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X-33 PHASE II

ANNUAL PERFORMANCE REPORT

JULY 2, 1996 - JUNE 30, 1997

LOCKHEED MARTIN SKUNK WORKS
COOPERATIVE AGREEMENT NCC8-115

This data was generated by Lockheed Martin, AlliedSignal Aerospace, Rocketdyne - A Division of Boeing North American Rockwell, Rohr, Inc., and Sverdrup under NASA Cooperative Agreement No. NCC8-115, dated July 2, 1996.

LOCKHEED MARTIN   AlliedSignal AEROSPACE   ROHR   BOEING Rocketdyne Division   Sverdrup   NASA

INTRODUCTION

In response to Clause 17 of the Cooperative Agreement NCC8-115, Lockheed Martin Skunk Works has compiled an Annual Performance Report of the X-33/RLV Program. This report consists of individual reports from all industry team members, as well as NASA team centers.

Contract award was announced on July 2, 1996 and the first milestone was hand delivered to NASA MSFC on July 17, 1996.

The first year has been one of growth and progress as all team members staffed up and embarked on the technical adventure of the 20th century...

the ultimate goal. . .

a Single Stage to Orbit (SSTO) Reuseable Launch Vehicle (RLV).

X33

TABLE OF CONTENTS

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LOCKHEED MARTIN SKUNK WORKS

This performance report spans the first year for the Phase II X-33 Program and includes all efforts for the Conceptual and Preliminary Design Phase and a substantial portion of the Critical Design Phase for X-33 vehicle development. The program accomplishments reported herein are for the vehicle and vehicle systems developments in line with the program schedule for vehicle first flight in July 1999

Vehicle Design

The X-33 external configuration (Moldline) has been finalized and released. This configuration reflects a scaled version of the RLV concept and emphasizes configuration traceability. Configuration adjustments to the X-33 flight control surfaces and body loftlines have been incorporated for flight performance improvements which will be carried forward to the RLV design.

Vehicle Primary Structure

Thrust Structure, LH_2 Tanks, Intertank Structure, LOX Tank, Control Surface and Landing Gear Attachments

The X-33 primary structure design is complete and is at 100 % detail drawing release.

The manufacture of the thrust structure is in progress with the major components already through the first manufacturing phase. The first set of truss tubes for the thrust structure and intertank structure have been manufactured and assembled . A sample of the truss tubes have undergone static loads testing, temperature cycling (-175 ° F to + 350 ° F) and impact loads tests. Test results for the truss tubes indicated an 18 % margin beyond the 70,000 lbs. of ultimate load capability thus verifying achievement of a weight critical design.

The Lobe skins, Bulkheads and tank septums for the LH_2 Tanks have entered the manufacturing phase. The LOX tank is in its final phase of

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manufacturing and assembly.

Primary Structure Engineering Development Testing

The primary structure development is supported with 32 engineering development tests of which 8 have been completed, 12 are in progress , 9 have test plans released and the remainder are in the planning stages.

Thermal Protection System (TPS) Support Structure

The TPS support structure was redesigned following PDR in order to alleviate concerns with the TPS panels / Support structure response due to acoustic loads. The redesign has resulted in a structural concept which meets requirements for allowable deflections within the estimated temperature and acoustical environment.

The support structure is currently at 20 % detail drawing release and is on track with the revised development schedule issued after PDR and which includes the impacts of LH_2 design modifications.

Design of the TPS / support structure test article for the combined environments test is initiated. The test will subject a sample of TPS /support structure to combined acoustic, vibrational, and temperature environments for structural performance verification of the redesigned TPS support structure.

Vehicle Systems

The propellant slosh damping configuration was defined and incorporated into the tank designs. Subscale Plexiglass models of the LOX and LH_2 tanks where built and tested at MSFC. The LH_2 tank with its septum design showed satifactory fuel slosh damping characteristics. Baffles were required for the LOX tank and are incorporated into the LOX tank design.

Vehicle venting configuration defined.

Flush Air Data System installation design completed.

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Avionics Bay at 100 % Drawing release

MANUFACTURING ACCOMPLISHMENTS

Tooling

Major progress has been accomplished in tool design and fabrication including:

- thrust structure assembly fixture, design 100%, build 85% complete
- thrust structure fabrication tooling, design 100%, build 100% complete
- canted fin fixtures design 60%, build 30% complete
- upper TPS assembly tool family, design 60%, build 25% complete
- lower TPS assembly tool family design 60%, build 25% complete
- LH_2 tank composite seal fabrication tooling, design 90%, build 75% complete
- workstands, design 100%, build 90%
- nose gear subassembly, design 20%
- nose cone subassembly, design 20%

Fabrication

The following progress has been made in fabrication, primarily in composites and machining.

- two center composite thrust structure webs complete, the third is in process
- approximately 20 composite I-beams complete (feeds thrust structure)
- first titanium hold down fitting in heat treat after roughing, second is one week from completing roughing
- upper and lower titanium thrust structure caps complete through roughing, waiting heat treat
- LH_2 tank titanium fittings in programming

Facilities

Building 704 final assembly facility complete and on-line.

Personnel

All manufacturing disciplines with the exception of assembly, is fully staffed.
Assembly staffing will follow a programmed build-up commensurate with component deliveries.

OPERATIONS

Reliability, Maintainability / Testability, Supportability, & Population Hazard Analysis (RMS&A)

An extensive amount of progress has been made by the RMS&A IPT over the past year toward ensuring the X-33 system includes requisite operability characteristics, namely those specified in the X-33 Cooperative Agreement (CA) and those needed to pave the way for RLV. The RMS&A Team is led by LMSW, and spans 19 team companies and NASA centers. A core RMS&A team has been successfully positioned in Palmdale, and is leading activities undertaken throughout the country.

Reliability Task Team

The Reliability Engineering Team established Safe Recovery Reliability, R(SR), allocations which were flowed-down to all system hardware design teams. These allocations drove the architecture of both the Vehicle and Ground Support System. While use of off-the-shelf main engine components is limiting our ability to attain the lofty R(SR) targets we established, our current predictions indicate we will deliver a vehicle more reliable than any present-day launch system. Reliability participated heavily in the recent weight and cost tiger teams: To date, we have been successful in ensuring reliability is not significantly degraded by the weight reduction design changes. For some subsystems, reliability will improve significantly due to reduction in functional complexity. In June, the reliability team held an intensive three day interim design review. The review covered all subsystems, and spanned all reliability analyses, from FMECAs to Fault Trees: a very large amount of work has been done to date.

Maintainability Task Team

The Maintainability Team has achieved significant successes in delivering a prototype vehicle that has good access and repair characteristics. Successes include adoption of aircraft-like horizontal processing/maintenance; use of large TPS panels to simplify ingress to equipment areas; an avionics bay that contains most all avionic equipment; rapid "remove & replace" attachment concepts for the TPS elements; minimization of special tools; etc..

Elapsed time predictions have been developed for all maintenance and operations tasks. The Maintainability Team has evolved 2-Day "Quick Turn" timelines which show that -- absent a large amount of unscheduled maintenance tasks -- we will be able to demonstrate the requisite 2- Day Turn. As an adjunct to the discrete event timelines, RMS&A has developed a Monte Carlo-based turnaround simulation model which evaluates the probability of achieving the 2-Day Turn, and the three consecutive 7-Day Turns.

Testability Task Team

The Testability / Integrated Diagnostics Team required a little extra time to get up and running, but is now yielding top-quality testability assessments. Fault detection rate, fault isolation rate and false alarm rate are the target figures of merit.

Given cost and schedule constraints, X-33 will not have the diagnostics capability that RLV will have, but the X-33 team is paving the road toward RLV by tackling initial diagnostics design problems for key non-avionic subsystems, such as Cryo Tanks / MPS, and Main Engines.

A detailed assessment has been completed of X-33's testability characteristics. The Testability Team has brought on-board an advanced modeling / trades tool, as well as the tool's development company, Detex Inc., to complement the manual assessment. Additionally, a top-level integrated test plan -- spanning production to operations -- is nearing completion. The plan will identify overall test strategies as applicable to ensuring any hardware weaknesses are identified prior to first flight.

Logistics Task Team

The Logistics Team has made good progress on many fronts. Field support analyses have been developed which identify repair and restoration methods for each subsystem. When team/supplier repair turn-around times can be completed in a short amount of time, spares requirements are limited. Special programs are being developed to support repair of subsystems for which a large number of spares can not be provided, e.g., TPS.

A special Maintenance / Operations Task Analysis team has been formed to tackle the significant challenge of developing repair and operations procedures in a quick and efficient manner. One key to this effort is our forthcoming purchase of a commercial Logistics Support Analysis (LSA) database program, namely OILS from Omega, Inc.. The tool will allow us to archive our RM&S data in an efficient way, and build upon that data to deliver on-line maintenance and operations procedures.

Hazard Analysis Team

The Population Hazard Analysis Team is small, but effective. This team is responsible for coordinating development of the Expected Casualties E(C) predictions. These E(C) predictions are used to gain approval to overfly the limited population corridor planned for X-33. The team has brought ACTA Inc. on-board to help in the E(C) activities.

Initial predictions addressing the nominal X-33 trajectory indicated that even if our R(SR) predictions drop as low as .996 per launch, we still only reach 33% of threshold E(C) levels. LMSW is not stopping there, however, and continues pushing forward to explore the impact of off-nominal trajectories that could conceivably arise from certain failure modes and / or looser range destruct criteria. The Reliability team is compiling a list of most probable failure modes, and the Flight Sciences team will calculate resultant trajectories. The results will then be fed to ACTA for assessment.

Budget and Schedule

RMS&A is under budget; RMS&A team efficiency allowed some budget to be returned to the Program Office for possible re-allocation. Most RMS&A tasks are on schedule, and no difficulties continuing on schedule are forseen.

LOCKHEED MARTIN ASTRONAUTICS-DENVER

RLV-X33 research accomplished by Lockheed Martin Astronautics during the reporting period (for the 1st year from contract ATP on 2 Jul 96) occurred in four of the major areas. Astronautics provided support to Lockheed Martin Skunk Works in X-33 Development, RLV Development, Systems Engineering, and Business Operations.

X-33 Development

- Completed X-33 Payload Container according to plan
- Developed X-33 GSS Integrated Health Management (IHM) according to Feb 97 replan
- Developed X-33 Truss tubes according to Apr 97 replan scope revision
- Drafted X-33 Flight Test plan according to plan

RLV Development

- Supported RLV development plan review and update
- Supported RLV development according to updated plan
- Supported RLV to X-33 traceability and risk reduction

Systems Engineering

- Prepared and coordinated X-33 System Requirements Review, including Payment Milestone report
- Supported X-33 Preliminary Design Review, including preparations and RFA tracking to closure
- Developed and coordinated X-33 Risk Management plan, including Payment Milestone submittal
- Supported X-33 requirements development and specification, including Vehicle spec preparation
- Supported X-33 interface definition and control, including ICD preparation and maintenance

- Supported X-33 requirements traceability, flowdown, and TBD resolution
- Supported X-33 Risk Board and Risk Management activities, including tracking and mitigation
- Developed X-33 Flight SW Independent Verification and Validation according to plan
- Supported X-33 cost and weight reduction tiger teams

Business Operations

- Supported RLV mission model review, update, and application
- Supported Enterprise Development business plan development

LOCKHEED MARTIN ENGINEERING & SCIENCES COMPANY

LMES/Houston's primary responsibility for the X-33 Program is the design of the Terminal Area Energy Management (TAEM) and Approach/Land (A/L) guidance and flight control. We have released our initial design and subsequent updates with the following major deliveries:

TAEM and A/L Guidance and Flight Control Design

- Delivered initial release of TAEM and A/L guidance and flight control requirements on 2/3/97.
- Delivered updated flight control requirements and I-loads on 3/14/97.
- Delivered FORTRAN implementation of guidance and flight control requirements and I-loads to NASA Dryden on 4/24/97.

Additionally, we have assisted in defining the requirements for the navigation software and the air data system, and have coordinated with Allied Signal/Teterboro in defining test cases for validating the flight software requirements.

Evaluation of Vehicle Configuration

LMES/Houston has played a critical role in evaluating changes to the vehicle configuration, including:

- Modifications to the forebody camber and outer mold line
- Elimination of the upper flaps and lower center flap
- Larger lower flaps and changes to lower flap strake
- Flattened camber on upper deck
- Addition of deployable canards
- Larger vertical rudders

- Canted vertical rudders
- Addition of spoilers

LMES has responded very rapidly to these changes, typically providing a preliminary evaluation within several days of receiving the latest aero data set. We have also helped to identify and address the issues that have driven many of these configuration changes, such as the large subsonic drag in the L1-M configuration, the negative supersonic pitch moment in the FLOFT configuration, and the adverse roll/yaw coupling in the 5/16 configuration.

TAEM and A/L Dispersion Analysis

LMES has performed various studies to characterize the vehicle performance and robustness with respect to system and environment dispersions. These analyses have typically been updated with configuration changes and as model information has matured. The following are the types of analysis that have been performed:

- TAEM interface dispersion capability
- Sensitivity to aero dispersions, synthetic and measured winds, and gusts
- Effects of transport delay, sensor quantization, navigation errors, etc.
- Rollout vs. brake energy tradeoff studies

Modeling and Simulation

The SES 6-DOF simulation has been the key to our success in developing guidance and flight control algorithms, performing dispersion analyses and providing rapid turnaround evaluations of changes to the vehicle configuration. The SES has also been installed at NASA Dryden, the Skunk Works and Allied Signal/Teterboro in order to provide these organizations with simulation capability. The major releases of the SES are summarized below.

- Released SES V1.2 on 2/7/97. This was the first version that flew an end-to-end trajectory from TAEM interface to wheel stop. Highlights of this release include incorporation of the FLOFT aero, redesigned flight control and guidance I-loads, updated gear model and incorpration of an ensemble of measured wind profiles.

- Released SES V1.3 on 4/24/97. This release featured guidance and flight control coded directly from the GN&C DDD. Other highlights of this release include an increased base simulation rate of 100 Hz, assignment of MSID's to I-loads, new routines to calculate stability derivatives, addition of a simplified actuator model and implementation of the latest mass properties.
- Released SES 5/16. This was an unofficial release delivered to the Skunk Works to support the evaluation of the 5/16 aero database.

LMES has taken the lead in coordinating development of the landing system models (gear, brakes, tires, and nosewheel) with Allied/South Bend and have shared aero, atmosphere and actuator models with NASA Dryden's Integrated Test Facility.

Documentation

LMES/Houston has been responsible for delivering inputs for the following documents:

- Initial release of the X-33 GN&C Design Description Document on 2/7/97.
- Revision A of the GN&C Design Description Document on 3/14/97.
- Revision B of the GN&C Design Description Document on 5/16/97.
- X-33 GN&C Analysis and Simulation Document on 5/22/97.

Technical Meetings

LMES has supported the following technical meetings:

- 7/9/96 - 7/12/96 Palmdale X-33 Phase II Kickoff Meeting
- 8/12/96 - 8/16/96 Palmdale X-33 GN&C Coordination Meeting
- 9/16/96 - 9/20/96 Palmdale X-33 GN&C Coordination

Meeting

- 9/23/96 - 9/26/96 Huntsville X-33 GN&C Requirements Meeting
- 10/21/96 - 10/25/96 Palmdale X-33 GN&C Coordination Meeting
- 11/4/96 - 11/8/96 Dryden X-33 Preliminary Design Review
- 12/3/96 - 12/6/96 Palmdale X-33 Technical Coordination Meeting
- 2/9/97 - 2/21/97 Dryden DFRC ITF Preliminary Design Review
- 3/17/97 - 3/21/97 Palmdale X-33 Avionics Integration Meeting
- 4/7/97 - 4/12/97 Palmdale X-33 Technical Coordination Meeting
- 4/25/97 - 5/1/97 Teterboro X-33 Flight Software Meeting
- 5/5/97 - 5/9/97 Palmdale X-33 Vehicle Design Meeting
- 6/1/97 - 6/11/97 Palmdale X-33 Vehicle Design Meeting
- 6/15/97 - 6/21/97 Palmdale X-33 Vehicle Design Meeting
- 7/7/97 - 7/19/97 Palmdale X-33 Vehicle Design Meeting

LOCKHEED MARTIN MICHOUD SPACE SYSTEM

X-33 2219 LO2 Tank Progress 1996-1997

The design and development of a multi-lobe X-33 LO2 tank has provided significant insight into the integration challenges of an LO2 tank into a lifting body vehicle and provided a more accurate database to estimate RLV tank weights. The fast track nature of the X-33 program has additionally required design engineering, procurement, and production to meet significant challenges in order to meet the demanding schedules.

A summary of the significant progress during the first year and a review of the lessons learned are highlighted below:

Significant Progress:

1) Four (4) aft domes have completed fabrication and have completed welding into the flight and STA dome assemblies. The design was conducted using CATIA and translated to IGES for the machining vendor in record time. The fabrication processes used included spin forming, turning and profile machining, and chemical milling. One of the four dome plates was damaged during the spinning process requiring the use of the remaining spare plate with minimum schedule impact to the critical path of tank delivery.

2) Thirty two (32) cones and barrel panels were machined and formed with only one panel damaged during the forming process. Engineering was provided to the machining vendor in CATIA and NC programming was done using the CATIA models. A sub-scale forming panel has been developed to act as a pathfinder forming panel. The forming of the panels with external ribs and dual sided machining provided some difficulty at the forming vendor, but with dedicated presses and staff, all panels were shipped in time to support program schedule.

3) With the pressure vessel hardware on dock and tank weld tooling completed, the tank close-out welds are in process and near completion. Tolerance analysis was performed to provide trim dimensions for the dome/ barrel/ cone assembly welds with accurate success. Incremental

trimming was required to insure proper fit with length and barrel circumference to acquire adequate peaking and miss-match in the welds.

Tank interfaces have been changed over most of the tank due to the TPS support structure redesign and weight reduction activities. Updated baseline interfaces are currently in work.

Lessons Learned:

1) Identify all interfaces and commit to ICD's at the beginning of the design

- All X-33 interfaces were changed on the LO2 tank
- Required redesign and hardware scrap

2) Establish accurate design loads and maximum tank pressures at design start

- Current tank is designed without known loads resulting in unknown margins
- A PDR/CDR loads approach is not compatible with Fast Track approach

3) TPS support structure interfaces require further optimization

- Increased the number of interfaces stiffen to support structure, and induce cryogenic shrinkage loading

4) Low cost soft tooling facilitates schedule, but not optimized weight

- Increased weld thickness required for more Peaking and Mismatch using soft tooling

5) Fabricated a pathfinder that was required for tank with new configuration and processes with little or no margins

- Wing panel shrinkage vs. weld thickness margin example
- Oil canning in cone panels vs. RCI and structural margins
- Weld thickness insured dome to barrel weld fit-up

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- Fast track schedule demands in place processes and skills

6) Complex geometry demands 3D CAD design data base

- Engineering fit-up and interfaces
- Tooling vendor data
- Flight hardware data
- Quality assurance

7) Control Point Product Structure

- Early definition of Drawing Tree/ Manufacturing Flow
- Insures Concurrent Engineering
- Single Bill of Materials
- Product Structure can change when manufacturing flow altered

8) Weld thickness margin required for complex tank shapes

- Permits successful fit up of complex shapes allows for weld shrinkage/panel deformations

9) Panel oils canning management required for complex shapes

- Design for more stiffening in panels
- Tighter contour deviation requirements panel forming process
- Increase structural and RCI design margins to accommodate oil cans

10) Real time engineering manufacturing floor support required

- Daily morning standup meetings
- CAD terminals at location

Quarter Scale Composite Multi-lobe Propellant Tank

A Reusable Launch Vehicle (RLV) quarter scale (10 Foot tank length) multi-lobe Liquid Hydrogen (LH2) propellant tank was designed and partially fabricated during the Phase I RLV/SSTO program. During Phase II activities this past year, the remaining tank fabrication tasks were completed. The second tank lobe fabrication was completed and the integration, assembly and checkout (I,A&C/O) of the tank mechanical joint, this is, the Closeout of the tank ring frames; the application of the tank Reusable Cryogenic Insulation (RCI) subsystem; and the attachment of the tank Vehicle Health Measurement (VHM) subsystem, were performed.

Upon successful I,A&C/O of the tank, it was cryogenically pressure cycled with LH2 at NASA's Stennis Space Center. Thirty cryogenic pressure cycles (8 @ 75 psi, 3 @ 100 psi, 19 @ 36 psi) were completed with numerous other ambient cycles. The mechanical bolted joint performed well through all testing cycles. Repetitive cycling initiated LH2 leakage in areas of structural discontinuity, bonded joints and laminate anomalies (i.e. wrinkles) without detectable damage to the tank

Several permeation repair techniques were attempted achieving various degrees of success. The most successful repair technique consisted of Lockheed Martin's proprietary cryogenic liner system. The liner system successfully repaired leakage sources in the bonded joint areas, areas with composite laminate wrinkles and other tank areas indicating leakage. The liner system performed successfully during all cycles (6 at 75 psi, 3 at 100 psi, and 11 at 36 psi).

Note: The RCI and VHM subsystem performed well throughout the test program.

Composite Material System Liquid Oxygen Compatibility

A Liquid Oxygen (LOX) compatibility test program was initiated to identify the capabilities of candidate composite material systems to perform in the LOX environment of a propellant tank. The initial tasks consisted of identifying the appropriate LOX compatibility requirements and understanding how these requirements apply to composite systems. A joint NASA/Lockheed Martin task force established the LOX compatibility requirements and criteria for use on the RLV program. The path chosen is to demonstrate that the materials are safe in the proposed application. A hazard analysis identified the following test criteria: friction, mechanical impact, puncture, particle impact, electric discharge, shock, pyrotechnic and adhesive failure.

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Over fifty materials, including composite resins and fibers, resins alone and liner systems were screened using the mechanical impact criteria. Five material systems were selected for further Phase II testing. They are a graphite/thermoplastic, three graphite/thermosets and an aluminized kapton bilaminate liner on a graphite/epoxy substrate. Testing to date has been successful, and indicates that all five candidates are resistant to ignition by all of the mechanisms tested.

RCI DEVELOPMENT PROGRESS PERFORMANCE

The Reusable Cryogenic Insulation (RCI) and Vehicle Health Monitoring (VHM) development efforts have made significant progress in the development and characterization of insulation and X-33 Tank Health Monitoring Sensors. The RCI efforts have concentrated on three materials as follows; 1) Airex R82.60®, a 3.8 pcf polyetherimide foam; 2) CryoCoat™, a 6.8 pcf filled epoxy system; and 3) SS-1171, a 2.5 pcf polyurethane spray foam. The VHM efforts have concentrated on the development of fiber optic temperature sensors, fiber optic strain sensors, fiber optic hydrogen sensors, acoustic emission sensing techniques, and adhesive tagging inspection techniques. A performance summary of each of these development areas are given in the following paragraphs.

Airex R82 - Polyetherimide Foam

Several test iterations comparing the thermal and mechanical performance of Airex R82.80 (5.0 pcf) and Airex R82.60 (3.8 pcf) were performed. A decision was made to baseline the lighter density Airex R82.60 as the acreage insulation for both the LO2 and LH2 tanks. This results in a weight savings of 380.4 lbs. Material characterization and application process development continues on the R82.60 material towards completing its material qualification.

Closeout Insulation - CryoCoat™

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Improved the thermal performance of CryoCoat™ to meet the elevated temperature requirement of +350°F. Several material iterations of CryoCoat™ were processed to achieve good dispersion of material, repeatability of mixing process, density, dwell time, and improved mechanical performance. Currently CryoCoat™ UL-79 material is the baseline formulation with improved cryogenic and +350°F capability and its material characterization continues. Its average density is approximately 6.8 pcf.

SS-1171 Spray Foam

Thermal mechanical testing was successfully completed on SS-1171 to demonstrate its capability at the +350°F environment and 50 cycles. Based upon the comparison of test data (thermal mechanical and material properties) for SS-1171 and Airex R82.60, it was decided that the traceability and operability factors were not strong enough to justify Airex R82.60 on the RLV LO2 tank. As a result, the baseline configuration was changed to SS-1171 on the LO2 tank and a hybrid configuration (SS-1171 and Airex R82.60) on the Main Propellant System (MPS) lines. This resulted in a weight savings of 165.4 lbs.

Task Agreement Summary

MSFC/ED71-02 Acoustic Testing

Completed 15 lift-off and ascent acoustic spectrum profiles for both LO2 and LH2 tanks with applied cryogenic back-face temperatures (-320°F and -423°F). All panels that were insulated using standard processing techniques passed with no loss of material.

LOX Tank Lift-Off / Ascent acoustic spectrum was reproduced with acceptable tolerance compliance. Compromises in the LH2 flight acoustic spectrum were accepted because the analytical predictions of panel deflections indicated negligible effect from acoustics that were above 500 Hz. The second reason was that the panel response did not duplicate the tank response above 500 Hz.

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LaRC-08 Thermal Mechanical Testing

Successfully completed Airex R82.60 polyetherimide (composite and metal substrates) and SS-1171 polyurethane (metal substrate) thermal mechanical testing for 50 cycles. The fifty cycles consisted of 25 pre-launch/abort cycles and 25 pre-launch/launch cycles. Ongoing tests consist of acreage and close-out insulations on composite and metal substrates for repeatability.

LeRC-01 Atmospheric Pressure Testing

Testing is scheduled to be conducted August - September, 1997 at Lewis Research Center in the Small Multi-layer Insulation Research Facility (SMIRF). The objective is to determine the thermal and mechanical performance of Airex R82.60 due to thermal cycling and vacuum pressures. Heat flow measurements will be used to evaluate thermal performance. Mechanical performance will be measured by no visible delaminations, debonds or loss / degradation of material.

The Airex R82.60 is bonded to a LeRC provided calorimeter with EA-9394 and SS-1171 is used as a closeout material for the remaining calorimeter exposed surface. Twenty five mission cycles using LH2 and elevated temperatures on the insulation surface will be conducted.

SSC-01 10 ft. Composite Tank RCI Support

RCI was bonded in selected areas of the 10 ft. composite tank being tested at Stennis Space Center. Both Airex R82.60 and CryoCoat™ UL-79 that were applied with standard processes were successfully demonstrated. The number of cycles conducted on the tank were eleven @ 36 psi, seven @ 75 psi, and two @ 100 psi for a total of twenty cycles.

VHM DEVELOPMENT PROGRESS PERFORMANCE

Distributed Temperature Sensor

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Distributed Temperature Sensor (DTS) system is a measurement system that measures temperature using optical fibers and laser light. This system is under development to replace thermocouples and metal wires to measure temperature. The DTS system has been in development to utilize this technology to monitor the surface of the cryogenic insulation in the high heat (+350°F) environment of the X-33 and VentureStar™ vehicles. The ability to bond the optical fibers to the outer surface of the cryogenic tanks is in development and has been demonstrated to survive the flight load testing. This sensor system was demonstrated on a composite cryogenic hydrogen tank to operate and detect cracks in the insulation system by measuring the location of the cold spots.

Distributed Strain Sensor

Distributed Strain Sensor (DSS) system is a measurement system that measures strain using optical fibers and laser light. This system is under development to replace conventional strain gages and metal wires. The DSS system has been in development to utilize this technology for the cryogenic (-423°F), high heat (+350°F), and high strain loads (6000με) environment of the X-33 and VentureStar™ vehicles. The three keys to making this system work for reusable launch vehicles are: 1) bonding the sensor effectively to the part to measure, 2) demonstrating the sensors at cryogenic temperatures, and 3) having a lightweight laser and analysis system. Significant progress has been made in all three areas. The bonding procedures and expertise have been developed and demonstrated through lab and field testing. These sensors have been demonstrated on the composite cryogenic hydrogen tank to measure strain. Development work led to improving the bonding and increasing the accuracy of the sensor. The signal to noise has increased by 4X, with further progress expected. The development of the flight instrumentation including a flight worthy tunable laser and all the electronics to read the sensors is being worked in collaboration with NASA Langley Research Center.

Distributed Hydrogen Sensor

Distributed Hydrogen Sensor (DHS) system is a measurement system that measures the presence of hydrogen using optical fibers and laser light.

The DHS system is similar to the DSS system with Palladium coatings at the strain sensing location. The Palladium expands upon exposure to hydrogen. The DHS system has been in development for usage on the X-33 and VentureStar™ vehicles. This system will be exposed to cryogenic (-423°F), high heat (+350°F), and high strain loads (6000µe) environment. Testing being performed at the University of Maryland is focused on improving the sensitivity of the sensor to hydrogen exposure.

Acoustic Emission

Acoustic Emission (AE) testing is a nondestructive inspection technique that monitors the sounds generated by defects such as cracking or delamination in a structure. Development is underway to implement this technology on the X-33 vehicle to detect impacts and crack formation along the critical bulkhead joint of the hydrogen tank. Testing for this technology has lead to the understanding of AE sound propagation in small composite tanks, with and without insulation. The ability to distinguish damaged tanks from undamaged tanks has also been demonstrated.

Tagged Adhesive

Adhesive Tagging is a technique of adding magnetic particles to the adhesive that can be detected remotely. After the tagged adhesive is used to bond materials together, the thickness of the adhesive can be detected using a probe such as an eddy current probe. The use of tagged adhesives will be used to detect adhesive voids and measure the thickness of bondlines, which is related to the strength of the bond. Tagging materials have been successfully added to adhesives and detected using an eddy current probe when the materials being bonded are non-metalic. Testing has indicated that a different remote sensor will be necessary for metal bonded parts. A flux gate probe is being developed at Westinghouse to allow the tagged adhesives to be used on metal parts. Both the eddy current probe and the flux gate probe systems are scheduled for delivery at Lockheed Martin Michoud Systems in July 1997.

Main Propulsion System

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Over the past year the Main Propulsion System (MPS) for X-33 was defined using concepts developed during Phase I and incorporating changes and requirements as they became better defined after Authority To Proceed (ATP).

During the past year of performance the following activities took place:

- The design effort to include the X-33 requirement review and baseline

- The baselined MPS components were designed and suppliers for the components were awarded contracts

- MPS component design strategies were developed to meet the X-33 Program goal of better, cheaper, faster

- MPS components fabrication began at the suppliers

- MPS changes during this period were assessed for impact and the MPS was modified as necessary.

- Computational Fluid Dynamics (CFD) analysis was performed on the LH2 feedline configuration to define Test Configuration Candidates to be water flow tested later this year at MSFC

- The MPS Preliminary and Critical Design Reviews and all actions resulting for these reviews were resolved.

- MPS components testing/validation were performed on the proposed fiber wrapped pressure vessel (A2100) and the X-33 Liquid Level Sensors.

The level sensor system was tested at Stennis on the 10 foot composite Liquid Hydrogen (LH2) tank. The results of this testing validated the system for use on X-33. The system was reliable and repeatable and was subjected to environments and cycling similar to what is to be expected during X-33 Program life.

The A2100 Tank which is composed of a titanium liner with a

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composite over-wrap has been subjected to a proof test at LH2 temperatures and 50 cryogenic/pressurization cycles also at LH2 temperatures. A cycle is defined as pressurizing the A2100 bottle to 3000 psi +/- 100 psi then submerging the A2100 bottle in a bath of LH2. The helium supply pressure of 3200 psi is left open while the helium inside the A2100 bottle is slowly cooled to LH2 temperatures. After soaking for 4 hours, the GHe pressure was lowered to 300 psi and the LH2 was drained to the 12 inch level. After completion of these 50 cryogenic cycles, this same bottle was subjected to 50 additional pressure cycles with warm GH2 surrounding the tank. The outer test chamber was removed and a die pen. inspection was performed on the exposed titanium surfaces. No indications of cracks or evidence of hydrogen embrittlement was found. The A2100 bottle was then shipped to California for a mass spec leak check at 3200 psi. The bottle passed this leak check and was returned to MSFC where it is currently being set up for a 6400 psi capability test which should occur on July 8.

The activities performed during the past year has laid the groundwork for the continued fabrication, qualification and installation of the MPS components for the X-33.

STRUCTURAL TESTING

Task Agreements

A Task Agreement (TA) is a procurement mechanism used on the RLV CAN to acquire Government services, tests, and flight hardware from the NASA Centers. TAs are jointly approved by LMSW and NASA and identify objectives, responsibilities, schedules and budget for a specific task. The Structural Test team is responsible for TA management at LMMSS. This responsibility includes generation of Test Plans (test requirement documents), preparing TA schedules which support X-33 program requirements, liaison activities between the Hardware Teams and the NASA Centers, submittal of TA changes as the program develops, and reporting on the performance of the NASA Centers.

Currently the LMMSS Structural Test Team is managing a total of forty (40) Task Agreements, of which seventeen (17) are currently active. These TAs cover activities at Marshall Space Flight Center (MSFC), Langley

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Research Center (LaRC), Lewis Research Center (LeRC), Stennis Space Center (SSC), and Johnson Space Center (JSC). Accomplishments under the TAs to date include testing performed to certify X-33 or evaluate RLV technologies:

- Completed test program on 10' LH2 Tank & VHM (SSC-01 & LaRC-13); thirty (30) cycles were completed with no outstanding issues.
- Completed Phases 1 and 2 testing on LOX Compatability (EH-01 & JSC-21) to support down select of materials for Composite LO2 Tank.
- Completed certification testing of A2100 helium tank for X-33 LO2 Tank pressurization system at MSFC (EP-16).
- Completed Thermo-acoustic testing of large-scale RCI panel at MSFC; no outstanding issues (ED71-02).

SYSTEMS INTEGRATION AND ANALYSIS

This team is responsible for supporting the X-33/RLV as applicable to:

Systems Engineering
- Requirements
- ICDs
- Design Reviews
- Engineering Changes
- Nonconformance
- Verification / Certification

Systems Analysis
- Performance Models
- Structural Analysis / Loads
- Materials
- Reliability
- Quality and Safety

<u>Systems Engineering and Analysis</u>

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The Systems Engineering effort for Lockheed Martin Michoud Space Systems (LMMSS) has been integrally involved in the design of the four major hardware flight hardware subsystems within our X-33 responsibility. Each of these major X-33 hardware subsystems (LO2 Tank, Main Propellant System, Reusable Cryogenic Insulation, and Vehicle Health Monitoring) has released requirements documents under configuration control.

The Interface Control Documents have been baselined and continue to be updated as interfacing subsystems are changed to reflect these subsystems maturing engineering design definition. Each of the flight subsystems has undergone Preliminary and Critical Design Reviews.

The Systems Engineering organization has planned and implemented numerous Engineering Changes originated both internally and externally. As the hardware build has progressed, Systems Engineering has managed the nonconformance disposition process insuring that LMMSS maintains the same high quality of hardware and traceability as our other programs. Finally, we have planned and implemented a comprehensive design verification and hardware certification effort to characterize the flight worthiness of the hardware within our responsibilities.

The Systems Analysis effort has included analysis (Propulsion, Thermal, Reliability, Structural, Loads and Dynamics, Material and Processes, Quality and Safety) of all of the hardware subsystems within our scope of work and provided key design and verification data for the basic engineering design activity.

Specific propulsion and thermal models of each of our subsystems have been prepared and used to direct and substantiate our designs and predict system performance. Loads and structural analysis have been performed based on the maturity of the vehicle environments to date and continue to be reevaluated as more mature environments evolve. Detailed finite element models have been developed and used in support these efforts. All drawings and specifications released to date have been evaluated by our X-33 material and process engineering group to insure proper hardware usage and verified processes.

A baseline Failure Modes and Effects Analysis (FMEA) has been prepared for each of our systems as part of the overall ground, vehicle and flight systems FMEA activity. A complimentary hazards analysis is on schedule and being integrated into the project level hazards data base. Quality plans have been developed and implemented for both the procurement and in-house build process.

RLV OPERATIONS

CRYOGENIC SYSTEMS OPERATIONS

LMMSS Cryogenic Systems Operations Team has provided the program technical lead and direction for the X-33 flight and ground cryogenic MPS systems operation definition activities. This team has performed operability, operations and maintenance assessments for our Reusable Cryogenic Insulation (RCI) and Vehicle Health Management (VHM) designs.

The MPS LH2 and LO2 lead test operations engineers participated in the design operability of LMMSS deliverable hardware to influence supportable design solutions for trade studies, such as inclusion of tank isolation valves, consolidation of helium requirements into a single integrated helium supply and delivery system and retention of the outboard fill and drain valves. Two of the operations team members have assumed shared duties as designers on the LMMSS Teams responsible for the MPS and VHM system. LMMSS has participated in the design operability of the ground systems including elimination of ground LO2 pumps in favor of pressure feed system and placement of critical components and instrumentation.

Based on our extensive cryogenic ground system and External Tank operations experience, LMMSS has provided expert input and coordination of cryogenic system requirements to development of the integrated X-33 test, operations and maintenance sequence. This sequence integrates all test, operations and maintenance requirements from roll-out at the factory through the 15 mission life cycle. LMMSS has built and analyzed the representative logic functional flow documenting the entire X-33 sequence. This flow has been translated to code as the basis for performing discrete event computer simulation analysis. The various reliability, maintainability and support requirement predictions were incorporated in to the computer simulated sequence of tasks and several analyses routines were completed to verify the probability of successfully executing the flight test program as planned.

With design maturation of the LMMSS deliverable systems and hardware demonstrated by successful incremental subsystem CDR completion and in preparation for X-33 System CDR, the Operations Team initiated the operations engineering documentation process. In preparation for executing the planned test, operations and maintenance tasks LMMSS has developed a draft series of Test, Operations and Maintenance Requirements, Specifications and Criteria (TOMRSC). These system specific volumes document the design driven requirements and approaches for testing, operating and maintaining the LMMSS deliverables. These requirements are the basis for decisions with respect to automated or manual procedure implementation, as well as, the technical basis for the procedural steps and software specifications and code. As a result of this requirement activity, LMMSS have also developed preliminary procedure lists and defined a flight and ground software architecture to test, operate and maintain these systems.

LMMSS is staffed and on schedule to support the continued operations engineering definition and development required to checkout and activate the ground system and implement the X-33 flight test operations.

SANDERS - A LOCKHEED MARTIN COMPANY

This progress report is focused on Sanders' contributions to the X-33 vehicle and ground system development. Sanders is developing a Vehicle Health Management system for on board X-33 with four major constituents: the Vehicle Health Monitoring Computer (VHMC) LRUs (2), the Remote Health Node (RHN) data acquisition LRUs (50), the Fiber Optic Bus (FOB) Networks (3), and the Advanced Technology - laser based fiber optic sensors.

Sanders is also responsible for the acquisition and development of the Launch and Mission Control Management System (LMCMS). The LMCMS consists of Ground Interface Modules (GIM), Telemetry and Range Interface Processors (TRIP), Storage and Retrieval System, GSS A&I Database Server, Command and Data Processors, Consoles, Independent Safing System, Operational Intercom System , and Operational TV System.

Together, the VHM and LMCMS systems represent the concept of Health Management System (HMS) which is focused specifically to address the X-33 needs with traceability to RLV. The HMS mission for X-33 is to perform monitoring functions of the vehicle's subsystems for in-flight performance in terms of temperature, vibration, and pressure, recording and reporting failure anomalies. HMS provides stress and failure data for pre-, in-, and post-flight diagnostics and prognostic in order to identify failed and near failure elements of X-33 for rapid remove and replacement, thus minimizing turnaround time.

VHM Progress To Date:

- Complied with Vehicle PDR in November 96.
- VHM Internal PDR was successfully completed in May 97.
- Completed HMS PDR with LMSW concurrence in June 97.
- Completed VHMC's Open Architecture with Off-the-Shelf components board orders by June 1997.
- Full Scale Software Development of VHMC completed PDR in June 97.
- Full Scale telemetry and disk drive board development for VHMC passed its PDR in May 97 and will be on schedule for CDR in July 97.
- Brassboard VHM and Software Build 1 for August 1, 97 delivery

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is on schedule and will be delivered to LMSW ITF on the promised date.

- VHM flight units will be made available to LMSW starting April 1, 98.
- Advance Technology (Generation II) Fiber Ribbon Cable and Multi-Fiber Positioning Connector development completed vendors' CDR in June 97, and will be ready for NASA / NavAir laboratory tests in September 97.
- Advance Technology, laser-based fiber optic sensor development is on track for laboratory demonstration scheduled for December 97.
- RHN electrical, mechanical, and software full scale developments are proceeding on schedule with production units available to LMSW starting in August 1, 98.
- RHN internal PDRs were completed in June 97 and development is well into the detailed design.
- RHN's universal analog interface design was completed, die vendors were selected, and Multi-Chip Module subcontractors have been identified.
- RHN's Rigid-Flex-Rigid board has been defined and drawings have been released.
- RHN's digital multi-Chip Module design has been completed and drawings have been released.
- RHN's software development passed its PDR milestone in June 1997, and proceeding on schedule.
- RHN's packaging design to survive the severe environmental conditions without cooling has been completed.

GSS Progress To Date:

- Participated in the successful Ground Operations PDR in December 96.
- Conducted a successful In Process Design Review in March 97.
- LMCMS Configuration Item Preliminary Design Review was completed in April 97.
- Completed HMS CDR with LMSW concurrence in June 97.
- Baselined functional and allocated requirement documents including System Specification, ICD, and SRSs.
- Conducted a successful sell-off of Ground Interface Modules under a NASA Task Agreement in June 97.

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- Procured LMCMS equipment required to support the ITF and Sanders laboratory including (2) TRIPs, (2) CDP, (2) Workstations, and (2) 100 BaseT switches and router in June 97.
- Selected the Satellite Control Language from ICS as the COTS script processor to support the development of application sequences in a forth generation language in May 97.
- Code/unit test and integration of software Build 1 is on schedule for August 1, 97 delivery.
- Detailed design of future software builds is on schedule.
- 28,000 Line Of Code (LOC) out of a projected 56,200 LOC for the LMCMS System Software has been completed in July 97.
- Prototyping and benchmarking system software performance on the CDP is proceeding on schedule.
- Major progress is reported from on-site support (3 automated sequence engineers) for ITOWG's definition of automated sequence requirements.
- Established Sanders LMCMS laboratory and integrated a LMCMS architecture consisting of a workstation, network switch, CDP, and TRIP.

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BOEING

Rocketdyne Division

PROGRAM STARTUP

The Boeing Rocketdyne RLV/X-33 team achieved a rapid ramp up from 30 to 220 EP in the first 4 months of the program. The Aerospike engine team was organized around an Integrated Product Team (IPT) philosophy. Teams were assigned work responsibilities closely associated with the XRS-2200 architecture breakdown. Each team was staffed with members representing engineering, manufacturing and quality assurance processes to provide broad cross-functional expertise.

IPT's were collocated in Building 106 on the DeSoto campus to improve communication and work efficiency. A significant team building and training effort was also accomplished during startup. The X-33 program was the first major program at Rocketdyne to utilize Pro-Engineer 3D design software for system development. All team members were given the required training for use of Pro-E in their X-33 jobs. Other important training was accomplished in the areas of team skills, systems engineering, and understanding variation, to improve overall team performance.

EARNED VALUE BASELINE

The first two months of the program focused on establishing an effective IPT organization, defining program requirements through a System Requirements Review process, and establishing a complete earned value baseline. Individual IPTs conducted intensive Integrated Product-Process Development (IPPD) planning sessions. The sessions fully defined the work scope and developed it into an integrated logic-linked schedule. Earned value budgets were then established for all key schedule activities. By October 1997, the entire program earned value baseline was established. The baseline has been updated monthly to maintain its value as an effective program management tool.

XRS-2200 ENGINE DESIGN

3-D DESIGN AND ANALYSIS APPROACH

A 3-D solid modeling design approach was used to create a virtual prototype of the X-33 engine (Figure 2.1-1). This capability allowed fit, interference, maintainability and producibility issues to be resolved using computer simulation before committing to hardware, and was a key enabler of concurrent engineering. The tight packaging requirements of the X-33 made it especially valuable to be able to evaluate component placement options for maintenance and assembly access. The ability to visualize a complete representation of all the parts in the engine and their relationships to one another not only makes these "-ility" evaluations possible, but also significantly enhances communication among members of the product definition team. The new design tools are provided a higher confidence of first time design success and reduced program risk by allowing engineering analysts to work directly from the solid model. Many of the finite element analysis models were generated directly from the CAD design model, eliminating lengthy geometry regeneration efforts and improving analysis quality by ensuring that the correct geometry was analyzed. The association of these models with the CAD model led to significantly shorter analysis cycles resulting in more complete design optimization, and in some cases enabled complete system analyses which could not have previously been performed (for example a complete engine radiation heat transfer model as seen in Figures 2.1-2 and 3).

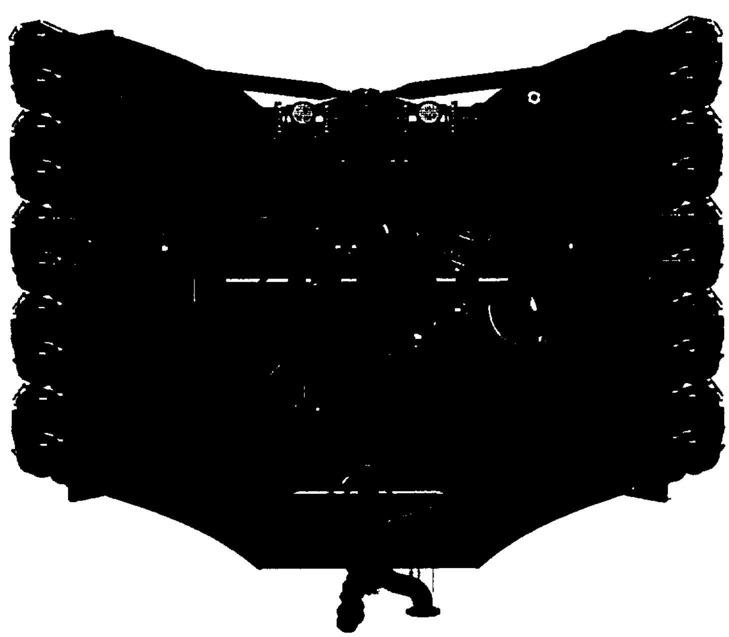

Figure 2.1-1. XRS-2200 Linear Aerospike 3D CAD Model

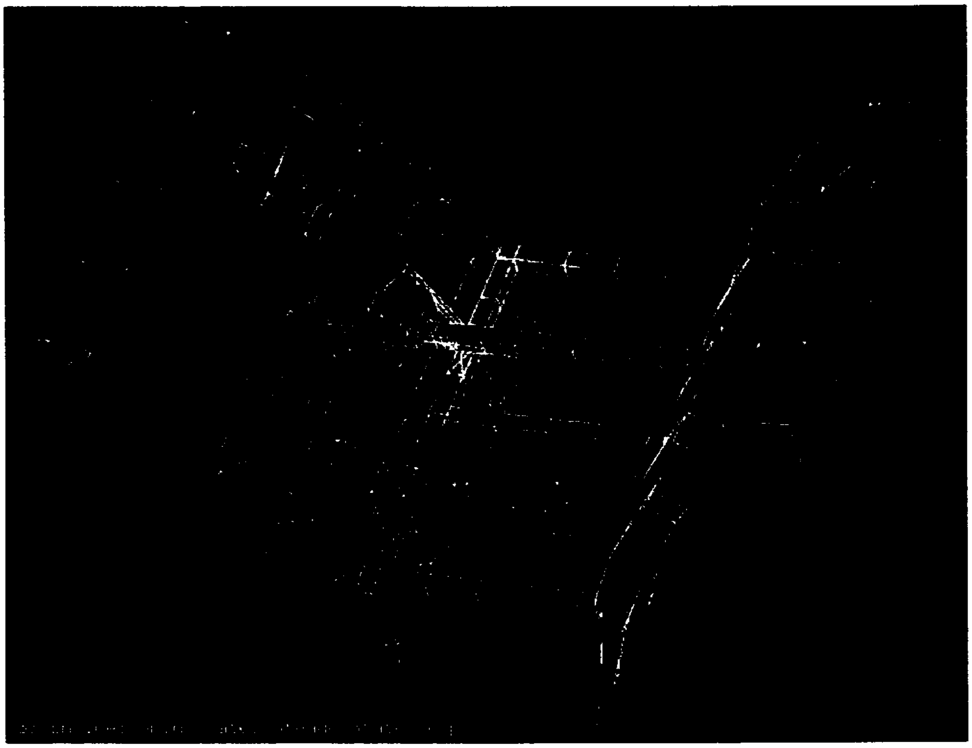

Figure 2.1-2. Engine Radiation Heat Transfer Model With No Thermal Insulation

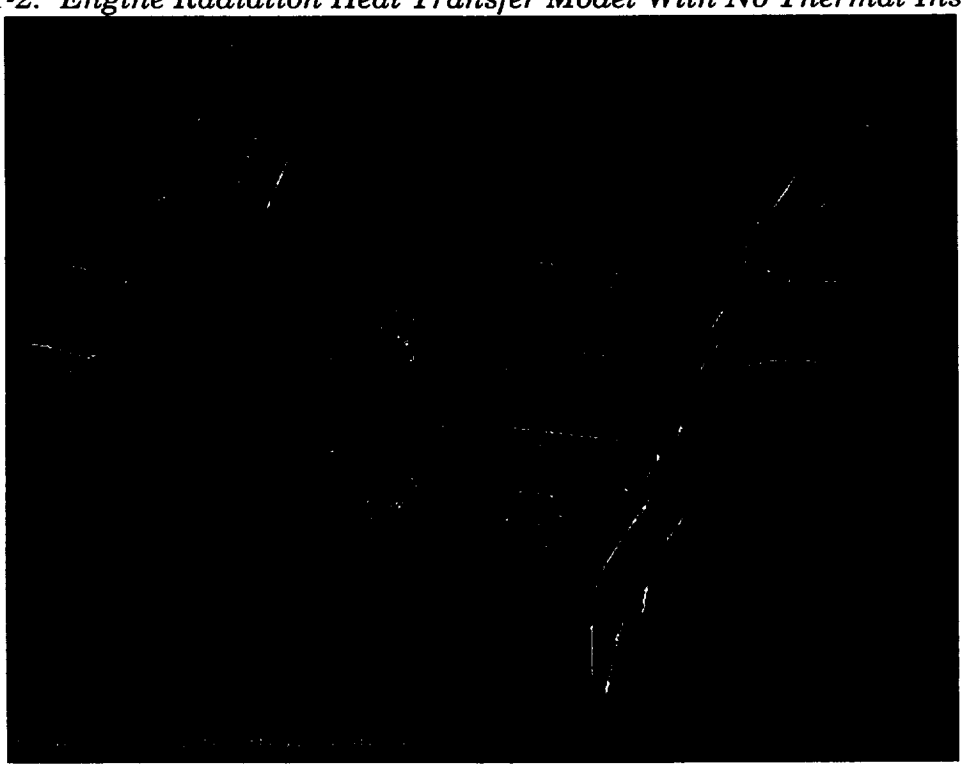

Figure 2.1-3. Engine Radiation Heat Transfer Model With Hot Components Insulated.

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METAPHASE

Cycle times for approval of engineering drawings have been reduced through the implementation of an electronic release process. Over two hundred and fifty documents have been released using the new process, including change documents. Design engineers prepare a release package and route it electronically to collect the signatures required by the release plan of action. Approvers are notified by E-mail that they have a document to approve and can view and approve the drawings using the Rocketdyne intranet. Drawings, release records and document associations are then vaulted electronically, and made available for use by the electronic work instructions, and for anyone with program authorization to view.

J-2 ENGINE DISASSEMBLY

The rigorous schedule requirements focusing on X-33 flights in 1999 necessitated the extensive use of existing heritage hardware wherever possible on the X-33 engine. Six flight-ready J-2 engines that had been in controlled storage at the Marshall Space Flight Center since the Apollo era were returned to Rocketdyne at the start of Phase 2 for use on the X-33 program (Figure 2.3-1) . The engines were disassembled in the SSME Assembly Room at the Canoga facility. Key components including turbopumps, gas generators, electronic control assemblies, spark igniters, valves, and hot gas ducts were removed and were found to be in excellent condition. All of the external hardware down to the basic thrust chamber assemblies was removed. Two of the thrust chambers have been returned to Marshall while the last four remain at Canoga Park awaiting final disposition. Figures 2.3-2 and 2.3-3 show the engines during disassembly with some of the components removed.

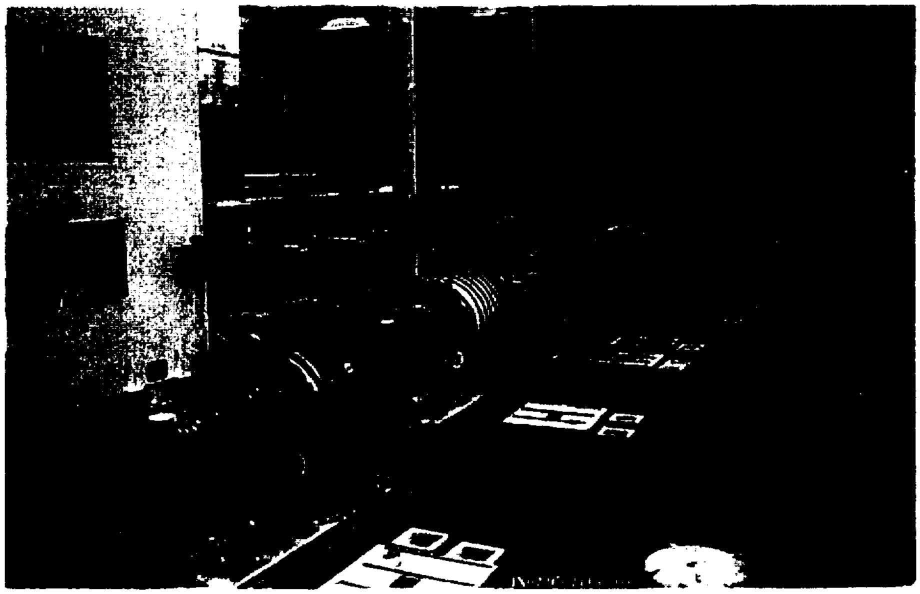

Figure 2.3-1.
J-2 Assets Maintained in Excellent Condition at NASA MSFC and Returned to Rocketdyne

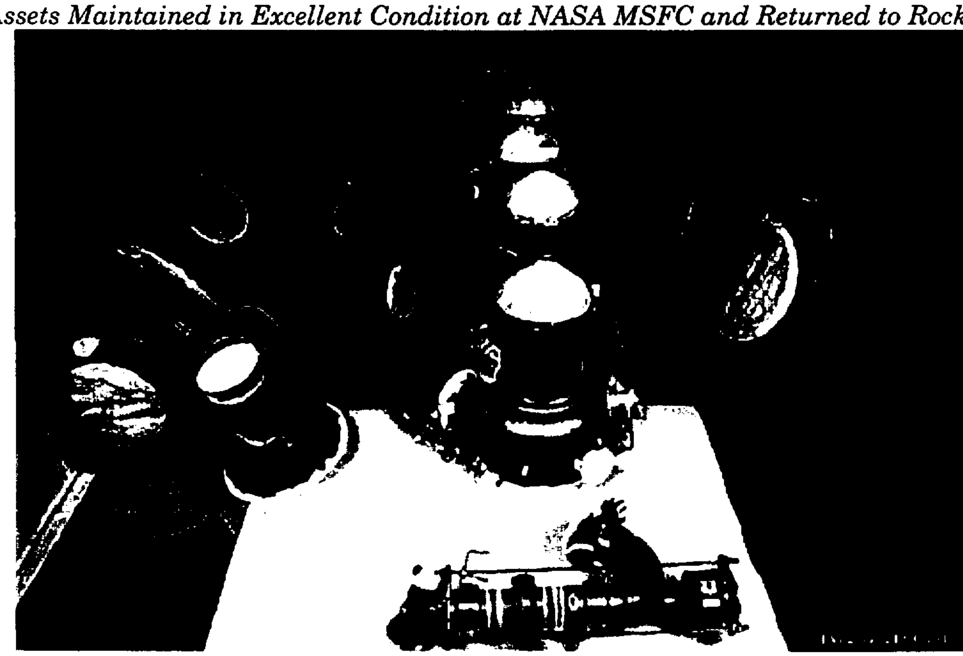

Figure 2.3-2. XRS-2200 Utilizes Rebuilt J-2 Components.

Figure 2.3-3. XRS-2200 Utilizes Rebuilt J-2 Components.

DESIGN EVOLUTION

The design of the XRS-2200 linear aerospike engine has evolved significantly since the beginning of the Phase 2 effort. As a point of departure, the baseline configuration from Phase 1 is shown in Figure 2.4-1.

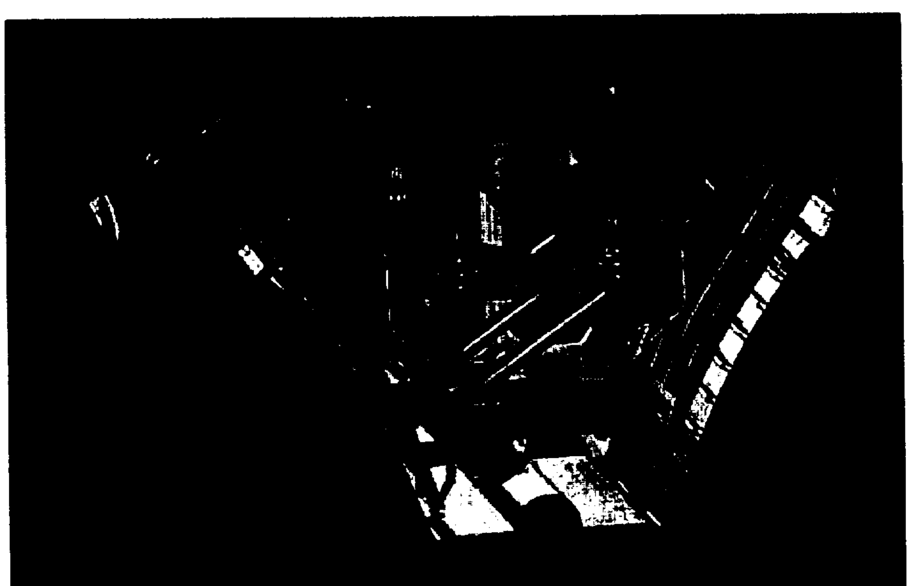

Figure 2.4-1. XRS-2200 Initial Baseline Configuration

In the initial XRS configuration little definition of duct valves and mounting support needs were included and the ducting layout was arranged for a "split engine" configuration. Details that needed to be added in the Phase 2 configuration included inter-engine ducts, ducts and valves needed to cool the non-operating ramp during an abort mode, mounts to support the turbomachinery, and. structure to attach the thrust cells back to the ribs.

The transition from CATIA to Pro-E also occurred during the first months of Phase 2 requiring a significant amount of effort to recreate the engine design in the new system.

The Engine System PDR was held on September 26, 1996 and, as shown in Figure 2.4-2, considerable changes to the design were made. New turbopump inlet locations were established that reoriented and lowered the pumps in the engine compartment. The change from the "split engine" to the "powerpack out" configuration was made which greatly reduced the number of valves required and the complexity of the ducting. The LOX system ducting was moved lower in the compartment to improve the thermal flexibility and access into the compartment. Preliminary locations were also found for the Digital Interface Units. On the structure, the asymmetric cross struts were replaced by symmetric cross braces. The primary load path for the thrust mounts was also moved from the rib ends to the top of the thrust cells in order to improve structural efficiency and reduce weight. The design still did not incorporate any mounting bracketry for the turbopumps.

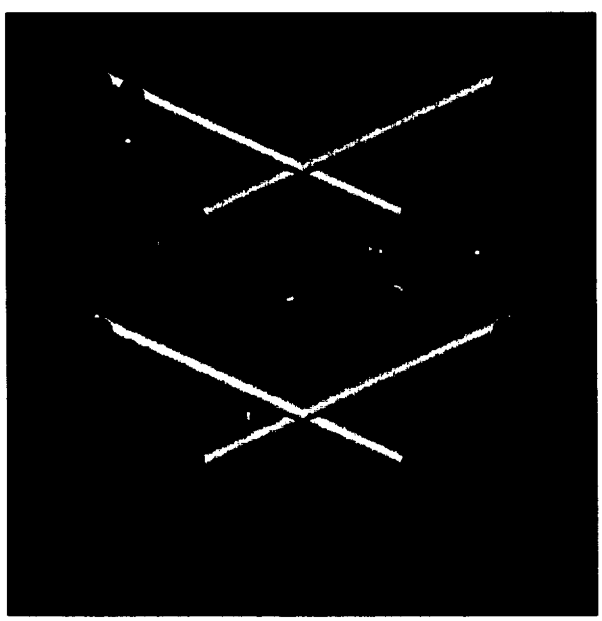

Figure 2.4-2- XRS-2200 at Engine System PDR September 26, 1996

The design continued to evolve in the ensuing months after the PDR, and a PDR Update was conducted on December 6, 1996 to review the progress made (Figure 2.4-3). Most of the effort during this period was focused on definition of the powerpack assembly. Preliminary designs for pump mounting brackets were established. Incorporation of these brackets resulted in interferences with the duct routings. Dozens of different approaches using different pump orientations, bracket configurations and duct routings were evaluated in order to develop an acceptable design solution.

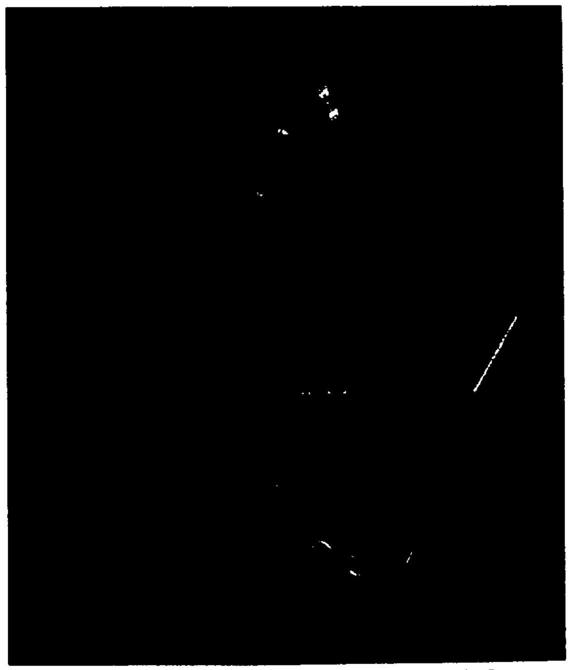

Figure 2.4-4. Separate Powerpack Assembly With Structural Frame

Numerous improvements and refinements were made to the design leading up to the Engine System CDR on February 25, 1997 (Figure 2.4-5). Interface coordinates for all major engine components were defined. The engine base closure was redesigned to reduce cost and weight. A preliminary design for the Engine End Closeout and manifolds for the Combustion Wave Ignition System were also incorporated. Definition and detail of the powerpack assembly improved (Figure 2.4-6). A welded titanium structure made from tubes and fittings was adopted for the powerpack frame. The turbopump mounts were better defined and now incorporated spherical mounting bearings. Routing of the ducts continued to be revised to improve accessibility and eliminate interferences.

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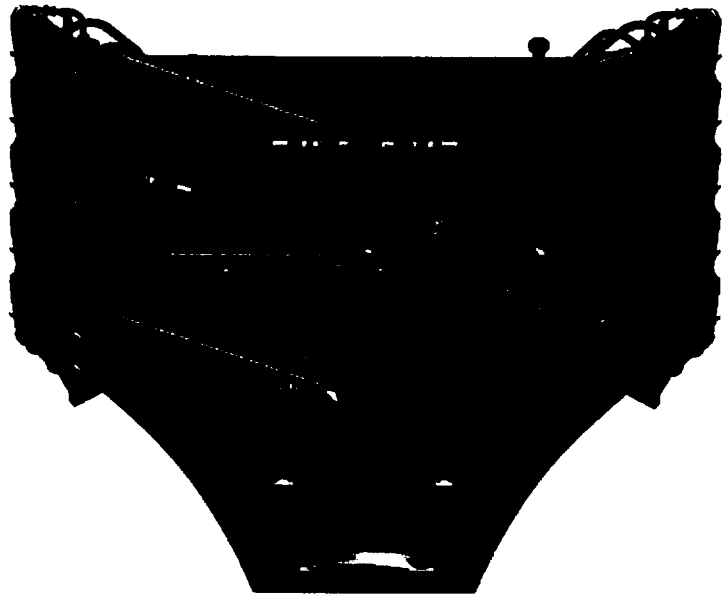

Figure 2.4-5. XRS-2200 Engine at the Engine System CDR, February 1997

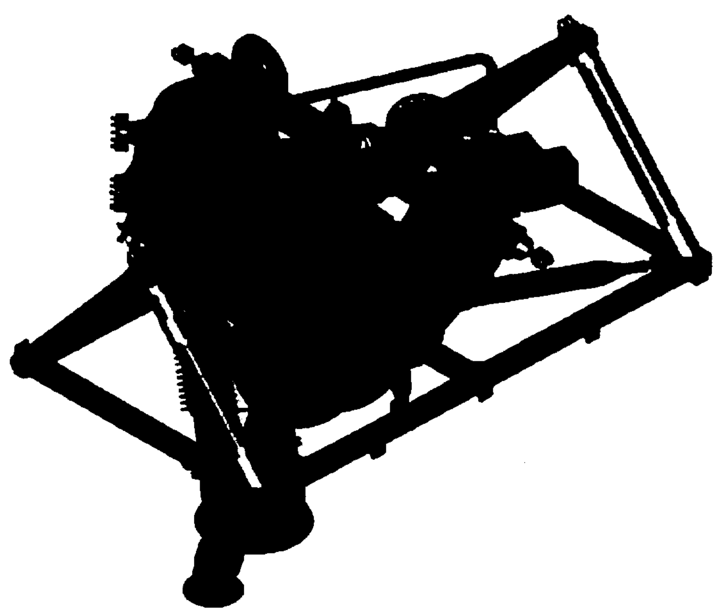

Figure 2.4-6. Definition And Detail Of Powerpack Assembly February 1997

Following the CDR, final analyses and detail drawings for the engine system hardware were started. The engine system design began to incorporate the details of pneumatic actuation, purge and drain lines, electrical harnesses, small valves and instrumentation. A view of the design as of May 29,1997 is shown in Figure 2.4-7. This view shows the final routings for the inter-engine propellant ducts. Figures 2.4-8 and 2.4-9 show internal views of the purge valve panel and the combustion wave system. Effort on the engine design continues in preparation for a final engine design review scheduled for August 12 - 14, 1997.

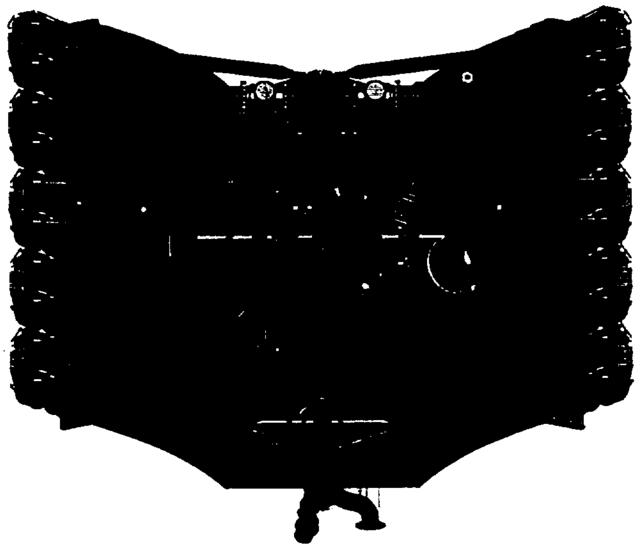

Figure 2.4-7. XRS-2200 Linear Aerospike Final Routings for the Inter-Engine Propellant Ducts.

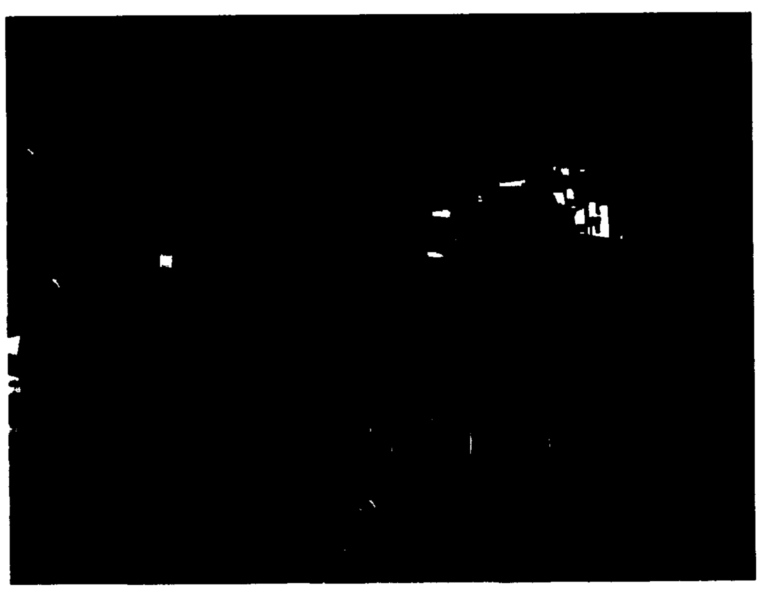

Figure 2.4-8. Combustion Wave Ignition System

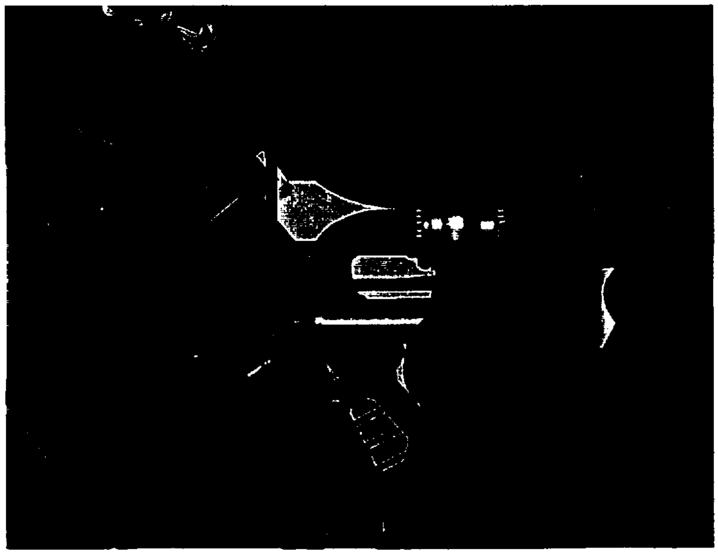

Figure 2.49. Purge Valve Panel

acceptable design solution. The concept of a separate powerpack assembly with its own structural frame was also presented during this review (Figure 2.4-4). This approach allows the powerpack to be assembled, tested at the Stennis Space Center, and then returned to Rocketdyne for assembly in the main engine as a complete unit. The Electronic Control Assembly and numerous secondary lines were also incorporated in the engine model.

KEY DESIGN TRADES

As is the core of any design effort, trade studies are continually conducted to iterate the design toward performance weight and operability goals. The process is also driven by both concurrent engineering based adjustments and continual engine/airframe integration activities. Approximately fifty trade studies were conducted with six key studies summarized below.

1. A powerpack out abort mode was chosen over a split engine configuration due to less complexity, less weight, less cost and higher reliability.

2. A trade was performed to optimize performance considering five variables: thruster area ratio, thruster length, thruster contour, nozzle plug length and nozzle plug contour. The best performance advantage was found by increasing the thruster length two feet from the baseline design. The other four variables did not change from the baseline design.

3. A trade was performed on injector stability aid configuration. Three options were considered: baseline flat face, acoustic cavities or baffles. A

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decision to maintain the baseline flat face was made due to the need for stability aids is expected to be refuted by test and analysis, increased weight, added cost and potential development issues with the other two stability aid configurations. Stability rating tests and a back-up tri-vane baffle design are scheduled to help mitigate the risk.

4. Open loop mixture ratio control was chosen over the baseline closed loop mixture ratio control due to reduce weight, schedule risk, and cost while increasing reliability.

5. The Helium spin start valve location was re-baselined to the flight/test facility due to decreased engine weight with no performance impact.

6. A decision to use a fixed orifice instead of a CCV (chamber coolant valve) in the thrust cell coolant loop was made to reduce weight, cost and complexity.

COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics (CFD) has been extensively utilized during the Phase II X-33 design effort. Rocketdyne has applied its USA code, which has been developed and validated over the past ten years to solve the compressible Navier-Stokes equations. This tool provides a high level simulation of two and three-dimensional flows where the effects of turbulence and reacting chemistry are significant. CFD analysis has supported two areas of engine development: flight environment definition, and installed performance prediction.

The aerospike nozzle provides superior performance for SSTO applications due to its aerodynamic altitude compensation. However, this feature results in a complex three-dimensional flowfield. The mechanical and thermal loads produced by this flowfield in the flight environment were predicted using CFD. Analyses of the thruster, nozzle ramp and seal cavities, cowl base and inter-thruster gap, engine array end closeout, and the nozzle base were conducted to define these loads. The cost and time required to obtain this data was reduced by using CFD rather than exploratory testing.

CFD analysis by Rocketdyne and NASA Marshall Space Flight Center is being used to support Lockheed's installed performance predictions. Full vehicle computations from launch conditions to Mach 1.5 are providing corrections to cold jet wind tunnel model data. These corrections include the effects of a hot jet, nozzle area ratio, and nozzle pressure ratio. A simple solution at launch conditions is shown in Figures 2.6-1 and 2.6-2. Pressure contours are shown on the surfaces, and Mach number contours are shown in the engine exhaust plume. Variations in pressure over the vehicle surface are due to flow induced by the engine plume, while variations in pressure over the nozzle ramp are due to three-dimensional flow exiting the individual thrusters. The exhaust plume is seen to be quite small at this operating condition due to altitude compensation. These figures demonstrate how CDF has proven to be an effective tool to assist the XRS design evolution.

Figure 2.6-1 - USA Solution of X-33 Flowfield at Liftoff Conditions

Figure 2.6-2. Details of Engine Flowfield

DESIGN/ENGINE SIMPLIFICATION

The XRS-2200 was faced with a significant design challenge in terms of cost, schedule and weight. In order to meet this challenge a significant effort to simplify the engine design was undertaken. Lessons learned from many of the successful rocket programs, including SSME and J2, were utilized to simplify the design. Engine simplification included a reduction in the number of sensors proposed, elimination of valves and movement of functions from the engine to the launch facility. Sensor reduction is possible by incorporating the engine model into the health monitoring process to synthesize parameters similar to systems which have recently been incorporated into the latest jet engines including the Boeing 777. Valves were eliminated by combining functions and using previous experience in engine design to eliminate the need for valves. Finally, engine/launch facility design integration was incorporated at an early stage allowing for functions which are only required during engine conditioning and start to be ground based simplifying the engine design and reducing engine weight and complexity.

2.8 DESIGN REVIEWS

Thirty-four design reviews were held including: Seven (7) Design Requirements Reviews, Nine (9) Preliminary Design Reviews and Eighteen (18) Critical Design Reviews.

2.9 DRAWINGS RELEASED

Approximately 1268 total drawings have been released. 268 new drawings were released through Metaphase and approximately 1000 heritage drawings.

3.0 AEROSPIKE MANUFACTURING

3.1 MANUFACTURING TECHNOLOGY DEVELOPMENT

Manufacturing Technology Development (MTD) projects are used in certain instances to facilitate in the development of the design and aid in the hardware fabrication process proofing. Each Integrated Product Team established a list of MTD projects for their hardware. Of the MTD effort defined, two are especially important to the success of the X-33 program; brazing of the nozzle ramps and HIP brazing of the thrust cell liner to jacket. For the nozzle ramp a full length, 24 inch wide ramp is being fabricated for the MTD. As of July 1 1997 all details have been put in work at Rocketdyne or at suppliers. The manifolds are complete and

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awaiting completion of the liner. The liner will complete next week and the first braze cycle will take place shortly. A second braze cycle will be performed to demonstrate the brazing and fit up of the honeycomb and edge pieces. This will occur later in 1997.

3.2 ELECTRONIC WORK INSTRUCTIONS

In our effort to reduce cycle times and reduce costs Production Operations is implementing a powerful new Manufacturing Execution System, called EWIP (Electronic Work Instruction Package). This is a PC based system that will have on line the work instructions, drawing, specification , NC set-up sheets, and MPP's and RMO's and electronic buy-off of the operations when complete. Shop personnel utilize the system through PC's located at their work stations. The X-33 program has been using EWIP from the beginning of the program and has seen several benefits already such as a reduction in the archived paper necessary for maintaining hardware traceability and the need for separate group to compile and issue paper books to the shop floor.

3.3 NOZZLE LINER MACHINING

As part of the nozzle MTD effort, the machining process of the hot gas liner needed to be developed. The liner configuration is a 60 inch x 90 inch flat NARloy-z plate with milled channels. To fabricate this efficiently required developing a gang cutter concept that allows for multiple channels to be machined at once. After several iterations a 4 gang saw cutter and 90 degree angle head on a horizontal boring mill was demonstrated as the optimum solution and will be used on the development and flight engines.

3.4 THRUST CHAMBER LINER NARLOY-Z DEVELOPMENT

Entering the X-33/RLV program, significant progress had been made toward developing a near-net shape process for fabricating a NARloy-Z forging for the X-33 thrust chamber liner. A final hurdle remaining to be overcome was a process to produce a uniform, fine grain microstructure in the complex round-round-rectangular liner forging. Early in the X-33 program, a systematic thermomechanical processing study was undertaken to define the complicated interactions between processing temperature, strain and heat treatment on the resultant microstructure. This study led to the development of a combined hot spinning/ cold forming process which produced the desired microstructure and properties in the NARloy-Z liner. Benefits of the near-net shape technology include a 50 percent savings in material and machining costs over the existing process. (Figure 3.4-1)

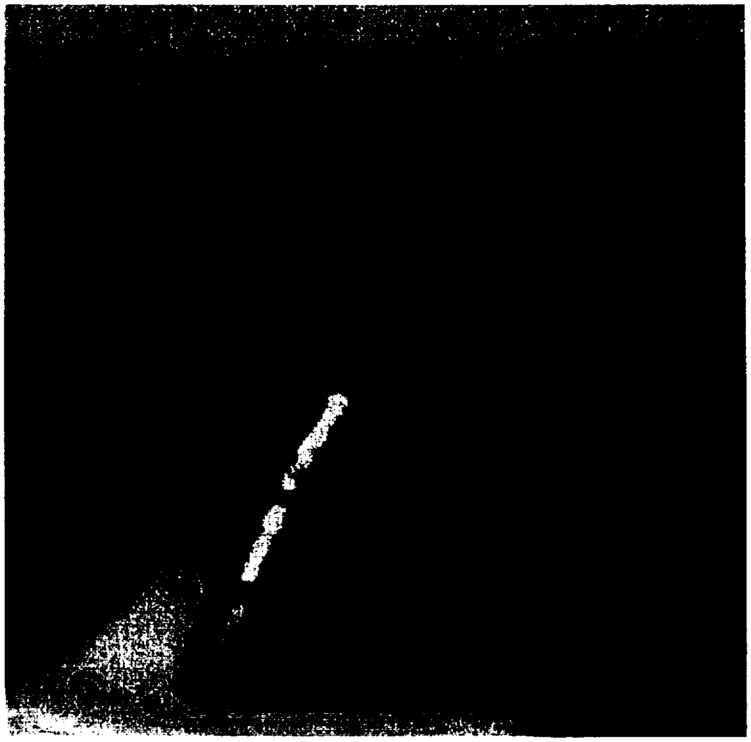

Figure 3.4-1. Near-Net Spin Formed Liner Forging

4.0 AEROSPIKE HARDWARE TESTING

4.1 GG TESTING AT MSFC

The first phase of the X-33 gas generator testing was successfully completed on 30 June 1997 (Figure 4.1-1). The X-33 gas generator is an upgraded J-2 configuration with a thicker combustor shell. A total of fourteen tests were conducted in seven days on the Preburner Position at NASA's Marshall Space Flight Center, TF116 facility. Six were ignition/transition tests and eight were mainstage tests varying in duration from 30 to 90 seconds. Major Phase I test objectives, including verification of proper operation at flowrates and mixture ratios outside of J-2 experience, have been achieved. The maximum flowrate tested was more than twice the nominal J-2 operating condition. Phase II testing will develop helium start characterization with spark plugs and demonstrate operational margin.

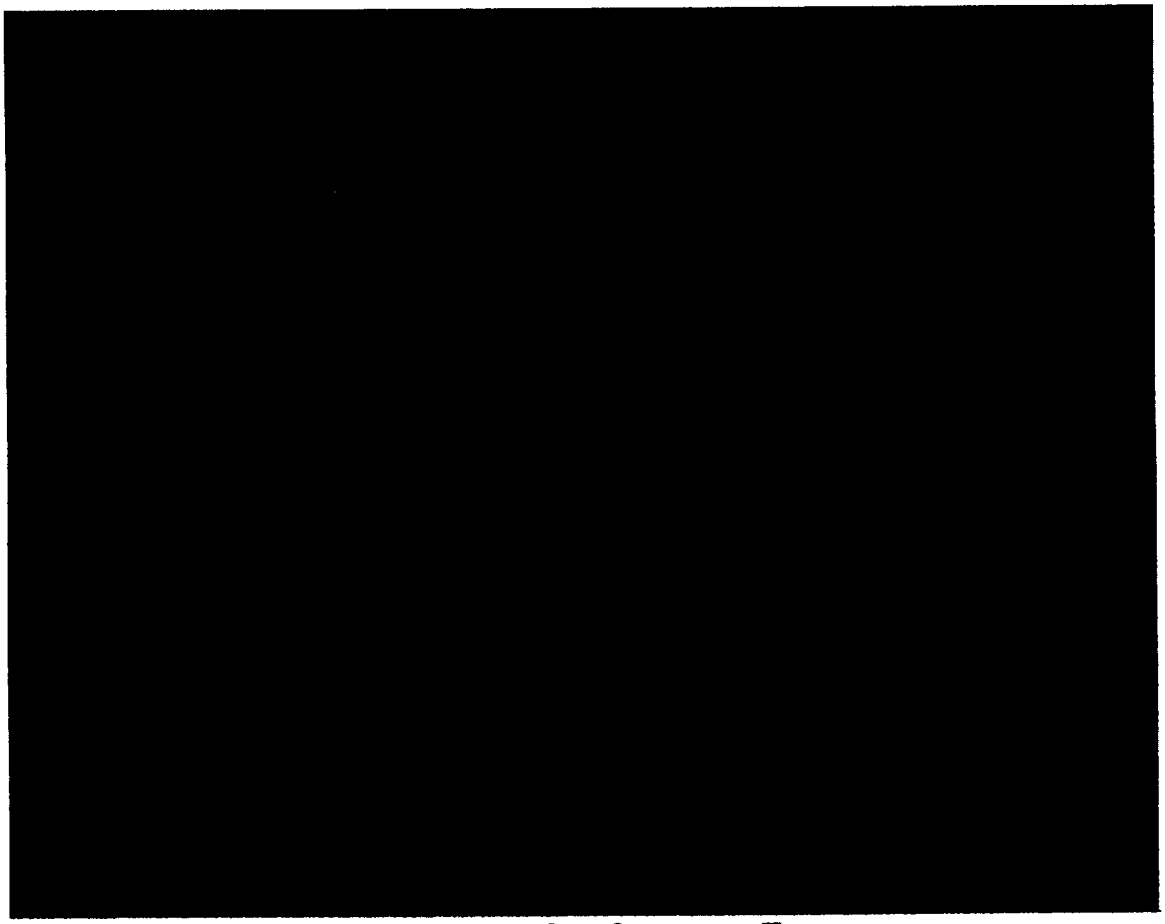

Figure 4.1-1 Gas Generator Test

4.2 COMBUSTION WAVE IGNITION SINGLE IGNITER TESTING AT LERC

The first phase of testing was completed in June of 1997. The X-33 CWI (combustion wave ignition) single element test series was successfully completed at the NASA Lewis Research Center. A total of 159 tests were conducted, successfully mapping the entire combustion wave premix and pilot igniter envelope including all three mission tank conditions plus limits testing. In addition, a series was conducted in which a slave injector provided by LeRC was successfully ignited. A series of cold propellant tests characterized the sensitivity of chilled propellants on the ignition box. A final series examined failure mode effects. The CWI testing met all objectives characterizing data to permit the design to proceed to the full up 20 igniter system.

The first test series used a combustion wave premixer and a single triaxial CWI igniter. Limits of operating pressure, mixture ratio, and timing were determined in this program for fundamental tank head operating pressures and flowrates. This provided the confidence to proceed with production of the flight CWI system. The second test series which will be conducted during the second year of the X-33 program utilizes a full-up array of 20 triaxial igniters with the same premixer system and near flight like tubing and valve components. This testing will define the final timing and limits development prior to development engine test.

4.3 MULTI-CELL TESTING AT MSFC

During the Phase I activities leading up to X-33 contract award, three development hydrogen cooled thrusters and injectors were fabricated in the round-round-rectangular configuration with the objective of demonstrating aerospike multi-cell feasibility. The preliminary XRS-2200 engine balance resulted in a 1,060 psia chamber pressure combustor for 100% nominal power whereas the current engine thrusters now balance out at 854 psia. The chambers, nearly identical to the current XRS-2200 shape, were two inches shorter in the nozzle end (trade studies later showed a marked gain in Isp for longer thruster nozzles). A water cooled ramp similar in dimensions to the XRS-2200 ramp was fabricated and a stand-alone test skid constructed to mount the 3 cell aerospike segment for hot fire testing at MSFC. (Figure 4.3-1)

Figure 4.3-1 Hot Fire Testing at MSFC.

In April and May of 1997, ten successful tests of the multi-cell test unit were conducted with durations varying from about 1.5 seconds to approximately 10 seconds. All of the test objectives were met. The multi-cell test skid performed well. There were no detected cell-to-cell interactions, the hardware was in excellent condition, and high quality data was obtained throughout. The rig was removed intact from test stand 116 and put into storage on site at MSFC Huntsville in the event it might be used later for unplanned anomaly resolution testing. This data permitted the XRS-2200 design to move forward.

Due to conflicting test priorities the multi-cell firing was delayed well into the X-33 Phase II program. The original objectives were to observe combined thruster interactions, demonstrate multi-cell ignition and feasibility, and demonstrate 50 percent throttle range for a bank of thrusters firing onto an aerospike ramp. In addition to the original objectives, the multi-cell was used to evaluated the following design issues

1. Confirmation of exact nozzle ramp heating prediction methodologies. It was not sufficient to just over predict cooling needs because the coolant distribution on the XRS-2200 was delicately balanced between the chamber circuit and the ramp circuit to avoid the complexity of coolant control valves.

2. The acoustic environment for the vehicle shell was unknown for an aerospike engine and required definition. New concerns were raised for high dynamic loads on the ramp due to shock recompression oscillations. Data was needed to understand or refute this phenomenon.

3. New CFD / thermal predictions for the base region between thruster exits showed unanticipated high heat loads. The test hardware needed to be modified to evaluate various candidate materials to survive this uncooled region.

4. The engine balance had evolved to a broader operating band for sea level operation including mixture ratio excursions from 4.2 to 6.0, and chamber pressures as low as 42 percent nominal. The test matrix was updated to demonstrate these key points as well as full power and mid power operating conditions.

5. A concern for delivered Isp and aerodynamic prediction methodologies raised the question of how performance would vary with side wall fences installed. Fences were constructed and installed for the last firing which provided valuable heat load and aero-pressure profile comparison data to anchor models.

6. To develop future RLV health monitoring instrumentation methodologies a typical plume environment was needed for evaluating instruments such as infrared video, ultraviolet video, spectroscopy, and laser induced fluorescence. Launch

platform designers also needed realistic input on what to expect from the aerospike plume expansion and how it might interfere with the adjacent platform structure. Test photographic coverage complimented by CFD predictions would provide that information.

4.4 ELECTRO-MECHANICAL ACTUATORS (EMAS) TEST AT ALLIED SIGNAL

Traditional rocket engines and vehicles rely on hydraulics to actuate engine valves and vehicle aero-surfaces. Hydraulics are construed as less maintainable than solid state electronic mechanical solutions. To achieve the maintainability and turn-around goals of the X-33/RLV program hydraulics were eliminated from the vehicle. To accommodate this design challenge the XRS-2200 incorporated sector ball valves and EMAs. EMAs provide the accurate valve control required to provide vehicle thrust vector control. EMAs are utilized extensive in the aircraft industry but have not been traditionally utilized in the rocket industry due to the high torque requirements. Flowrates and delta pressure across rocket engine valves place a tremendous torque requirement on valve actuators. This torque requirement would require large, heavy traditional actuation valves. Therefore, incorporation of EMAs requires lower torque valves. Rocketdyne has developed a sector ball valve which reduces valve torque by more the 10 times the torque required for a traditional ball valve.

Significant progress in the design, build and test of these valves and EMAs has been accomplished. A preliminary design review was held only two months into the program. After eight months critical design reviews had been completed for both designs. The April XRS-2200 program milestone of completing the valve detail design and initiation of fabrication was completed on schedule and 30% of the details have been developed. The first two EMAs have been fabricated and assembled. Testing of the prototype EMA has been completed including testing of the EMA motor drive and brassboard controller. Acceptance testing of the EMAs has been initiated and data indicates excellent performance.

LASRE

The team of Rocketdyne, Lockheed Martin, NASA Dryden, and Air Force Phillips Lab designed and constructed the 10% scale (of X-33,) Linear Aerospike Rocket Engine (LASRE,) experiment - conceived to provide test data on aerodynamic engine and vehicle slipstream interaction affects at altitude.

In April of 1997, ground "hot-fire" tests of this experiment at the Air Force Phillips Lab achieved steady state combustion at predicted chamber pressures while meeting expected performance (Figure 4.5-1). Downstream integration of this experiment onto a NASA Dryden SR-71 is expected to further correlate analytic and CFD models with actual flight and ground test data.

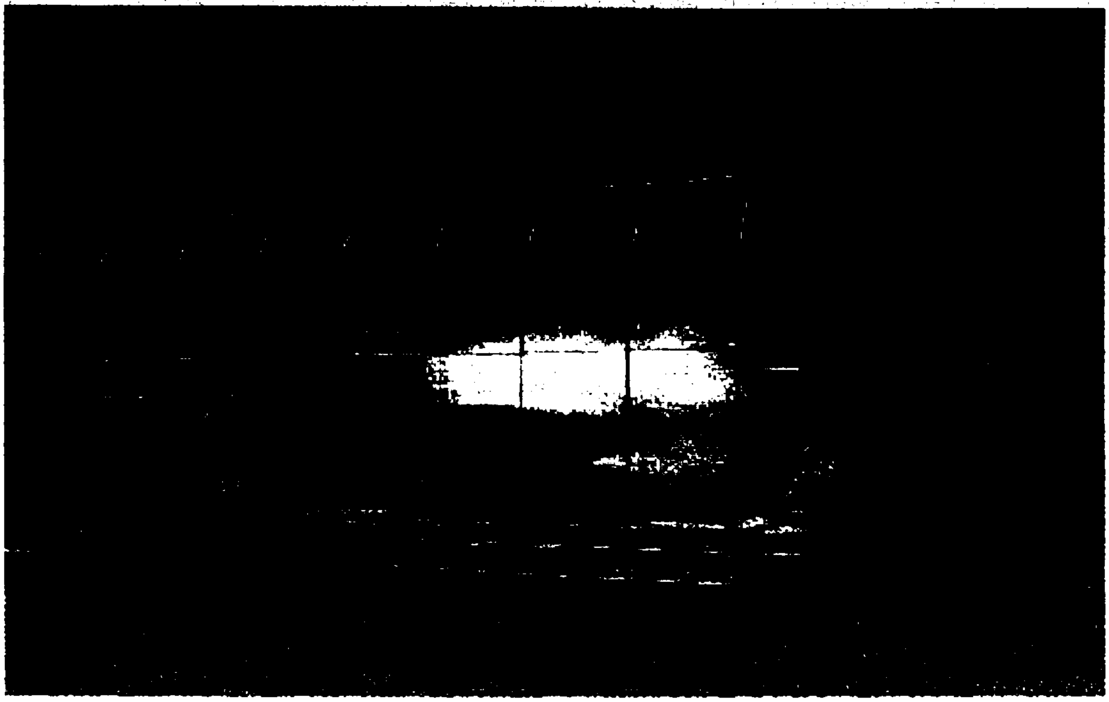

Figure 4.5-1. April 1997, Ground "Hot-Fire" LASRE Test.

5.0 RCS STATUS

5.1 THRUSTER IGNITER AND VALVE DESIGN VERIFICATION TESTING

Early tests were conducted to verify the designs of the thruster igniter and propellant supply valves. The testing successfully evaluated design modifications incorporated into the igniter assembly since it's development for the DC-X program. Also, the testing characterized the performance and durability of the internally piloted propellant supply valves allowing early fabrication and delivery of qualification valves.

5.2 POSITIVE EXPULSION OF LH2 DEMONSTRATED

Testing was completed that successfully demonstrated the technical feasibility of two separate expulsion device concepts for expelling liquid hydrogen from a storage tank. The piston testing demonstrated acceptable seal life, tank surface finish and leak rates. The bellows testing was used to verify structural integrity of the bellows. Both concepts successfully completed cycles equal to four times their expected life

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cycles. Due to less cost, superior schedule and lighter weight, the piston concept was selected for the flight design over the bellows concept.

5.3 "BARSKE" IMPELLER DESIGN CHARACTERIZED

Early risk reduction testing was conducted to characterize the hydraulic performance of a forced vortex impeller design intended for use in the low flow liquid hydrogen turbopump. Since the impeller design commonly referred to as a Barske impeller was historically used for pumping water, no cryogenic performance data was available. Although the testing proved the Barske impeller to be unacceptable for this application, the testing provided valuable performance information that can be used to assess future applications. The testing encompassed a wide range of flow rates, shaft speeds, and inlet and exit configurations allowing detailed assessment of stage efficiency, suction performance and throttling characteristics with liquid hydrogen.

5.4 GAS GENERATOR AND HEAT EXCHANGER HOT FIRE DEVELOPMENT TESTING

Hot fire development testing was completed on a flight configuration gas generator and heat exchanger. The testing verified that both components operated as designed. Hot fire testing was in process on a flight configuration augmentor when the program was redirected eliminating the need for combustion devices.

5.5 METHANE IGNITION TESTING

In response to a program redirection to switch from liquid hydrogen to gaseous methane as the fuel for the RCS thrusters, ignition testing with methane using a flight configuration igniter assembly was performed. The tests demonstrated consistent ignition within the expected thruster mixture ratio range, and pulse firings representative of flight duty cycles. No sooting or thermal / chemical compatibility problems were observed. Testing of a flight configuration thruster with methane is in process.

5.6 VALVE DESIGN AND FABRICATION

Ninety-five percent of the valve designs for over forty applications were completed. A gaseous oxygen (GOX) compatibility review was performed at White Sands Test Facility for all valves requiring GOX service. Qualification valves were received form two vendors. All remaining valves were complete through fifty to ninety percent of the fabrication cycle.

5.7 CONTROLLER DESIGN AND FABRICATION

All controller board designs were completed. Greater than ninety percent of all controller components were delivered allowing assembly of the first controller box to begin. Two main controller boards, STE boards, and the EGSE completed fabrication and checkout. The controller software was ninety percent coded and seventy percent tested. The EGSE and STE software were nearly completely coded and tested.

5.8 GH2 ACCUMULATORS FABRICATION

Fabrication of the flight gaseous hydrogen accumulators was essentially complete. Delivery is expected in mid-July. Since they will not be required for the methane fuel system, the tanks will be placed in storage.

5.9 GO2 TANK DESIGN AND FABRICATION PROGRESS

Significant development and fabrication progress was made on the gaseous oxygen storage tanks. Analog tanks were fabricated and burst / cycle tested to verify the composite overwrap design. Dome elements for three tanks and two cylinder sections completed fabrication. A trial wrap mandrel and composite fiber were received. New cylinder section designs are in process to support the vehicle weight reduction effort.

5.10 COMBUSTION DEVICES COMPONENT FABRICATION

Gas generator (GG), heat exchanger (HEX), and augmentor designs were completed and significant fabrication progress was achieved on each component. Three sets of GG components, four flight HEXs, and three flight augmentors completed fabrication. All three components were redesigned to meet the requirements of the X-33 application. The innovative new HEX design successfully reduced the component weight to less than half of it's predecessor.

5.11 THRUST CHAMBER ASSEMBLIES COMPLETED

Fabrication of one shipset (8) of thrust chamber assemblies (TCA) was completed. Each TCA is a welded assembly consisting of (1) igniter assembly, (1) platelet injector assembly with associated feedlines, and (1) thrust chamber. Enough parts were fabricated to produce (4) additional spare units.

5.12 WEIGHT REDUCTION

In response to the vehicle weight reduction effort, the RCS team evaluated alternate system options. The system that was recommended and ultimately adopted replaced liquid hydrogen with methane as fuel for the RCS. The new system reduced vehicle weight by approximately two thousand pounds and improved reliability. Over one hundred control components were eliminated including a high speed (80,000 RPM) turbopump and replaced by approximately ten valves. The new system concept was expeditiously developed and reduced program costs with little impact to component delivery schedules.

6.0 COMMUNITY RELATIONS

6.1 AEROSPIKE WEB SITE

Rocketdyne has constructed a detailed publicly accessible website on Aerospike propulsion for the X-33/RLV. This website has already been explored by over 700 individuals. The Aerospike site, (available at http://www.rdyne.bna.boeing.com/x33) includes: technical background/history, information of how an Aerospike works, performance descriptions of both the X-33 and RLV engines and detailed graphics describing the propulsion system and engine/airframe integration. This site works on both an educational/informative levels and as a more technical review of "rocket science". Linkages are included to NASA, Lockheed Martin, Boeing and other teammate's relevant websites.

6.2 UNIVERSITY INVOLVEMENT

Rocketdyne has also worked with a local University's Aerospace engineering department (California State Northridge,) to develop a mockup of the X-33 aerospike engine (Figures 6.2-1 and 6.2-2). The day to day 'hands-on' experience, knowledge and contacts developed by the involved students through their interactions with Rocketdyne engineers in order to design and construct this mockup will serve them well in their downstream career pursuits.

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Figure 6.2-1 - XRS-Linear Aerospike Engine Mockup

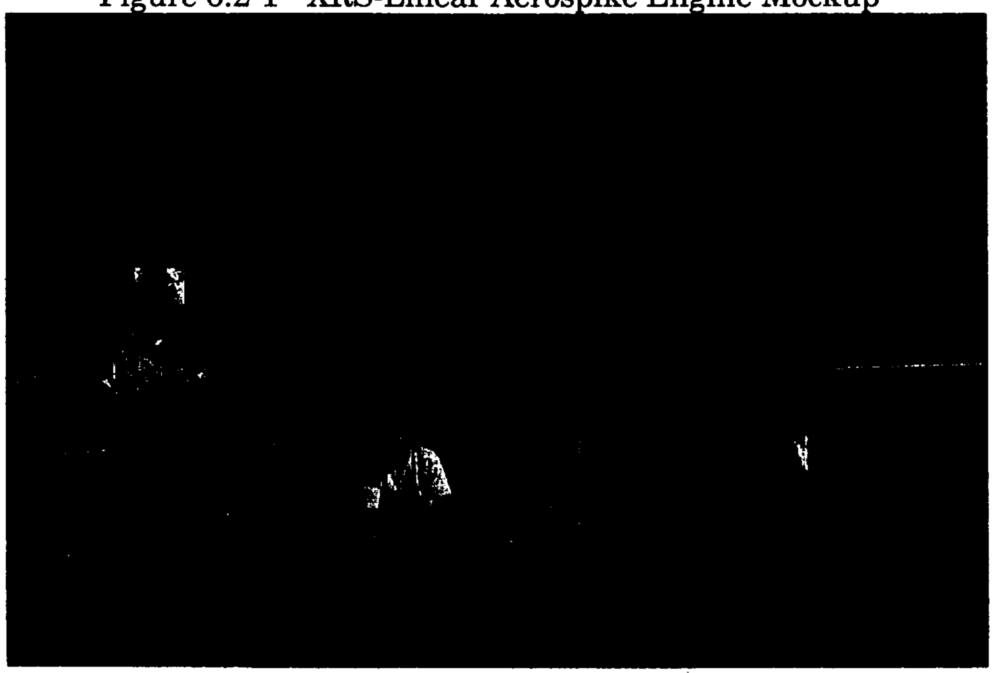

Figure 6.2-2 CSUN XRS Mockup Team.

Rocketdyne has also supported the requests of numerous students and grassroots space organizations for informative materials and information on our efforts on X-33 and RLV propulsion. Grassroots organizations briefed have included the AIAA, National Space Society and the Space Frontier Foundation.

These activities have helped establish a base constituency and public awareness/support for the X-33.

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ALLIEDSIGNAL INC.
ALLIEDSIGNAL AEROSPACE
ELECTRONIC SYSTEMS

ENVIRONMENTAL CONTROL SYSTEMS

Active Thermal Control System

Work on the baseline Active Thermal Control System continues on schedule for hardware delivery to LMSW in early January, 1998. All drawings, including all fabrication details, are complete and released for production. Production of the first (Qualification Units) Cold Plates and Ground Cooling Heat Exchangers is nearing completion in the AlliedSignal Torrance Facility.

As part of the vehicle weight reduction initiative, numerous revisions to the Active Thermal Control System have been evaluated and some have been processed through the AlliedSignal Program Control Board (PCB) and submitted to LMSW Change Control Board (CCB). Presently, the most attractive of these changes include changing the Pump Package manifold to a lighter weight material (titanium), eliminating the Pump redundancy, and changing the flight heat exchanger cooling media to Helium. These changes are being processed through the change process although formal approval of them has not yet been finalized. It is anticipated that these changes can be incorporated without impacting the overall vehicle schedule if approval is finalized in July.

Purge & Vent System

Vendor activities on the major procured item on the Vent Door Assembly continues. Hardware deliveries are presently estimated to be in time for assembly and delivery to LMSW without impact to the overall vehicle schedule. Delivery of the TPS for the Door Assembly is being coordinated with Rohr as is the routing of hardware between AlliedSignal

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and Rohr prior to delivery to LMSW for vehicle installation. The vendor CDRs for the door actuator and position resolver have been successfully completed and part production has been initiated.

The vendor activities for the VME controller for the door actuator is also progressing as planned. The interfaces with the DIU electronics, both hardware and signals, have been resolved with AlliedSignal Electronic Systems. The VME controller CDR has been successfully completed and production has been initiated. Deliveries of the VME controllers for DIU integration activities at the AlliedSignal Teterboro SIL and the NASA Dryden ITF are anticipated to be in time to meet their schedule requirements.

The Purge Ducting design and procurement has been placed on hold pending impacts from the vehicle weight reduction initiatives and finalization of the vehicle equipment layouts. A weight reduction change to a lighter weight material (carbon fiber) has been processed for the Purge Ducting but it has not yet been given final approval. It is anticipated that the change can be incorporated and ducting procured in time to meet the vehicle assembly schedule needs if the design and change approval are completed by mid-August.

Leak Detection System

Vendor activities for the design and production of the Hydrogen Sensors is progressing as planned. Initial prototype sensors were completed and successfully tested with hydrogen gas. The Sensor CDR was successfully completed and production of the flight units was initiated. Hardware delivery requirements have been coordinated with the assembly requirements of the Vent Door Assemblies (in which the sensors mount) and hardware receipt are expected on time to meet the needs.

The vendor activities for the VME monitor of the sensors is also progressing as planned. The interfaces with the DIU electronics, both hardware and signals, have been resolved with AlliedSignal Electronic Systems. The VME monitor CDR has been successfully completed and production has been initiated. Deliveries of the VME monitors for DIU integration activities at the AlliedSignal Teterboro SIL and the NASA Dryden ITF are anticipated to be in time to meet their schedule requirements.

POWER MANAGEMENT AND GENERATION SYSTEMS

Electric Power & Actuation System (EPAS) Systems Engineering

The EPAS system team and the systems engineering elements of each subsystem actively supported LMSW vehicle-level X-33 PDR in November 96. The EPAS Systems Preliminary Design Review (PDR) was held in February 97. The EPAS "A" spec. was released at Rev NC in March 97. Traceability between this spec. and the LMSW 604D documents has been established and is being tracked.

The EPAS Failure Modes Effects and Criticality Analysis (FMECA) was completed and released in May 97.

A dynamic simulation model of the EPAS system was developed and refined, with three releases from Nov. 96 to May 97. Completed EPGS turbo-alternator dynamic simulation model and control law design in April 97.

The EPAS Verification and Validation (V&V) Plan was released at Rev NC in March 97. This addresses end-to-end V&V and includes plans for integration test at Marshall Space Flight Center.

Flight Control Actuation System (FCAS)

Completed PDR and CDR on the FCAS System, controller and actuator, with the latest review being 5-30-97 for FCAS CDR with Lockheed in attendance.

Actuator Components on order are Gears, Bearings, Ball Screws, LVDTs and Electric Motors. Electronic Controllers' individual components are also on order.

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The FCAS system is in the process of changing through the addition of a Pneumatic Load Device, which will assist vehicle weight saving initiatives while enabling flap loads to increase. This change is being actively supported by the FCAS team and technical agreement has been reached with LMSW..

Electric Power Control & Distribution System (EPCDS)

The System Preliminary Design Review was held in February 1997. Since the review, the definition of power distribution and control requirements has been improved and the loads database has been extended, resulting in improved knowledge of the users' needs. In the same time frame, the vehicle's avionics bay went through a re-design that restricted the room available for the EPCDS LRUs. This led to a redefinition of the EPCDS, involving substantial growth in capability, cost and volume. The change is being progressed through the appropriate CCBs. The following refers to the redesigned system.

All system-level and LRU-level documentation has been fully released and is now at NC or a higher revision level. The hardware has completed internal phase gates IR#1 and IR#2; IR#3, roughly equivalent to hardware PDR, is planned for July 1997. The Software Requirements Review was held in March and Software PDR is planned for early August. The Software Requirements Specification has been released at Rev NC. The main interface specification to the Vehicle Management Computer, the EPCDS/VMC IRD, has also been released at Rev NC.

Preparation is being made to build development models; parts selection has been made and several parts are on order.

Electric Power Generation System (EPGS)

Design and release of drawings and documents was approximately 85% complete when the Turbo-alternator EPGS program was put "on hold" on June 2nd, 97. This was to accommodate an 1800 pound vehicle weight reduction achieved by eliminating the Aerojet RCS gasifier. As the turbo-alternator was powered by the waste heat from the gasifier, it was then without a lightweight source of propellant and too had to be removed. Several fuels and oxidizer candidates available on X33 were studied, however with the additional quantity of them required due to their lower energy and the dedicated tankage to contain them, the weight savings was reduced. Recent mission duty cycle studies indicate that the electrical power and total energy required to perform the X33 flight is substantially less than originally estimated and therefore batteries became a suitable replacement for the Turbo-alternator. All "long lead" hardware orders have been put on "Stop". The program diligently followed the IPDS process and was preparing for both the component and sub-system PDRs when the "Stop Work" direction was received.

Presently it is concluded that batteries cannot meet the requirements of the RLV. A plan is being proposed to provide X-33 traceability by means of a lower cost parallel development program for the turbo-alternator design. These units would not fly on X33, but would continue development via ground testing and demonstrations that would validate their technology for the RLV. Also the development of this technology would be further advanced when needed by the RLV.

III. Vehicle Management Systems

Hardware Elements:

Hardware for the Vehicle Management System is progressing on, or ahead of, schedule in most areas. The Electrical/Mechanical Schematics for all VMS hardware elements delivered 1 May 1997, and the Source Control drawings for those elements were delivered 9 May 1997. Actual hardware delivered to this date includes two Commercial DY4 Processor Cards (Model 171) to LMSW on 27 February 1997, a Commercial DY4 Communication Card (422 bus) and cable to LMSW on 21 April 1997 (ahead of schedule), and one Commercial Software Development Engine Control DIU (Processor, 1553 & chassis) to Rocketdyne 29 May 1997, 3 months ahead of schedule.

Software Elements:

Software is also progressing well, with some elements now being delivered ahead of schedule. In order to meet the stringent constraints of the software development schedule, a tiered integration plan was established with the following key aspects:

- a tightly looped Rapid Prototyping environment, with code exercised in the SIL,

* working models transferred to the ITF for detailed testing, and
* independent verification at LM Denver.

The first key area of software is the Redundancy Management System (RMS).
The Final Software Requirement Specification (SRS) was delivered on schedule on 9 May 1997 with the Data Acquisition Package Billing Milestone. All source files for RMS Simplex version (no CCDL) & a sample application were delivered to the SIL on 7 May 1997, and the demonstration program was executed without errors. The preliminary S/W Functional & Fault Insertion Test Plans were also delivered 7 May 1997. The Design Review of the next RMS version (Triplex with CCDL) was completed 8 May 1997.

The Flight Manage Software's SRS (Rev. A) was delivered 9 May 1997 as part of the aforementioned Data Acquisition Package. That data management package also included the SRS and Select Database for the Vehicle Subsystem Manager (4 volumes). The Interface Requirement Specification (IRS) for the Vehicle Mission Computer, which consisted of 20 volumes and 5,500 pages, was delivered at along with the above SRSs on May 1997. Another deliverable was the Software Test Plan, which was delivered on 14 May 1997.

The beginning of hardware/software integration development completed a major milestone when VxWorks Commercial Operating System and the Tornado Development Environment were recently integrated and are now working with the DY4 CPUs.

Systems Integration Laboratory (SIL):

To facilitate the transfer of hardware and software from AlliedSignal, the SIL was re-designed to mirror the Dryden Laboratory (ITF). The development of the AlliedSignal SIL has also accomplished significant milestones in the initial year of the program. Among the most significant accomplishments are the establishment of high speed, direct communications capability between the ITF and the SIL, installation and operation of the Onyx / Indigo computer systems, and establishment of communications between the Onyx and the VMC/VME 1553 controller.

Two VMCs were established. VMC #1 was established with (4) CPUs executing in the VME chassis. Features of VMC#1 included:

- 1553 communications established,
- Analog In & Analog Out established over the VME backplane, and
- Reflective memory executing in concert with VxWorks.

VMC #2 was established with (2) CPUs executing in the VME chassis with the following features:

- Simplex version of RMS executing
- Sample application established on second CPU

Air Data Subsystem

The X-33 Air Data Subsystem was redirected from a conventional air data subsystem to a flush port air data subsystem on January 24, 1997. In order to reduce cost and weight, the Flush Air Data Subsystem (FADS) was then redirected to use remote pressure sensors May 9, 1997. Both of these redirections were accomplished with only minor changes to the delivery schedule and configuration was completed June 30, 1997. The current FADS consists of AlliedSignal supplied remote pressure sensors, flush air data software in the AlliedSignal Vehicle Mission Computer, NASA flush air data algorithms and Lockheed Martin Skunk Works flush ports and pneumatic plumbing. The Preliminary Design Review was accomplished on May 9, 1997

Communications Systems

The communications systems have accomplished several major milestones. Radar Altimeter, Communications, and Range Safety Subsystems all have complete flight hardware on order, with the singular exception of the Flight Termination System (FTS) battery. The test hardware is undergoing concept definition review, and in the case of the Radar Altimeter, is in the final stages of definition for ordering. Analysis currently shows the Communications and Range Safety Subsystems have sufficient margin except, with Range Safety, under conditions of plume blackout.

ROHR INCORPORATED

X-33 THERMAL PROTECTION SYSTEM DEVELOPMENT

Introduction

This report is a summary of the achievements and progress to date of the Rohr X-33 Thermal Protection System (TPS) team for the year dating from 2 July 1996 until 1 July 1997. Phase II of the overall Venture Star program commenced on 2 July 1996 and extends until 31 December 1999. Rohr Incorporated, under the Recipient Team Member Cooperative Agreement (RTMCA) No. 96-RHR-0001, is responsible for the design, development, qualification and build of the TPS for the X-33 SSTO Flight Vehicle. The X-33 is a subscale (53% photo scale) of the Reusable Launch Vehicle (RLV). Also, during Phase II some RLV Definition and Development Ground Demonstrations will be performed.

With the contract award, Rohr has formed three Product Development Teams (PDT) to effect the design and build of TPS components. The TPS has been broken down into the following PDT's: a) the Refractory Composites team responsible for the Nose Cap, Chin Panels, Skirt Panels, Ruddervators, Canted Fin Leading Edges, Canted Fin Forward Fillets, Body Flaps and Engine Skirts. The last two items have just recently been changed to a ceramic tile construction and are no longer a Rohr responsibility; b) the Metallics Team responsible for the Windward Aeroshell body panels, Windward surface of the Canted Fin and Nose and Main Landing Gear Door Assemblies; c) the Leeward Aeroshell Team responsible for the Leeward Aeroshell, Avionics Bay Door and Payload Bay Door.

Rohr presented the TPS during the vehicle Preliminary Design Review (PDR) during the week starting October 6th 1996. The presentation was electronically delivered to Palmdale as a milestone deliverable. This PDR initiated an additional aeroshell structural refinement and design update which was presented at Rohr on January 15th 1997. This successfully completed the PDR. All request for answers generated at PDR have been responded to and closed.

Vehicle Configuration (Design and Analysis)

Structural Advancements

Metallic TPS Structural Analysis

The Inconel 617 and PM1000 TPS panel skins, core and standoffs have been sized to the liftoff, ascent and reentry acoustic loads with preliminary fatigue data. Rohr has completed the hand sizing of the Inco 617 and PM1000 panel's skins and core for aerodynamic and thermal loads with preliminary stiffness and strength models. The first detailed analysis iteration of the nominal Malmstrom 4 trajectory for a highly loaded flat and curved Inco 617 panel assemblies with preliminary stiffness, strength and creep models have been completed. The FE models are unique in that they include time, temperature and load dependent material response. This analysis was perormed with MARC non-linear structural response software. It should also be noted that Rohr is incorporating MARC in performing combined thermal and structural analyses for metallic TPS evaluation.

Leeward Aeroshell TPS Structural/Dynamic Analysis

Material options have been evaluated and a final selection was made. Finite Element Models were created for each panel on the Leeward Aeroshell. Panel parameters including core height, ply count, and edge closures have been defined. Preliminary analysis including static, acoustic, and thermal loads completed. Structural optimization studies performed. Flutter analysis completed for Avionics and Payload Doors. Structural tests designed, scheduled or in progress. Materials testing completed or in progress. Flight test instrumentation defined. Initial weight savings studies have been completed.

Thermodynamics Advancements

Panel Bowing Analysis

Augmentation of aeroheating rates due to panel bowing is being assessed by NASA-Ames. As the metallic panels heat up, and cool off, the temperature differential between the inner and outer facesheets causes the panels to bow into, or out of, the external flow. The bowing, in turn, effects the magnitude of the local heating rates. Analysis will be correlated to Arc jet testing at NASA JSC. The testing will determine the amount of deflection due to a series of delta T's across the panel. Section 3.7 will describe the testing in more detail.

Initial results from the Ames analysis show that the peak to valley temperature differential is likely to be small - on the order of 50 to 100^{o}F. The increased heat rates will be accounted for in the insulation sizing.

The final panel bowing analysis should be completed this year and will be compared with ARC-Jet test results.

Insulation Sizing Analysis

Sizing of the insulation beneath the Carbon-Carbon components and metallic panels is an ongoing effort. As the environments are becoming better defined, as well as the vehicle configuration, the required insulation is being updated on a vehicle wide basis. In general, the trend has been toward smaller insulation requirements. Improvements in the aeroheating database format have made the task of insulation sizing considerably less time consuming.

Insulation on Carbon-Carbon components varies from 0.5 inches to 2.0 inches. Insulation on the metallic panels varies from 0.75 inches to 1.75 inches. There are some areas where tank structure extends into space originally dedicated to TPS. These areas are of particular interest, and the current analysis shows that all internal temperature requirements can be met with some additional LMSW provided radiation shielding.

Leeward Aeroshell Insulation Splitline Definition

As with the rest of the vehicle, better definition of the aeroheating environments and vehicle configuration has resulted in a general reduction in the vehicle insulation requirements. With regard to the leeward aeroshell, this translates into less AFRSI and more FRSI. The most recent aeroheating data shows a reduction in the aeroheating rates on the leeward aeroshell. Analysis is currently underway to quantify the associated splitlines and blanket thickness requirements. Initial estimates indicate that there might be as much as a 30 percent reduction in the AFRSI requirements.

The leeward aeroshell splitlines and blanket sizing are being actively managed to respond to changes in environments and vehicle configuration. The current blanket thickness is 0.58 inches for both the AFRSI and FRSI.

AeroThermodynamics Advancements

Aerothermal Environments

The requirements for the aeroheating database needed for TPS design were defined by Rohr personnel. This effort included the definition of the heat transfer parameters and locations (body points) to be provided. The preliminary database for acreage locations was provided by NASA-ARC and NASA-LaRC. Algorithms for deflected control surface heating were defined with coordination from LMSW. Plans were put in place for defining localized heating on steps, gaps, and bowed panels. Engine plume-induced heating environments were obtained from NASA-MSFC. Rohr personnel coordinated the effort for obtaining Reaction Control System (RCS) plume-impingement pressure and heating environments from NASA-MSFC.

Boundary-Layer Transition

Preliminary step/gap/waviness criteria were defined by Rohr personnel. The step/gap criteria were corroborated by discrete roughness-induced transition wind tunnel tests conducted by NASA-LaRC. Transition wind tunnel tests to address the effects of bowed panels on transition were coordinated with NASA-LaRC. Wind tunnel models with simulated bowed panels shall be tested in July-August 1997.

Based upon the allowable step/gap/waviness criteria, a consistent boundary-layer transition criteria to be used for defining the application of laminar and turbulent heating rates was coordinated with NASA-LaRC.

Material Splitlines

Based upon aerodynamic heating Computational Fluid Dynamic (CFD) predictions at several points in the design trajectory and on preliminary estimates of boundary-layer transition, the splitlines between the Carbon-Carbon TPS, the metallic TPS, and the ceramic blanket

TPS were defined for the initial vehicle configuration. Material selection for the control surfaces were negotiated with LMSW.

Design

Design Advancements

Knowledge Based Engineering (KBE) Applications for X-33

Knowledge Based Engineering (KBE) has been applied to the X-33 in various applications. The two primary applications that have been developed are: 1) to create the Catia solid model of the metallic TPS panels including the honeycomb panel, seals, and insulation , 2) to create the 2D Catia drawing from the solid model including the parts list.
The KBE includes algorithms that calculate weights, fills the parts list by interrogating the solid model, and duplicates many of the actual steps a user would execute manually. These two applications reduce a task that would typically take a week to couple of hours.

Other applications were developed when a repetitive task was apparent. One application was to create TPS standoff bracket vectors based on the panel grid line layout. Since there are over 1500 panels, this tool was helpful in reducing the time to define the locations and vectors. Another application was also utilized to check for commonality of metallic panels with respect to each other. This program would evaluate individual loft deviations of size and contour and group them by size. A program was also developed that created the single curvature loft of a complex curvature panel. This application evolved from a design-to-cost effort to reduce the cost of TPS panels. Single curvature panels were a significant cost reduction because skins and core could be rolled instead of stretch formed.

TPS Panel Splitline Pattern

The original TPS panel split line pattern consisted of rectangular panels and was released on ICD 10/96. To integrate with the newly developed substructure, all metallic TPS splitlines were revised. The new splitline pattern was developed based on oxygen and hydrogen tank frame pattern and positioning. It does mean that some rosette fittings will have to span across tank frames. This resulted in a new "diamond"

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pattern over the entire fuselage of the vehicle. Additionally, this pattern improved seal orientation to airflow. This new pattern was released on ICD on 3/13/97. See Figure 1 for comparison of 'old' and 'new' panel splitline pattern.

Refractory Composite Control Surfaces

Innovative refractory composite control surface components were designed. An all refractory composite, minimum weight, hot structure body flap consisting of seven sections and top covers was designed using buried fasteners and minimum insulation around the fasteners. Refractory composite ruddervator components were laid out incorporating an integral torque box and a minimum of metallic hardware. This is the first Refractory composite control surface to be utilized on a flight vehicle.

Design Methodology

Vehicle Loft Development Assistance

LMSW has primary responsibility for the definition of the X-33 vehicle loft in terms of its' aerodynamic shape. Once this has been defined Rohr has reviewed the loft and made minor modifications in order to enable efficient downstream usage. The Rohr Loft Group was able to contribute to the "E" Loft. The canted fin cap and fillet were improved and there were some anomalies removed from the body. These enhancements resulted in loft surfaces that are smoother, less complex and easier for application by down stream users.

Leeward Aeroshell Basic Panel Design

The Leeward Aeroshell design team was established in September of 1996. Since that time, the splits between the individual leeward aeroshell panels and the panel extremities have been defined. Since the panels are non-structural, the panel motion with respect to the tanks/substructure has been identified. The materials for a basic panel have been identified and over half of the panels (10) have been fully sized. The final insulation thickness and bond procedure are defined. The locations for the substructure attachments and fastener sizes have been fully defined for the forward 2/3 of the vehicle. The sealing arrangement of the panel-to-

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metallic, panel-to-panel, and panel-to-vertical fin have been fully designed. The sealing of panel-to-canted fin and panel-to-base have been concepted. To prove out several innovative manufacturing techniques, a producibility panel was manufactured successfully.

Leeward Aeroshell Penetrations

The leeward aeroshell accommodates twenty-five penetrations. (Two of the penetrations, turbo-alternator exhausts are in the process of being deleted.) All of the penetrations have been identified, sized, located, and interfaces have been fully defined and agreed with appropriate partners. One ECS vent panel/door configuration (typ 8 loc) is fully designed with drawings released. The second two ECS configurations are being modeled. Brackets have been fully modeled for each of the 4 antenna types (7 locations). General arrangements for the hydrogen exhaust and oxygen exhaust vents have been agreed to and the details of attachment are in work. Four access panels have been identified, sized, and located. Two panels permit access to the vehicle hoist brackets, one provides access for installing the oxygen exhaust, and one provides access for the hydrogen exhaust.

Windward Aeroshell Metallic Panel Assembly Basic Design

Baseline panel design has been established, including fastener concept and insulation method. The basic panel is .5 " thick honeycomb panel with .006 " thick skins and a core thickness of .0015 ". The seal will be an overlap design integral with the outer facesheet. The four fasteners holding each panel is combined with the outer protective cap on the wetted surface. Two material systems have been chosen a) PM1000 and b) Inco 617. First production drawing is in sign off to support the first production lot of 248 TPS panels.

TPS Substructure Tiger Team

A multi-company team convened in Palmdale to develop and evaluate alternative TPS support structure designs. The aim was to increase the stiffness of the substructure to ensure acceptable OML definition and step and gaps during all flight conditions. The chosen design consisted of upright composite beams tying into the tank frames, which supported the Rohr TPS. To properly integrate with the substructure design, new TPS panel split lines were developed (the "diamond" pattern).

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Refractory Composite Basic Design

Three internal and external component reviews have been held in Chula Vista (1 NASA, 2 Rohr). Orbiter design approaches for the nose cap and leading edge components were reviewed and incorporated into the X-33 designs.

System Optimization / Trade Studies

Body Flap Trade Studies

Rohr has conducted (2) independent trade studies on the configuration and structural design of the X-33 body flap. The first trade study weighed an all Carbon-Carbon design against an Inconel hot structure, and a hybrid Ti structure with Inco leeward TPS and C/C windward TPS. Based on weight, the all C/C design was selected. After the vehicle configuration changed, requiring a 30% larger body flap, a second trade study was performed, again comparing the all C/C baseline to a hybrid Ti structure with C/C and Inconel TPS, and a hybrid Carbon Epoxy structure with AETB ceramic tile. Although heavier, the ceramic tile body flap was chosen due to program schedule constraints brought on by the late configuration change.

Ruddervator Trade Studies

Rohr conducted two (2) ruddervator trade studies on the X-33. The first study compared different structural design concepts and material types. An all C/C ruddervator was traded against an all Inco hot structure and a hybrid Ti with Inco TPS. The hybrid Ti and Inco was selected, although heavier, the cost was considerably less then C/C and the vehicle trajectory called for locking out the ruddervators during peak heating. the vehicle control philosophy matured, the ruddervator deflection history changed requiring usage all through the flight. With the increase in temperatures, the decision was made to switch to a carbon ceramic ruddervator.

The second trade study, requested by LMSW, asked Rohr to consider combining the inboard and outboard ruddervator into a single structure. The result of this trade showed a significant weight

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penalty would be incurred, and the resulting surface would be too large to be controlled by a single actuator.

Base Region Trade Studies

Rohr conducted a trade study to determine the optimum configuration for the X-33 base. Structures considered were the initial baseline of C/C around the engine cowl with Inco TPS over the acreage below 1700 F, and an all AETB ceramic tile base, and an all ablator base with ceramic tile around the engine perimeter. The latter design was selected due to reduced cost, reduced weight, and the base area being considered non RLV traceable structure. LMSW will design and fabricate the graphite/BMI substructure carrier panels, LMMS will design and fabricate the ceramic tile TPS, and Rohr will specify and install the ablator material.

PM1000 vs. PM2000 Material Usage Trade Studies

Trade off studies have been performed in order to down select the high temp alloy's that will be used on the X-33 Metallic TPS. PM 1000 has been selected over PM 2000 because of its better material strength at temperature, ductility and braze characteristics.

RLV Methodology / Application

RLV Definition Studies

Trade off studies have been performed with the RLV definition team in Palmdale. Several tank to TPS configurations have been looked out and cost / weight trades are completed. Also, different metallic windward aeroshell panel configurations were taken under consideration e.g. 36" x 36" panels fastened by nine (9) attachments to the substructure.

RLV Weight Comparisons with X-33

The X-33 weights were used as a baseline and calculations were made based on the assumption that if we had additional time and funds how much weight could the X-33 current weight be reduced. Additionally, a weight projection of the RLV was completed taking into account maturing technologies that would meet the RLV timelines. This will be used to

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show that the RLV is viable in terms of mass fraction.

TEST AND VALIDATION

Overall Testing Program

The test program for the X-33 TPS will develop the required data to support structural and thermal analysis and perform functional testing to verify key performance characteristics and qualify the design. Material characterization, design development and validation, and qualification tests will be performed throughout the program. High temperature metallic and refractory composite material systems will undergo arc jet characterization testing for thermal/optical properties and mechanical testing to develop the necessary structural design data.

The TPS seals will be tested in the Hot Gas Facility at NASA Marshall to quantify leakage rates for different portions of the X-33 flight trajectory. Aerothermal performance of the TPS will be characterized in panel and subcomponent testing in arc jets at the NASA-ARC and -JSC centers. Thermal characterization of TPS panels and subelements will be performed in radiant heat facilities at NASA-JSC and -LaRC. The durability of the TPS will be verified through mechanical vibratory testing on shaker tables and acoustic tests performed in Progressive Wave Tube facilities at Rohr and Wright Patterson Air Force Base. The ability of the TPS to withstand the rapid de-pressurization during vehicle ascent will be confirmed during tests at NASA-JSC in a thermal-vacuum chamber.

The 8" High Temperature Tunnel at NASA-LaRC will be utilized to evaluate the metallic TPS seal performance and determine the structural response of the system in Mach 7 flow. A model representative of the Leeward aeroshell will also be tested to verify the ceramic blanket's ability to survive hot, supersonic flow. NASA-MSFC will perform an integrated system test with the different structural/thermal environments simultaneously applied. The model will consist of TPS panels, the supporting substructure, and a simulation of the LOx tank. The test will be used the verify the ability of the TPS and supporting structure to survive combined loading effects.

Basic material characterization and design development testing has been initiated to support vehicle design. Panel and subelement testing has

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also started and will continue into the program to validate the design and analytical models. Qualification testing will be initiated later in the program when the design is mature and will be completed in advance of the flight readiness review.

Metallic Panel Emissivity Coating Test

Paints and coatings were evaluated for emissivity and catalysis through exposure to arc-jet conditions. Substrates tested were Inco 617, PM 2000 and PM 1000. Coatings included several paints and a two-phase glass, compared to a pre-oxidized surface. Results from the initial round of tests showed that one paint and the two-phase glass performed best in reducing weight-loss caused by oxidation. Emissivity and catalysis testing is still incomplete but is anticipated to be completed within two months.

Combined Environments Test

The test objectives have been determined and agreed to by all parties. Preliminary test plan for Phase A (Metallic to Metallic panel) has been written and reviewed. At suggestion of LMSW and LM Michoud the cryogenic and bi-axial loading have been eliminated to reduce scope to control costs. Preliminary schedules for Phase A have been/are being worked by each facility. Preliminary Phase A models are in work. LMSW is currently modeling and costing Sub-Structure. LM Michoud is beginning work on Simulated LOX Tank. Phase B (Leeward to Leeward panel) and Phase C (Leeward to Metallic panels) have been approved by LMSW. Instrumentation requirements for each facility involved are being discussed.

Thermo-Vibro-Acoustic (TVA) Test

The TVA test plan was released in January 1997. Minor un-incorporated changes reduced the test matrix for each material group, taking advantage of design and material down-selections and test duplication. The current flight spectrum parameters were updated by LMSW report 604D0017 Rev. B

Refractory Composite TPS Material Systems

Thermo-vibro-acoustic testing at the Rohr test facility and at Wright Labs

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will subject the selected refractory composite materials and design concepts to simulated flight environments in a progressive wave tube facility. The testing will include representative liftoff, ascent, cruise and re-entry temperature and Overall Sound Pressure Level (OASPL) conditions. The sub-components will be tested to flight sequences for up to sixty (60) simulated missions. Rohr's sonic fatigue test facility is a high temperature PWT capable of simultaneously testing panels of up to 33 inches by 23 inches in size to overall sound pressure levels up to 166-168 dB at temperatures a high as 1800°F. Wright Labs can accommodate 48" x 110" panels to dB levels of 172dB and temperatures of 2500°F. Nose cap and ruddervator configurations are planned for these types of tests.

Metallic Panel TPS Material Systems

Thermo-vibro-acoustic testing at the Rohr test facility will consist of 2 panels each of Inco 617 and PM1000 types fully intact. There will also be some damage tolerance testing with fastener out and impact damage. The TVA testing at Wright Labs is scheduled and the test fixture design is in drawing signoff. Testing is currently scheduled for late August 1997. The test specimen will be a 4 panel array tested in their PWT facility. 2 samples will be constructed of Inco 617 and 2 will be constructed of PM1000.

Leeward Aeroshell TPS Material Systems

Two single panel PWT tests will be run at the Rohr facility. One will be a typical leeward aeroshell panel with AFRSI thermal insulation blanket installed and one with FRSI blanket installed. Both PWT tests will take place after the sample has been exposed to Arc jet testing.

Subelement Shaker Testing

Design verification shaker testing will evaluate seal and panel attachment concepts

Windward Aeroshell Metallic Seal Durability Shaker Test

Specimen and test fixturing will be first tested July 2, 1997. Full testing continues until July 10 to evaluate secondary seal and panel integrity first for in-plane vibrations; normal / out-of-plane vibration may follow. This study has established experience in the first fabrication of a phase II

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metallic aeroshell panel using inconel 617 production honeycomb core and skins with the MBF-50 braze alloy cycle, including MA 754 inserts, inconel foil closeouts and Q-fiber insulation pan. The shaker test setup uses Rene 41 rosettes to support one 18"x18" panel with two 5"x18" panel strips along adjacent edges. Panels and rosettes are strained gauged at critical locations based upon Stress Photonics Thermographic stress studies.

Leeward Aeroshell Carrier Plate Durability Shaker Test

A representative carrier plate attachment joint will be tested mid-July for panel durability and wear and attachment concepts. This study built the first carrier plate and panel assembly utilizing production representative materials, processes and lay-ups. The test set-up will apply sinusoidal, normal out-of-plane loads to the assembly through LMSW designed Support Tee structure at flight design strain levels.

Additional shaker tests for sinusoidal fatigue strength are underway evaluating two panel fabrication alternatives, precure and co-cure.

Arc Jet Testing

FRSI Blanket Arc Jet Testing

FRSI blankets were arc jet tested at NASA Ames in the January-February 97 timeframe. This series of tests was terminated due to the fact that Ames was unable to provide test conditions which were requested. Models were exposed to a temperature which was above what they will see in flight and above what the materials will survive. Additionally, the materials tested were found to be unacceptable for use due to low through-plane tensile strength. Current plans include arc jet tests at NASA JSC at lower temperatures of a different material with a higher density and higher tensile strength.

Four (4) Panel Array Arc Jet Testing at NASA JSC

Metallic Inconel honeycomb 4 panel array was arc jet tested at NASA JSC in March, 1997. This model had been tested in Phase 1 and was re-tested. Model was tested in several attitudes, the most severe being "backwards" with the shingle seals heading into the arc jet flow.

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Testing of a 4-panel array in the Arc-Jet at JSC has been performed to validate thermal models and qualitatively assess seal leakage. The results of both objectives were encouraging. The metallic panel models correlated well with test results. Substructure temperatures were maintained below the 350^{0}F limit. Backside air temperatures near the seals did not indicate a gross leakage problem. No structural anomalies or failures occurred.

This model is currently being modified, and fixturing built by JSC to allow the measurement of mass flow and heat flow below the honeycomb panel to evaluate leakage past the shingle seals. A plenum and calorimeter are being added to the backside of the array so these measurements can be made.

Material Characterization Arc Jet Tests at NASA Ames & JSC

Materials characterization arc jet tests were carried out at NASA JSC and Ames, from February 97 to present. Data includes emissivity, mass loss, surface recession survivability, and catalysis (recombination rate). This was done at NASA JSC for a ceramic composite and at NASA Ames for several metals with a variety of coatings on them. Further testing is planned at both facilities.

Additional Near Term Arc Jet Testing

The following testing are scheduled near term:

a) FRSI arc jet tests at JSC, July-August;
b) Arc jet tests of a metallic single panel at Ames, August-September;
c) Materials characterization arc jet tests at Ames and JSC, July-October;
d) Metallic Inconel honeycomb 4 panel array arc jet test at NASA JSC, July- August;
e) AFRSI arc jet tests at Ames, July-August

Radiant Heat / Panel Bowing Testing

A test plan was written and approved for the Radiant Heat test at NASA JSC. An innovative test model for panel bowing was designed using

LVDT's (linear variable differential transformers). The radiant heat test to evaluate thermally induced bowing of a metallic honeycomb panel was performed at JSC in June 97. In this test, the surface of a honeycomb panel is heated rapidly, generating a thermal gradient through the honeycomb and causing the panel to bow. The purpose of the test was to verify analytical predictions. Preliminary results seem to show that the bowing is slightly (10%) less than predicted. Data is still being analyzed and the testing continues.

Cold Flow Seal Testing

The Cold Flow Seal Team was formed October 1996. Ten TPS panel seal configurations were selected, from 40 different designs, for the cold flow seal testing. Testing was done at room temperature for various pressure differentials (both crush and burst conditions) across the seal. Simulation of panel in-plane gaps were also incorporated in the test hardware. The objective of these tests was to obtain the relative leakage rate among the seal concepts. Three metallic seal concepts were selected for further seal leakage testing at the NASA-MSFC Hot Gas Facility. The test results were also used to assist the preliminary ventilation and thermal analysis and to assist MSFC in predicting the sensitivity of the compartment temperature to seal leakage rate.

Hot Gas Seal Testing

Seal leakage tests have been and are currently being conducted in the Hot Gas Test Facility at MSFC. The tunnel is being used to simulate both subsonic and supersonic external flow conditions across a representative seal. The leakage rates at various seal pressure ratios and temperatures are being measured and subsequently reduced into effective leakage areas. The leakage data is being provided to MSFC for inclusion the vehicle ventilation model.

The Hot Gas Facility has not previously been used to perform these types of tests. Consequently, there was a shake down period required to develop reliable operation methods, and to understand the nature of the tunnel flow. This period is now over and tests will soon resume according to the test plan.

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The initial test results are favorable in that they compare well with existing analytical estimates of seal leakage. The effective leakage areas measured in the tunnel, for the metallic seals, have been less than 0.015 in^2 per linear foot of seal, which was the analytical estimate made early on in Phase II.

PRODUCIBILITY TRIALS AND DEMONSTRATIONS

Single Curvature Metallic Panels

In order to reduce the cost of tooling, scrap rate and schedule impacts, a single curve (using a ruled surface rather then double curvature) approach was adopted in the design of the metallic TPS panels. This has contributed a large portion to the overall cost reduction of the program.

MATERIALS AND PROCESSES

Selection of High-Temperature Alloy (1900F - 2100F)

Rohr has examined several Oxide-Dispersion Strengthened (ODS) alloys (MA 754, MA 956, PM 1000, PM 2000) for use in high-temperature metallic panels. PM 1000 was selected and worked with the supplier to produce foil suitable for core-forming. Previously the material was available only in sheet form. Initial vacuum braze joining studies with the supplier were performed. Rohr also determined that the most promising braze alloy was the discontinued MHF-157, subsequently renamed MBF-100 by the manufacturer and put back on the market. The braze cycle is still in development. Final definition will be made after PM 1000 core is fabricated. Preliminary results show adequate ductility in the PM 1000 after brazing.

MANUFACTURING PROCESSES

Inconel 617 Metallic Panel Brazing Process Definition

Several brazing alloy foils were evaluated with Inco 617 facesheets and core to replace the salt-and-pepper shaker method used in Phase One of the program. MBF-80 foil was selected, and the manufacturer will produce 1-mil thickness foil for a weight reduction in the finished panel. The basic brazing cycle has been set, although slight adjustments may be made in the next week or so to optimize the microstructure and panel physical properties. The cycle was modeled on the heat-up rates anticipated during multi-panel brazing runs, which are thought to be slower than the rates usually achieved in single panel runs.

Inconel 617 Brazing Furnace Cycle Time

Furnace cycle times will be able to be reduced by applying metallic tool concepts in the panel bond cycle, reducing schedule and cost hazards.

Inconel 617 Core Fabrication Process Improvements

The Metallics team has developed the tooling dies required for the 1.5 mil. Inco 617 net core manufacturing process in conjunction with our HTA facility in San Marcos TX. This activity shall support the production panel core and panel assembly fabrication.

RELIABILITY, MAINTAINABILITY, SUPPORTABILITY AND ANALYSIS (RMS&A)

Reliability

Line Replaceable Unit (LRU) Reliability Prediction

The LRU Reliability Prediction is a point estimate analyses based upon the design details for the TPS which are available at that point in time. The Reliability Prediction considers the anticipated X-33 operational environment (including ground transportation and handling) and will be readjusted/reallocated as the design matures.

Failure Modes, Effects and Criticality Analysis (FMECA)

The TPS function is evaluated at the LRU level of indenture to analyze, assess and document the effects of potential failures upon launch

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vehicle reliability, safety and logistics impacts. All operational phases are included in the FMECA. Severity classification and probability of occurrence assignments are consistent with MIL-STD-882. This analysis is completed and has been submitted to LMSW.

Critical Items List (CIL)

A CIL has been created and submitted to LMSW. Any LRU with a failure mode which is assigned a hazard severity of catastrophic or critical is contained in the CIL.

Preliminary Hazard Analysis (PHA)

The PHA is performed early in the design. It is used to identify hazards and assist in establishing safety requirement early in the program.

Subsystem Hazard Analysis (SSHA)

The SSHA expands the PHA and the analysis will continue until all actions required on the identified hazards have been completed.

Qualification Test Environmental Assessment/ Reliability Testing Plan

A listing for the proposed tests and the environmental criteria the tests need to meet has been formulated.

Preliminary Risk Analysis for Reliability

The purpose of the risk analysis is to identify risks associated with the TPS which may impact the system reliability. This analysis has been completed.

Maintainability

Scheduled Maintenance Tasks

Rohr has provided a preliminary list of the Scheduled

Maintenance Tasks for the TPS. The scheduled maintenance consist of required inspections and tasks necessary to process the TPS for each flight test. These maintenance tasks will be limited to the time available during horizontal processing of the X-33 vehicle. Since other X-33 subsystem are located underneath the TPS panels there will be additional close out activities on the TPS during flight test operations.

Fault Detection Methods

Rohr has provided a preliminary list of the Fault Detection Methods for the TPS. The TPS has three material type that must be evaluated prior to flight test to provide confidence that the system is flight ready. The fault detection methods consist of flight test instrumentation, 100% visual inspections and detailed testing of critical areas. The fault detection methods will also be used to rapidly isolate hardware failures to the line replaceable unit (LRU) for maintenance.

Line Replaceable Units (LRU)

Rohr has provided a preliminary list of the Line Replaceable Units for the TPS. To facilitate logistical processing the TPS components are identified by line replaceable units. A line replaceable unit (LRU) is a component or group of components that perform a particular function and can be easily removed and replaced as a unit. Each LRU is assigned a logistics control number that will expedite the vehicle processing and support reliability centered maintenance on the X-33 vehicle. To provide standardization, ATA 100 (similar to Mil Std 1808) was used to define Logistics control numbers. The control number for each LRU is composed of three elements which consist of two digits each: system, subsystem, and unit. This simple, uniform numbering system specifies numbers for the system and subsystem. The unit numbers and their sequence may be selected by the manufacturer to fit the coverage requirements of the vehicle system.

QUALITY ASSURANCE

Quality Assurance Plan

A Quality Assurance Plan based on ISO 9001 was written and will

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ensure that the quality requirements for the TPS are met and consistent with the RTMCA. The Quality Plan is tailored to meet the unique requirements of the X-33 with primary focus on the monitoring and control of critical characteristics.

Software Quality Assurance Plan

A Software Quality Assurance Plan was written and will ensure that the X-33 configuration is maintained throughout Rohr's CAD/CAM/CATIA system, from receipt of customer data to end item acceptance. This SQP applies to product definition, product development, manufacturing and inspection software. Rohr will not be providing any flight software for the X-33 vehicle.

X-33 Material Review Board Procedures

Procedures specific to nonconformances occurring during performance of the X-33 hardware manufacturing were written. Two Quality Instructions were written: 1) For the control of nonconforming laboratory test hardware. This procedure is designed to perform in an R&D environment where rapid evaluation and dispositioning is required. 2) For the control of nonconforming flight hardware. This procedure is design to provide the control of flight hardware manufactured in a product development environment and will provide the visibility of quality costs (scrape, rework, repair).

Quality System Surveys of Suppliers

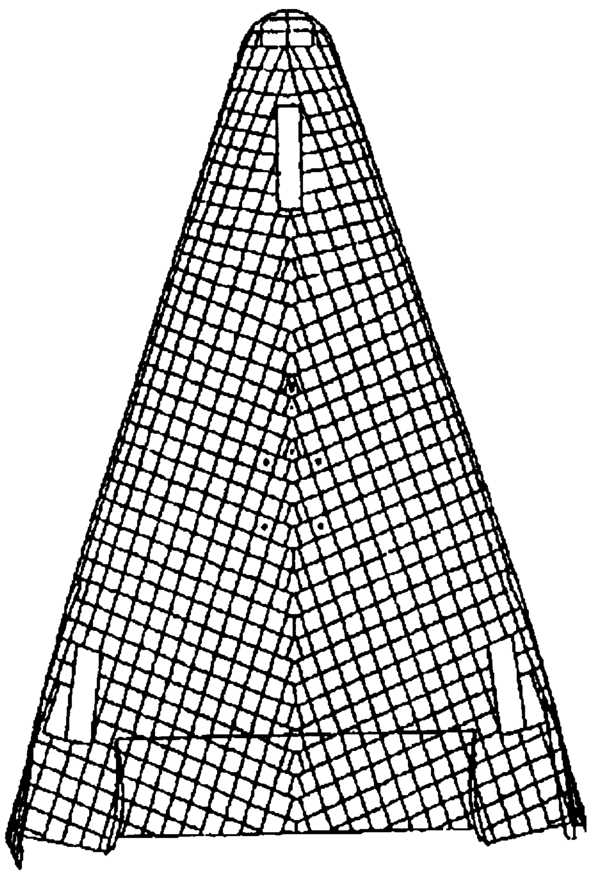
Quality system and process surveys were performed at suppliers that posses the unique abilities and processes to manufacture lightweight, high temperature resistant materials. The surveys included examination of inspection systems, inspection documentation, metrology, calibration, special process controls, material storage handling and purchase material controls.

Evaluation of Alternative Nondestructive Testing Methods

A series of test samples with programmed defects were manufactured representing the X-33 metallic TPS panels. The specimens were then inspected using ultrasonic pulse echo and through transmission techniques (Rohr's standard method), pulsed infrared thermography methods, shearography and optical holography methods. A Probability of Detection (POD) study was performed to quantify each inspection methods capability. The test results show that the Pulsed Infrared Thermoraphy method has an equivalent POD to the Ultrasonic method and is by far the preferred system from a cost and operation stand point.

FIGURE 1

TPS WINDWARD AEROSHELL METALLIC PANEL SPLITLINE EVOLUTION



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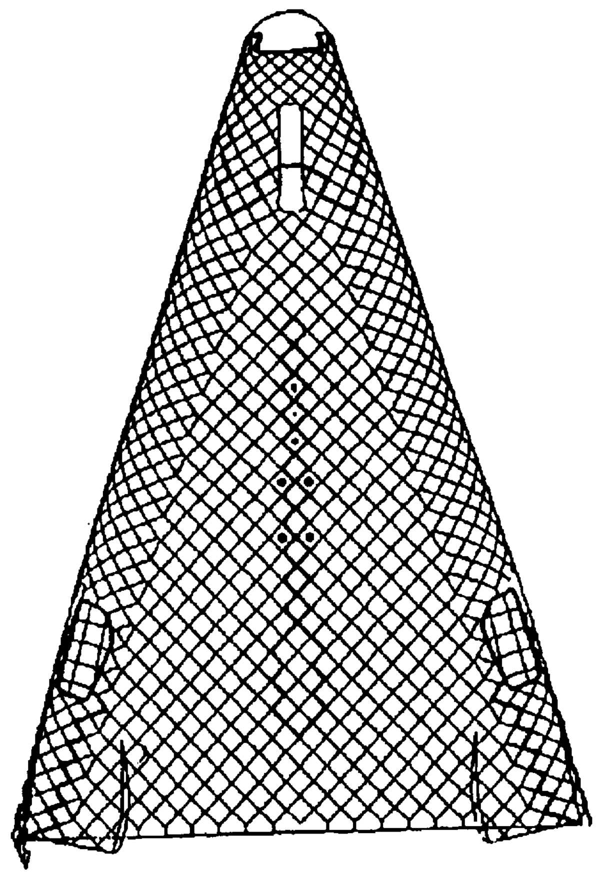

NOW

SVERDRUP TECHNOLOGY, INC.

LAUNCH AND LANDING FACILITIES

Excellent progress has been achieved over the past year on the development of the X-33 Launch and Landing Facilities. All Landing Facilities are being provided by the Government using existing facilities. Costs for this GFE usage are being negotiated. The Launch Complex Facilities will be developed by the X-33 team starting from a green field site.

Early launch complex site selection trade studies identified the site location near Haystack Butte, southeast of Phillips Lab on Edwards Air Force Base to be the optimum choice considering safety, all EAFB operational activities, costs and schedule. The launch complex facilities design, which has been developed concurrently with the vehicle design, is complete except for some specific areas on hold awaiting the latest vehicle design modifications. The pre-final (90%) facilities design review meeting will be mid August, 1997. The X-33 facilities design has achieved direct traceability to RLV facilities and operations concepts in all critical areas of design.

In addition to accomplishing the facilities design, considerable progress has been achieved in preparation for on-site construction of the launch complex facilities. The program EIS has been released in a draft form for comment and the process is on track for a Record of Decision in time to permit start of construction in October, 1997. Similarly, progress in obtaining construction and operation permits is on track to allow the construction start date. All site characterization surveys and analyses, including geographic, topographic, geotechnical, endangered species, hazardous materials, and archeological have been completed and no barriers to an October, 1997 construction start date exist in these disciplines.

A major achievement of the Operations IPT has been the control of the X-33 Launch Complex facilities costs. The primary detractor of the Haystack Butte site was a $5 million cost increase over the baseline estimate. Through value engineering, use of a Cooperative Research and Development Agreement (CRDA) for X-33 use of the site, joint X-33 / EAFB utility system

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improvement programs, receipt of a $1 million Highway-to-Space Grant from the State of California, and the use of GFE and leased equipment, the team has been able to absorb the additional costs of the Haystack Butte site while actually reducing the total launch complex facility costs below the baseline estimate. Additional cost avoidance opportunities are being pursued.

The team is poised to complete development of the X-33 facilities by October, 1998. All long-lead equipment is on order, pre-qualified subcontractor bidders lists are established, and the construction bid package are structured and ready for incorporation of the final technical design documents prior to release for bids. Many of the candidate bidders are small businesses or small disadvantaged businesses. Two of the three subcontractors awarded to date have been to small business firms. One of these firms was a Native American small business.

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NASA CENTERS
TASK AGREEMENT SUPPORT

AMES RESEARCH CENTER

- Provided 45 aerothermal CFD solutions that cover the X-33 flight range of Mach No., Reynolds No., angle of attack, control surface deflection angles and both laminar and turbulent flow.

- Released Version 2 of the Aerothermal Environments Design Database for the Malmstrom-4 trajectory. The new analysis approach of making the benchmark CFD database independent of trajectory, reduces cycle time from 9 weeks to 1 week.

- Completed independent TPS sizing analysis for the new released Malmstrom-4 aerothermal environment. This analysis will be compared with the Rohr analysis to resolve any differences and thus reduce design risk.

- Completed parametric CFD/structural response analysis of metallic panel bowing, seal design concepts, and step heights.

- Supported thermal design of the Combined Environments Tests at MSFC.

- Expanded the X-33 Thermal Design Database to include thermal properties for all vehicle materials. The protected website site has had 300 hits in less than a month by X-33 teammates.

- Provided blanket TPS data, bonding testing, and guidance to the leeward TPS design team.

- Supported the TPS seals downselect team and initiated a development program for a backup seal concept.

- Provided requirements for Flight Test Instrumentation (FTI) and hardware instrumentation concepts for implementation on the leeward

TPS.

- Participated as a member of the Weight Reduction Tiger team.

- Completed surface material characterization over complete temperature range for all TPS surfaces including potential coatings.

DRYDEN FLIGHT RESEARCH CENTER

- The subscale Linear Aerospike Engine ground test firings were completed at Edwards. These firings of a reduced size engine will lead to a configuration that is being planned for firing on an SR-71 Supersonic Aircraft later this year.

- The Dryden Aerodynamic group provided a Flush Air Data System (FADS) design that has now been incorporated into the X-33 vehicle as the air data source of information. The FADS design provides many solutions to overcoming design issues with pop-out probes on a Hypersonic Flight vehicle.

- Dryden and Lockheed personnel jointly built up a Software Integration Laboratory Facility at Dryden's Research Aircraft Integration Facility (RAIF) at Edwards.

- This laboratory collocated the initial X-33 vehicle & aerodynamic models for preparation for the first avionics integration effort starting next year.

- Dryden's Flight Control Engineers provided an initial design of a reconfigurable flight control system. This design will be refined as the overall vehicles design matures.

EDWARDS AIR FORCE BASE - AIR FORCE FLIGHT TEST CENTER

Launch Site Selected

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An area on the western edge of the East Precision Impact Range Area (PIRA), next to the Phillips Lab at Edwards AFB (EAFB), has been set aside for the X-33 Launch facilities. The plan to get approval (permits, etc.) from the various Air Force and Government Agencies to use this site is complete and the execution of that plan initiated. A Cooperative Research and Development Agreement (CRDA) has been drafted as the means to provide the land to LMSW for the duration of the X-33 program.

The site has been surveyed and soil core sampling completed. An environmental assessment of the site has been completed by the EAFB Environmental Office and has been included in the X-33 Environmental Impact Statement. A building near the launch site has been committed to the X-33 program for the Operations Control Center.

Range Safety Analysis Initiated

The EAFB Range Safety office has become an active participant in defining the X-33 range safety system, and the flight approval process. The regulation governing the Range Safety Requirements, Eastern and Western Range 127-1, has been tailored to the X-33, and the review process for getting its approval by the EAFB Range Commander has been initiated.

Flight Test Maneuver Planning Initiated

Automated maneuvers (pitch axis pushover-pullup) for extracting performance and heating data from flight test have been documented in a draft design description document, and these requirements are being refined through the X-33 avionics IPT. These maneuvers have been used on many previous test programs, but this would be the first time they will be done autonomously.

Range and Landing Site Coordination Initiated

AFFTC is an active member of the range systems definition team, headed by NASA Dryden, that has defined the complete extended range requirements for tracking the X-33 and collecting the real-time flight data. This has required extensive coordination with other test ranges as well as the

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downrange landing sites.

Flight Planning/Trajectory Consultations

The AFFTC's extensive experience with testing low lift-to-drag ratio lifting body configurations was been, and continues to be, passed on to the X-33 team through the Flight Sciences IPT and various working groups.

Task Agreements Expanded

A Program Introduction Document has been received from LMSW outlining the expanded services being requested from EAFB. The process to cost and commit these services to the X-33 program has been initiated.

JOHN F. KENNEDY SPACE CENTER

Holddown Post Testing

- Revised and updated the Task Agreement to reflect the current scope of anticipated testing in FY 98.
- No testing to be accomplished until FY 98.

Umbilical Plate Testing

- Revised and updated the Task Agreement to reflect the current scope of anticipated testing in FY 98.
- No testing to be accomplished until FY 98.

Programmatic support

- Provided periodic programmatic reports and support to the X-33 Program Office.

Support to IHM Development

- Supported LMCMS development and architectural studies.
- Provided on site support to the LMCMS IPT through PDR.
- All work was stopped on this Task Agreement at the direction of the Program Office.

Phase II EA/EIS Support

- Developed and published programmatic Environmental Assessment.
- Supported public Scoping meetings at multiple proposed launch and landing sites.
- Provided detailed meeting minutes and transcripts of the Scoping meetings to MSFC.
- Prepared the Biological Assessment for the program as required by Section 7 of the Endangered Species Act.
- Supported MSFC preparation of the Draft Environmental Impact Statement (DEIS). Prepared large sections of the document, performed detailed environmental impact analyses and graphics for the document.
- Supported second set of public meetings associated with the publication of the DEIS.

Ground Interface Modules (GIM)

- Designed and built software that added a TCPIP protocol to the existing TCMS IO FEP software, and adapted that combined software to run on HIM II hardware, in accordance with Sanders requirements.
- Built a GIM rack by configuring a HIM rack with 4 I/O cards of the type needed by X-33.

- Performed a Design Verification Test on the configured GIM rack to verify that it met X-33 Requirements.

- Demonstrated good communication between the GIM rack at KSC and Sanders in Nashua using existing networks.

GSE Design Support

- Conducted umbilical system and vehicle positioning system (VPS) trade studies.

- Provided a preliminary design concept of a Holddown post blast shield for the
- Program PDR.

- Supported the X-33 Program PDR.

- Prepared umbilical system and vehicle positioning system (VPS) design drawings and provided 60% complete drawings for the umbilical and VPS Mid-term review.

- Provided cost estimates for the umbilical system and VPS.

LANGLEY RESEARCH CENTER

Aerodynamics

- Conducted initial hypersonic configuration screening tests in M=20 helium
- In response to a request from Rohr for 7 runs on F-Loft to determine the heating due to sideslip in support of the PDR, conducted 39 experimental heating (phosphor thermography) tests over AOA range of -3 to 45 deg. and 6 deg. of yaw. In addition to effects of yaw on heating, also showed heating on the canted and vertical fins and deflected body flaps
- Completed low speed force and moment and Flush Air Data System (FADS) calibration tests of Model C in LaRC LTPT

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- Conducted M=20 fins and flap configuration modification tests
- Completed transonic force and moment and FADS calibration tests in 16-Ft tunnel
- Conducted M=20 flap configuration modification tests
- Completed supersonic force and moment and FADS calibration tests in the UPWT
- Obtained X-33 surface pressures for several trajectories in support of venting and aerodynamic loads analyses at MSF

Thermodynamics

- Generated inviscid LATCH code to benchmark time histories for D-Loft geometry and Malmstrom 4 trajectory
- Provided on-site CFD support at LMSW in Palmdale by detailing Frank Greene for six months
- In response to a request by LMSW, delivered plasma analysis for signal loss to range safety during blackout. To lessen the resulting 6 min. of blackout, an expensive option to replace the UHF-Band antenna with a higher frequency L-Band might be needed
- Heating from LAURA CFD sent to LMSW/Rohr to define TPS split lines
- Provided consultation to the NASA X-33 Program Manager on flight test requirements for the X-33. Specifically addressed the technical "requirement" for Mach 15 flight, versus other (more phenomenon-based) "requirements," such as assurance that laminar-to-turbulent boundary-layer transition is achieved and measured.
- Assessed impact of outboard sweep of body flap on edge heating
- Provided consultation to the NASA X-33 Deputy Program Manager, Flight Test, regarding flight test instrumentation requirements that included coordination of multi-Center input to establish instrumentation requirements for aerothermodynamics.
- Responded to a request to refine the earlier radio blackout analysis. Plasma properties at two additional trajectory points were delivered to LMSW. Also delivered a signal attenuation analysis of Shuttle entry. Received a letter of appreciation for LaRC support from X-33 Range Mgr.

- Provided LMSW/Rocketdyne with laminar Navier-Stokes fine grid solutions for the base flow region showing heating for Malmstrom (M=11) trajectories
- 11 flight heating cases sent to LMSW/Rohr for heating data base and canted fin design
- Four fine-grid CFD flight heating cases supplied to LMSW (3 D-Loft and 1 F-Loft) for M=15 and 11.4 Malmstrom-4 trajectories
- Delivered heating approximations for D-Loft to replace F-Loft values
- Sent boundary-layer transition criteria to LMSW for data base

Wind Tunnel Test Models

- Completed design and fabrication of Model C for low-speed testing
- Completed fabrication of 12 ceramic models for hypersonic force and moment and heating tests
- Completed design and fabrication of model J (F-Loft) for ground effects tests in the 14X22 tunnel

RLV System Concept Maturation and Trade Studies

- At request of NASA X-33 Deputy Program Manager, Flight Test, drafted a Program "Traceability" Control Document format to assure that the X-33 vehicle development and flight test programs would meet RLV "traceability" objectives.
- Participant in the Phase II RLV Planning Team meetings.
- Preliminary sizing assessment performed for RLV reference vehicle.

X-33 Reliability, Maintenance and Logistics

- Developed an analysis methodology for estimating the confidence level for the predicted Safe Recovery Reliability
- Support LMSW/RMS&A team and Rohr in developing Thermal Protection System test plans.

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Cryogenic Insulation

- Completed structural testing of a Al-2219 panel with SOFI (Spray on Foam) and PIP (Poured in Place) insulation in the 1'x2' rig.
- Initiated testing Phase II graphite-epoxy panels with Airex and Cryocoat blocks bonded together.
- Completed Phase I testing for Boeing K3B panels (failure occurred in the built-up block region).
- A second test stand was brought on-line. (Used a sandwich panel with Graphite-Epoxy facesheets and a Rohacell core to checkout the system. Maintained a change in temperature of 600_F through the thickness of the panel.)
- Completed testing of one Phase II panel for LMMSS.
- Started testing a second Phase II panel for LMMSS.

X-33 Pressure Box Test

- New Universal Loads Introduction Plates and Drill Rig have been developed and built for the Cryo Pressure Box
- Universal drill rigs have been designed fabricated and assembled.
- Apparent strain rig has been modified.

Subscale Composite Health Monitoring Evaluation

- Installed optical fiber sensors onto 1x2 foot composite panels (for mechanical testing with a cryo backface) and tested light loss in the system before and after cryogenic cycling for fiber integrity

X-33 RCTS VHM Sensor Suite

- Installed fiber optic draw tower and laser system for fiber sensor manufacturing

- Continued development support of VHM sensors to measure strain and hydrogen gas (leaks) as well as monitored development of temperature sensors for X-33 flight instrumentation

Dual Lobe Ground Test VHM Sensor System

- Supported Lockheed Sanders in converting laboratory Distributed Strain Sensor (DSS) system to flight system
- Developed DSS demodulation system for strain and hydrogen measurement
- Manufactured Fiber Optic Bragg Gratings for DSS system to be installed onto 17' composite tank
- Installed DSS and Distributed Temperature Sensor (DTS) sensors onto 17' composite tank
- Measured fiber optic distributed strain and temperature on 17 foot composite cryogenic tank at NASA Stennis.

Thermal and Structural Analysis and Design

Panel flutter analysis:

- Task initiated with ODU to incorporate hypersonic panel flutter analysis into commercial f.e. code (11/96)
- Flutter analysis of payload bay doors indicated no flutter problem
- Two day flutter seminar presented by Dr. Mei and Roger Chen of ODU at Rohr's request (5/97)
- Currently negotiating with MARC for access to source code required to implement flutter analysis capability
- Thermal analysis:
- analysis of metallic TPS tested at JSC shows good agreement with experiment for panel center
- model, including radiation and attachment details, developed and being checked out

Design:

- Coordination meeting and subsequent biweekly telecons with Rohr metallic TPS design team
- Critique of current X-33 metallic TPS design identified several

potential improvements

- Two additional panel-to-panel seal concepts suggested
- Alternative X-33 metallic TPS concept identified (preliminary weight estimates made)
- Structural analysis:
- Analysis of outer honeycomb panels with through-the-thickness temperature gradient (stresses and deflections calculated for worst case engine plume heating of typical TPS panel)

Consultation:

- Presented "lessons learned" on metallic TPS under phase 1 of X-33 at Rohr (10/96)
- Provided reports on LaRC experience in metallic TPS, including coated columbium heat shields, insulation, surface properties of high temperature metals exposed to hot gas flow, etc.

Thermal Characterization Tests

- Initiated heater development for thermal vacuum test facility

Impact Testing of Metallic and Carbon-Carbon TPS

- Initiated discussion of low speed impact tests for upper surface blankets

High- temperature, High Speed Tests

- Working with Rohr to define meaningful tests of panel to panel seals

Program Management and Cost Reporting

- Negotiated final set of 27 tasks with the X-33/RLV Phase II industry team, LMSW, for a total of $10.8M for LaRC
- Successfully recruited a LaRC person for a six-month assignment to

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the LMSW Palmdale plant to support the X-33 team in the area of CFD

- Supported LMSW in the Preliminary Design Review at DFRC
- Presented overview of LaRC X-33 activities to T. K. Mattingly, V. P. Lockheed
- Martin for the X-33 RLV Program
- Met the FY96 Code R 100% Obligation metric
- Attended X-33 Quarterly Review at Rocketdyne, Canoga Park, CA
- Obtained additional 1000 hr on the NAS super computer for CFD
- Submitted Agency requirements for FY98 IT super computing hours

  At the request of the LMSW X-33 Vehicle Manager, two LaRC individuals participated in X-33 Weight and Cost Reduction Tiger Team activities and one served on the Independent Technology Review Team.
- Began interfacing with the local OIG in the audit of the Langley X-33 task activities

Aerothermodynamic Database Development and Validation - X-33

- Windward acreage heating environments sent to LMSW on Phase I geometry (1001A)
- Engineering/LATCH code methodology modified to better predict center-line heating
- Windward acreage heating time histories for 78 points supplied to LMSW and MSFC for D-Loft, Malmstrom 4 to update the analysis of the internal insulation requirements. The LATCH and MINIVER solutions at peak heating closely matched the detailed CFD results using the LAURA code. This significantly reduces the computational requirements associated with running the number of CFD solutions typically required for such an analysis.
- Proposed and evaluated external flight test instrumentation layout
- Delivered eight D-Loft inviscid/LATCH heating cases
- Supplied predicted heat-transfer coefficient time histories (using LATCH code) at selected locations on the canted fin (54 windward, 12 leading, and 37 leeward) for the D-Loft and Old Malmstrom 4 trajectory to Rohr and ARC.

- In response to a LMSW request, an assessment of the effect of heating on the X-33 canted fin due to reducing the dihedral from its current value of 37 deg to a proposed 20 deg was performed. Engineering estimates show potentially a 20-25% increase in heating to the leading edge for a 36 deg angle of attack at the peak heating condition.
- Assessed potential impact of negative angle of attack on leeside TPS requirements
- At the request of MSFC, simulated an alternate trajectory strategy for the Mach 15 mission to Malmstrom AFB where the flight path angle was controlled using yaw steering instead of pitch steering while the vehicle was thrusting. The results showed an increase in aerodynamic loads on the X-33 and a decrease in performance because the vehicle flew lower in the atmosphere during ascent. (The trajectory team at MSFC had tried unsuccessfully to simulate this trajectory.)
- Supported MSFC on the X-33 flight test trajectory development including an abort for the M 9 mission into Michael AFB and a M 15 trajectory to Moses Lake. The results were included in the Preliminary Design Review.

LEWIS RESEARCH CENTER

RCS Thruster and T/A Exhaust Plume Impingements

Under a grant with the NASA Lewis Research Center, Cornell University provided modeling of the plume flowfields from the X-33 Reaction Control System (RCS) thrusters and turboalternator (T/A) exhaust ports. Axisymmetric descriptions of the RCS plumes, expanding into three different back pressures (simulating different altitudes) were developed. Two-dimensional descriptions of the T/A exhaust expanding into three different hypersonic cross-flows were also developed. The plume descriptions included contours of Mach number, pressure, temperature, density, and species. The plume descriptions were provided to Lockheed Martin and Rohr, for assessment of the plume impacts on the X-33 vehicle thermal protection system.

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XRS-2200 Engine Combustion Wave Ignition Tests

NASA Lewis Research Center (LeRC), in cooperation with Rocketdyne Boeing, successfully completed the X-33 Combustion Wave Ignition (CWI) Single Element test series. This innovative ignition system will be used on the XRS-2200 aerospike engine being developed by Rocketdyne as the main propulsion system for the X-33 vehicle. The combustion wave ignition concept enables multiple combustion chambers (thrust cells) to be ignited from a single ignition source.

A total of 158 tests were conducted at LeRC, successfully mapping the entire combustion wave system operational envelope. The testing, which began in April 1997, met all program objectives and allowed the X-33 CWI design team to close major gaps of knowledge, complete its design, and proceed in hardware fabrication.

This test series tested a sub-scale, single element ignition system with gaseous hydrogen and oxygen propellants. The next test series, also to be performed at LeRC, will test a multi-element, flight prototype, ignition system using liquid hydrogen and oxygen propellants. This next phase of testing is scheduled to begin in August, 1997 at LeRC.

MARSHALL SPACE FLIGHT CENTER

X-33 Safety, Reliability, Maintainability, and Mission Assurance:

Jointly with Rocketdyne and Lockheed Martin Manned Space Systems (LMMSS), quantitative reliability predictions for the linear aerospike engine and the main propulsion system (MPS) were performed.

This included reliability modeling and data analysis. Parts of the Failure Modes and Effects Analysis (FMEA) were performed on both the linear aerospike engine and the MPS. For the linear aerospike engine, the FMEA effort involved PowerPack components, control valves, pneumatic system, combustion devices, and the engine controller data interface unit (DIU). For the MPS, the FMEA effort involved the tanks, GO2 and GH2 pressure/vent/relief systems, and the LO2 and LH2 feed, fill, and drain

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systems.

The fault tree for the linear aerospike engine was developed and supported given in the development of the MPS fault tree, including quantification of basic events. Using FTA, sensitivity analysis and engine configuration trade studies such as dual independent engines versus PowerPack out configurations were performed. Maintainability analyses were performed which supported Rocketdyne by providing a SSME-based operations/maintainability database.

Additionally, during the past 12 months, significant contributions have been made to the X-33 Reliability, Maintainability/Testability, Supportability, & Population Hazard Analysis (RMS&A) Team effort. This was performed through active participation in special task teams (Flight Termination System) and program reviews, providing computer aided fault tree analysis (CAFTA) software, technical support, and consultation in the various S&MA areas.

Natural Terrestrial Environment:

Jimesphere detailed wind profiles were provided for Edwards Air Force Base (EAFB) and Vandenberg Air Force Base (VAFB) and a monthly enveloping vector wind model developed for EAFB (delivered 9/96) for X-33 preliminary design studies (delivered 8/96). Also, provided were EAFB ground winds data for liftoff drift analysis (delivered 3/97).

Support was provided for the Flight Sciences Team Preliminary Design Review; the launch site was visited and recommen-dations for atmospheric sensors for the launch site made (6/97). Currently, support is being provided in the development of a meteorological plan for launch, operation and landing of X-33. The current EAFB rawindsonde wind profile pairs database is being archived and distributed as needed and a new version of the GRAM-95 is being tested in order to meet site specific needs of the X-33 Program.

RF Communication System Design and Coverage Analysis:

Major contributions were made to Allied Signal in the design of the entire RF system communication system including ground station interfaces. Procurement specifications to be used in the purchase of the RF equipment were prepared and delivered. An independent evaluation and certain testing of the aydin vector receiver to be used on X-33 was performed.

Allied Signal has been provided with initial look angle data from Marshall Space Flight Center's (MSFC's) three-dimensional computer simulation that utilizes both program trajectory and attitude data developed by MSFC for the X-33 Program. Final vehicle and ground site look angle data is being provided to Allied Signal for the Silurian_2b, Michael_5b, and Malmstrom_5e missions.

Updates will be provided for the new mission trajectories as they are defined and baselined. Work has also begun on reading theoretical antenna pattern data, provided by Allied Signal, into the simulation and performing communication system link analysis calculations. This work will provide Allied Signal with an assessment of the X-33 communication system capabilities

Electromagnetic Compatibility Support:

Electromagnetic compatibility (EMC) support has been provided through review and interpretation of X-33 vehicle, EMI requirements, and how those requirements apply to the area of vehicle grounding, bonding, EMI, and electrical power bus quality specification; the performance of corona testing of electromechanical switchgear; and the flight control actuator system EMI testing to be performed at MSFC.

Selection and Test of Electrical Switchgear:

Engineering support was provided in the overall power system design and in the selection of the electrical switchgear to be incorporated in the electrical power distribution and control system. A major role was played in drafting the X-33 Corona Guidelines Document (604D0024) and in the performance of corona testing of electromechanical switchgear to be flown on X-33. Support was also provided in the X-33 redesign from a turbo alternator system to a battery system.

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Hydrogen Sensing System:

Engineering support has been provided, primarily to Allied Signal, for the development of the flight hydrogen detection system for X-33. Purchase specifications and statements of work to be used in the procurement of the system were supplied and consultation provided in the selection of smoke detection equipment and oxygen sensors.

Optical Plume Anomaly Detection (OPAD):

OPAD support was provided for the multi-cell component hot-fire tests conducted at Test Stand (TS) 116 at MSFC. Various types of instrumentation, including standard video cameras (as well as IR and UV cameras) and spectrometers configured for absorption and emission spectroscopy were utilized. Results from the instrumentation/test were provided to Rocketdyne.

Antenna Testing:

Radiation distribution comparison tests on the S-band (Hurley-Vega model 815S) and the C-band (Hurley-Vega model 820C) antennas were performed. Principle-plane cut azimuth antenna patterns, circularity, and VSWR were measured with both the S-band and C-band antennas mounted on aluminum and composite ground planes. Two types of thermal protection system materials (thermal blanket plus RTV 560, and AFRIZI plus RTV 560) were tested.

Automated Rendezvous and Capture (AR&C):

With the accomplishment of two technical interchange meetings with our industry partners a thorough understanding of the technologies involved with the AR&C project has been communicated to all concerned parties.

Integrated Power and Distribution System Support:

Engineering support was provided to Allied Signal in the area of vehicle grounding, bonding, EMI, and electrical power bus quality specification. Several documents related to power generation, power distribution and control, and transients associated with the EMA loads were reviewed and red-lined. General support in the area of electrical conductors and wire terminations and connectors was provided.

INS/GPS Hardware in-the-loop Simulation:

The set up for the INS/GPS hardware in-the-loop simulation in the MSFC MAST lab was begun. The MAVRIC simulation, being modified to run in real time, will provide the GN&C algorithms to operate he GPS/INS hardware in the simulated X-33 vehicle environment.

Propulsion System Testing:

An initial misunderstanding concerning the injector test scope was resolved with Rocketdyne by moving the combustion wave ignition testing to NASA/Lewis Research Center. The test planning and hardware preparation for stability testing to be performed at MSFC has been completed. The testing is scheduled to start 7/23/97 and to be completed by 8/5/97.

Initial testing to support the verification operating modes of the J2 gas generator (GG) were conducted. Strain gages were mounted to the J2GG, a helium supply system was installed for simulation of the helium spin start, and the hot-fire GG was assembled and mounted into the thrust mount. Following this, the J2 hardware was installed into TS 116 preburner position and leak checks and facility preparations completed.

A Test Readiness Review was conducted 6/17/97 and the first phase of J2GG hot-fire testing was completed using a pyro ignition system. Phase I resulted in data at chamber pressures from 320 psi to the emergency power level GG chamber pressure of 900 psi. Phase I tested revealed a higher than ancticipated pressure drop in the GG that will be accounted for in the phase II testing, which will also incorporate the flight spark ignition system. Phase II testing will commence following completion of the removal of the hydrogen tank at TS 116.

X-33 Linear Aerospike Engine Multi-Thrustcell Testing

(This testing was not a part of the X-33 Cooperative Agreement but rather was

a propulsion technology effort to directly support the development of the X-33 linear aerospike engine.) The objectives of the multi-cell test program at MSFC's TS 116 were to demonstrate and investigate: multi-cell ignition; cell-to-cell plume interaction; cell-to-cell feed system interaction; base, plug, fence, and cowl heating; thrust and thrust vector control (multi-cell throttling) over a wide range of power levels and mixture ratios. The multicell test program was completed on 5/5/97.

Reaction Control System (RCS) Analytical Modeling:

The steady state RCS model was completed and results presented at the RCS Critical Design Review (CDR). The RCS transient model was begun with the ROCETS code but was put on hold when the turbopump test failure occurred. Model development remains on hold until further direction from our Rocketdyne/Aerojet industry partners.

X-33 Power System/Actuator Simulation and Integrated Test:

Extensive planning and coordination with our industry partners to expand this initial test to an end-to-end system test was performed. This involved adding hot-fire testing. However, after discussions with our industry partner it was mutually determined they could not support the required funding and schedule. It was established that to perform an end-to-end test would result in 3-5 months schedule slip. MSFC agreed to rescope the task when it becomes clear what testing will be performed on site. Since a vehicle weight reduction exercise resulted in a change from a turboalternator to batteries for system electrical power, the test is being revised/planned to incorporate the changes.

Flight Control Actuator Model Development and Test:

A test requirements matrix was developed including tests to be performed, data requirements, needed instrumentation, and support equipment. After a preliminary design for an inertia simulator for testing was agreed to, modified drawings for use in the inertia simulator clevis designs for the actuator were received from Allied Signal. Clevis drawings of the 100k load bench were completed and fabrication contracts for the clevises awarded. Inertia simulator drawings were completed and procurement initiated for hardware delivery with award by 7/23/97.

Facility preparation for testing is underway in the actuator laboratory with cables being installed from the fixtures to the data room. New schedules, released at the actuator CDR's, and requested changes to hardware to be tested, directly impact this testing and are currently being evaluated.

Helium Storage Subsystem Test:

After completion of five loading cycles on the A2100 composite tank (helium), to provide quick look results to our industry partner, a 3750 psi cryo proof test and 50 planned pressure load cycles were completed on the tank. At the request of our industry partner, LMMSS, an additional 50 pressure cycles of testing in GH2 to test for hydrogen embrittlement were completed. Requests to perform (1) capability/burst test of a A2100 helium bottle when exposed to X-33 thermal/pressure environment, and (2) additional proof tests on eight flight bottles are currently being evaluated.

Hydrogen Tank Joint Seal Test:

Initial setup for quick testing in 9/96 to evaluate leakage of various composite LH2 tank joint designs was completed. However, delivery of test article was delayed due to X-33 hydrogen tank design changes and testing was not performed. Initial rescoping of the test effort to include the new double cylinder with woven composite joint is currently being worked with LMSW. Test article delivery is now estimated to be mid 8/97.

Propulsion System Design Reliability and Operability Modeling:

Initial reliability estimates and models were developed and provided to Lockheed Martin Skunkworks (LMSW). Quantification of J2 and MPS reliability based upon existing design information was performed. Preliminary and final reliability analysis of Rocketdyne multi-cell test data were also provided. Initial operability analysis was performed and OPS/maintainability models provided to the LMSW. The STS OMRSSD's and OMFSD's were evaluated and their applicability to X-33 engine discussed with Rocketdyne and the LMSW. Inputs were provided in support

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of the design reviews.

Propulsion Health Management System Development:

An STS MPS/SSME health management system analysis and an STS process/HW analysis was provided to LMSW. Worked quick look integrated diagnostic/testability (ID/T) analysis. A quick look ID/T analysis was performed and the HMS and engine fault tree issues of mitigation and isolation were resolved. All results were reflected in the ID/T matrix that was finalized and provided to LMSW. Final engine integrated diagnostics were provided to Rocketdyne and LMSW. A proposal for an integrated ground based engine HMS included was submitted to Rocketdyne at their request.

Ascent and Entry Trajectories, Guidance, and Flight Control:

Numerous X-33 trajectories to various landing sites, trading off vehicle parameters, trajectory shaping methods, margins, constraints, and other parameters have been generated. The X-33 reference trajectories used by the rest of the program were generated and guidance algorithms developed that successfully fly the desired X-33 ascent, transition, and entry flight phases for nominal and dispersed trajectories. The effects of vehicle and environmental dispersions were simulated and examined and the algorithms and analysis results documented in detail.

The initial X-33 mission manager logic to reside on-board the vehicle and evaluate mission performance during flight was developed. The logic reshapes trajectories as necessary to accommodate various dispersion and abort conditions. Use of on-board software to examine ascent and entry performance, to retarget to alternate landing sites, if necessary, and to perform closed-loop guidance from liftoff to handle significantly off-nominal cases represents new technology.

X-33 design criteria were provided to LMSW, including slosh damping requirements, aerosurface and engine actuator requirements, flight control system detailed design requirements for flight software design, and RCS sizing and location requirements. Load indicators for loads analysis and structural design based upon both annual and day-of-launch wind criteria were provided. Also, delivered were ascent, transition, and entry flight

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control sections to LMSW for inclusion in the GN&C Detailed Design Document and the GN&C Analysis and Simulation Document.

LMSW was provided with an initial version of the MSFC 6-DOF simulation "MAVERIC" and several subsequent updates which was subsequently provided to several other organizations including Allied Signal (Avionics and Software Developer) and Dryden (Integrated Test Facility). A trade study to define techniques for accommodating the vehicle's low roll axis control authority to roll aerodynamic torque ratio was performed and the results provided to LMSW. Suggestions that day-of-launch wind biasing be adopted was accepted for X-33 flight operations. Engine and feedline models for use in analysis and design of a pogo suppressor have been created.

Structural Loads & Dynamics:

Vehicle loads analyses have been performed and loads provided for the prelaunch, liftoff, ascent, reentry, landing, shuttle carrier, and maximum thermal loading events. Ascent loads used the results of MSFC computational fluid dynamics (CFD) analyses benchmarked by jet effects 2 wind tunnel data. Individual finite element models of the launch platform, vehicle aeroshell, and aero surfaces were generated and integrated with other partner's models into a total finite element model of the X-33 and the structural dynamics characteristics determined.

Slosh damping verification has been performed for the slosh baffle designs. Acoustic structural transmission losses for the X-33 vehicle were calculated and internal acoustic environments determined using external environments supplied by MSFC. Random vibration criteria were developed for 19 different locations around the X-33 vehicle and an acoustic test performed on a sample of composite honeycomb panel in support of vibration criteria development. The deflection of an avionics panel due to acoustic excitation was also calculated. Sections of the Environmental Criteria Document (ECD) dealing with test philosophy and methodology were written.

Induced Environments:

The MSFC Trisonic Wind Tunnel has been utilized extensively in phase II of the X-33 Program. Since 11/96 the facility has almost exclusively tested X-33 configurations. The transonic aerodynamic data for the initial aero database was completed 1/97 revealing for the first time several controllability issues/concerns. Subsequently, extensive parametric Wind Tunnel testing of configuration modifications to resolve these issues was performed. This involved model modifications, several thousand run, and sometimes round-the-clock operations.

Predictions for liftoff, ascent, and reentry acoustic environments have been generated and active assessments made of the launch stand changes to reduce the liftoff environments. Support has been provided for the development of the Environmental Impact Statement and its presentation to the public.

CFD analyses have been performed for numerous X-33 flight loads conditions (alpha, beta, mach). Surface pressure data from these calculations were the inputs to the integrated finite element model runs for the ascent loads cases used for structural design. Jet effects series Wind Tunnel test data were analyzed to benchmark CFD analyses and to support the aerodynamic, loads, and plume induced database development efforts.

CFD analysis of five test points of the jet effects 2 Wind Tunnel test have been completed. The domain includes the entire X-33 vehicle and aerospike engine and contains appoximately 3.5 milllon nodes. The forebody pressure coefficients match the data very well and the vehicle base pressure and nozzle ramp pressures agree well with the data. These CFD cases will be used to help determine the plume effects on the X-33 aerodynamics.

Cycle 1 Preliminary Design Review (PDR) and Cycle 2 Post PDR X-33 ascent plume induced thermal design environments have been generated and released. A first order engineering assessment of potential hydrogen concentration levels downstream of the X-33 turboalternator exhausts was performed. For various ascent trajectory time points, the analysis defined resulting burning exhaust gas temperature distributions downstream of the exhausts indicating a potential for gas ingestion in the aft vent ports. Preliminary X-33 RCS thruster plume impingement heating and pressures for both hydrogen and methane RCS systems were generated.

Compartment venting requirements were assessed and preliminary ascent and reentry aeroshell and fin/rudder venting analyses conducted yielding design delta pressures and inputs to vent door open/close schedules.

Required flight test instrumentation measurement locations and specifications have been identified to provide flight data for comaprison with X-33 preflight predictions to validate prediction methodology for the Reusable Launch Vehicle (RLV).

Fluid dynamic analysis of the Saturn S-IVB LOX and LH2 feedlines was performed to establish part of the X-33 propulsion system to engine ICD. Analyses were also performed on the X-33 LOX feedline and the currently baselined X-33 LH2 feedline with turning vanes and variable cross-section designed and analyzed. Test planning with RHOR and LMSW and design and fabrication of the combined environments testing apparatus is continuing. This facility will provide combined biaxial tension, acoustic, and thermal testing of X-33 TPS.

Thermal Assessment and Thermal Control:

The internal compartment environments of the X-33 during ground purging, flight and post landing operations have been determined. The affects of air leakage thru the TPS, venting, cryo-tanks, and aero heating were included. Various sensitivity studies were performed to aid in the design. The performance of the ATCS was determined for the various modes of operation and the response of the avionics to operations without the ATCS was predicted.

A trade study was also completed to quantify the impact of an alternative cooling method utilizing phase change materials. Aerothermal TPS sizing has been accomplished for several windward and leeward TPS concepts and configurations based on heating environments for the baselined trajectories. This will be updated using new areothermal environments based on the latest configuration changes. Base area TPS sizing for metallic panels for two cycles of base heating environments was accomplished.

Also, various studies have been conducted for control surfaces TPS sizing with appropriate environments for comparison with analytical results from our industry partner, Rohr. These models will be updated with the new base configuration approach assuming shuttle tile and ablative TPS material. Several models for TPS support structure analyses have been developed. This includes models for both the LOX and LH2 tanks, TPS support structures during prelaunch, and flight, the intertank structure, LH2 thrust structure attachment and body flap beam structure, and for cryogenic acreage insulation thicknesses for the LOX and LH2 tanks.

Preliminary results have also included heat leaks due to the intertank, thrust structure attachments, and TPS support structures. Numerous small separate studies to address Skunkwork thermal issues in addition to the above large efforts have also been performed.

Structural Testing:

Several test programs have been performed and several other tests are in the preparation stages. Program restructuring (including cancellation of STA testing) has greatly affected this work. Development acoustic tests on X-33 TPS panels was completed. A total of six panels, of various substrate, TPS material combinations, and temperatures were exposed to acoustic input for periods of time equivalent to 15 missions. Some panels were tested without any damage to the TPS components and some incurred damage. The panels are being returned to the Lockheed Martin Michoud Assembly Facility, where they will undergo further non-destructive evaluation testing. This completes the initial series of planned acoustic tests. However, future panel testing is anticipated.

X-33 fuel tank slosh testing has been underway since the Fall of 1996. Due to the unique design of the X-33 fuel tanks, experimental data was required to verify analytical slosh models used in vehicle control and stability analysis. Little analytical or experimental data was available for similar designs. Plexiglas models were designed to represent cross-sections of an LH2 tank quarter, an LOX tank half, and the LH2 tank with septums. Resonant frequencies and damping values were measured and flow of the water through the septum cutouts at resonance was observed. Similar data was acquired for the LOX tank half and the LH2 tank quarter to determine fundamental resonant frequencies, damping, and effective slosh force magnitude and location. The most recent series of slosh tests was to investigate and verify the damping effects of the ring baffles, as designed, for the LOX tank.

A ground vibration test of the X-33 vehicle is currently scheduled for the Fall of 1998 in Palmdale, California for which MSFC will be responsible for test instrumentation, test conduct, and data analysis. Several vehicle test

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conditions are planned with various fuel fill levels. MSFC has participated in the over all test planning has provided input to the design of the suspension system required to simulate a free-free test condition.

LO2 Composite Material Characterization:

Testing to determine the oxygen compatibility of composite materials in a liquid oxygen tank structural application was conducted. Phase I tests consisted of mechanical impact testing of a variety of composite material systems. From this, a down-select to five composite materials systems was made, based on mechanical impact threshold. Phase II of this test plan conducted a variety of ignition and flammability tests on these five material systems. This test series included puncture, spark, pyrotechnic shock, and friction tests. Phase III testing is in the planning stages with testing to begin in late fiscal year 1997.

Vehicle Health Monitoring Unique Sensor Testing:

The goal of this testing is to detetmine acoustic emission transducers and attachment procedures for sensors that can be attached to the composite LH2 tank. Testing has been completed on off-the-shelf transducers, and has shown them to be robust with respect to cold temperatures down to liquid nitrogen temperatures. Testing using liquid helium to produce temperatures matching that of liquid hydrogen are planned but not yet complete.

Engineering Cost/Business Planning Support:

Support was provided through participation with the RLV SteeringGroup, a joint government/industry body that comprises representatives from LM and each of their team members, independent consultants, and several government agencies. The mission of this group is to guide the enhancement of the operational vehicle concept from the proposed concept that began phase II to the most economically-viable concept, given the changing nature of the launch vehicle market. The group is critical because it also strives to advise the X-33 demonstration team in maintaining relevance with the requirements imposed by the operational vehicle.

Another advisory board to which engineering cost contributions were provided was the RLV Incentives Working Group. Engineering cost contributions have also been made in an advisory capacity to VentureStar Enterprise Development efforts in such areas as standard government fiscal analysis and evaluation practices, information about past and present analysis efforts, legislative requirements, and precedents, probable ranges for analysis variables, characteristics of various business and financing structures, and possible transition scenarios from ELVs and STS to VentureStar.

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Thirty cryogenic pressure cycles were performed on the 10' Multi-lobe composite tank beginning January 27, 1997, and ending June 30, 1997. The first series of ten cycles was completed and some hydrogen leakage was detected. The tank was removed and shipped back to LMMSS for internal repairs were five different repair techniques were effected.

Damage tolerance was also address by drilling a hole in the tank wall and repairing it before returning to cryogenic service. The tank was returned for an additional 20 cryocycles. For each cryocycle, the tank was filled with liquid hydrogen and pressurized to pressures from 36 to 100 psig. Over 400 strain, temperature, pressure, displacements were measured. A leak detection system isolated seven critical areas of the tank for quantified, calibrated leak rate detection. Test panels of reusable cryogenic insulation materials were tested along with several fiber optic stain and temperature measurements planned for the Vehicle Health Monitoring system. A summary of all cycling on the tank is:

Summary of Test Cycles

Fill Media	0 psig	5 psig	15 psig	36 psig	55 psig	75 psig	100 psig
GN2		1					
GHe		8	2	6		3	1
GH2				6		6	
LH2	3			16	1	11	2

Date	10' Multi-Lobe LH2 Tank Test Log
1/22/97	Inert/purify time baseline - 36 psig GHe Proof (Test ID #61 & #62)
1/23/97	36 psig GHe Varian (portable helium mass spectrometer) Sniffs in 4"X4" Baggies/36 psig GH2 (Test #62A)
1/24/97	Partial Chill/Fill w/ LH2 (Bad weather abort) (Test #63)
1/27/97	36 psig LH2 (Test #63A)
1/29/97	75 psig GHe proof Varian Sniffs in 4"X4" baggies/75 psig GH2 (Test #64)
1/30/97	75 psig LH2 (Stopped @ 55 psig by LMMSS) (Test #65)
1/31/97	75 psig GH2 (Test #66)
2/3/97	75 psig LH2 (Test #67)
2/5/97	75 psig LH2 (Test #68)
2/6/97	75 psig GH2/75 psig GHe (Test #69)
2/7/97	5 psig GHe Varian Sniffs & soap bubbles/36 psig GHe Varian Sniffs in 4"X4" Baggies (Test #70)
2/13/97	5 psig GHe Varian Sniffs & bubbles (Test #71)
2/14/97	5 psig GHe Varian Sniffs & Bubbles/5 psig GN2 Bubbles (Test #72)
2/24/97	36 psig GH2 (Test #74)
2/25/97	0 psig LH2 (Test #75)
2/26/97	36 psig GH2 (Test #76)
2/27/97	36 psig LH2 (Test #77)
2/28/97	36 psig LH2 3 Pressure Cycles from 15 TO 36 psig (Test #78)
3/4/97	36 psig LH2 (Test #79)
3/5/97	36 psig LH2 (Test #80)
3/6/97	36 psig GH2/75 psig LH2 (Test #81)
3/7/97	75 psig GH2 (Test #82)
3/11/97	36 psig GHe Varian Sniffs in 4"X4" Baggies (Test #83)
3/12/97	5 psig GHe Bubble (Test #84)
5/19/97	36 psig GHe Varian Sniffs in 4"X4" Baggies (Test #87) Bad Weather
5/20/97	36 psig GH2 (Test #88)
5/21/97	Partial Chill/Fill -Thermocouple Problem (Test #88A)
5/22/97	36 psig LH2 (Test #89)

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5/23/97	36 psig LH2 (Test #90)
5/27/97	36 psig LH2 (Test #91)
5/28/97	36 psig LH2 (Test #92)
5/29/97	36 psig LH2 (Test #93)/36 psig GH2 (Test #94)
5/30/97	5 psig GHe Varian Sniffs & Bubbles (Test #95)
6/3/97	36 psig LH2 (Test #96)/36 psig LH2 (Test #97)
6/4/97	36 psig LH2 (Test #98)/36 psig LH2 (Test #99)
6/5/97	36 psig LH2 (Test #100)/36 psig GH2 (Test #101)
6/6/97	5 psig GHe Varian Sniffs & Bubbles (Test #102)
6/9/97	75 psig GHe Proof & Varian Sniffs in 4"X4" Baggies (Test #103)
6/10/97	75 psig LH2 (Test #104)
6/11/97	75 psig LH2 (Test #105)
6/12/97	75 psig LH2 (Test #106)
6/13/97	75 psig LH2 (Test #107)
6/14/97	75 psig LH2 (Test #108)/75 psig GH2 (Test #109)
6/17/97	5 & 15 psig GHe Varian Sniffs & Bubbles (Test #110)
6/18/97	36 psig LH2 (Test #111)
6/19/97	75 psig LH2 (Test #112)
6/20/97	100 psig GHe Proof & Varian Sniffs in 4"X4" Baggies (Test #113)
6/21/97	100 psig LH2 (Test #114)
6/23/97	100 psig LH2 (Test #115)
6/24/97	75 psig LH2 (Test #116)
6/25/97	75 psig GH2 (Test #117)
6/26/97	5 & 15 psig GHe Varian Sniffs & Bubbles (Test #118)

Summary

Ambient Temperature Tests

Pressure	# of Tests
5 psig	9
36 psig	12
75 psig	9
100 psig	1
Total	**31**

LH2 Tests

Pressure	# of Tests
0 psig	3 (2 Partials)
36 psig	16
75 psig	11
100 psig	2
Total	**32**

In preparation for RLV turbopump testing, several equipment buys were made and design efforts initiated. This included a Pro/Engineering workstation to perform piping design, stress analysis, and Easy 5 fluid flow models for the X-33 PowerPack Assembly (PPA) facility discharge piping. This system is compatible with the Rocketdyne Pro/E 3D solid models of the PPA and adapter hardware, and involves facility interface piping and support layout to the PPA, pipe stress and flow analysis, and verification of PPA interface limit load tolerance.

This effort is a direct precursor to the RLV turbopump facility piping design that will occur in FY98 for the E1 facility. The support contractor was also tasked to procure the hardware and develop the software for the Programmable Logic Control System that will perform backpressure control for the X-33 PowerPack Assembly testing. This control approach and hardware will be utilized at the E1 facility for RLV turbopump testing.