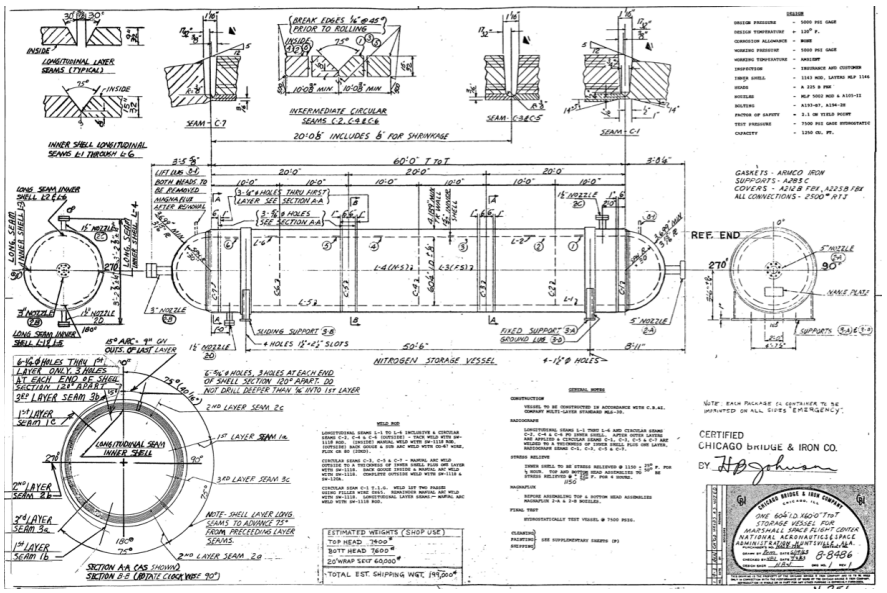

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 14

MSFC Materials and Processes Laboratory
Flash Report

MSFC Engineering Directorate
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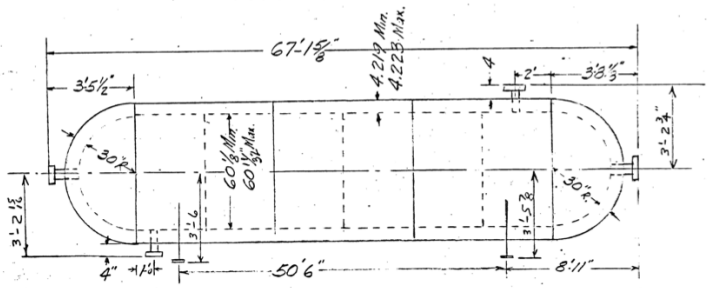
"AS FABRICATED"
CB#1 8-8486
N.A.S. 8-7981



We certify that the final measured dimensions are as indicated above.
10.11.12 Louis Boucher

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 15

MSFC Materials and Processes Laboratory
Flash Report
MSFC Engineering Directorate
Materials and Processes Laboratory

MATERIAL RECORD
FOR PLATES, HEADS, FORGINGS AND BOLTS

CUSTOMER NAT'L. AERO. & SPACE ADM. - HUNTSVILLE, ALA.
CONTRACT NO. 8-8486
CB&I SERIAL NO.
DATE DECEMBER 13, 1963

1. INNER SHELL
2. WRAP PLATES
3. 3" NOZZLE
4. 5" NOZZLE
5. 14" NOZZLE
6. HEADS

Chicago Bridge & Iron Co.
Central Operations
Chicago, Illinois
BY W. A. Thompson
Purchasing Agent Central Operations

MILL TEST REPORT

No.	Steel Produced by	Melt, Slab & Serial No.	CHEMICAL C	MN	P	S	Si	Ni	V	PHYSICAL El. Limit	Ult. Str.	Elong*	Bend
1.	USS	NHG6W-160348	.24	1.45	.014	.016	.28	.65	.15	82,180	98,360	40.0	
		NHG5W-160349	.24	1.45	.014	.016	.28	.65	.15	80,170	98,480	44.0	
		696332-972116	.23	1.48	.011	.018	.32	.68	.13	79,930	97,420	34.0	
		696332-977118	.23	1.48	.011	.018	.32	.68	.13	79,930	97,420	34.0	
2.	USS	160582 7-3	.24	1.30	.013	.021	.25	.53	.14	91,340	120,600	27.0	
		7-4								86,960	114,000	30.0	
		149928 1-1	.23	1.78	.017	.019	.27	.53	.15	84,190	118,500	28.0	
		1-2								85,030	117,300	31.0	
		2-1								85,410	119,200	20.0	
		2-2								86,690	118,800	31.0	
		3-1								85,660	121,300	30.0	
		3-2								85,640	114,500	31.0	
		4-1								87,360	117,100	30.0	
		4-2								83,870	115,000	31.0	
		5-2								82,690	117,700	31.0	
		5-3								83,880	118,600	30.0	
		1-4								87,740	109,900	34.0	
		2-4								88,840	111,100	31.0	
		3-3								88,770	113,450	31.0	
		3-4								89,980	113,000	32.0	
		4-4								89,230	111,400	35.0	
		5-4								90,070	108,800	31.0	
		6-3								90,040	115,200	29.0	
		6-4								89,310	113,600	30.0	

(CONT'D)

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 16

MSFC Materials and Processes Laboratory
Flash Report
MSFC Engineering Directorate
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MATERIAL RECORD
FOR PLATES, HEADS, FORGINGS AND BOLTS

CUSTOMER NAT'L. AERO. & SPACE ADM.
CONTRACT NO. 8-8486
CB&I SERIAL NO.
DATE DEC. 13, 1963

Chicago Bridge & Iron Co.
Central Operations
Chicago, Illinois
BY W. A. Thompson
Purchasing Agent Central Operations

MILL TEST REPORT

No.	Steel Produced by	Melt, Slab & Serial No.	CHEMICAL C	MN	P	S	Si	Ni	V	PHYSICAL PH Hrs	El. Limit	Ult. Str.	Elong*	Bend
2.	USS	160582 2-2	.24	1.30	.013	.021	.25	.53	.14		97,080	123,300	30.0	
		2-3									91,900	119,300	30.0	
		3-2									85,080	126,500	25.0	
		3-3									93,220	120,700	28.0	
		5-1									93,300	122,300	28.0	
		5-2									93,120	123,450	27.0	
		149928 9-1	.23	1.78	.017	.019	.27	.53	.15		93,170	114,600	29.0	
		6-1									87,820	117,100	31.0	
		8-1									91,200	113,900	30.0	
		7-3									88,390	114,750	30.0	
		7-2									91,910	117,300	28.0	
		7-4									90,970	111,150	30.0	
		1-3									87,020	110,700	34.0	
		6-2									95,360	122,650	30.0	
		9-4									87,320	110,700	32.0	
		202646 9-1	.22	1.26	.014	.022	.30	.50	.16		93,450	115,200	34.0	
		10-3									91,820	116,050	32.0	
		372642 6-1	.24	1.47	.018	.019	.31	.53	.17		95,720	128,300	27.0	
3.	A.E. PASMUSSEN	LENAPE GEN. CAT. PAR. 25 ASTM A/05-11												
	VICTOR PRODUCTS	CR-264851	.41	.75	.013	.013	.30			86.24	120,800	135,375	21.4	
4.	A.E. PASMUSSEN	LENAPE GEN. CAT. PAR. 25 ASTM, A/05-11												
5.	VICTOR PRODUCTS	RE-6822074	.42	.67	.017	.025	.29			81.19	124,400	138,900	22.0	
	MIDVALE HEPPENSTALL	102-502	.25	1.31	.010	.010	.20	.54	.15		71,250	97,000	30.6	
6.	U.S.S.	622618 1-2	.17	1.27	.010	.016	.21		.10		52,640	76,340	32.5	
		3-1	.17	1.27	.010	.016	.21		.10		52,720	76,830	34.0	

* Percent in 2".

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 17

MSFC **M**aterials and **P**rocesses Laboratory
Flash **R**eport

MSFC Engineering Directorate
Materials and Processes Laboratory

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 database. 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.

Title: General Information on Layered Pressure Vessels	SBU Controlled? NO	Number: MPFR-14-007	Page 18

Appendix D. Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment Presentation, February 28, 2014

MSFC **M**aterials and **P**rocesses Laboratory
Flash **R**eport
MSFC Engineering Directorate
Materials and Processes Laboratory

Title:	Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment		
Author: Doug Wells and Preston McGill	Org: EM20	Phone: 256-544-3300	email: douglas.n.wells@nasa.gov preston.b.mcgill@nasa.gov
Date: February 28, 2014	Supported Element/System: Pressure Systems: Layered Pressure Vessels Assessment		
Keywords:	Non-Code Layered Pressure Vessel (LPVs)		

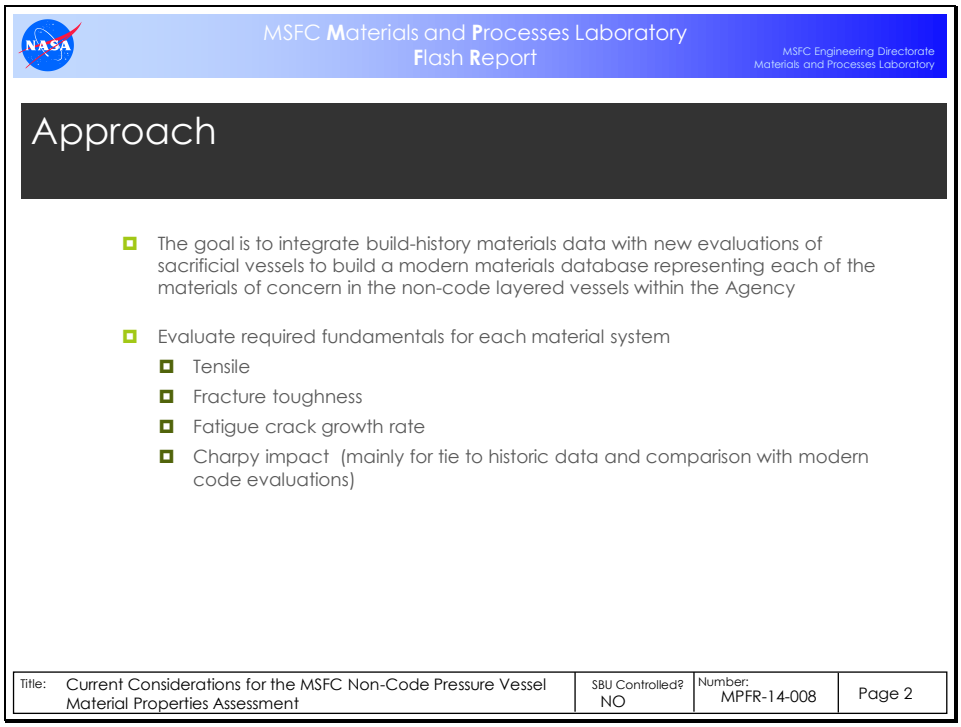
Executive Summary: (Purpose and Result)

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

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment	SBU Controlled? NO	Number: MPFR-14-008	Page 1

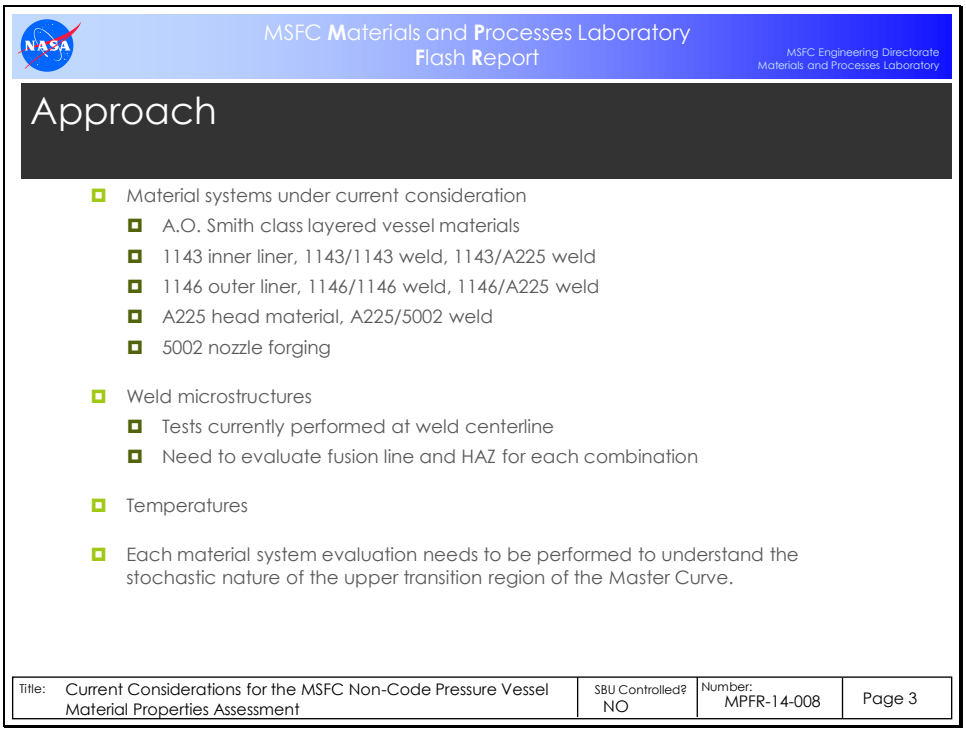


MSFC Materials and Processes Laboratory
Flash Report
MSFC Engineering Directorate
Materials and Processes Laboratory

Approach

- 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)

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment	SBU Controlled? NO	Number: MPFR-14-008	Page 2



MSFC Materials and Processes Laboratory
Flash Report
MSFC Engineering Directorate
Materials and Processes Laboratory

Approach

- 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.

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment	SBU Controlled? NO	Number: MPFR-14-008	Page 3

MSFC Materials and Processes Laboratory Flash Report
MSFC Engineering Directorate Materials and Processes Laboratory

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_{Ic} 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

Title: Current Considerations for the MSFC Non-Code Pressure Vessel Material Properties Assessment	SBU Controlled? NO	Number: MPFR-14-008	Page 4

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Current Testing

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

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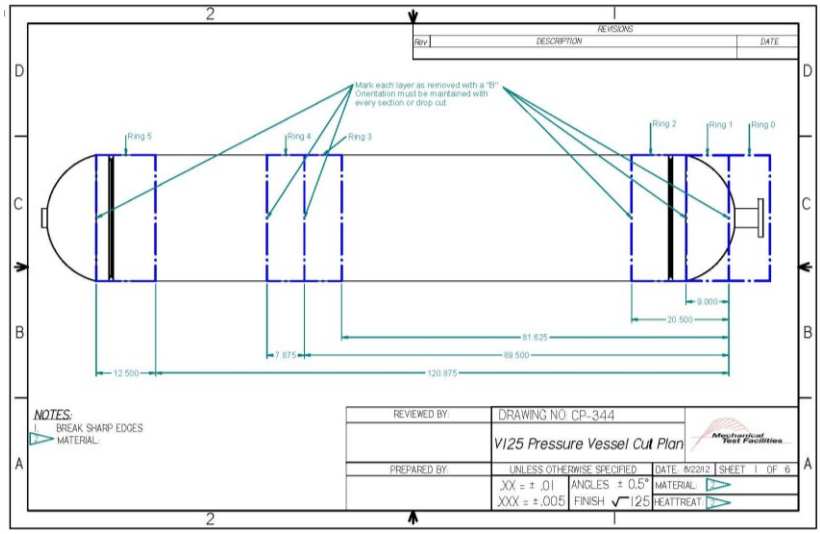
Basic Vessel Cut Plan



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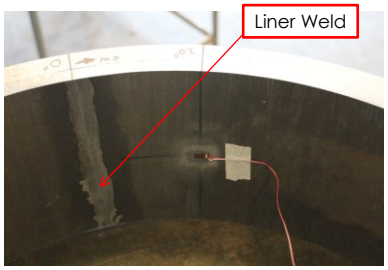
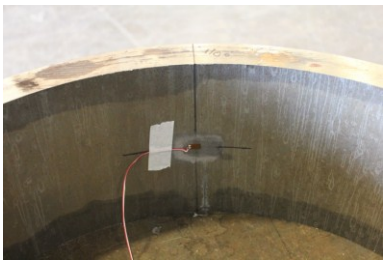
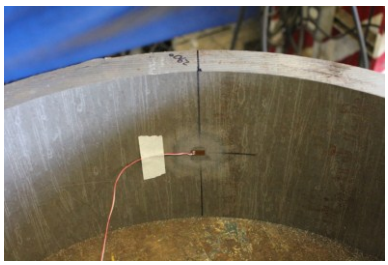
Strain gage installation on Ring #3 prior to cutting and removing the 3 wrap cylinders around internal cylinder.







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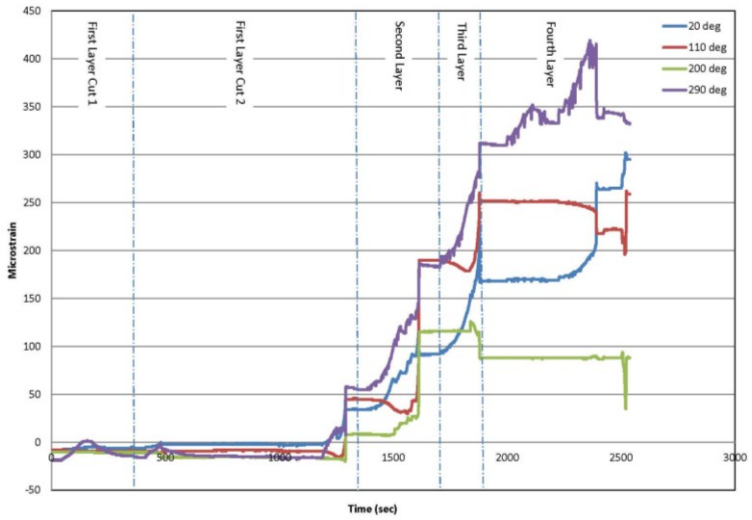
Strain measurements as layers sequentially cut



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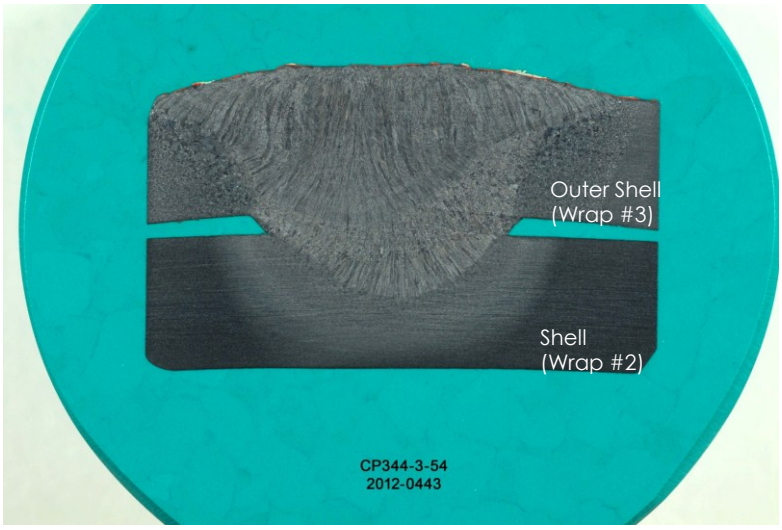
Cross-section micrograph of multi-pass axial shell weld



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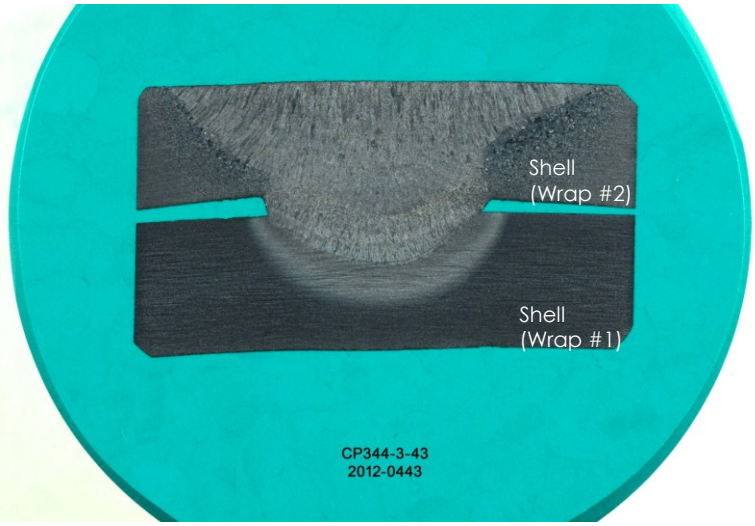
Cross-section micrograph of multi-pass axial shell weld



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Cross-section micrograph of multi-pass axial shell weld

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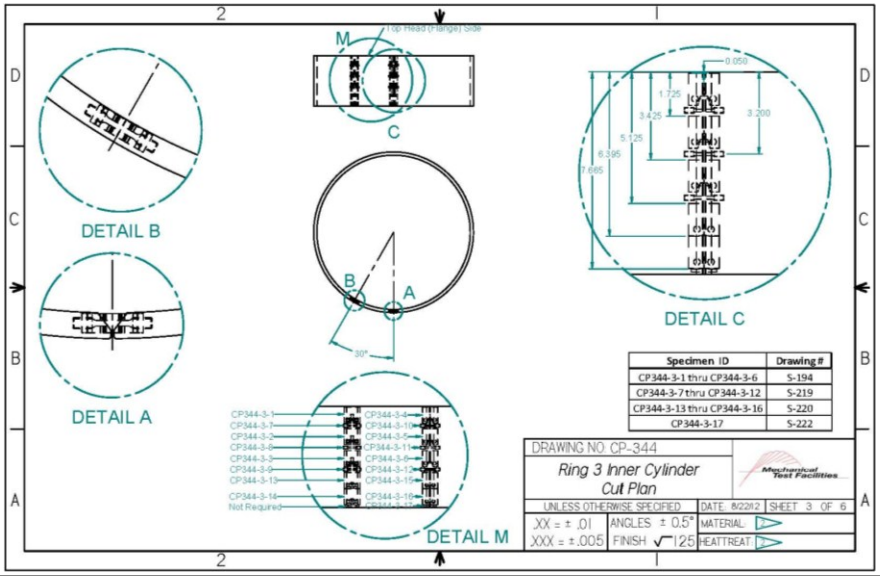
Excerpt from Detail Cut-Plan for V125



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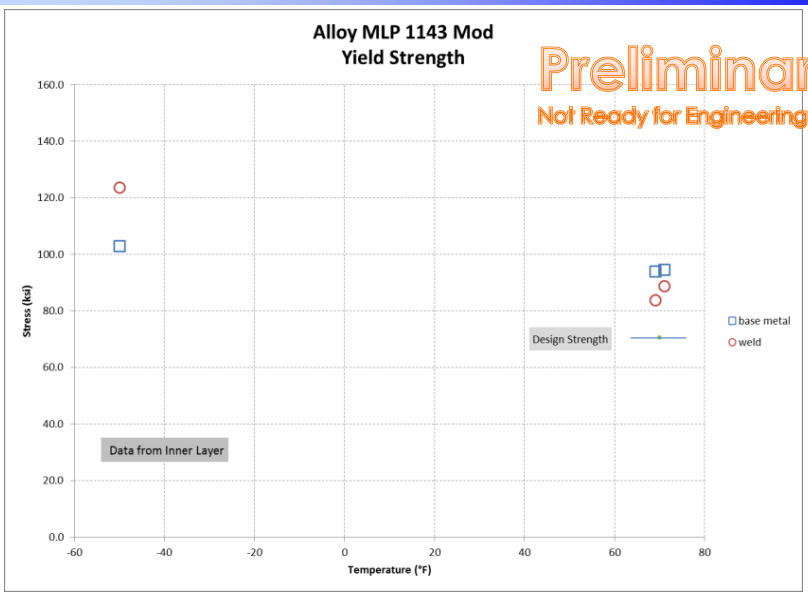

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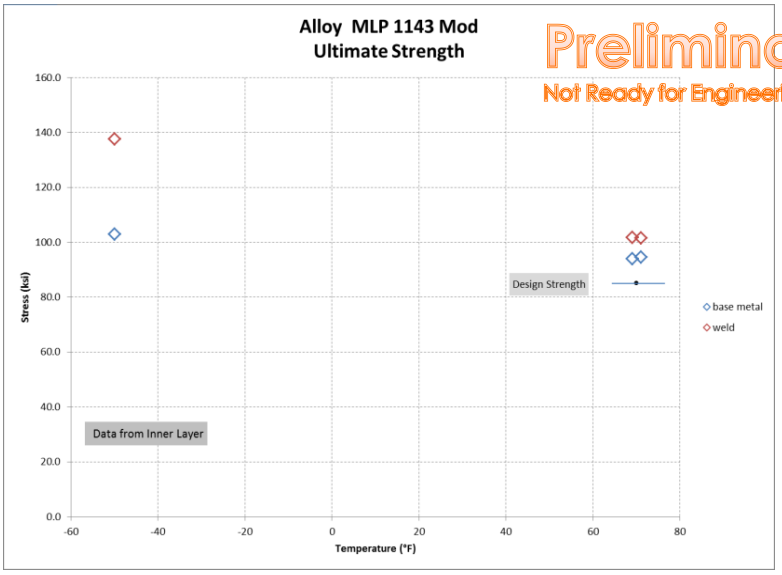

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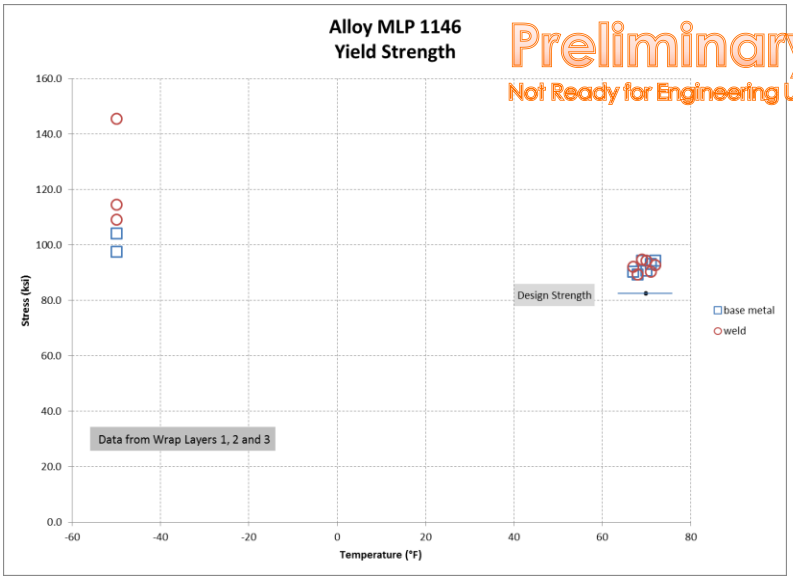

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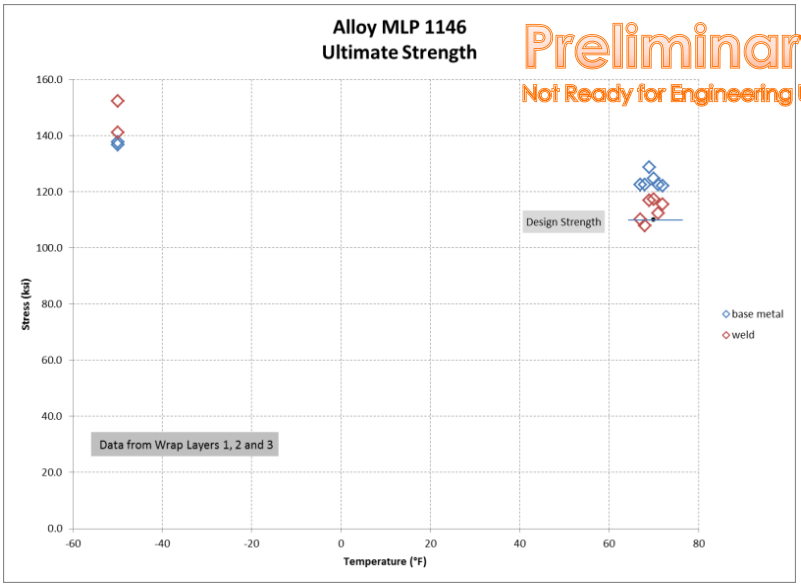

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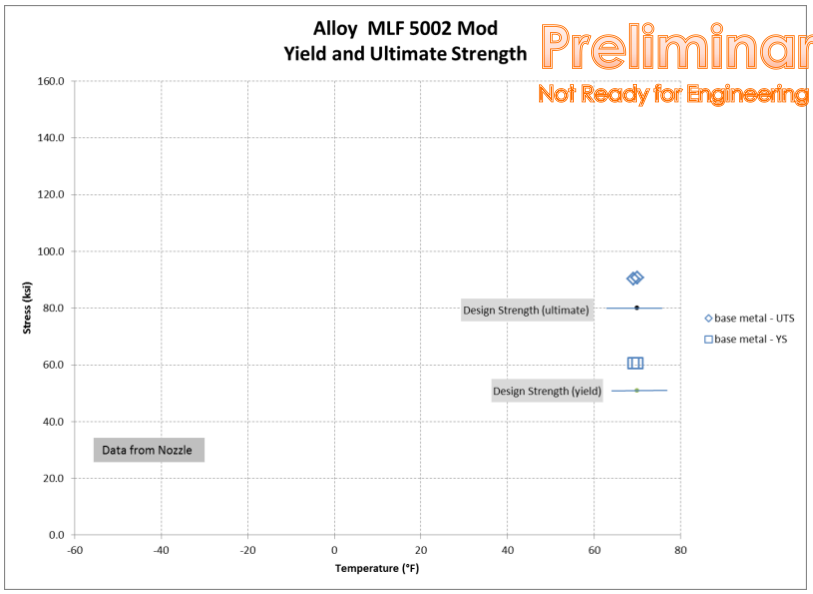

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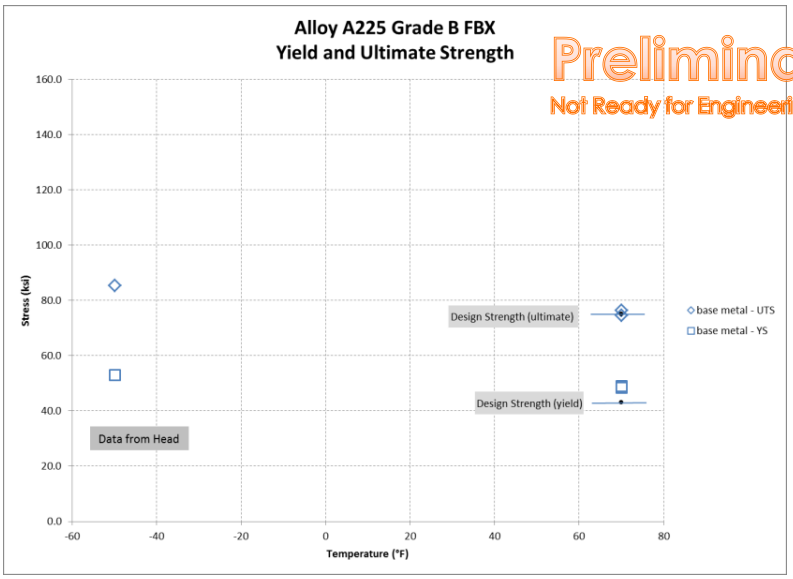

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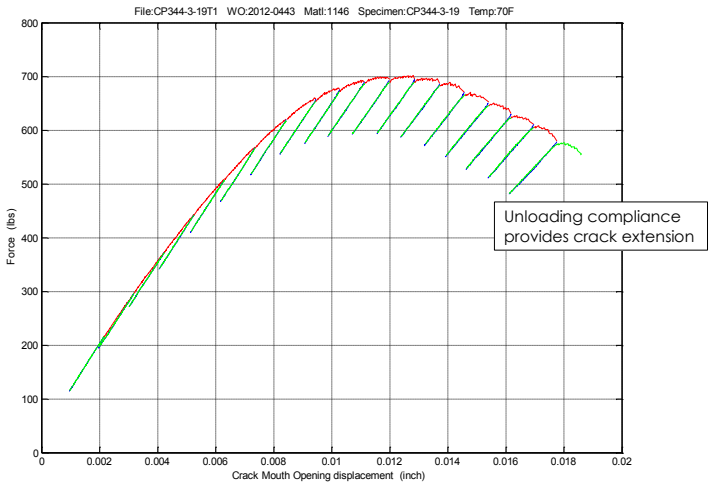
Fracture Toughness, The Jlc Test



Force versus load-line displacement is fundamental test data

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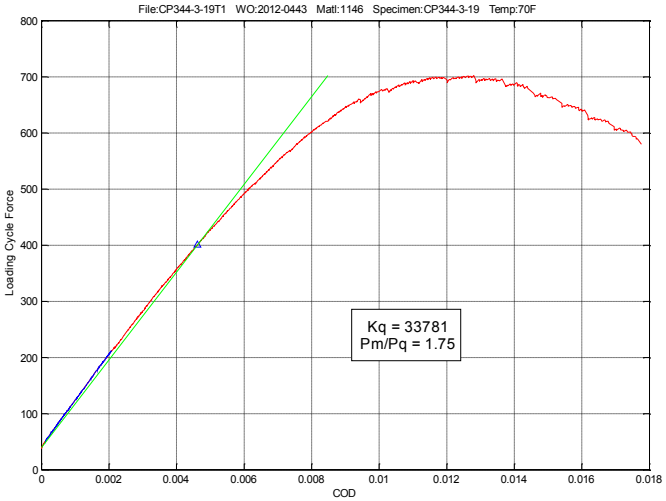
Fracture Toughness, The Jlc Test



K analysis is not informative. Plasticity obscures crack extension

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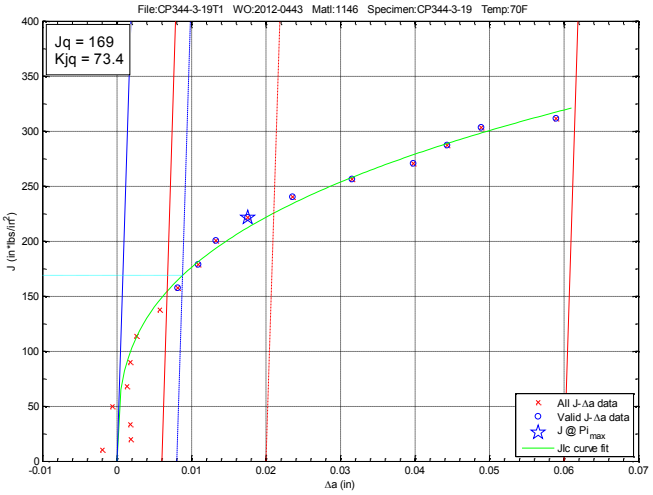
Fracture Toughness, The Jlc Test



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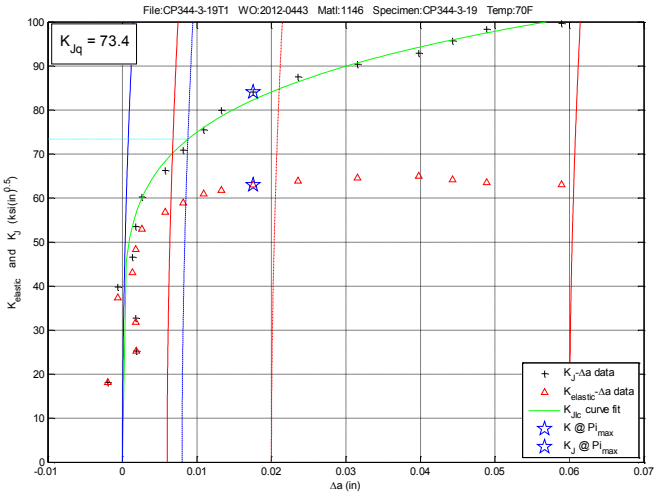
Fracture Toughness, The Jlc Test



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Fracture Toughness, Jlc Test Summary (Preliminary)

Preliminary
Not Ready for Engineering Use

Specimen	Alloy	Weld or Base	Temp (F)	J_{Ic}	K_{JIc}
344-3-1	1143	Base	70	333	103
344-3-2	1143	Base	70	355	106
344-3-3	1143	Base	-50	468	126
344-3-4	1143	Weld	70	579	135
344-3-5	1143	Weld	70	556	133
344-3-6	1143	Weld	-50	209	84
344-3-18	1146	Base	70	201	80
344-3-19	1146	Base	70	169	73
344-3-31	1146	Base	70	217	83
344-3-32	1146	Base	70	223	84
344-3-44	1146	Base	70	222	84
344-3-21	1146	Weld	70	973	176
344-3-22	1146	Weld	70	810	160
344-3-23	1146	Weld	-50	760	158
344-3-34	1146	Weld	70	517	128
344-3-35	1146	Weld	70	566	134
344-3-36	1146	Weld	-50	497	128
344-3-46	1146	Weld	70	745	154
344-3-47	1146	Weld	70	624	141
344-3-48	1146	Weld	-50	369	110
344-5-4	1146/A225	Weld	70	600	138

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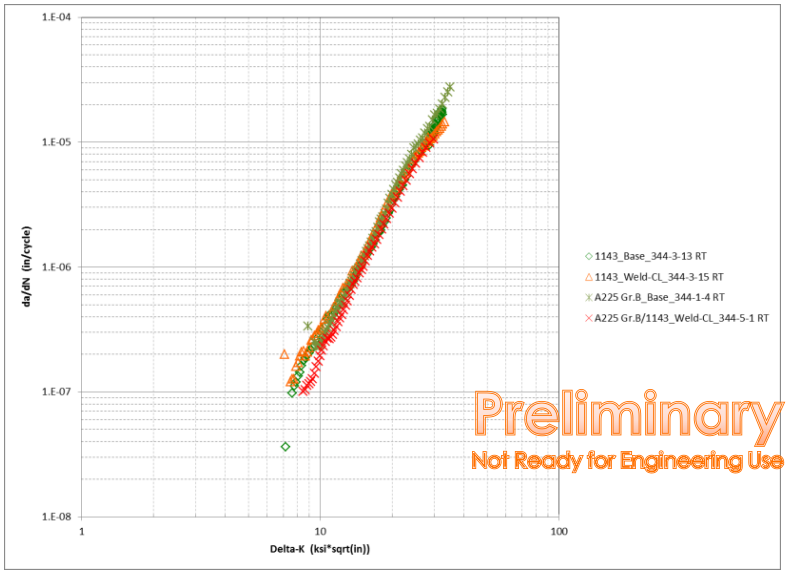
Fatigue Crack Growth Rate (Preliminary)



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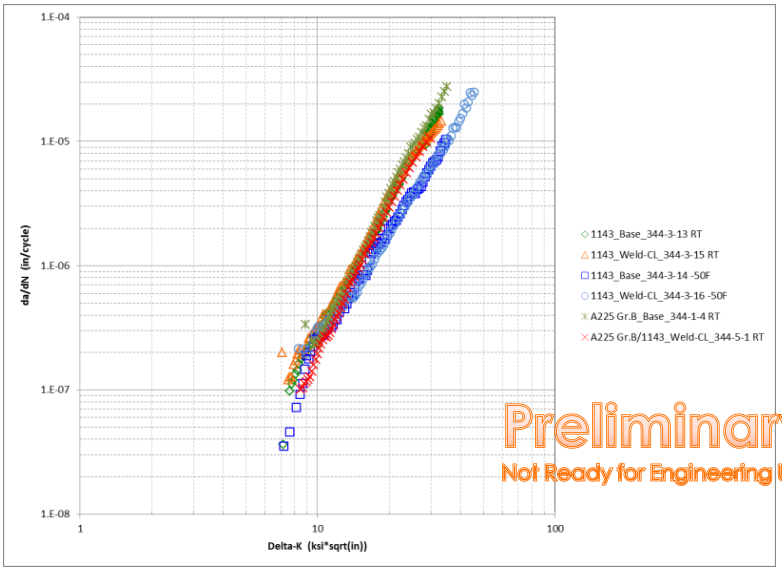
Fatigue Crack Growth Rate (Preliminary)



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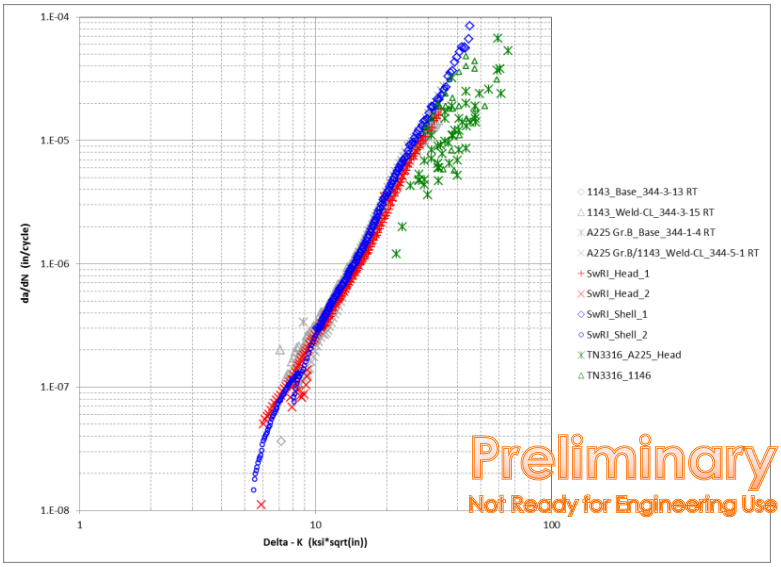
Fatigue Crack Growth Rate (Preliminary)



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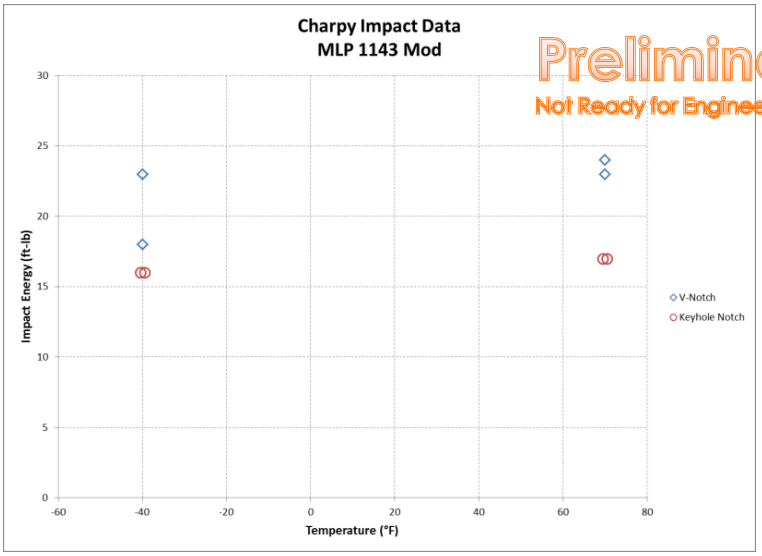
Charpy Impact Tests, 1143 Base Metal (Preliminary)



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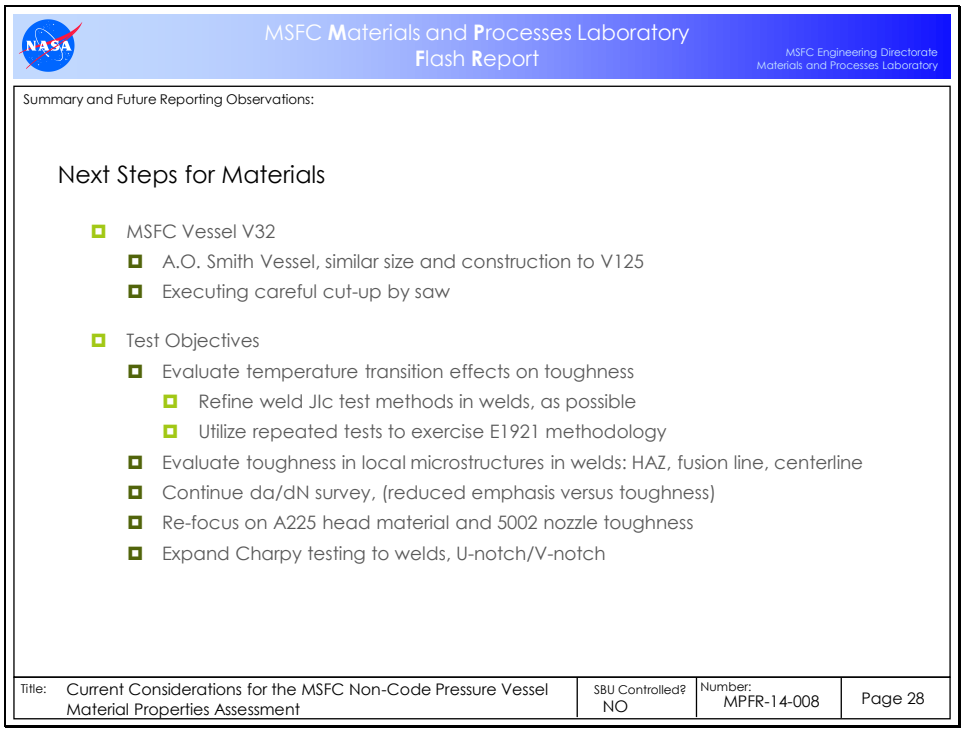

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Summary and Future Reporting Observations:

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	SBU Controlled? NO	Number: MPFR-14-008	Page 28

Appendix E. LPV Technical Interchange Meeting – September 18, 2013: Current Considerations for the MSFC Non-Code Layered Pressure Vessel Material Testing Tasks Presentation, February 28, 2014

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Title: LPV TIM - September 18, 2013: Current Considerations for the MSFC Non-Code, Layered Pressure Vessel Material Testing Tasks			
Author: Doug Wells	Org: EM20	Phone: 256-544-3300	email: douglas.n.wells@nasa.gov
Date: February 28, 2014	Supported Element/System: Pressure Systems: Layered Pressure Vessel Evaluation		
Keywords: Layered pressure Vessels (LPVs)			

Executive Summary: (Purpose and Result)

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.

References: (work orders, reports, etc.)
Work order references:
Other: LPV TIM - September 18, 2013, TI-13-00852 Evaluation of Agency Non-Code Layered Pressure Vessels

Title:	SBU Controlled?	Number:	
LPV TIM - September 18, 2013: Current Considerations for the MSFC Non-Code, Layered Pressure Vessel Material Testing Tasks	NO	MPFR-14-009	Page 1

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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.

Title: LPV TIM - September 18, 2013: Current Considerations for the MSFC Non-Code, Layered Pressure Vessel Material Testing Tasks	SBU Controlled? NO	Number: MPFR-14-009	Page 2

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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

Title: LPV TIM - September 18, 2013: Current Considerations for the MSFC Non-Code, Layered Pressure Vessel Material Testing Tasks	SBU Controlled? NO	Number: MPFR-14-009	Page 3

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

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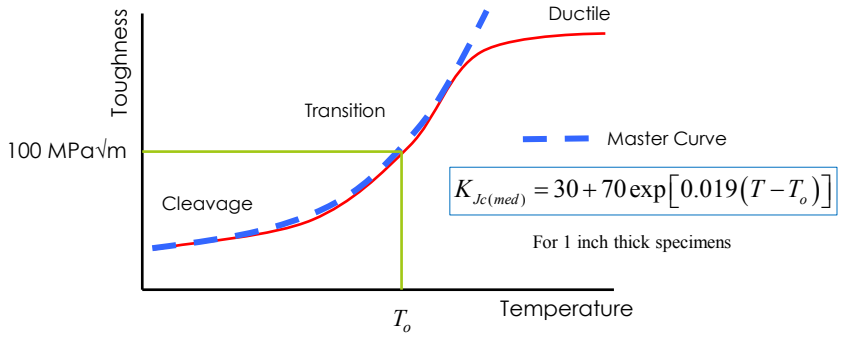
Master Curve Background

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



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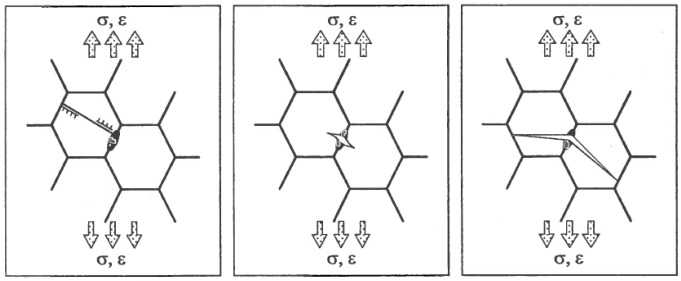
Master Curve Background

- 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.

Ref 1.

References

1. Wallin, Kim, *Fracture Toughness of Engineering Materials, Estimation and Application*, EMAS Publishing, 2011
2. McCabe, D., Merkle, J., Wallin, K., *An Introduction to the Development and Use of the Master Curve Method*, ASTM Manual 52, ASTM International, 2005

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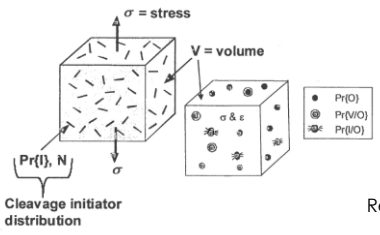
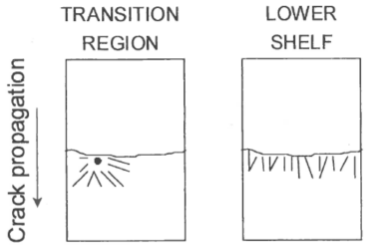
Master Curve Background

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



Ref 1.



The transition region exhibits a mixture of ductile and brittle fracture mechanisms. Fracture is governed by the statistics of local initiation mechanisms, giving rise to a "weakest link" pattern of failure. On the lower shelf, the fracture is propagation driven, initiation sites are not as influential, and the toughness is fairly constant.

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Master Curve Background

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

$$P[J_C \le J_I] = 1 - \exp\left(-\left(\frac{J_I}{\theta}\right)^b\right)$$

Scaling parameter for 63.2% failure probability

Weibull slope (empirical)

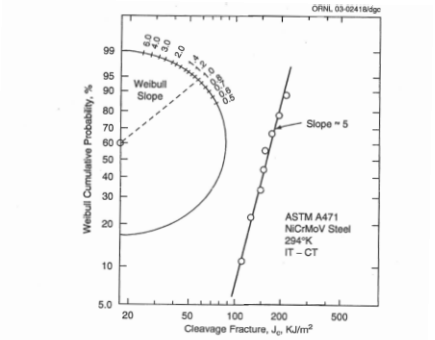

Fig. 1—Failure probability versus J_c plotted in Weibull coordinates (from Landes and Shaffer [12]).

Ref 2.

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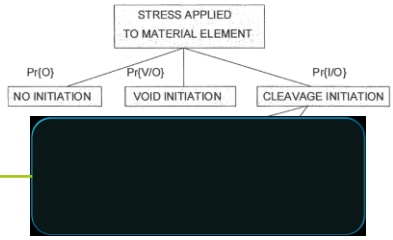
Master Curve Background

- An engineering model reflecting the lower shelf
- Three-parameter Weibull model from Wallin

$$P[K_C \le K_I] = 1 - \exp\left[-\left(\frac{K_I - K_{\min}}{K_o - K_{\min}}\right)^b\right]$$

Conditional probability after initiation models the $K_{\min}$ lower shelf



Power of the model:
- Model fits most all ferritic/BCC steels with b = 4 and $K_{\min}$ = 20 Mpa√m,
- This pre-establishes scatter expectation via the model's Weibull slope
- Only need to test for the scaling factor, K_o

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Master Curve Background

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

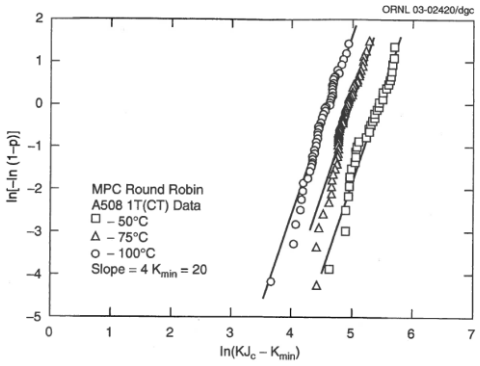

Fig. 3—Data taken from the MPC/JSPS round robin activity, plotted in Weibull coordinates showing constant Weibull slopes independent of test temperature.

Ref 2.

Master Curve Background

- 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)

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

Master Curve Background

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

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

- 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

$$T_o = T_{test} - \left(\frac{1}{0.019}\right)\ln\left[\frac{K_{Jc(med)} - 30}{70}\right]$$

Master Curve Background

$$K_{Jc(med)} = 30 + 70\exp\left[0.019\left(T - T_o\right)\right]$$

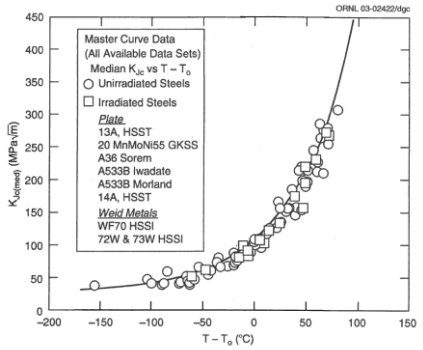

Fig. 5—Median K_{Jc} values from eight data sources; all data have been converted to 1T equivalence, and test temperature normalized to T_o temperature.

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Master Curve Background

- Bounding Values from the Master Curve

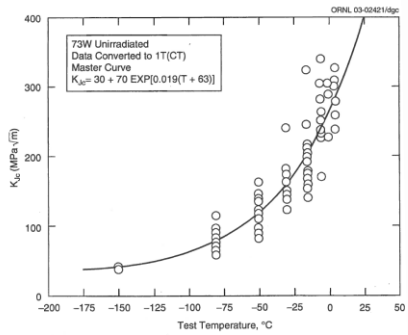

Fig. 4—K_{Jc} data scatter about the Master Curve, for weld-metal 73 W of the HSSI Fifth Irradiation series; specimen size varied from 1T(CT) to 8T(CT), and all data shown were converted to 1T(CT) equivalence. T_o = –63°.

Ref 2.

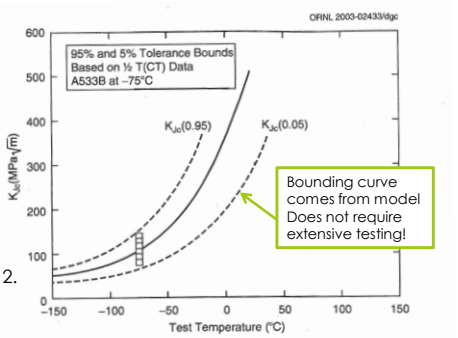

Fig. 16—Six K_{Jc} data values (open squares), the Master Curve determined therefrom and the 95 % and 5 % tolerance bounds on data scatter.

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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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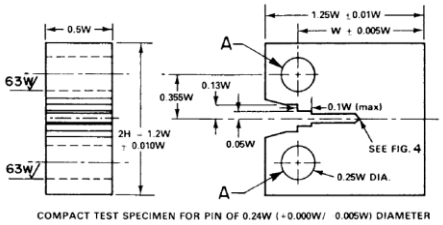
Planned Testing Tasks

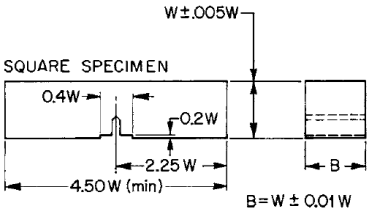
- Fracture testing will utilize two specimen types to accommodate material orientation limitations

Compact Tension



COMPACT TEST SPECIMEN FOR PIN OF 0.24W (+0.000W/ 0.005W) DIAMETER

Charpy-sized 3-pt Bend



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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

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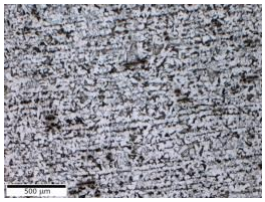
Planned Testing – Base Metal

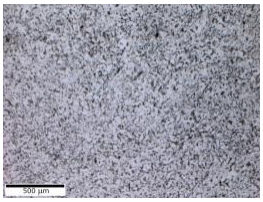
- Orientation more important than expected
- Test data from SwRI Phase II indicates strong dependence

A225 Head Material - Metallography

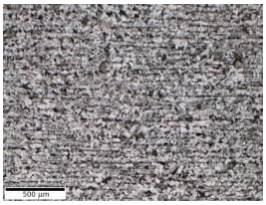
Looking into Radial Face



Looking into Meridional Face



Looking into Circumferential Face



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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

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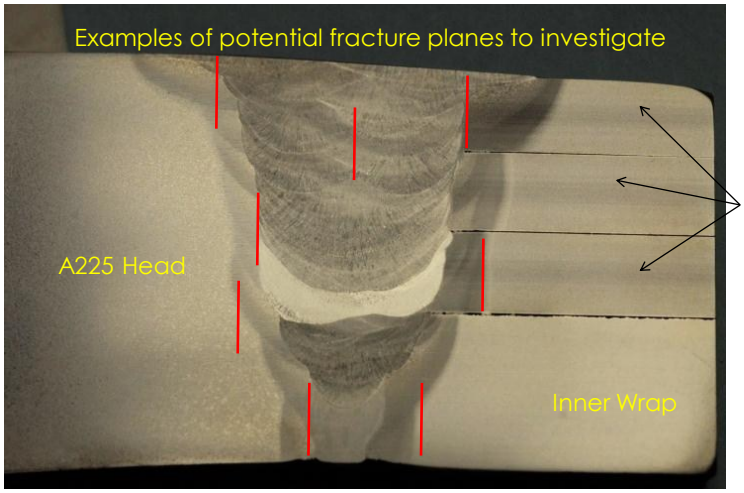

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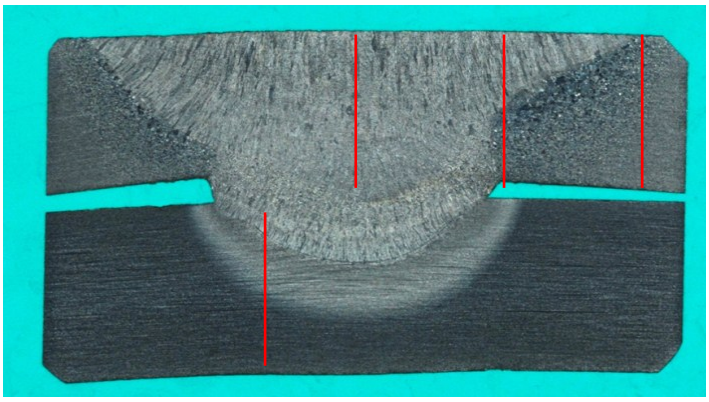
Examples of potential fracture planes to investigate



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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?

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Summary and Future Reporting Observations:

A summary of the current status of the materials testing at MSFC was presented along with planned testing. ASTM E1921 has been selected as the methodology to evaluate transition temperature based on a limited number of specimens.

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

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Title: MSFC Layered Pressure Vessel Analysis Activities/ LAPVAT			
Author: Joel Hobbs, P.E.	Org: EM20	Phone: 256-544-0297	email: joel.r.hobbs@nasa.gov
Date: March 17, 2014	Supported Element/System: MSFC Non-Code Pressure Vessel Material Properties Assessment		
Keywords: Test Facilities, V256, Pressure Vessel, API 579, Layered Vessel, Non-code Pressure Vessel, LAPVAT			

Executive Summary: (Purpose and Result)

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.

References: (work orders, reports, etc.)

Work order references:

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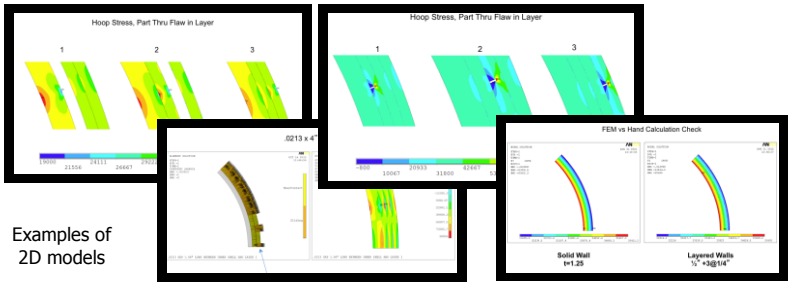
Foundational Work

- 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

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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 crystalize 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.

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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.

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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.

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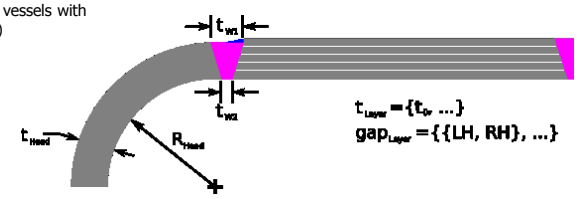
LAPVAT Inputs

- 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



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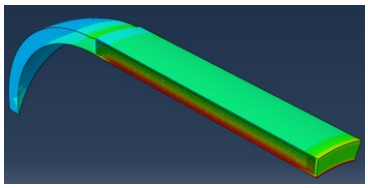
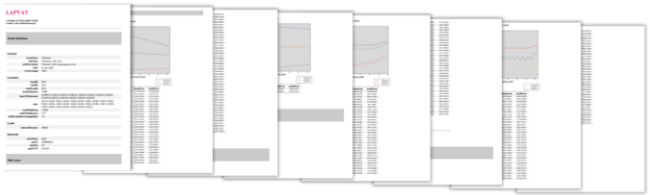
LAPVAT Post Processing

- 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.



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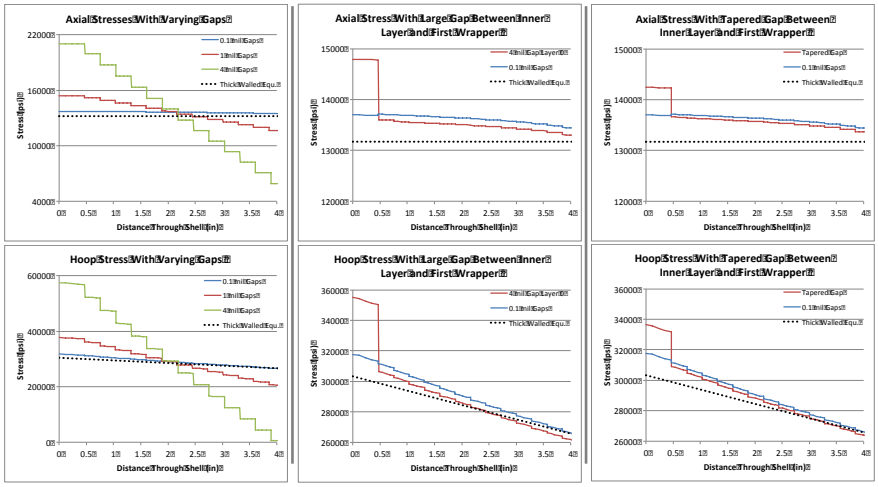
LAPVAT Example Results

- Example Results: 14 layer vessel with thicker inner liner layer, 60" ID, 4000 psi



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Appendix G. ARC Modal Acoustic Emission Validation Effort Summary

Validation of AE for use on Layered Vessel Inspections

Contents

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 most 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 siting 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 publically 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 1146a 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 ¼ 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

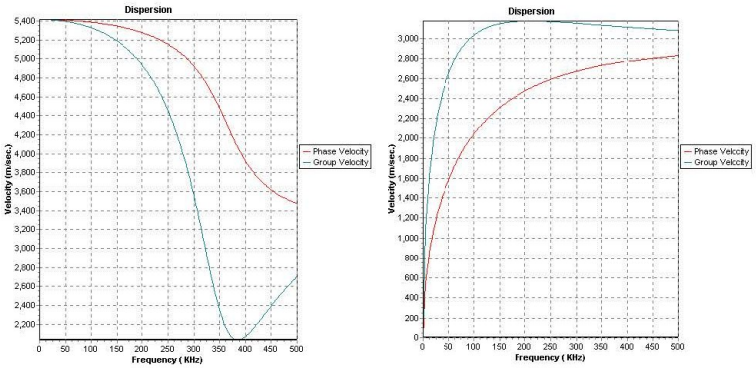
As discussed above for pencil lead break tests, captured AE waveforms for PLBs on the inner vs. outer surfaces of these 2.635 inch thick layered vessels showed only slightly greater attenuation for inner surface breaks due either to the greater distance they travel through the thickness, or as a result 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 on 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

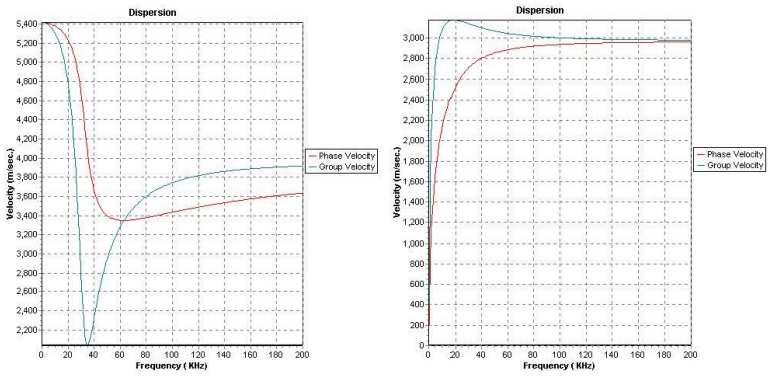
different frequency dependence, and thus there are separate dispersion curves for each. These are shown in Ref. 1, Fig. 3, and are reproduced below for 0.25 inch steel plate.



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 4600 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. X1.2 and Table X1.2 of the E-1419 Standard (see note on dBV vs. dBae below). Although X1.2 is in a non-mandatory appendix, it is stated in para. X1.2 that the settings in Table X1.2 are based on "criteria for determining the need for secondary examination" "while working with the equipment and setup conditions listed in Table X1.2", 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 20log$_{10}$ base from the reference signal, rather than 10 log$_{10}$. 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 nonrelevant 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.

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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 MV50466-8

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 a 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) indication 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 ¼ 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.

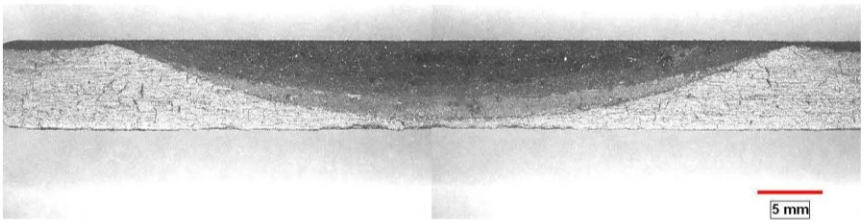
The test matrices are shown in detail in the SwRI Phase 2 report, along with detailed results. The appendices of that report contain all of the detailed test records. Note that no testing was performed on VMS 5002 nozzle material.

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.



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 uncertainly 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 ksiVinch) 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 (ΔK) 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.

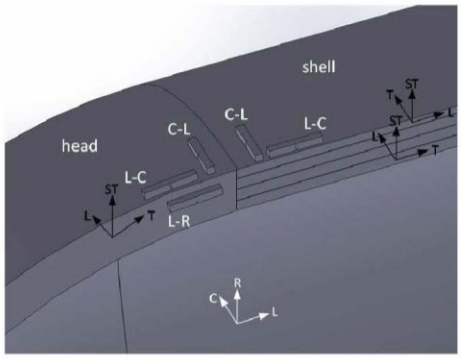
1) Shell Layer Testing:
The phase 2 SwRI report discusses shell and head tests in separate chapters, and that format is followed in the discussion below.

   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

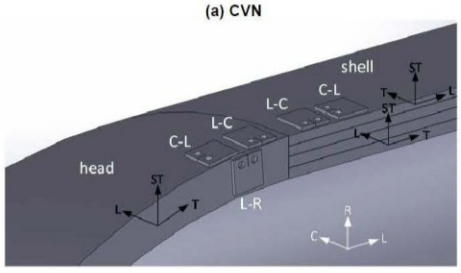
on outer shell material in the vessel circumferential direction, which corresponds to the rolling direction of that plate. Tensile tests were not performed on the inner layer material. The average tensile properties increased slightly at -20 F, with average measured yield stress (YS) of 90.9 ksi at -20 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.



(a) CVN



(b) Toughness and FCG

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 sub-size 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 (T_0) 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 slighter 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 mills 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 ksiVinch) those reported in Phase 1 (86 – 90 ksiVinch) 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 ¼ 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 ksiVin 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_0) 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_0 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 (J1C per ASTM E1820):
Elastic-plastic J1c 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 J1c 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 ksi√in at RT, 93 – 140 ksi√in at -20 F) results are generally consistent with K1e values previously reported by LaRC (76 – 122 ksi√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 = of 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√in for R = 0.15 and 20 ksi√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 ($da/dN = 3.6E\text{-}10\ (\Delta K)^{3.0}$) 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, K1c was considered to be 90 ksi√in, while based on the phase 2 data for the inner shell, the more appropriate value of 170 ksi√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√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 by 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.References

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16. Cardinal, J.W. and Popelar, C. F., Multilayer Pressure Vessel Materials Testing and Analysis (Phase 2), Southwest Research Institute, SwRI® Project No. 18.17633, Final Report (Rev 01), September 2013

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 F 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 discus 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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August 19, 2013

NASGRO FAD & Pressure Vessel Analysis Development Tasks:

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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.

[redacted]

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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.

[redacted]

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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*)

- 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.

[redacted]

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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.

[redacted]

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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.

[redacted]

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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
- EC04 – embedded elliptical crack (offset) in plate – bivariant WF

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

[redacted]

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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, Lr) 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, Lr) 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.

[redacted]

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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 (univarian/bivariant) to adequately compute SIFs for more complicated PV geometries (e.g., see Task 9 list).

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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.

[redacted]

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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.

[redacted]

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

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.

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