FINAL REPORT

Support to X-33/ Reusable Launch Vehicle Technology Program

Reference: Purchase Order # H-31417D

Lee & Associates, LLC

November 29,2000

X-33 LH2 Fuel Tank Failure

Reference: P.O. # H-31417D

INTRODUCTION

The Primary activities of Lee & Associates for the referenced Purchase Order has been in direct support of the X-33/Reusable Launch Vehicle Technology Program. An independent review to evaluate the X-33 liquid hydrogen fuel tank failure, which recently occurred after-test of the starboard tank has been provided. The purpose of the Investigation team was to assess the tank design modifications, provide an assessment of the testing approach used by MSFC in determining the flight worthiness of the tank, assessing the structural integrity, and determine the cause of the failure of the tank.

The approach taken to satisfy the objectives has been for Lee & Associates to provide the expertise of Mr. Frank Key and Mr. Wayne Burton who have relevant experience from past programs and a strong background of experience in the fields critical to the success of the program. Mr. Key and Mr. Burton participated in the NASA established Failure Investigation Review Team to review the development and process data and to identify any design, testing or manufacturing weaknesses and potential problem areas. This approach worked well in satisfying the objectives and providing the Review Team with valuable information including the development of a Fault Tree. The detailed inputs were made orally in real time in the Review Team daily meetings.

The results of the investigation were presented to the MSFC Center Director by the team on February 15, 2000. Attached in report #1 are four charts taken from that presentation which includes 1) An executive summary, 2) The most probable cause, 3) Technology assessment, and 4) Technology Recommendations for Cryogenic tanks.

SNECMA Capability Review

Reference: PO# H-31417D Mod 01

INTRODUCTION

The primary effort required by Modification 01 to the purchase order was to provide technical guidance and consultation in support of " High Risk, High Payoff Actively Cooled Ceramic Matrix Composite Aerospike Nozzle Ramp". This was accomplished through an independent assessment by Mr. Jan Monk focused on the propulsion manufacturing capability and focused propulsion technology readiness of SNECMA, Bordeaux and Vernon, France. The purpose of this assessment was to determine the best approach to meet the X-33/RLV technology Demonstration Program objectives. It is the opinion of Lee & Associates the objectives were met as demonstrated in the attached report #2.

X-33 Critical Design Review

Reference: PO # H-31417D Mod 02

INTRODUCTION

The primary effort required by Modification 02 was for Mr. Frank Key to participate in the X-33 Critical Design Review (CDR) held in Michoud LA on September 13, 14, and 15, 2000. Mr. Key accomplished this task to the satisfaction of both Lee & Associates and the X-33 Program Office Representatives. The final CDR report was submitted through real time inputs during the meeting based on inputs made by Mr. Key and others participating in the meeting. . The attached report #3 is a summary of the activities during the review.

ATTACH. #1

X-33 LH_2 Tank Investigation
Center Director Presentation
February 15, 2000

X-33 LH_2 Tank Investigation
Executive Summary

- November 3,1999: after completion of the protoflight test and tank drain, the outer skin and core material of Lobe 1 separated from the inner skin.
- The cause of this failure was a combination of:
  - Microcracking of the inner skin / hydrogen infiltration
  - Cryopumping of the exterior purge gas (nitrogen used for safety)
  - Reduced core bondline strength and toughness
  - Manufacturing flaws and defects
- An investigation, using a Fault Tree approach, was conducted by a team from NASA, Lockheed Martin, and independent consultants.
- The investigation identified an unexpected failure mechanism (hydrogen infiltration into the core).
- Results of the investigation do not invalidate the use of composite materials for cryogenic tanks.
- Lessons learned in the development program clearly demonstrate that scale-up of any advanced composite concept requires a vigorous technology development program.

X-33 LH_2 Tank Investigation
Results of Inspections

- Hydrogen was found in the core of all remaining lobes. Hydrogen is still present 3 months later. Safety issues were addressed in all post-test operations.
- Separation of outer skin/core from inner skin was an adhesive failure (classical peel failure).
- Pre-test NDE did not identify all bondline defects observed
  - 1/2 -inch-wide by 3-inch-long "J-shaped" piece of PTFE tape
  - 7/8-inch by 7/8-inch "pear-shaped" piece of plastic film
  - .050-inch-wide by 2-foot-long disbond between the inner and outer skin
  - Multiple small disbonds along a longitudinal core splice
- Destructive evaluation identified extensive microcracking in the inner skin.

X-33 LH_2 Tank Investigation
Results of Analyses

- Outer skin temperatures and core pressure rise rates require cryopumped nitrogen and infiltration of hydrogen from the tank into the core.
- Core pressures could range from 108 - 202 psia depending on hydrogen infiltration level.
- Microcracking threshold is reached with thermal residual stresses alone. Thermal and biaxial mechanical loads would produce microcracking in all layers of the inner skin.
- Fracture mechanics analysis showed that a flaw, the size of the observed pieces of FOD (foreign object debris), or disbonds would be unstable (peel) at approximately 114 psia core pressure.

X-33 LH_2 Tank Investigation
Issues Relating to Technology Assessment

- Technical Issues:
  - Concept selection based on 3 and 10 foot diameter, non-load-bearing tanks
  - Microcracking/hydrogen infiltration
  - Scale-up of the manufacturing process
  - NDE
  - Cryopumping
- Programmatic issues:
  - Design assumptions were made to fit "short" schedule
  - Communication among all parties
  - Robust fracture control plan needed (NDE, proof-pressure testing, and fracture mechanics analysis)

ATTACH. #2

Assessment of the SNECMA High Risk - High Payoff Composite Nozzle Review Contract NAS8-99112

August 28-31, 2000

Bordeaux, France
Vernon, France

Prepared by:
Jan C. Monk

Trip Purpose

Independently evaluate and assess the Snecma Aerospike Actively Cooled CMC Nozzle Ramp Review relative to schedule and cost associated with the technology maturation of cooled composite nozzle ramp, RLV engine nozzle concept design and design/fabrication of Large Scale Test Article to be delivered in 2001.

Review Agenda

<u>August 28 Bordeaux</u>

9:00 Welcome
9:15 Snecma Overview
9:45 Thermostrucutral Composites
12:30 Lunch
2:00 Composite Nozzle Ramp
4:00 Manufacturing Tour
5:00 NASA SLI Overview
5:30 Questions/Discussions

<u>August 29 Bordeaux</u>

9:00 National Center for Scientific Research Overview
10:00 Facility Tour
12:00 Questions/Discussions

Review Agenda (Cont'd)

August 30 Vernon

12:00	**Welcome**
12:30	**Lunch**
2:00	**Large Liquid Propulsion Unit Presentation**
3:00	**Exhibition Hall**
4:00	**Test Facility Tour**
5:30	**Questions/Discussions**

August 31 Vernon

8:45	**Welcome**
9:00	**NASA SLI Overview**
10:00	**Ariane 4 Assembly Hall**
11:00	**Vulcain Assembly Hall**
12:00	**Questions/Discussions**

Attendees

Review was conducted on August 28-29, 2000 at the SNECMA facilities in Bordeaux, France and August 30-31, 2000 in Vernon France. Attendees included:

Gene Austin	**MSFC X-33 Program**
Jeff Bland	**MSFC X-33 Program**
Charlie Dill	**MSFC X-33 Program**
Steve Richards	**MSFC Space Transportation Directorate**
Corky. Clinton	**MSFC Engineering Directorate**
Jan Monk	**Consultant**
SNECMA Management	
SNECMA Presenters	

General Observations

Solid Propulsion and Composite Division (Bordeaux)

- **Snecma Moteurs continues to be an internationally recognized leader in thermostructural materials.**

- **The Solid Propulsion and Composites Division (Bordeaux) is well suited to be the supplier of composite structures for Second Generation RLV.**
  - Major investments in facilities for manufacturing
  - Process over 400 Tons of Carbon-Carbon material yearly (primarily for aircraft brakes)

- **Extensive facilities are available for characterization of materials, processing of performs, needling, Carbon/SiC and Carbon furnaces, and processing of carbon fabric.**

- **Newly implemented processes should improve structural capability**
  - Needling (transfers fibers perpendicular to fabric)
  - Needling also provides design solutions to eliminate mechanical attachment.

The Solid Propulsion and Composite Division capabilities, technology, facilities and people, continue to be impressive. The are clearly a world leader in their knowledge of thermostructures. 400 tons of Carbon-Carbon material processed per year is a good illustration of production capability.

The needling process provides a "near 3-D weave" capability for preforms that improves the strength of the basic structure as well as potentially eliminating the need for mechanical attachment for some applications.

General Observations (Cont'd)

- **New large densification furnace is operational.**
  - Provides capability to process RLV Aerospike nozzle.
  - Currently used to process RL-10B composite nozzle extension.

- **Current composite nozzle production**
  - C-C nozzle for Ariane 5 SRMs

  - C-C (Novoltex) nozzle for RL10B
    - Length - 2.524 m (99.4 inches)
    - Diameter - 2.1 m (84.1 inches)
    - Weight - 93 kg (202 pounds)

The Solid Propulsion and Composites Division clearly have the production capability to produce composite ramp structures of the size needed for VentureStar.

Facilitization costs to produce a composite structure sized for the VentureStar engine ramp should me minimal.

Significant production activities supporting the Ariane 5 and the RL10B engine are in place.

General Observations (Cont'd)

- **C/SiC demo nozzle for HM7 (Lox/Hydrogen)**
  - Length - 988 mm (38.9 inches)
  - Diameter - 938 mm (36.9 inches)
  - Weight - 24.7 kg (54.4 pounds)
  - Accumulated 750 and 900 seconds in two tests
  - No damage
- **A number of C/SiC structures have been produced to demonstrate C/SiC capability in support of the Hermes Program and other programs.**
  - Vehicle TPS Panels
  - Wing leading edge
  - Winglet Box Structure
  - Nose Cap

The HM7 nozzle is not available for viewing but has been examined during a previous trip to Bordeaux. The inner surface and nozzle-to-chamber interface showed no effects from the hot fire tests.

The C/SiC vehicle components have undergone various tests and have all performed as expected. This should be of particular interest to the vehicle community for reusable hot structures.

General Observations (Cont'd)

<u>**Laboratoire Des Composites Thermo-Structuraux (Bordeaux)**</u>

- **The Laboratory for Thermostructural Composites in Bordeaux and provides an excellent source of technology improvements.**
  - Snecma is one of four partners
    - National Center for Scientific Research (CNRS)
    - Snecma
    - CEA (Center for Nuclear Applications)
    - The University of Bordeaux
- **Mission is to generate scientific knowledge on Carbon, C-SIC, and related materials for processes, environment, etc.**
- **Clearance is required by Snecma/CEA prior to research publication**
- **Facilities, equipment and personnel produce an impressive research capability.**

Having direct access to a research facility such as the Laboratory for Thermostructural Composites is a significant asset. During the tour of the facility, state-of-the-art equipment and top notch personnel were evident. We were impressed with the basic material and process technologies that were in work. Having full time Snecma employees on site provide a direct link to ongoing activities.

General Observations (Cont'd)

Large Liquid Propulsion Division (Vernon)

- **The Vernon facility provides an excellent source of cost effective liquid rocket engine technology, design and manufacturing.**
  - Excellent production capability.
    - Propulsion System for Ariane IV
      - Propellant Feed System
      - Tank Pressurization System
      - Pneumatic System
      - Viking engine (storable propellants)
      - HM7 engine (Lox/Hydrogen)

- **Vulcain and Vulcain II engines are high performance Lox/hydrogen engines.**

	Vulcain	Vulcain II
Thrust, kips	258.5	303.5
Isp, sec	431	441
Pc, psia	1647	1736
Weight, lbm	3747	4299

Viking engines are produced at a rate of 70 per year at about $1M each. Both the Viking and Vulcain assembly areas were very well organized and operate with a minimum number of personnel.

General Observations (Cont'd)

- **State-of-the-art design, analysis and production capabilities**
- **Very clean, orderly state-of-the-art engine and component test facilities.**
- **State-of-the-art test/flight data analysis system**
- **The industrial organization of the Ariane 4 and Ariane 5 Programs with multiple country/multiple company requirements provide Snecma with significant experience that could be applied as a participant in a U.S. led multi-company program. The Vulcain II engine program consists of 13 companies in 7 different countries with Snecma as the integration lead.**

The Vulcain component test facility utilizes a test sled approach to improve test article throughput. Test articles are prepared offline including instrumentation installation and use standard interfaces.

Very impressive test/flight data analysis system. Demonstrations included comparison of a particular engine parameter during acceptance test and flight. High speed data capability included three dimensional frequency vs amplitude vs time plots. Data is distributed on a need to know basis to all engine suppliers.

Nozzle Design Observations

- **Significant maturation of the cooled composite nozzle design has taken place since the Kickoff Meeting in April of this year.**
- **Overall schedule is somewhat optimistic but doable.**
- **Recently issued requirements changes impact baseline design**
  - Heat flux reduction
  - Re-entry heating requirement
  - Coolant delta-P reduction
  - Coolant pressure reduction
  - Coolant flowrate reduction
- **Access to the Large Liquid Propulsion Division in Vernon provides experience link for liquid hydrogen, brazing and manifolding.**
- **Questions raised by SNECMA seemed to be mature and detailed indicating a good understanding of the design requirements and the design/fabrication process.**

Options and concepts shown indicate significant maturation of the nozzle ramp since the April Kickoff Meeting. The schedule presented has slipped somewhat but may be more consistent with available funding.

Recent requirements changes have perturbed the design and will require some additional analysis. Some changes have eased the design challenge but other such as the re-entry heating environment and allowable coolant delta-P have produced the need for dropping some concepts and re-evaluating a number of trade studies.

Nozzle Design Observations

- **Reduction in coolant pressure requirement should increase number of candidates for coolant tube material.**
- **The current Snecma design results in fabricating the full-scale ramp in two sections**
  - No fabrication capability issues.
  - Scaling of the two sections is within their experience base with the RL10B composite nozzle extension.
- **Access to Large Liquid Propulsion Division in Vernon provides experience link for liquid hydrogen, brazing and manifolding solutions.**
- **Function of the braze alloy between coolant tubes and CMC is to enhance heat transfer and is not necessary for structural strength. This should provide a level of robustness in the fabrication process.**

The coolant supply pressure requirement change (reduced by a factor of 2) should help resolve the coolant tube material by allowing previously discarded materials to enter the trade space.

The two piece design of a individual ramp section easily fits into existing densification furnaces.

Considerable experience is available through the Large Liquid Engine Division in Vernon for understanding hydrogen and classical rocket engine techniques for manifolding, etc.

Concerns/Issues

- **Use of Inconel 718 as coolant tube material**
  - Snecma recognizes hydrogen embrittlement issue but has not identified any resolution.
- **LMSW is provides primary engine and vehicle integration**
  - Several engine/vehicle trades and internal engine trades remain to be conducted
  - Rocketdyne role is minimal (not a Snecma issue but a LMSW/Boeing issue) but at a minimum, needs strengthening for internal engine trade support
- **Several trades remain open**
  - Coolant flowrate
  - Coolant delta-P
  - Backing structure trades will need to be repeated.
- **Care should be exercised to make sure passages on the back side of the coolant tubes continue to be vented to prevent cryo-pumping.**

Cryo-pumping could become a problem if cooled areas are not permitted to vent. This is not a problem with the current design but should be kept in mind if redesign occurs.

Recommendations

- **With limited Rocketdyne participation due to funding constraints, NASA and Snecma should freeze requirements for Large Scale Test Article (LSTA) as soon as possible.**
  - Base requirements on reasonable best estimates.
  - Use follow-on second generation LSTA to confirm design updates as VentureStar engine design matures.
- **Hydrogen sensitivity is a highly visible and sensitive issue within NASA and resolution of this problem should be up front and clear (overkill).**
- **A follow-on activity should be pursued applying technology to bell nozzle designs.**

Rather that constrain the time available to demonstrate the basic capabilities of this technology, it would be advisable to baseline a set of requirements for the Large Scale Test Article configuration as soon as possible. If engine design maturation results in requirements changes for the ramp, the program should consider a second updated LSTA.

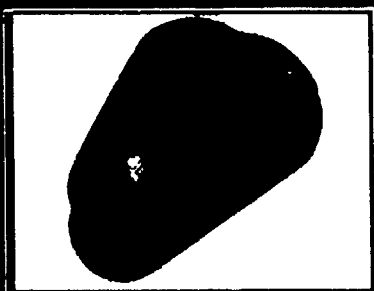
Because hydrogen embrittlement is such a highly visible issue, Snecma should make sure this potential problem is resolved early and in a clear manner.

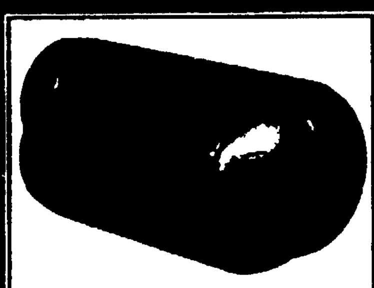
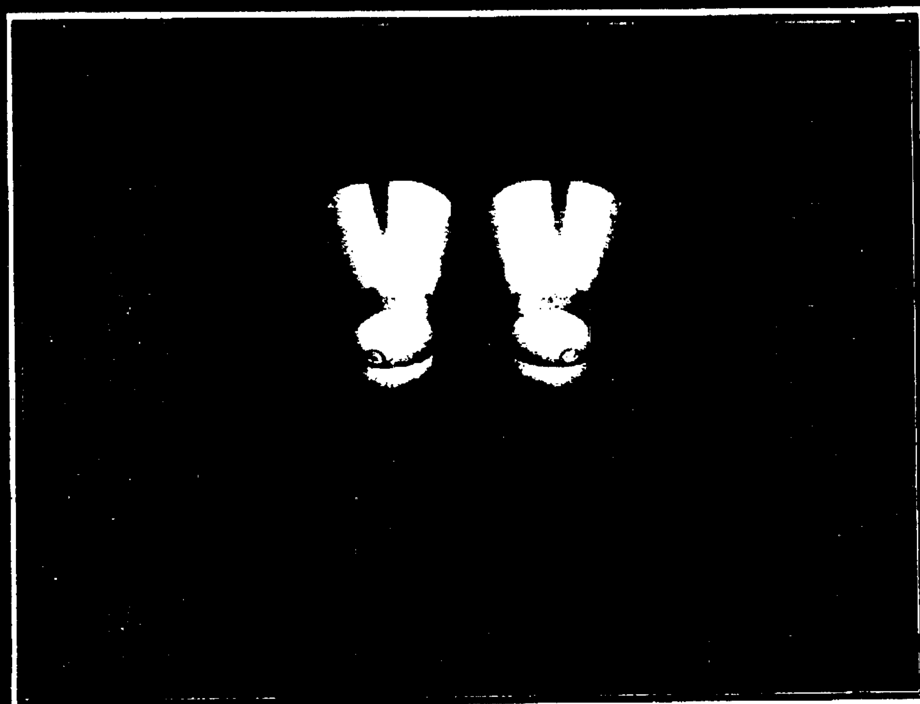
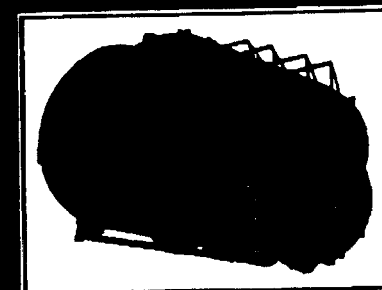
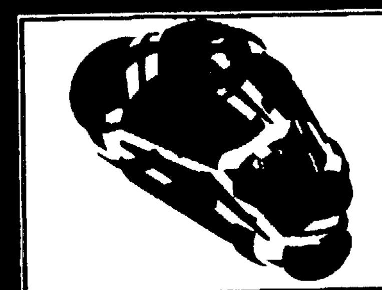
As this technology is demonstrated, the capabilities of actively cooled composite structures should be made know.

ATTACH #3

LOCKHEED MARTIN

X-33 Metal LH2 Tank Critical Design Review




Pressure Shell

September 13-14, 2000

Lockheed Martin Space Systems Company-Michoud Operations

CDR Approach

- Scope of the Review
  - Focus is on the X-33 Metallic Tank Pressure Shell (Welded Structural Shell)
  - Update on non pressure shell tank hardware and selected MPS elements
- CDR Objectives
  - Detail design status of the Pressure Shell to validate producibility and weights
  - Baseline Verification Approach
  - Update overall Metal LH2 Tank Program Status
- Tank Assembly CDR planned for second quarter 2001

LH2 Tank Project Approach

100% Mission Success

Utilize ET Heritage (Best Practices) and LO2 Tank Lessons Learned

Aggressive weight management program to meet tank weight requirement

Externally Sprayed RCI

Baseline Is LMAC LH2 Composite Tank Released IML

Utilize AL 2219 for Welded Pressure Shell

Selectively utilize Al-Li 2195 for Mechanically Attached Hardware

LH2 Tank Project Approach (cont.)

Protoflight Test Both Tanks at MSFC

- Criteria Defined for Single Protoflight
- Coordinated with MSFC and LMAC

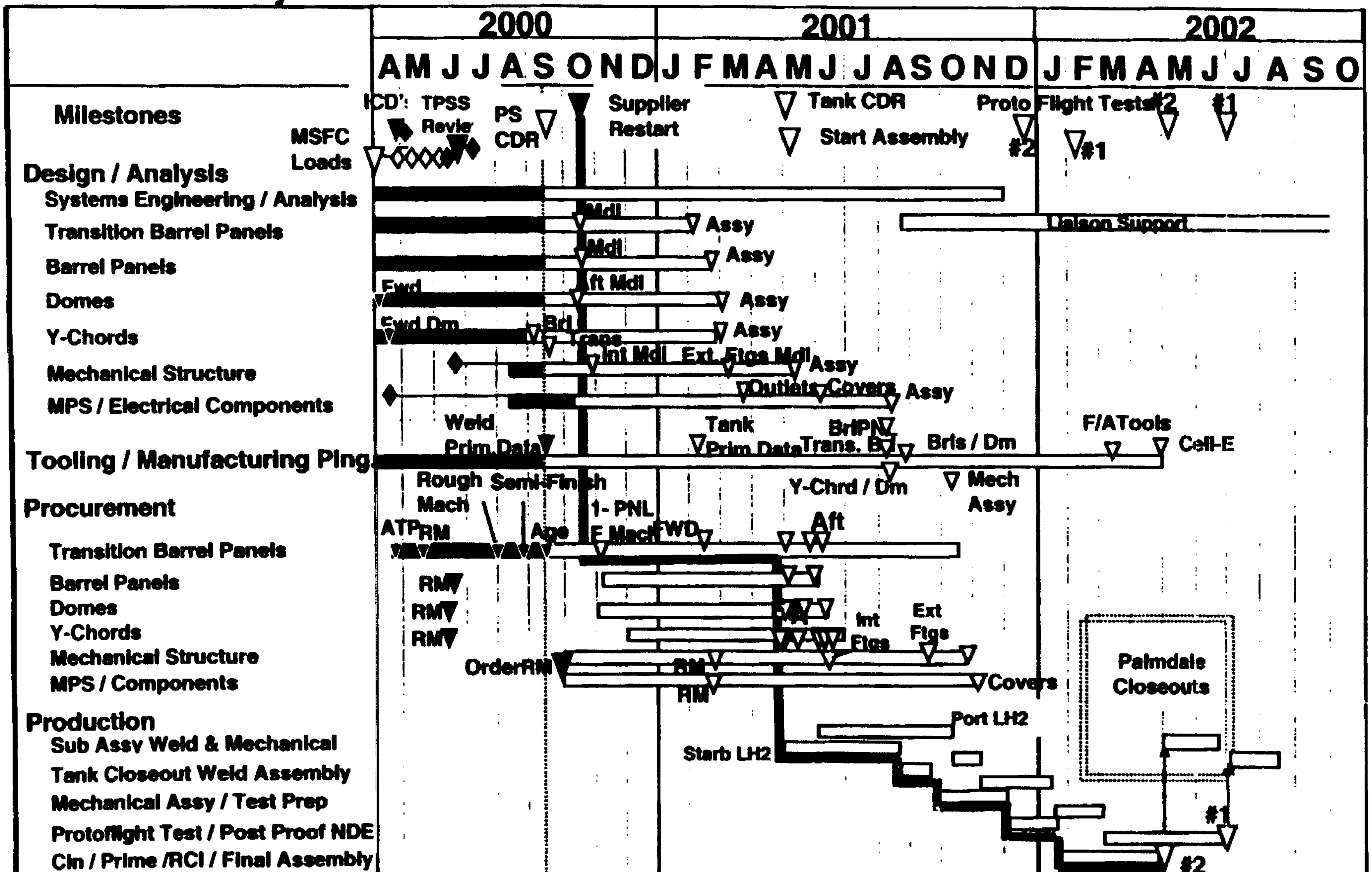
Tanks Delivered FOB at MSY Airport

- LMAC Responsible for Loading & Transport to Palmdale

NASA (TA) Responsible for:

- Ambient Protoflight Test of Starboard and Port Tanks
- Air Transport From MSY to Palmdale (2 tanks)
- Barge To/From MAF/MSFC

Phase 2 Recovery Schedule



Key PDR Programmatic Issues	Mitigation
Vehicle Specification Tank Volume • Min Volume of 7550 ft^3 per Vehicle Specification is inconsistent with propellant inventory	- As Designed Volume = 7,645 ft^3 - See Propulsion Analysis CDR Section
Malmstrom Environments Exceed Maximum RCI Surface Temperature on LH2 Tank	- Program to Validate Requirement (Ref PDR Action Item 014)
Vehicle Specification Revisions	- Program needs to update Specifications
1 vs. 2 Protoflight Tests	- Plan for Two Protoflight Tests

Program Status

	Pressure Shell CDR Status Assessment	Comments
Requirements Definition	G	CIDS Released
Loads Definition	G	C 6.0 Released C 6.1 Due 10/31 - 11/30
Interface Definition	G	Rev A Released -- Rev B in Review
Verification Approach	G	Verification Plan Released
Suppliers Selection/Fabrication	G	Suppliers Selected -- awaiting fab funding
Weight Assessment	Y/G	Sufficient Margin Exist to offset growth
		Additional weight savings candidates identified
		TPSS CR approval pending
Tool Design	G	Tool design on schedule
Manufacturing Plan	G	Pressure Shell Mfg'rg Data Doc released
Facility Plan	G	No Change
PDR Action Item Status	G	Final closure plans in work

Systems Requirements & Integration

Approach	Status
Utilize Composite LH2 Tank Project as Starting Point for Metal LH2 Tank	
• Applicable, Requirements, etc.	Complete
• Existing ICD Information, Models etc.	Complete
Identify Critical Design Requirements:	
• Program Systems Specifications	Complete
Develop Critical Item Development Specification for Metal LH2 Tank (LMSSC-MO 10570000003)	
• Document Systems and Derived Requirements	Complete
• Ensure Flowdown and Allocation of Requirements to LH2 Tank Designs	Complete
• Establish Verification Approach and Matrix	Complete
Define and Establish Interface Controls Methodology	
• Document Interface Requirements and Agreements	Complete
• Develop Interface Control Documentation (IC604H6602)	Rev B In Review

CDR Summary

Requirements Defined
- LH2 Tank CIDS Released
- Verification Plan Released
  - Proof and Protoflight Test Approach Defined
- ICD's Released
  - Incorporated TPSS CR, minor FTS and Static Ground requirements in work

Tank Weight Requirement Achievable
- Weight Reduction Options
- Management Process

Engineering Design / Analysis
- 50% of Pressure Shell Engineering Released
- Non Pressure Shell Engineering In Work
- Integrated CATIA Database Developed

Procurement Plan Defined for all Major Hardware
- Pressure Shell Raw Material at Suppliers
- Fwd Transition Barrel Supplier on Contract
- Remaining Pressure Shell Suppliers Selected

Manufacturing Plan Defined
- Tank Mfg. Flow Complete through Install into FAJ
- Manufacturing Primary Data for Welding Released, Mechanical and Processing in Work
- Major Tool Designs Complete
- Weld Development in Work