NESC Review of the 8-Foot High Temperature Tunnel (HTT) Oxygen Storage Pressure Vessel Inspection Requirements

March 16, 2006

NESC Request No. 05-034-E

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Volume I: Technical Consultation Report

1.0 Authorization and Notification

The request to conduct a consultation on the 8-Foot HTT Liquid Oxygen (LOX) Storage Pressure Vessels was submitted to the NASA Engineering and Safety Center (NESC) on June 6, 2005.

The initial evaluation of the request was presented to the NESC Review Board (NRB) and the consultation was approved on August 12, 2005. The consultation review was held on September 7-8, 2005, and a report documenting findings, recommendations, observations was written.

On October 5, 2005, the consultation team reconvened to review additional information and results pertaining to the LOX Run Tank fatigue and fracture analysis results. After reviewing the new information, the consultation team developed revised recommendations. The revised recommendations, documented in the Addendum to this report, were approved by the NRB on October 6, 2005, and presented to the NASA Langley Research Center (LaRC) Executive Council on October 7, 2005.

2.0 Signature Page

Consultation Team Members

Original signed on file

Michael Gilbert, NESC Lead

Eric Hoffman, LaRC

Ivatury Raju, NESC

Robert Piascik, NESC

Kenneth Cameron, NESC

Michael Kirsch, NESC

Pappu Murthy, GRC

George Hopson, NESC

Owen Greulich, HQ

Wayne Frazier, HQ

3.0 Team Members, Ex Officio Members, and Consultants

Michael Gilbert, NESC	Chief Engineer, Team Lead
Eric Hoffman, LaRC	Materials
Pappu Murthy, GRC	Structures
Wayne Frazier, HQ	Safety & Mission Assurance (S&MA)
Owen Greulich, HQ	S&MA
George Hopson, NESC	Propulsion Discipline Engineer and Technical Warrant Holder
Ivatury Raju, NESC	Structures Discipline Engineer and Technical Warrant Holder
Robert Piascik, NESC	Materials Discipline Engineer and Technical Warrant Holder
Kenneth Cameron, NESC	Deputy for S&MA
Michael Kirsch, NESC	Principal Engineer
Terri Derby, Swales	Administrative Support

4.0 Executive Summary

The 8-Foot HTT (refer to Figure 4.0-1) is used to conduct tests of air-breathing hypersonic propulsion systems at Mach numbers 4, 5, and 7. Methane, Air, and LOX are mixed and burned in a combustor to produce test gas stream containing 21 percent by volume oxygen.

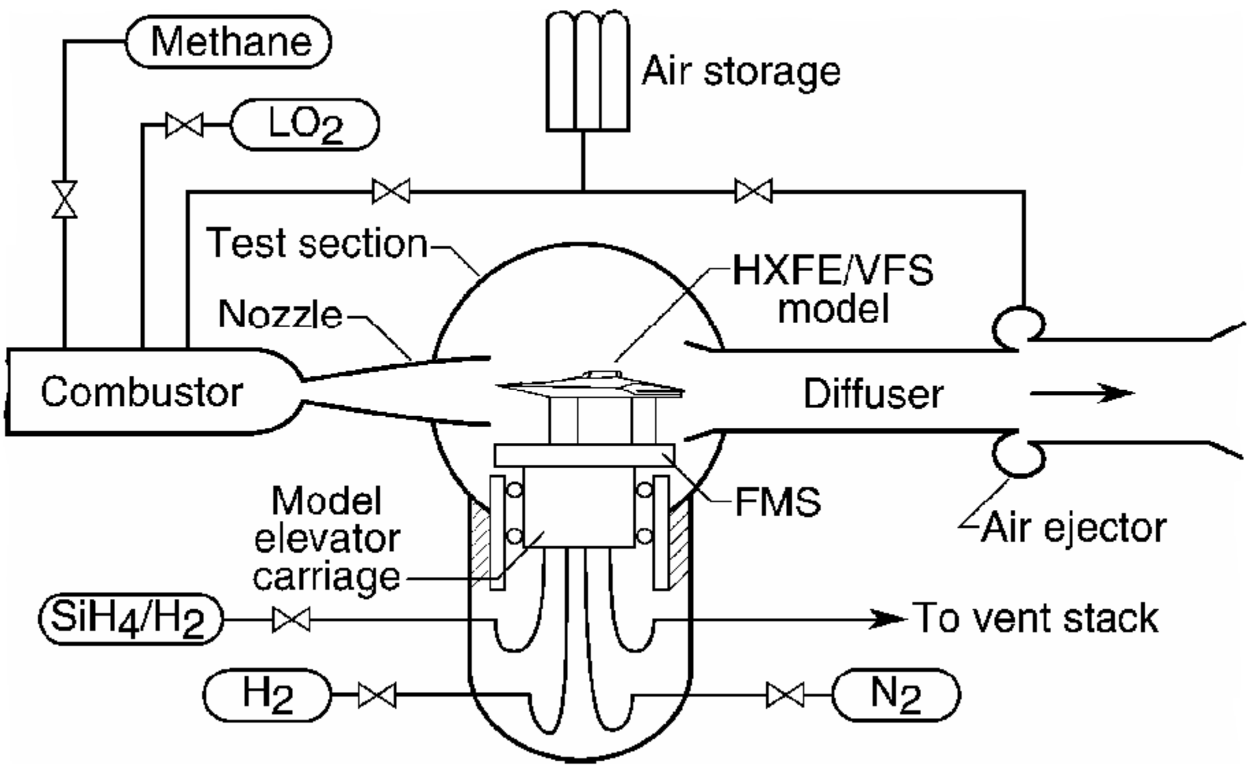


Figure 4.0-1. Schematic Drawing of the 8-Foot HTT for Air Breathing Propulsion Testing

The NESC was requested by the NASA LaRC Executive Safety Council to review the rationale for a proposed change to the recertification requirements, specifically the internal inspection requirements, of the 8-Foot HTT LOX Run Tank and LOX Storage Tank. The Run Tank is an 8,000 gallon cryogenic tank used to provide LOX to the tunnel during operations, and is pressured during the tunnel run to 2,250 pounds per square inch gage (psig). The Storage Tank is a 25,000 gallon cryogenic tank used to store LOX at slightly above atmospheric pressure as a supply source for the Run Tank. Both tanks consist of an inner pressure vessel surrounded by an external shell, with space between the shells maintained under vacuum conditions.
The proposed changes to the inspection requirements include:

- LOX Run Tank: from 10 years internal/external inspection to internal/external inspection after 1,000 pressure cycles.
- LOX Storage Tank: from 10 years internal/external inspection to 10 year visual external inspection only.

In reviewing the rationale for the proposed changes, the NESC Review Team determined that the fracture analysis was deficient and that the LOX Run Tank was not a "Leak-Before-Burst" (LBB) vessel. The NESC Review Team recommended immediate stand-down of the 8-Foot HTT until either the analysis deficiencies were corrected or the tank was inspected. The recommendation was accepted and the 8-Foot HTT stood-down operations on September 8, 2005. Efforts to correct the analysis deficiencies began immediately thereafter.

The NESC Review Team also determined that there were no analyses supporting changes to the LOX Storage Tank requirements and recommended that such analyses be performed.

5.0 Consultation Plan

The NESC assembled a team of technical experts, NESC Discipline Engineers, Discipline Technical Warrant Holders, and S&MA personnel, led by the LaRC's NESC Chief Engineer.

The team met on September 7-8, 2005, to conduct a review and accomplished the following:

- Toured the facility.
- Reviewed the materials, stress, fatigue, and fracture analyses results.
- Interviewed the analysts that performed the analyses.
- Reviewed the fabrication, service, and repair history of the tanks.
- Interviewed Facility, S&MA, and Pressure Systems Managers.
- Consulted with a Non-Destructive Evaluation expert.

6.0 Description of the Problem, Proposed Solutions, and Risk Assessment

6.1 Description of the Problem

Both the LOX Run Tank and LOX Storage Tank were due for internal inspection and recertification in calendar year 2000. A review by the Pressure Systems Subcommittee of the NASA LaRC Executive Safety Council in late 2004 identified that the 8-Foot HTT LOX Storage and Run tanks had not been recertified. Systemic issues related to the missed recertification are being addressed by the NASA LaRC.

It was determined that continued operation of the facility beyond the recertification date was warranted based on the following conditions:

LOX Run Tank (Refer to the sketch in Appendix B)

- The tank was determined to be LBB by analysis.
- Monitoring of the vacuum level between the inner pressure shell and the external shell would identify the presence of through-cracks in the pressure shell and allow the facility to stop operations before catastrophic failure would occur.

Storage Tank

- The tank operates at constant temperature and pressure, whereas crack growth is a function of temperature and pressure cycles.
- The tank has an operational safety factor of 8 on ultimate material strength.
- The allowable working pressure of the tank is 100 psia. The tank nominally operates at 45 psia.

6.2 Proposed Solution

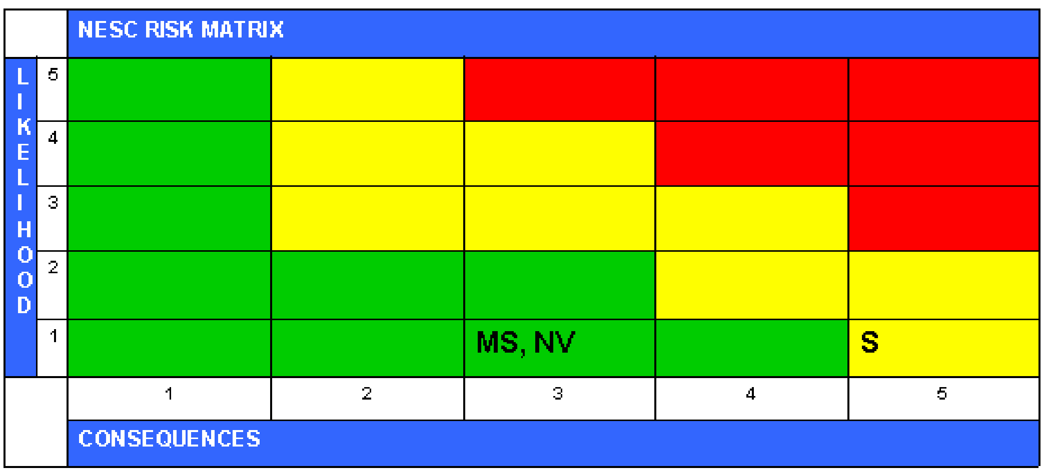
The Pressure Systems Subcommittee recommended to the NASA LaRC Executive Safety Council, based on contracted analyses, that the recertification requirement for the 8-Foot HTT LOX tanks be changed as follows:

1. Change LOX Storage Tank requirement to time-based visual external inspection techniques only.

2. Change LOX Run Time Tank to use 1,000 pressure cycles instead of 10 years in operation as basis for inspection.

6.3 Risk Assessment

There were no immediate safety risks at the time the review request was evaluated. The analyses at that time indicated that sufficient margins existed to allow continued operations even though the tanks were at approximately 150 percent of the required inspection interval. The risk assessment is shown in Figure 6.3-1. Refer to Appendix D for a description of the NESC Risk Assessment likelihood and consequences.



S – Safety NV – National Visibility MS – Mission Success

Figure 6.3-1. 5 x 5 Risk Acceptance Matrix

Safety

- Probability: Very low probability of immediate failure, based on large analytical margins.
- Consequence: Explosion and/or fire in proximity to inhabited buildings.

National Visibility

- Probability: Very low probability of immediate failure, based on large analytical margins.
- Consequences: Publicity from failure to address Office of Inspector General (OIG) audit report.

Mission Success

- Probability: Very low probability of immediate failure, based on large analytical margins.

- Impact: Assumed hardware loss between $10M - $100M; no immediate impact to flight projects, might impact Exploration initiative.

7.0 Data Analysis

The NESC Review Team reviewed the stress, fatigue, and fracture analyses of the LOX Run Tank. The individuals that performed these analyses were interviewed by the NESC Review Team to gain full understanding and to resolve any questions. The results of the data analyses are documented in Section 8.1, Findings.

Refer to Appendix C for key analyses figures reviewed by the team.

8.0 Findings, Recommendations, and Observations

8.1 Findings

F-1. The damage tolerance analyses are insufficient to demonstrate LBB for the LOX Run Tank for the following reasons:

- Critical crack size is predicted to be less than the tank wall thickness.
- Fracture mechanics analyses did not account for weld material properties or residual stresses.
- The structural finite element models do not capture changes in thickness, geometry, loading, and material properties.

The tank, as constructed, contains welded-in forgings for the upper access port and nozzles at both the top and bottom of the tank. The properties of the weld material and the forgings differ from the properties of the material used for the tank walls, even though both the tank wall and forgings are 347 Stainless Steel. The crack growth analysis assumed uniform material properties for all sections of the tank and did not include analyses of the welds. In addition, material properties for 304 Stainless Steel were used in the analyses as being representative of 347 Stainless Steel because material properties for 347 Stainless Steel were not readily available.

Although a critical crack size less than the tank wall thickness was predicted, it was assumed that the crack would also grow perpendicular to the thickness until reaching an adjacent nozzle opening, which would act as a crack stop. The crack would then be stable (not growing) and be more than twice the wall thickness in length, thus satisfying LBB criteria.

This assumption did not account for the weldments or the changes in material properties along the assumed path of the crack and, therefore, is invalid. Also, the NASA standard for LBB is crack length 10 times the wall thickness, whereas the analysis was based on crack length 2 times the wall thickness. Refer to Observation O-3.

F-2. The fatigue analysis method used is inconsistent with the original fabrication inspection performed on the LOX Run Tank for the following reasons:

- The fatigue analysis was performed according to the American Society of Mechanical Engineers (ASME) Section VIII, Division 2. Application of this analysis is based on construction of the tank to ASME Section VIII, Division 2, which requires stringent manufacturing inspections. These inspections set the initial crack size to be used in subsequent fatigue analyses based on the actual minimum detectable flaw size at the time the inspections were conducted.
- The LOX Run Tank was actually constructed to ASME Section VIII, Division 1, with much less stringent quality assurance, inspection, and process controls.
- The ASME Section VIII, Division 2, fatigue analysis was performed based on an *assumed* crack size rather than the minimum detectable size from the manufacturing inspection process.

F-3. The LOX Run Tank fatigue life calculations do not currently account for pre-LaRC use. The tank was manufactured in 1959, but was first put into service at the HTT in 1989. Since 1989, the LOX Run Tank has been subject to about 600 pressure cycles. The tank operational history prior to service at the HTT is not accounted for, nor has it been demonstrated that the tank was restored to "zero-time" status in 1989.

F-4. All previous tank inspections have revealed cracks and/or crack-like indications that were repaired or removed. The inspection history, shown below, suggests that cracks continually initiate or that the inspections may not have found all flaws.

- 1965: Cracks in 4-inch boss weld repaired
- 1986: Four linear indications found and ground out
- 1991: Six linear indications found and ground out

F-5. No analysis or prior inspection data was available to establish a rationale to change the inspection requirements for the LOX Storage Tank.

F-6. The physical location of the LOX Run and Storage Tanks necessitated a waiver to requirements on proximity of LOX tanks to occupied buildings. The waiver has as an acceptance rationale maintaining the tanks in a certified state.

8.2 Recommendations

R-1. Remove the LOX Run Tank from run-time pressure service until the LBB rationale is verified and the risk of continued operation is accepted, or until an inspection is performed and any detected flaws are properly dispositioned (F-1, F-2, F-3, F-4 and F-6).

R-2. Develop analyses to support a rationale for changing the LOX Storage Tank inspection requirements (F-5).

- The tank can continue in current operation while rationale is developed.
- The Storage Tank must be determined to be LBB or fracture-critical to establish appropriate inspection intervals.

8.3 Observations

O-1. Inspection intervals should be determined by *both* cyclic-loading and maximum time, based on industry practices and standards. Lengthening of inspection intervals should include as rationale prior inspection history and data.

O-2. During the review, the team inquired about the Oxygen Hazards analysis for the HTT. Retrieval of records was not completed by the time the review team meeting ended.

O-3. The "ten times the thickness" NASA standard is applicable to thin-walled pressure vessels and pipes. For thick-walled pressure vessels (such as LOX Run Tank of 4.73 inches in thickness), the NASA standards are not clearly defined and the Nuclear Industry Code for LBB conditions should be used. The Nuclear Industry Code LBB conditions require the development of a through-the-thickness crack with sufficient crack opening for the fluid to leak and be detected.

9.0 Lessons Learned

There were no lessons learned during this consultation.

10.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the technical assessment/inspection.
Requirement	An action developed by the assessment/inspection team to correct the cause or a deficiency identified during the investigation. The requirements will be used in the preparation of the corrective action plan.
Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 Minority Report (Dissenting Opinions)

There were no dissenting opinions during this consultation.

Addendum. Summary of Activities from September 8, 2005 to October 7, 2005

Summary of Activities from September 8, 2005 to October 7, 2005

On September 8, 2005, following a two-day review, the NESC 8-Foot High Temperature Tunnel (HTT) Oxygen Storage Pressure Vessel Inspection Requirements Technical Consultation team issued a safety recommendation to the Director, Safety and Mission Assurance (S&MA), NASA Langley Research Center (LaRC), to immediately stand-down operations of the HTT until deficiencies in the fatigue and fracture analyses of the LOX Run Tank could be corrected. This recommendation was based on the fact that deficiencies in the analyses negated the then current "Leak-Before-Burst" (LBB) result for the LOX Run Tank. "Leak-Before-Burst" was an essential part of the rationale for continuing to operate the tank 5 years beyond its specified inspection and certification date. The Director, S&MA, LaRC, accepted this recommendation and ordered the immediate stand-down of HTT test operations. The findings, recommendations, and observations developed by the NESC Technical Consultation Team from the review on September 7-8, 2005, are fully documented in the main body of this report.

Subsequent to the HTT stand-down, an analysis team was formed by the NASA LaRC to update the fatigue and fracture analyses. The NESC provided technical assistance to, and consulted with, the Center analysis team in critical areas of materials properties and fatigue and fracture analysis methods. As a result of improved models, materials data, and revised analytical techniques, the Center analysis team determined:

a. The LOX Run Tank is fracture-critical and ***not*** a LBB design.

b. Conservative damage tolerance analyses showed large analytical margins (factor of 10+) for a limited number (<100) of additional LOX Run Tank pressure cycles.

On October 5, 2005, the NESC Technical Consultation Team reconvened via telecon to review the results [ref. 1] of the NASA LaRC HTT LOX Run Tank re-analysis efforts. The NESC Technical Consultation Team concurred with the results (items a. and b. above) and developed a set of revised recommendations and additional observations (listed below). This set of revised recommendations and additional observations were reviewed and approved by the NESC Review Board on October 6, 2005 and presented (in briefing format) to the NASA LaRC Executive Safety Council on October 7, 2005. The NASA LaRC Executive Safety Council accepted the NESC recommendations as written.

Revised and Additional Recommendations

R-1 (Revised). Based on conservative analysis assumptions and large analytical margins in the revised fatigue and fracture analyses, the NESC Technical Consultation Team's position on the LOX Run Tank is:

- Completion of the Air Force Research Lab (AFRL) Ground Demonstration Engine test program is acceptable, based on an assumed test program of less than 100 additional pressure cycles of the LOX Run Tank.
- The LOX Run Tank should be inspected and recertified immediately following the completion of the AFRL tests before any additional test programs are conducted.

R-2 (Revised). Written and approved rationale for external inspection on the vacuum shell only of the LOX Storage Tank is required.

R-3 (New). Stennis Space Center and other NASA facilities should be consulted and surveyed for high-pressure LOX tank inspection methods, techniques, and capabilities.

Additional Observations

O-4. Atmospheric pressure load modeling in the revised analysis needs to be updated; the overall effect is expected to be very minor (order of 14/2250 psi).

- The atmospheric pressure acts on the external vacuum jacket shell and transfers to the LOX Run Tank pressure shell as point loads through standoffs, not as a uniform load on the pressure shell.

O-5. Changes to the baseline inspection requirements may require changes to the NASA HQ-approved site waiver for the tank locations.

- "Waiver-of-the-waiver" approval requirements to conduct the AFRL tests, if any, needs to be determined.

O-6. Vacuum monitoring of the LOX Run Tank as a safety precaution may lead to a false sense of security.

Reference

1. Forth, S.C.; Harvin, S.F.; Gregory, P.B.; Mason, B.H.; Thompson, J.E.; and Hoffman, E.K. "Damage Tolerance Analysis of a Pressurized Liquid Oxygen Tank", NASA/TM-2006-214274, 2006.

Volume II: Appendices

Appendix A. ITA/I Request Form (NESC-PR-003-FM-01)

NASA Engineering and Safety Center Request Form

Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 6/6/2005 12:00 AM	Status: New	Reference #: 05-034-E
Initiator Name: Roy Bridges	E-mail: Roy.D.Bridges@nasa.gov	Center: LARC
Phone: (757)-864-4111, Ext _____	Mail Stop: 105	
Short Title: 8' HTT Oxygen Storage Pressure Vessel Inspection Requirements		
Description: The LaRC Pressure Systems Committee has recommended to the LaRC Executive Safety Council that the inservice inspection requirements for two liquid oxygen storage pressure vessels at the 8' High Temperature Tunnel be changed from 10 years to 1000 pressure cycles. The vessels were installed in 1989 and the high pressure tank has about 600 pressure cycles total. The chair of the LaRC Executive Safety Council, Mr. R. Bridges, requested NESC evaluation of the proposal before final consideration. Continued interim operations of the system were approved based on existing safety procedures and instrumentation for detecting leaks. Other considerations include the proximity of these systems to occupied buildings (a siting waiver was required), and the fact that the original 10-year inservice inspection due in 2000 has yet to be completed.		
Source (e.g. email, phone call, posted on web):		
Type of Request:		
Proposed Need Date: 8/1/2005		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 6/6/2005 12:00 AM		
Potential ITA/I candidate? ☒Yes ☐ No		
Assigned Initial Evaluator (IE): Mike Gilbert		
Date assigned (mm/dd/yyyy): 6/14/2005		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? ☐Yes ☐ No		
If yes:		
Description of action:		
Actionee:		
Is follow-up required? ☐Yes ☐ No If yes: Due Date:		
Follow-up status/date:		
If no:		
NESC Director Concurrence (signature):		
Request closure date:		

NESC Request Form
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Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? ☐Yes ☐ No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		
Section 4: NRB Review and Disposition of NCE Response Report		
ITA/I Approved: ☐Yes ☐ No	Date Approved:	Priority: - Select -
ITA/I Lead: , Phone ( ) - , x		
Section 5: ITA/I Lead Planning, Conduct, and Reporting		
Plan Development Start Date:		
ITA/I Plan # NESC-PL-		
Plan Approval Date:		
ITA/I Start Date	Planned:	Actual:
ITA/I Completed Date:		
ITA/I Final Report #: NESC-PN-		
ITA/I Briefing Package #: NESC-PN-		
Follow-up Required? ☐Yes ☐ No		
Section 6: Follow-up		
Date Findings Briefed to Customer:		
Follow-up Accepted: ☐Yes ☐ No		
Follow-up Completed Date:		
Follow-up Report #: NESC-RP-		
Section 7: Disposition and Notification		
Notification type: - Select -	Details:	
Date of Notification:		
Final Disposition: - Select -		
Rationale for Disposition:		
Close Out Review Date:		

NESC Request Form
NESC-PR-003-FM-01, v1.0

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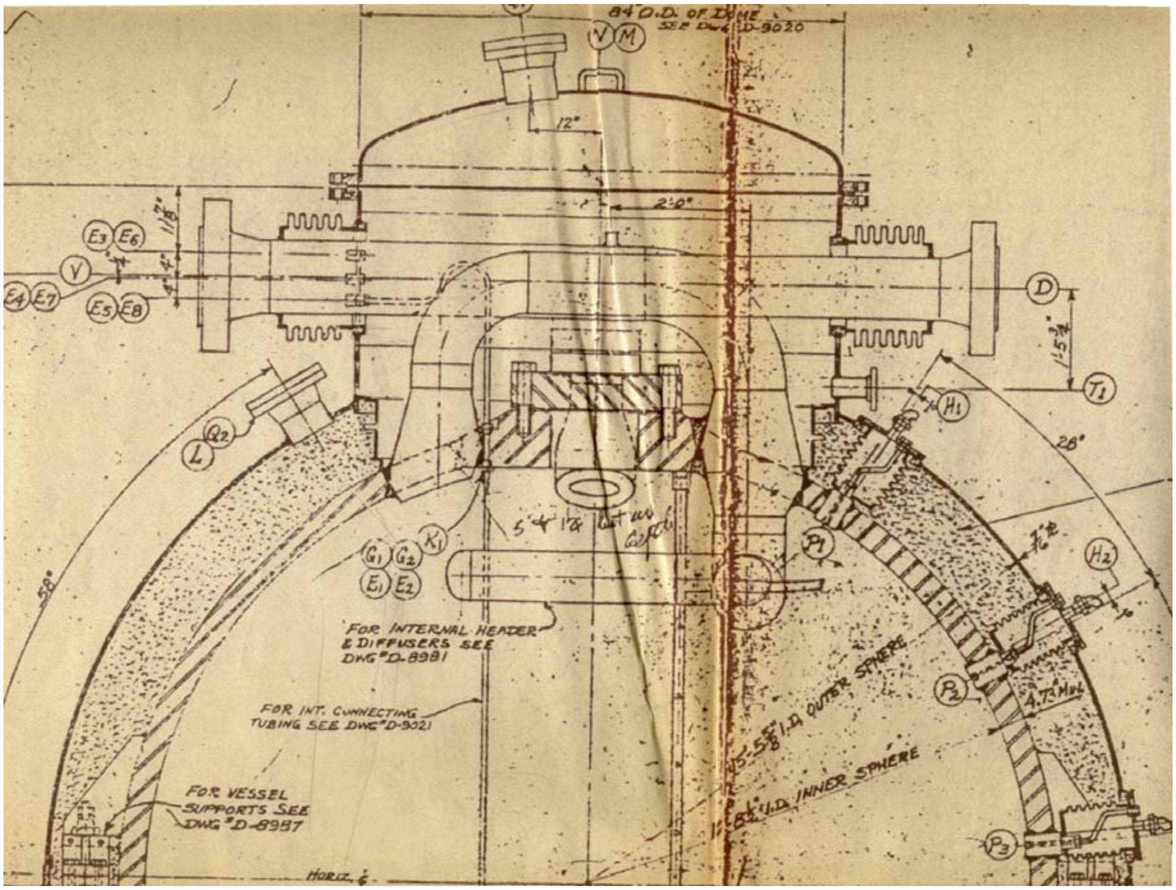
Form Approval and Document Revision History

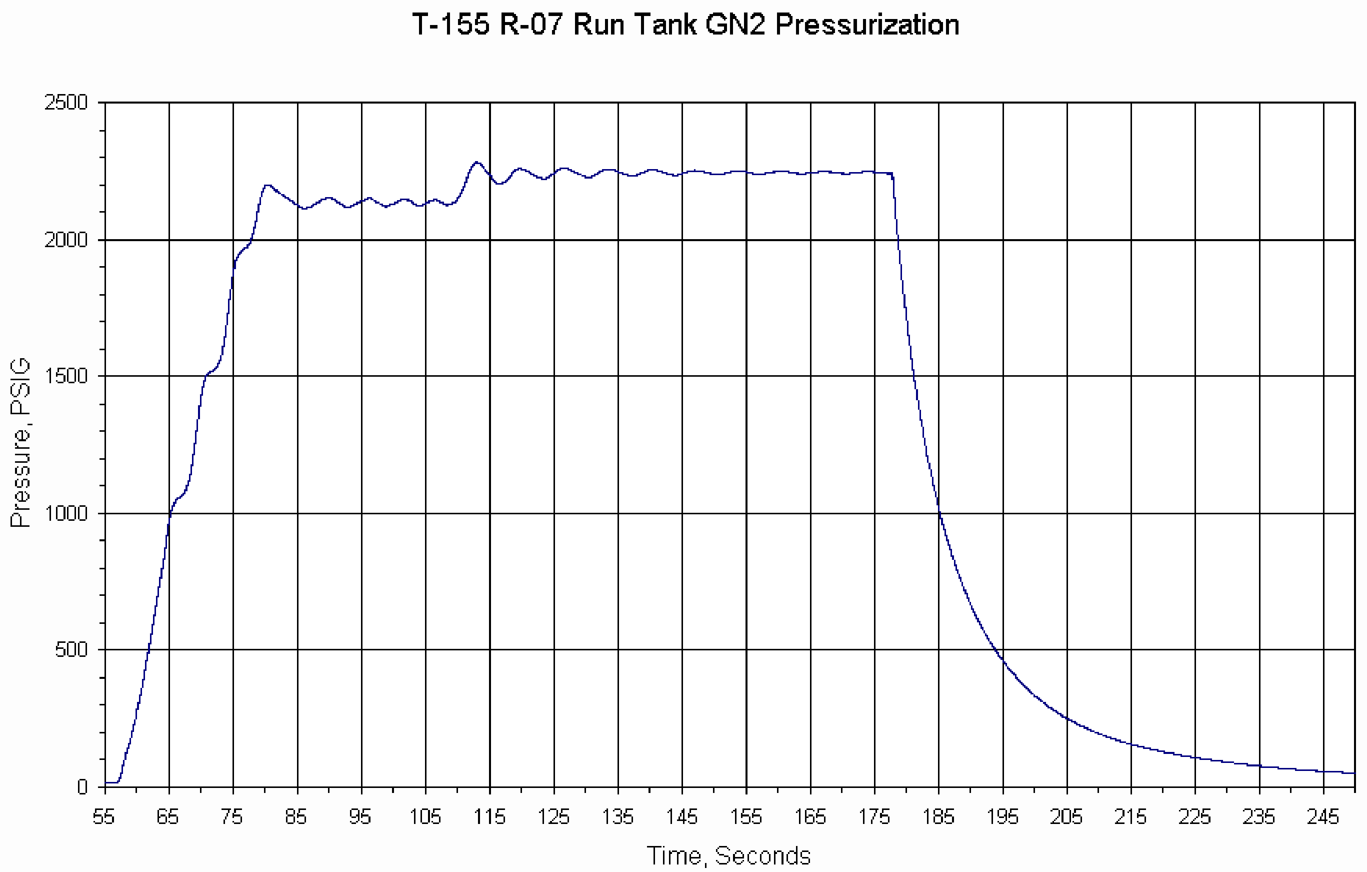
Approved: ____________________ ________
NESC Director Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

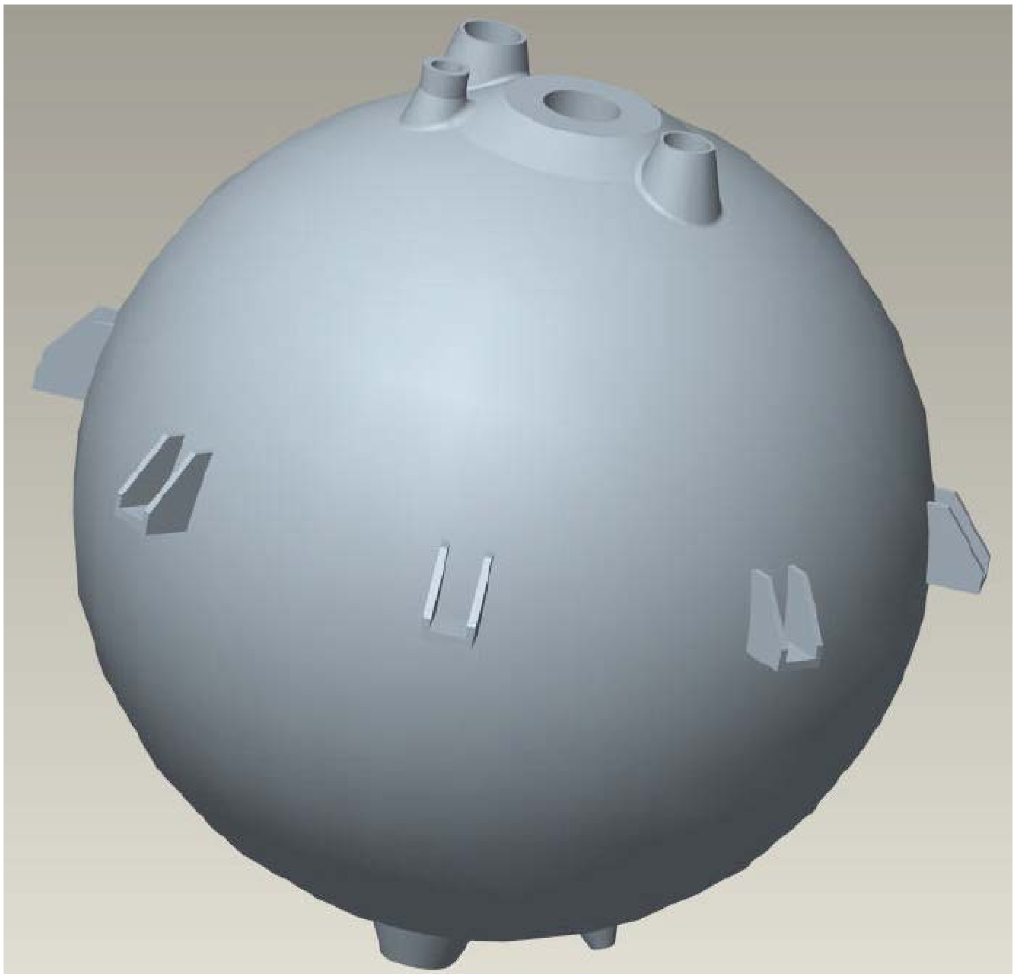
Appendix B. LOX Run Tank Sketch



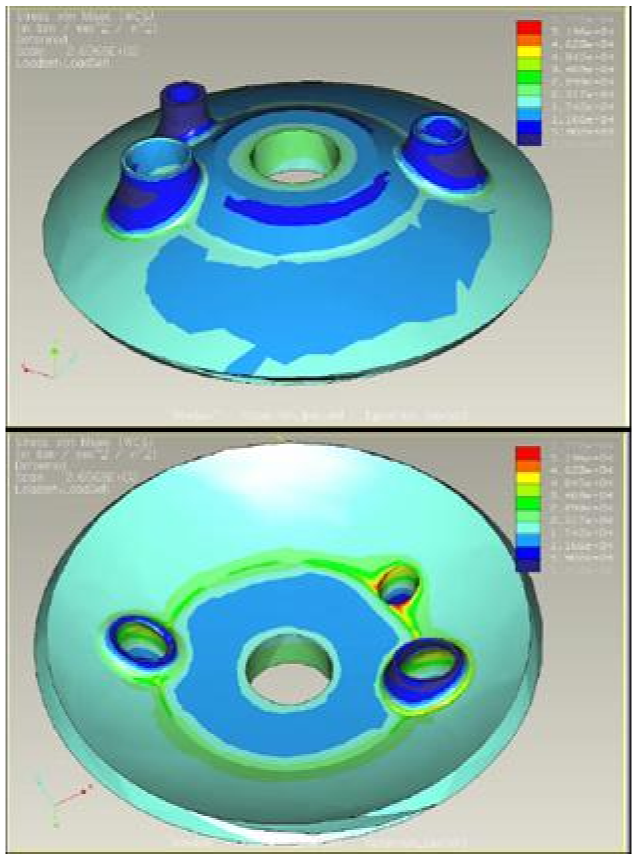
Appendix C. LOX Run Tank Analyses



LOX Run Tank Pressure Profile



LOX Run Tank Model



LOX Run Tank Top Stresses

Appendix D. NESC Risk Assessment

Rev A Annex.

NESC RISK ASSESSMENT

RISK DEFINITION

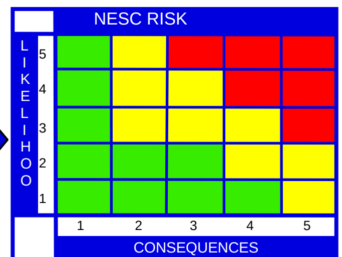
Risk: Measure of the potential inability to achieve overall program objectives within defined constraints and has two components: (1) the probability/likelihood of failing to achieve a particular outcome, and (2) the consequences/impacts of failing to achieve that outcome
Consequence: Impact (typically categorized as negative) to program/project (loss, injury, disadvantage)
Likelihood: Ordinal scale: Relative ranking of probability of occurrence. Numerical scale: estimated probability an event will occur combined with the uncertainty in the probability assessment

RISK MANAGEMENT: An organized, systematic decision-making process that efficiently identifies risks, assesses or analyzes risks, and effectively reduces or eliminates risks to achieving program goals. (NESC Risk Management Plan)
NESC ASSESSMENT RISK MANAGEMENT APPLICATION (NARMA): The NESC database used to assess and prioritize concerns brought to the attention of the NESC. URL: http://xx

What is the likelihood the situation or circumstance will

LIKELIHOO

Level	Probability	. . . or –. . .	Example
5	Very Likely	Likely to occur often. Likelihood of occurrence is estimated to be greater than 0.10 (10-1) per operational opportunity	Lost work case per worker over a 20 year private industry career
4	High	Expected to occur some time in the life of the item. Likelihood of occurrence is estimated to be between 0.01 and 0.10 (10-2 and 10-1) per operational opportunity	Failures per US ELV Launch (1988 - 2001)
3	Moderate	Likely to occur some time in the life of the item. Likelihood of occurrence is estimated to be between 0.01 and 0.001 (10-2 and 10-3) per operational opportunity	Place holder
2	Low	Unlikely but possible to occur. Likelihood of occurrence is estimated to be between 0.001 and 0.000001 (10-3 and 10-6) per operational opportunity	Fatal crashes per automobile trip
1	Very Low	Likelihood of occurrence is estimated to be less than .000001 (<10-6) per operational opportunity	Fatal crashes per passenger airplane departure



LEGEND

- High – Accepted for NESC Board review. Probable NESC follow-on IA.
- Medium – Accepted for NESC Board review. NESC or other NASA IA action required.
- Low – Not Boarded by NESC. Direct referral to other NASA IA org.

RISK CONSEQUENCE SCORING TERMS

1 Safety, Health, Environment is defined as impact to life, health, working environment and natural environment
2 Mission Success definition includes impacts to Major Mission
3 Objectives (MMOs) as well as hardware loss
National Significance is defined as the degree to which national
4 prestige, visibility and public relations are impacted
5 Safety, Health, Environment, Mission Success and National Significance can exist concurrently and are not mutually exclusive
Risk scoring is accomplished by "multiplying" Likelihood (L) X Consequence (C). Note: numerical value is reflective of the ordered pair L, C. Care must be taken when using multiplied falues as measures. When determining risk consequence among Cost, Schedule, and Technical, the highest score is represented in the NESC Risk Matrix as a single score value.

What is the Consequence (Safety, Health, Environment, Mission Success, National Significance) of this NESC

CONSEQUENC

Leve	1	2	3	4	5
Safety, Health, Environment	Minimal/no safety or health plan violations / Minimal to no environ impacts	Could result in injury or illness not resulting in lost work day / Minimal envirnmtl damage	Could result in injury or occupational illness resulting in one or more lost work day / Mit. envirnmtl damage w/o law viol	Could result in permanent partial disability, injuries or occupational illness / Reversible envinmt damage – violates law	Could result in death or perm. total disability / Irreversible severe environ damage that violates law or regulation
Mission Success	Hardware loss between $200K and $1 Million / Failure to any one MMO	Hardware loss between $1M and $10 Million / Failure to meet > 50% of supplemntl objectives	Hardware loss between $10M and $100 Million / Failure to meet any one MMO	Hardware loss between $100M and $250 Million / Failure to meet > 50% MMO's	Hardware loss exceeding $250 Million / Failure to meet all Major Mission Objectives (MMO's)
National Significance	Minimal or no identified National Prestige or Visibility	Low National Prestige and Visibility	Moderate National Prestige and Visibility	Significant National Prestige and Visibility	High National Prestige and Visibility

Appendix E. List of Acronyms

AFRL	Air Force Research Laboratory
ASME	American Society of Mechanical Engineers
GRC	Glenn Research Center
HQ	Headquarters
HTT	High Temperature Tunnel
LaRC	Langley Research Center
LBB	Leak-Before-Burst
LOX	Liquid Oxygen
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
OIG	Office of Inspector General
psig	pounds per square inch gage
S&MA	Safety & Mission Assurance

Approval and Document Revision History

Approved:	Original signed on file	3/24/06
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	NESC Chief Engineer's Office	3/16/06