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X-33 PHASE II

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ANNUAL PERFORMANCE REPORT

JULY 1, 1997 - MARCH 31, 1998

LOCKHEED MARTIN SKUNK WORKS
COOPERATIVE AGREEMENT NCC8-115

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

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 second year has been one of significant accomplishment in which team members have demonstrated their ability to meet vital benchmarks while continuing on the technical adventure of the 20th century...

the ultimate goal...

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

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LOCKHEED MARTIN SKUNK WORKS

This performance report spans the second year for the Phase II X-33 program and includes efforts supporting the Critical Design Review (CDR) and System Requirements Review (SRR) for the X-33 vehicle. In addition, significant progress has been made in the areas of Site Development, Manufacturing, and Initial Vehicle Assembly for the Phase II X-33 program. The program accomplishments reported herein are for the vehicle systems developments in line with the program schedule for vehicle first flight in July 1999.

X-33 Vehicle Design

The X-33 vehicle and its subsystems successfully completed critical design review (CDR) in November 1997. The vehicle released detail design is at 100% and the assembly and installation drawing status is also nearly 100%. The refinements to the aerodynamic surfaces and the Thermal Protection System (TPS) of the vehicle aft-end and canted fin which were derived following the CDR are also included in the released drawing status. Assembly of the vehicle has begun with the thrust structure and Liquid Oxygen Tank already in the vehicle tooling jig.

X-33 Vehicle Primary Structure

Thrust Structure - the center structural components are installed in the vehicle assembly jig.

LH 2 Tanks - detail parts fabrication is at 75%, and tank assembly stands at 15% completed . The fabrication of the 3 ft. test tank is completed and testing of the tank has been initiated.

Intertank Structure - Fabrication and proof testing of the 2" and 4" truss tubes is underway.

LOX Tank - Completed Tank is in vehicle assembly jig.

Control Surfaces - Details parts fabrication of the Verticals is underway. Details parts fabrication for the Canted Fins is 20% completed. Body Flap design completed. The TPS for the Canted Fins and the Body Flaps was revised from carbon-carbon to ceramic tiles to preserve manufacturing schedule and reduce vehicle weight. Detail design of the tiles and fabrication of ceramic tile stock is underway.

Landing Gear Attachments - detail design is completed. Component fabrication is underway.

Landing Gear - design of gear and installation is complete.

Thermal Protection System (TPS) Support Structure

The TPS support structure detail design is 100% completed, and assembly and installation stands at 75% completed. The installation of the LOX tank TPS support structure is underway.

The TPS for the aft end of the vehicle was changed from ablatives to HTP-6 ceramic tiles and the substructure was changed from metallic to BMI composites. This was done to reduce weight and avoid potential costs associated with ablative refurbishment.

The Elevon TPS was changed from carbon-carbon to ceramic tiles because the carbon-carbon could not meet the Elevon design load requirements. This necessitated a change to a Titanium substructure for the Elevons.

Vehicle Systems

Vehicle Ballast system and Avionics Bay detail design are 100% complete.

Ground Operations

Ground Operations Introduction

The Ground Operations function is responsible for preparing the X-33 system for each test event. Specific measures of ground Operations effectiveness are the two day and consecutive seven turnaround requirements and crew size limitations imposed by the X-33 Cooperative Agreement (CA). By achieving these requirements/limitations, the X-33 system will demonstrate techniques to control a significant portion of RLV Operational costs.

Ground Operations Flow Progress

Refinements in the ground operations flow continue to take place with emphasis on safety and maximizing the ability to achieve turnaround goals within the Cooperative Agreement-mandated crew size limitation. Ground Operations activities commence soon after vehicle lift-off, as the Haystack Butte launch site is safed and preparations for the next launch begin. These launch site safing/preparation events include:

- Propellant drainback and delivery system inerting
- Sound suppression water servicing
- Rotating launch mount servicing
- Propellants, liquid nitrogen and gaseous helium servicing
- Unscheduled (corrective) maintenance

Upon landing and completion of the autosafing sequence, another series of events prepares the vehicle for transport back to the launch site

- The vehicle is grounded to bleed off any static electrical charge that built up during flight.
- Wheels are chocked and the landing gear is pinned in the down and locked position.
- External services are provided and the vehicle is inerted and configured for loading onto the overland transporter while flight test instrumentation data is downloaded.

The method of transporting the vehicle back to the Haystack Butte launch site was changed in November 1997. Program cost risks and Shuttle Carrier Aircraft technical and modification schedule risks were mitigated by adopting overland transport in lieu of using the SCA. This change also allowed the landing site operation to be simplified by eliminating tasks and equipment. Contractors that specialize in transporting oversize loads along public roadways were contacted to recommend transportation routes and fabricate an overland transporter. The X-33 vehicle is taken directly from the runway to the launch site and the preparation-transport-offload cycle time is comparable to the SCA method. Further description of overland transportation is provided by LMTO.

Once the transporter/X-33 vehicle arrives at the launch site, the following events take place:

- The vehicle is lowered to the tarmac and is spotted at the launch mount using a standard aircraft tow bar and tug.
- It is aligned and mated to the launch mount and can receive any service required to support unscheduled maintenance.
- The translating shelter is rolled over the vehicle.
- The vehicle undergoes an aircraft-like set of pre-flight inspections and servicing. Any special safety inspections, as required of a one-of-a-kind flight test vehicle, are performed at this time. A key redesign to a "one deep" avionics bay in the summer of 1997 provided a significant access improvement over the "three deep" design.
- The Battery Power System, a palletized electrical power supply, is exchanged for freshly serviced pallets. (The BPS was adopted during the August 1997 time frame, to mitigate the weight and complexity risks associated with the propellant gassifier/ turboalternator electrical power generation system).
- The translating shelter is rolled back, the vehicle is rotated to the launch position and configured for propellant loading.
- The automated launch sequence is initiated with ground-based control center computers and vehicle computers operating in lockstep. Under the watchful eyes of skilled test personnel, the automated sequence activates and verifies flight systems health, loads propellants and, eventually, issues a "go" for engine start. Upon reaching the "go", the vehicle management system computers take over and flies the mission.

Site Activation Progress

Activation of capabilities to support the X-33 flight test program continues at the launch site, landing site and other locations that are capable of providing services. Other Site Activation accomplishments are provided by Sverdrup (launch site), and LMTO (ground support equipment and transportation)

- The coordination with maintenance backshops at Edwards AFB and Dryden Flight Research Center continues. Flight test instrumentation calibration, battery servicing, ground support equipment servicing and wheel/tire/brake service are the primary areas of concentration.
- A draft Site Access Plan has been circulated to security personnel at Air Force Research Lab, Edwards AFB, Dryden Flight Research Center, Michael Army Airfield and Malmstrom AFB. General consensus has been reached on X-33 program personnel access to these facilities.
- A draft Maintenance Training Plan was prepared. It outlines the training requirements for the Operations personnel tasked with conducting the flight test program.
- Operations personnel received Foreign Object Damage prevention training that is applicable to the vehicle and Ground Support System equipment at the launch and landing sites.
- The Launch Site computer resources and network was defined.
- Coordination of Operations personnel skill/manpower requirements and availability continues. At this writing, a crew of 45 provides the Cooperative Agreement-mandated operational capability for the duration of flight test program.

Reliability, Maintainability/Testability, Supportability, & Special Analysis (RMS&A) Progress

Extensive progress has been made by the RMS&A IPT since the last activity report toward ensuring the X-33 system includes requisite operability characteristics. Simultaneously, RLV activity has ramped-up. The RMS&A Team is led by LMSW and spans 19 team companies and NASA centers. A core RMS&A team is still positioned in Palmdale and is leading activities undertaken throughout the country. The following are activities specifically led or performed by LMSW:

Reliability

- X-33 Safe Recovery Reliability (R_{SR}) Modeling/Allocation/Prediction: Allocation revisions were released to reflect previous predictions, and several additional prediction iterations performed. The predictions continued to be used to make design/configuration decisions. Our current predictions still indicate we will deliver a vehicle more reliable than present-day launch systems. We have been successful in ensuring reliability is not significantly degraded by weight reduction design changes.

- X-33 Fault Tree Analyses (FTA): Many more trees were developed in support of predictions. A tracking system was established to monitor FTA status. A hard copy was forwarded to NASA Headquarters' S&MA Office.
- X-33 Failure Modes, Effects, & Criticality Analysis (FMECA): A FMECA configuration management system was established at LMSW. All vehicle and ground FMECAs were completed in time for CDR. LMSW reviewed all team FMECAs. Minor updates are being made in conjunction with design changes. FMECA has uncovered many issues which are being addressed; one example: On LMSW request, Allied design agreed to replace battery protection diodes with fault-tolerant units. A hard copy was forwarded to NASA Headquarters' S&MA Office; presently 892 pages.
- X-33 Critical Item List (CIL) Mitigation Plan: A CIL database was established at LMSW, working from FMECA database (Cat I and II line replaceable unit failure modes). Progress was made toward populating the database (redundancy & fault tolerance provision, preliminary scheduled inspection intervals, Environmental Stress Screening, qualification levels, etc.). CIL is expected to be major topic at the Flight Readiness Review.
- Support to X-33 Flight Assurance: Prepared material for two major program reviews addressing flight readiness analyses and associated preparations for first flight.
- X-33 Environmental Stress Screening (ESS): Negotiated / managed proposed ESS plans from applicable RMS&A team elements.
- X-33 Qualification Test Data Review: Continued to collect and evaluate this data, as related to reliability predictions and CIL mitigation. RMS&A team's data was distributed to team as baseline for LMSW qualification test review.
- Support to RLV Certification Team: Supported all team activities. Represented Lockheed Martin at AIAA industry RLV Certification Panel meeting, and prepared detailed certification program plan outline for team use.
- RLV Main Engine Reliability Working Group: LMSW established a special working group to systematically address engine reliability issues, up-front in development process. Team met three times during this reporting period.
- RLV Man-Rating Reliability Working Group: Prepared / hosted a special presentation and working meeting for a group that examined initial RLV

reliability issues as related to passenger/crew reliability/risk. The group included representatives from NASA Headquarters' S&MA Office.

- RLV Requirements Development: Prepared a major analysis/presentation for Systems Engineering addressing our progress in identifying system requirements and requisite trades.

Maintainability

- X-33 Maintainability, Testability and Logistics Reviews: Continued to host these reviews, to address/coordinate all technical issues.
- X-33 Design Influence: We have continued to interface with applicable team design organizations as required to attain best possible access and reparability characteristics.
    - Influenced Hazardous Gas Detection System design by deleting on-board filters, and worked with Design to insure the sense lines were not susceptible to blockage.
    - Influenced leeward TPS design by ensuring the inter-panel seal was removable, not bonded in place.
    - Influenced placement of Remote Health Nodes to improve access.
    - Influenced the location of the Rear Digital Interface Units -- ensured they remained in the Main Wheel Wells rather than deep behind structure.
- X-33 Reliability Centered Maintenance (RCM) Program: LMSW has identified the specific criteria and formatting to be used in the team's RCM analysis, then developed an *MS Access*-based automated tool that will significantly cut-down on analysis time. RCM identifies scheduled inspections and maintenance as required for risk reduction.
- X-33 Turnaround Timeline Analysis/Optimization: Progress on the discrete event timeline continued. Updated versions were presented at CDR. The statistical model for evaluating the Two Day Turn Around and the Consecutive Seven Day Turn Arounds continued to evolve, and are now supported by current team Maintainability predictions.
- X-33 Maintenance Planning: A consolidated list of expected servicing tasks and scheduled maintenance tasks was compiled, and loaded into Logistics database.
- RLV Maintainability Allocations: Have recently begun re-assessment of the preliminary Phase I Maintainability allocations.

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Testability / Integrated Diagnostics

- X-33 Fault Detection & Fault Isolation Predictions: LMSW provided oversight over development of the predictions; 2nd major iteration of which was completed in time for CDR.
  - 16 of 19 major vehicle subsystems have automated (on-board and GSS-based) detection levels of at least 97%.
  - The predictions and associated design interface led to changes in vehicle and ground system configurations, such as improvement in ambiguity level through elimination of 6 Active Thermal Control System sensors.
  - Identified limitations to Testability which must be supplemented by RCM to satisfy program requirements.

The T/ID team was significantly down-sized after CDR, but is expected to increase again on RLV program during Phase III.

Special Analysis

- Support to X-33 Expected Casualty Rate Study: Reliability inputs for first major update to E(C) assessment were delivered on schedule. This update includes unpowered flight, and joins flight dynamics assessments with failure mode quantification. ACTA will process team inputs when they are completed.
- X-33 Operations Simulation Modeling: Progress has been made developing a better, more efficient modeling process, using *Extend* program. The simulation is assisting in making operations decisions relative to turnaround optimization (*2 Day* and consecutive *7 Day*).
- RLV Operations Simulation Modeling: A top-level model has been completed, examining VentureStar fleet operations over expected life cycle. The model is being used to support various operations and RM&S trades.
- RLV Life Cycle Cost Modeling: A low-cost simulation software upgrade was procured which will facilitate the use of our operations simulation model in developing Launch Commit Criteria estimates.

Logistics

- X-33 Logistics Database Development: The Integrated Operations Management System function has been replaced with an Operations, Maintenance, and Logistics Support computerized data file structure that contains the information to facilitate effective operations during X-33 system ground and flight tests. The Operations and Logistics Support computerized data file structure will provide the following IOMS-like capabilities:
  - Collection of task resource requirements
  - Preparation of Operations and Maintenance (O&M) task work packages
  - Documentation of Operations parameters and characteristics as required by the Test Operators
  - Documentation of system discrepancies and corrective actions
  - O&M task scheduling
  - Configuration control of O&M procedures and documentation

- X-33 Maintenance & Operations Procedure Development: Analyses are currently being developed which identify repair / restoration methods for each subsystem, to the LRU level. Analysts/authors have been assigned, templates have been negotiated, and task development is underway. Approach is to have procedures on-hand for all operations tasks and for repair of equipment having the highest likelihood of needing repair during the flight test program.
- X-33 Ground Support Equipment and Consumables: Requirements are being refined for landing site and launch site for both the vehicle and ground support system.
- X-33 Launch Site Logistics Facilities: The warehouse and staging vans have been identified/obtained for use and are currently being outfitted to meet X-33 requirements.
- Site Support Personnel Assessments: We are working with Operations management to determine proper level of support from LMSW Supply Support (transportation / expediting personnel, etc.).

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Integrated Test Facility

The X-33 Integration Test Facility (ITF) has the responsibility of integrating and performing, for Verification and Validation testing on the computer systems used in the operation of the vehicle. These systems are comprised of three major groups: (1) Vehicle Avionics; (2) Launch and Mission Control Monitoring System (LMCMS) computers; and (3) Range Systems. These systems are to be tested using a sophisticated hardware-in-the-loop (HWIL) simulation system centered on the ITF at NASA's Dryden Flight Research Center in building 4840.

Plans call for three simulation systems based on Silicon Graphics Onyx computers. To date, two of the three systems are operational, with the third scheduled to come on-line in October of 1998. The simulations consist of high-fidelity models of the various system components and a six degree-of-freedom (6-DOF) dynamic motion model of the vehicle. Models include vehicle avionics and subsystems, radar and data-link simulations, and ground system models. These models are updated as development test data becomes available from the various developers.

Vehicle avionics hardware deliveries to date include two full sets of Vehicle and Mission Computers (VMCs), two Vehicle Health Monitors (VHMs), two Engine Control Data Interface Units (ECDIUs), and a Flush Air Data System (FADS) sensor package. These units are all prototypes, built from commercial equivalents of the flight hardware.

The dedicated lab variant of the LMCMS system has been installed at the ITF and is being used to integrate the third incremental release of LMCMS software with the VMCs and VHMs. A fourth version of this software is scheduled for delivery before the end of April 1998.

Phase one of range integration is in progress. This requires development of a pure software simulation of the antenna patterns and radar performance for use in evaluating range coverage of the intended flight paths. Range equipment is being installed at the ITF in preparation for the second phase of range integration, scheduled to begin in July. This phase consists of using actual ground and vehicle communications equipment to connect the vehicle avionics with the LMCMS.

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Version three of the VHM software has successfully been integrated, with version four due in on July 1. This version will be used in range integration.

The third incremental version of VMC software is due to be delivered on May 1 for the start of integration testing. This will be the first version submitted for Verification and Validation (V&V) testing. With this delivery, completely closed-loop communications between the LMCMS and the vehicle will be established in the ground maintenance mode.

The first release of the V&V plan has been released, with an update scheduled for June. Test procedures for use in Build 3 are in preparation.

The first Inertial Navigation System/Global Positioning System (INS/GPS) unit is scheduled for delivery to the ITF in late May. This unit will be connected to the simulation system, which will drive it with simulated gyro and accelerometer data and with radio frequency (RF) signals from a GPS satellite simulator already in place. This testing will ensure that the problems observed on the first Ariane V launch do not occur on X-33.

The first ship-sets of S-band and L-band radios will be delivered in June and integrated with the range systems and the rest of the vehicle avionics.

MANUFACTURING

X-33

Tooling

We are in the last portion of our tooling program with the large majority of the work behind us. The thrust structure tool is complete, as is the upper and lower LOX tank area TPS tooling. We have also completed the assembly tools for the nose landing gear structure and the lower TPS structure residing between the LH2 tanks. Significant progress has been made in the completion of the control surface tooling with the fixture frames for the canted fins, vertical fins and body flaps all being complete. Detail components for these tools are in fabrication both in-house and at several vendors. The last flight control assembly tool is scheduled to be released to production by middle summer. The upper "inner"

TPS tool which supports B.F. Goodrich in the fabrication of the upper TPS panels is complete less two small details yet to be installed because of a design change. The majority of the tool has been released to BFG to begin their activities. Other assembly tool activities currently being completed include the shipping fixtures for both LH2 tanks, a work stand and positioning device to install the canted fins and a subassembly tool used to build-up the main landing gear wheel well areas.

Nearly all the fabrication tooling is complete with only a few lay-up tools still outstanding in support of body flap components and miscellaneous brackets. Significant accomplishments include the extremely large 4-piece consolidation tools built for the **3D composite longeron and C-frames** for the LH2 tanks. All of these tools have successfully completed producing their parts.

Fabrication

Major progress has been made in fabrication and we are better than half way through our fabrication program. To accomplish the extremely compressed schedule for the X-33, we have had to utilize a multitude of sources working in parallel to produce the large volume of complicated parts being designed for this vehicle. We have significantly pushed the envelope of large 6-2-2-2-2 titanium billet and plate production to machine the large monolithic parts for the X-33. We have also pushed the envelope on producing large BMI/graphite composite parts which are of unprecedented size. To accomplish this we have used a collation of Skunk Works, sister Lockheed Martin companies and outside vendors to manufacture these parts. Our attention has been focused particularly on mitigating the lack of large 3&5 axis machine time as well as composite capability competent to handle the BMI/graphite materials we are using on the program. Our in-house capabilities are saturated supporting not only X-33 but a group of other programs. We have successfully accomplished this goal and have parts working all over the country. We have received thousands of these parts already with the bulk due to arrive this summer and the balance arriving through the end of the year. Most of the large machined parts for the thrust structure have been delivered. All the LOX tank area TPS substructure components have been delivered with a few shortages. Components for the tail surfaces have begun to deliver and the majority will arrive by July.

All Skunk Works deliveries of 3D composite frames to Sunnyvale in support of LH2 tank assembly will be complete by May 15th.

Fabrication of functional systems is progressing with the completion of all wire harnesses in support of the ITF (Integration Test Facility) and all plumbing/wiring in support of Allied Signal's landing gear SIL (Systems Integration Lab). Ship side plumbing and wire harnesses are already starting to arrive in stock, as are functional components such as valves and accumulators.

Assembly

Vehicle assembly commenced in the fourth quarter of '97 on the first segment referred to as the thrust structure. This is the aft most load carrying structure on which mounts the linear aerospike rocket engines and also acts as a mount for the canted fins, vertical fins and the body flaps. This structure, that is primarily made up of BMI/graphite composites and titanium is now complete for the center section. Work is just starting on assembling the outboard sections of this structure. We are also well into the assembly of the LOX tank area TPS sub-structure. The lower portion of this structure was complete enough to allow installation of the LOX tank which arrived in Palmdale in February of this year. The tank is now permanently located in the fixture and is being tied in to a series of composite frames and beams which carry the mounts for the stand-off aeroshell. Assembly will imminently start on the nose landing gear structure which is primarily made of titanium.

Functional systems installations will start in late May on the center thrust structure followed by the nose landing gear structure as it completes assembly.

LOX Tank Installation at LMSW (Side View)

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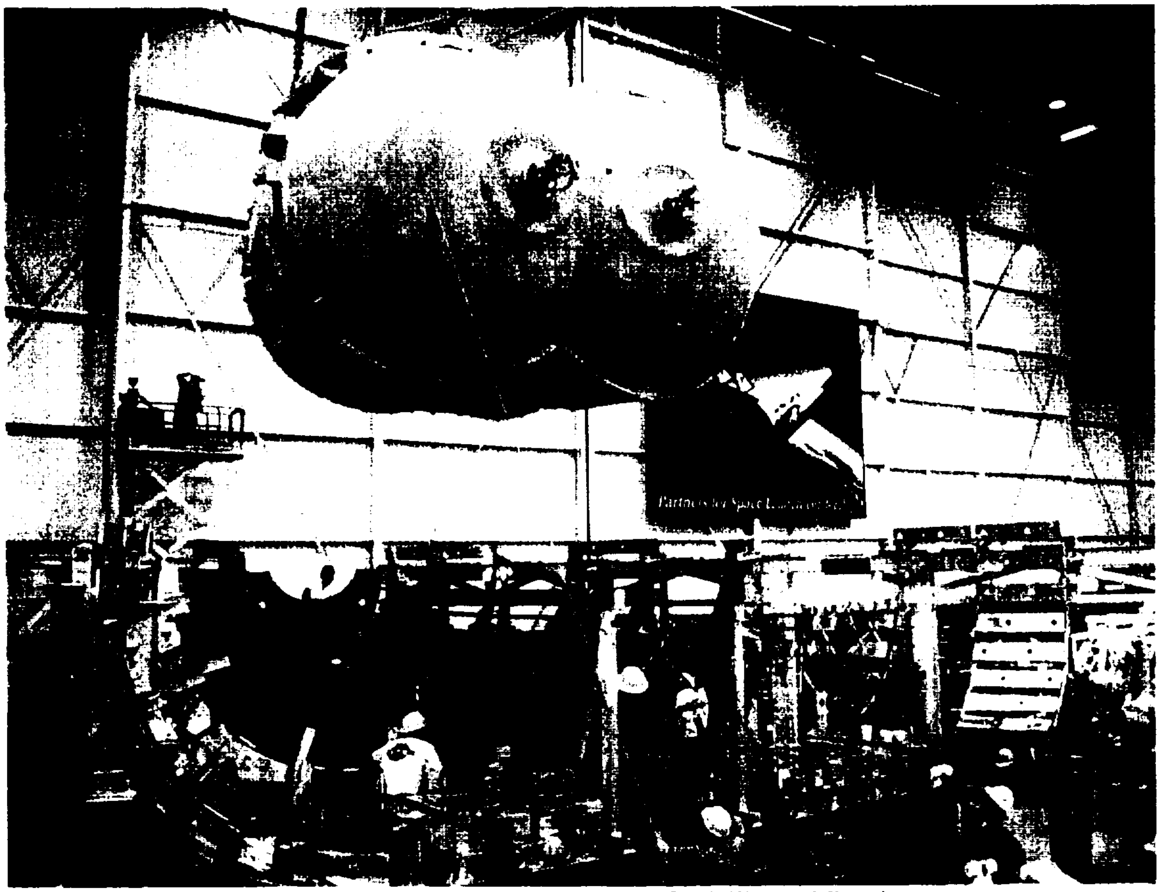

LOX Tank Installation at LMSW (Rear View)

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X-33 SYSTEM ENGINEERING

In June a team of co-located system engineering personnel was put into place to address integration across disciplines, issues resolution, system requirements, requirement's flowdown, test requirements and RLV traceability. The team was composed of system engineers, sub-system leads, ground system leads and design specialists. Additional specialists from the design groups were pulled into a specific system engineering work group whenever required to resolve issues or integration tasks. The reporting structure is a matrix organization with the team members reporting to Systems Engineering. This organization and methodology insured the design teams addressed integration issues and allowed the system integration team to resolve issues between the design groups. Members of the system integration team which did not have specific design roles were used to direct resolution of issues and perform primary tasks, such as defining system test requirements. Members of the team met each Monday to assign tasks and review progress. The team was divided into smaller working groups to address unresolved requirements, integration issues and documentation. Work groups include Purge & Vent, component certification and integrated test development.

The risk management methodology and tracking was modified to become a more direct management tool used by the program manager to mitigate X-33 program risks. Reporting of each risk was modified to show the movement of risk on the iso-risk chart and alert the program manager to risks not completing their mitigation tasks.

Configuration Management was placed under System Engineering and the procedures modified to incorporate an Engineering Review Board (ERB) prior to the presentation of changes to the Configuration Control Board (CCB). The ERB reviews each change on technical merit, weight and adequacy of the solution. The CCB then focuses on the cost and schedule issues required to implement the change. This has benefited the program by controlling the vehicle weight and reducing the average change processing time from 12 weeks to 6 weeks.

A Master Equipment List (MEL) was developed by System Engineering. The MEL contains the manufacturer, the part number, a description of the part, the "on-dock" scheduled delivery date and the manufacturing need date. Discrepancies between the need dates and the scheduled date are highlighted for review and coordination by Manufacturing, X-33 Program Office and the

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manufacturer. A weekly meeting now exists to resolve any continuing discrepancies.

In July, System Engineering began a methodical breakout and flowdown of requirements into the system design. Specification and ICD trees were established to provide a structured approach to develop requirements' verification and database. By the X-33 CDR, a requirements Compliance Matrix was created in an Excel database. The Compliance Matrix included a complete flowdown of the requirements and a trace of the verification methods beginning at the System Requirements Document and continuing through sub-system specifications and Interface Control Documents. The Compliance Matrix has continued development with sub-system element specifications. Qualification test procedures and Demonstration plans are entered into the Compliance Matrix when released. After the test or demonstration is complete, the report will be entered into the database.

In July a preliminary system test flow diagram was presented to the system integration team for review. The test flow described the tests and provided a test sequence for integration of the entire X-33 system. Beginning after receipt and acceptance of system elements at LMSW, the test flow diagram detailed a structured approach for system integration and check-out up to first flight.

RLV/SSTO SYSTEM ENGINEERING

System engineering tasks began on the RLV/SSTO program in July 1997. The initial task focus is to develop system requirements derived from the market and business segments. We have introduced Quality Functional Deployment (QFD), as a part of series of advanced system engineering tools along with Foresight (a system simulation tool), DOORS (requirements management tool), automated risk management database processing and configuration management to develop and manage the requirements.

In March 1998, a successful System Requirements Review was held to examine the market and business requirements and establish the RLV/SSTO system requirements.

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Requirements development is continuing with the establishment of lower level segment requirements using the advanced technical requirements management methodology being pioneered by LMSW's System Engineering department.

AVIONICS/SOFTWARE

Introduction

A top level functional flow of the X-33 vehicle avionics and software system is shown in the figure. The Mission/Comm Manager function is the top level command authority for the system. This function controls the vehicle and its subsystems during ground and flight operations. The Mission/Comm Manager receives commands via the umbilical interface while on the ground or via the Communications Subsystem while in flight. The Mission/Comm Manager controls all other parts of the system. Some are controlled directly, others indirectly through the Vehicle Subsystem Manager and the Flight Manager. In flight, the Mission/Comm Manager acts as the onboard intelligence to enable autonomous operation of the vehicle and subsystems. This "on-board intelligence" is derived from a mission plan that defines the primary mission and abort options. This mission plan is down-loaded to the Mission/Comm Manager during the preflight activities.

The Flight Manager function controls the navigation sensors, aerosurfaces, Reaction Control System (RCS) and Engine Manager. In flight, it determines and controls the vehicle motion required to accomplish the mission objectives.

The Vehicle Subsystem Manager function controls and monitors all the vehicle mechanical subsystems. The Vehicle Subsystem Manager will then issue the commands required to achieve that desired configuration.

The Mission/Comm Manager, Flight Manager, and Vehicle Subsystem Manager operate in three separate processors within the triplex set of Vehicle Mission Computers (VMCs). Reliability requirements have driven the design to a triplex set of VMCs. Each VMC has a fourth processor in which resides the Redundancy Manager. The Redundancy Manager keeps all functions in all three VMCs running in lock step on a frame basis. It also performs the voting function (mid value selection) on all commanded outputs.

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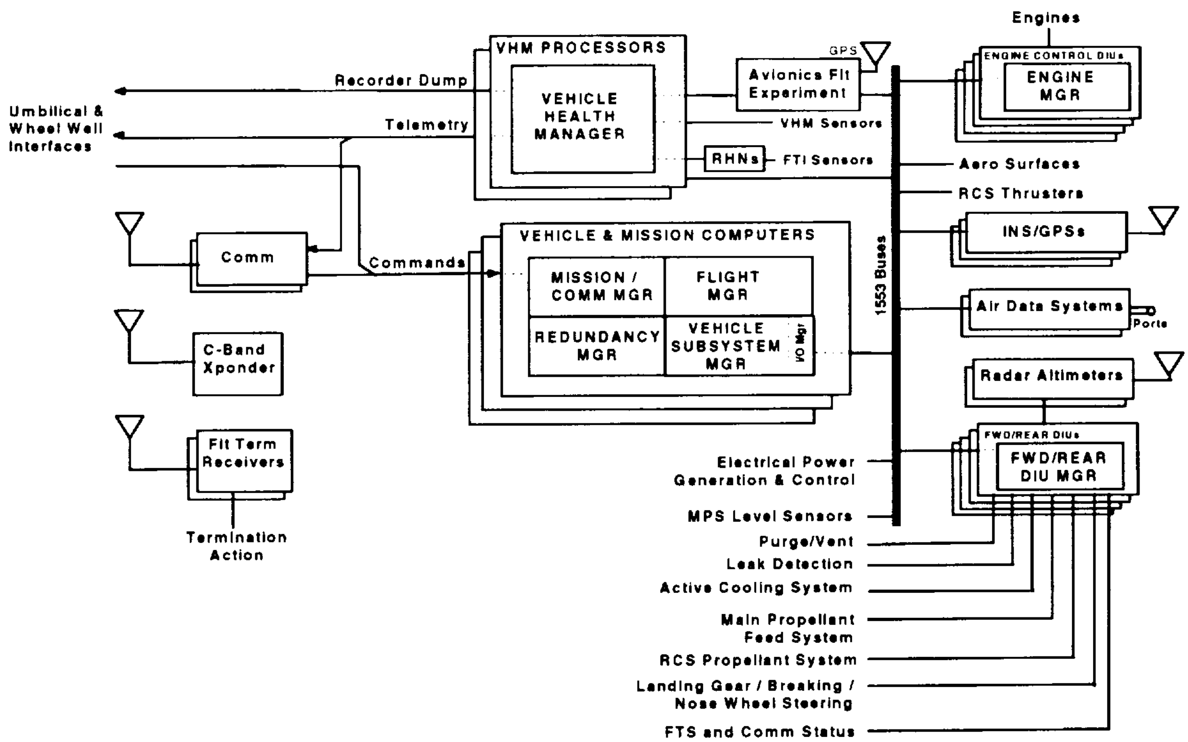
AVIONICS / SOFTWARE



The Vehicle Health Manager function collects VHM sensor data and Flight Test Instrumentation (FTI) sensor data. It formats the data, records it and sends a subset of the data down the telemetry link and the umbilical/wheel well interface. The VHM data is processed on the ground. Trend analyses are performed to predict impending faults. The FTI data is also processed on the ground to determine vehicle environmental conditions and performance.

Status

In support of software development and integration, eight brassboard Vehicle & Mission Computers (VMCs) have been delivered to the Integration Test Facility (ITF) and the LMSW software group. ASA has several more brassboard units for their software work. In addition, six brassboard Engine Controller Data Interface

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Units (ECDIUs) have been delivered to Boeing (Rocketdyne) for engine software development and two brassboard ECDIUs have been delivered to the ITF for integration. ASA has just completed assembly of the first flight VMC and has begun functional test and check-out. Qualification testing will start in a few weeks.

Sanders has delivered a single brassboard Vehicle Health Manager (VHM) processor for integration in the ITF. On 7-1-98, they will deliver a full functional brassboard system consisting of VHM-A and VHM-B processors and software.

Other brassboard hardware delivered to the ITF include a Flush Air Data System Remote Pressure Sensor from ASA and Avionics Flight Experiment from JPL. The only flight avionics hardware delivered is the Radar Altimeters.

Due to the weight saving changes made to X-33 mechanical subsystems, the hardware and software sensor and control interfaces to those subsystems have changed considerably since the beginning of the program. This has caused hardware interface changes in the Forward and Rear Data Interface Units (F/RDIUs) and control software changes in the F/RDIUs and in the Vehicle Subsystem Manager software that runs in the VMCs. These changes have now been finalized. In April 1998, a Subsystem Control ICD for each subsystem was baselined and released.

Software is being developed on an incremental basis. Build 1 was delivered to the ITF on 8-1-97 and Build 2 was delivered on 10-20-97. These builds comprise the software infrastructure that keeps the triplex VMCs operating in lock step and frame basis, provides the data voting functions, 1553 data bus management and communication with the ground system. Build 3 will be delivered to the ITF on 5-1-98. It will add many of the Mission/Comm Manager functions and some subsystem control functions. The first Flight Manager functions will be delivered to the ITF in Build 4 in July 1998. At this point in time (4-21-98), Build 3 is in final test by software developers in preparation for delivery to the ITF on 5-1-98. Build 4 is well into detail requirements definition and design. Build 5 has just begun the detail requirements/design phase.

Flight Assurance Office

The Flight Assurance Office (FAO) at Lockheed Martin Skunk Works (LMSW) is responsible for ensuring a safe/reliable operations environment for the X-33 flight test series and responsible for coordination with external agencies to achieve flight authorization. To accomplish this goal, the FAO has managed the efforts of several groups within LMSW. These groups, under the direction of the FAO, have produced many documents designed to meet the FAO objectives stated above. The overlying document is the Flight Assurance Plan, 604D0079, which was published this year. This document is a single reference for all tasks that are required to achieve "approval for flight". "Approval for flight" can be achieved by showing a skeptical observer that we have plans and procedures in place to: 1) build and fly a safe vehicle; 2) avoid excessive ground processing/maintenance and; 3) achieve our program/Cooperative Agreement objectives.

Three major reviews were conducted this year for the benefit of both internal and external organizations. The first was a Flight Assurance Review (FAR). The second was a dry run of a Program Readiness Review (PRR). The PRR is defined as the last program-level review to be conducted prior to first flight. The last was an overall FAO status presented to NASA HQ Office of Safety and Mission Assurance (S&MA) at their request. All reviews produced positive results.

Other offices under the jurisdiction of Flight Assurance have also produced significant results. Their accomplishments are listed below.

LMSW Flight Test

LMSW Flight Test has developed and coordinated the X-33 flight test objectives/requirements. These objectives/requirements have been incorporated into the released X-33 Vehicle Flight Test Plan, and into Rev A of said plan, to be released in late April 1998. This effort included the RLV traceability and programmatic objectives as well as the X-33 envelope expansion objectives.

LMSW Flight Test, with assistance from LMAD, developed the X-33 Integrated System Test Flow Chart, depicting the subsystem and system hardware and software test requirements leading to the vehicle system checkouts and ground tests.

LMSW Flight Test has developed and released the Flight Test Instrumentation Master Measurement List (MML). The MML gives details of the approximately 1300 Flight Test Instrumentation parameters, including measurement types, transducer technical data, locations, drawing references and pin-out information for interface with the Vehicle Health Management system's Remote Health Nodes. Instrumentation Installation Process drawings are being produced for typical transducer installations on the vehicle at this time.

LMSW Flight Test, in conjunction with the LMCMS group, has developed the X-33 Master Measurement Data Base (MMDB). This database includes input and output measurements and requirements for all data sources and users on the X-33 program. It will be the foundation for the dissemination of the vehicle and ground data to the X-33 team members and for their link to the common analysis of that data in order to meet reporting requirements as the program progresses through the ground test and flight test phase.

LMSW Flight Test has completed the initial requirements for the Operations Control Center flight manager and flight test consoles and has defined the real time displays. In conjunction with the LMCMS group, Flight Test has developed the software integration tools and plans required to implement these consoles into the LMCMS.

System Safety

The Sub-System Hazard Analysis was completed this year. We have instituted a monthly program management review of Category I hazards.

Environmental Management

The Environmental Impact Statement, Record of Decision, and Environmental Management Plan have all been completed.

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Range

The Range CDR has been completed. The Range Design Specification, Range and Range Safety Integration and Test Plan, and the Range ICD has been published.

Range Safety

Range Safety Requirements Document has been released. Furthermore, LMSW has submitted the Preliminary Flight Data Package to the Range Safety organization at AFFTC.

SINGLE STAGE TO ORBIT / REUSABLE LAUNCH VEHICLE

This performance report spans the second year of the Phase II SSTO / RLV Program. The program accomplishments reported herein are for the Vehicle Development, Manufacturing and System Operations organizations and are in line with the program schedule for Authorization To Proceed (ATP) to Phase III in December, 1999.

RLV Vehicle Design

The SSTO / RLV Vehicle Design has been focused on concept exploration this past year. Approximately 25 configurations have been generated for vehicle Gross Lift-Off Weights (GLOW) ranging from 2.40 to 2.87 million lbs. Structural arrangements and inboard profiles have been completed for each of these configurations. Several propellant tank arrangements and shape trades have been completed. Wind tunnel models have been designed, fabricated and tested for two aerodynamic configurations and analysis has been performed to investigate all flight regimes (subsonic, transonic and hypersonic mach numbers). The design activity is currently establishing an SSTO/RLV baseline configuration at 2.62 M lbs. GLOW.

RLV Flight Sciences

Two aerodynamic configurations have been wind tunnel tested to examine stability and control characteristics of the vehicle. The effect of different size fins

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has been investigated for both horizontal and vertical tail surfaces. Selected data from the various wind tunnel tests has been reduced and assembled into simulation database format for both 3 Degree-Of -Freedom (DOF) and 6 DOF analysis. Stability and controllability of the selected configurations has been analyzed in support of the vehicle configuration trade studies.

Ascent and reentry trajectories for various configurations have been evaluated. Refinement of the trajectory database (including the Vacuum Instantaneous Impact Points calculations and a refined Oblate Earth model) is continuing to support the vehicle performance predictions and the Launch Site Selection process. Development of lower heating rate trajectories during reentry is also continuing.

A heating algorithm has been developed and delivered to the trajectory analysis team to predict heating to a thermal control body point. This algorithm will provide local heating and temperature sensitivities to vehicle entry angle-of-attack profile and assist in the design of the vehicle's Thermal Protection System (TPS).

RLV Propulsion System

The propulsion development plan has been modified from the ground demonstration of a prototype engine to preliminary design of the SSTO / RLV flight engine with ground demonstrations of key prototype components and subsystems including the turbomachinery powerpack. This realigned program supports the demonstration of key technologies prior to the ATP decision at the end of Phase II.

The design of an actively cooled composite nozzle large scale test article is underway. The design of a Ceramic Turbine Technology Demonstrator is also underway. Engine power balance design codes were used to size the turbomachinery for the prototype engine powerpack to support the design of the ceramic turbine for the demonstrator. Alternate material architectures are being screened for this component. Material process studies are underway to select a vendor to fabricate the part.

Installation studies of the aerospike engine into the vehicle are on going with emphasis on integrated thrust structure and engine to minimize the vehicle weight and shift the center of gravity forward as far as possible. Alternate feed system configurations are being explored to support these installation studies.

RLV Structural Design

Various LOX and LH_2 tank configurations have been investigated to determine which propellant tank geometries contribute to the lightest vehicle without producing unacceptable deflections to the aeroshell. Intertank trade studies were performed to determine the preferred stiffening concept, to refine the parametric weight estimate and to identify load paths. The aft thrust structure analysis identified issues in the engine integration that are being incorporated into current designs.

Finite element analysis of advanced pressure shell geometry is being used to identify the structural and weight impacts of non-conventional pressure vessel geometry. Trade studies have quantified the sensitivity of vehicle weight to ultimate safety factor, ullage pressure, material properties and liftoff/ascent vehicle acceleration.

New TPS attachment concepts have been assessed. There are specific improvements over the X-33 TPS attach concept. Coordination with B. F. Goodrich ensures a dual role of tank frames for TPS attachment and for tank stabilization. Several concept TPS support structure weight estimates, with varying tank ring spacing, have been completed to support the integrated TPS-to-tanks weight trade-off study.

RLV Manufacturing

Tooling and fabrication concepts for assembly and the overall manufacturing process are being developed. Facilities identified to support the program will impact this process. The production of key elements, such as the LH_2 and LOX tanks, will drive manufacturing techniques due to their size, materials and process requirements to meet minimum structural weight.

Long lead purchased items, specific types and thickness' of titanium plate and composite materials are being queried for availability and their possible impact to

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schedules. The development of the Major Assembly Sequence Chart (MASC) and the supporting Manufacturing Schedule is also in process.

RLV SYSTEM OPERATIONS

The System Operations efforts this year have focused on reviewing and upgrading the baseline operations approach, revising and updating the operations functional flow and timeline and selection of the initial VentureStar™. Operations Center (VSOC) site(s).

Operations is developing the baseline concepts and strategies for the ground facilities, as well as the Mission module (payload) integration. Additionally systems and equipment requirements necessary to accomplish all the functions within the mission performance and mission operations are being developed.

System-level trade studies are currently being completed to evaluate alternatives for accomplishing fundamental operations such as: fixed versus mobile facility for vehicle checkout and payload installation / removal; vertical versus horizontal mission module (payload) integration; vehicle safing location; system throughput (flight rates); vehicle processing and maintenance from vehicle safing to vehicle erection.

These trade studies, which use life cycle cost (LCC) and turnaround times as the primary evaluation criteria, will define subsequent lower level trade studies to be performed. Design drivers from customer requirements continue to be more fully defined and incorporated. The system-level trades will be completed this year.

Work is progressing on flushing out the ground operations functional flow and timelines consistent with the above mentioned system-level trade studies. Analysis of the functional flow has often identified opportunities for significant improvements in specific functions as well as the overall functional flow. First drafts of mission integration, vehicle landing-to-landing and payload processing and integration functional flows have been developed. The Ground Operations are the critical path schedule items in the total turnaround cycle.

In January of 1998, prospective site providers met with the VentureStar™ team to begin the initial site(s) selection process. Representatives of 11 states were present at this meeting and were formally introduced to the program and our

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site(s) needs. Subsequent discussions have been held with these states as well as others who have since expressed a desire to be considered for VSOC siting.

A two-step selection process is being used to select the Operations site. First, a short list of acceptable sites will be identified based on their qualification to meet the basic system requirements. The selected sites will then be invited to formally submit proposals for evaluation. Proposal submittal is anticipated in the 2nd quarter of 1999 with final selection made by early 4th quarter. Current efforts are centered on continuing to develop interest on the part of potential site providers and developing the Request for Qualifications.

LOCKHEED MARTIN MICHOUD SPACE SYSTEMS

X-33 LO2 TANK PROGRESS

The X-33 2219 LO2 Tank completed the final design, fabrication, and proof test in the first quarter of 1998. The tank was delivered to Palmdale on schedule on an Airbus 300 Beluga transport on February 10th, 1998. The LO2 tank design and manufacturing plans were significantly impacted early in 1997 when several vehicle interface changes were implemented as a result of vehicle design maturity. Almost all of the tank aeroshell attachments and nose cap interfaces experienced changes that required redesign of fitting hardware. The primary structure remained unchanged by adding additional support webs and roll ties on the existing frames. Significant manufacturing flow workarounds were required to minimize schedule impacts on the program. In fact, the proof test was conducted ahead of several of the external frame modifications. The tank was proof tested to demonstrate adequate manufacturing processes and design requirements were satisfied. The tank was cleaned to meet the MPS cleanliness requirements for LO2. The tank was insulated with Spray RCI, instrument with the VHM/FTI instruments, and finally coated with ESD for static grounding. The number of interfaces on the tank grew from 136 to over 400 attachments during the design phase of the program. The entire tank program occurred for 21 months which is about one half of the time of a typical program. The ability to perform the tank program in a true concurrent engineering environment with streamlined processes and dedicated personnel has demonstrated that significant cost and schedule savings can be achieved for future tank programs.

X-33 MAIN PROPULSION SYSTEM

LO2 Feed Fill and Drain

100% of the drawings have been released for this sub-system. This also included the system change to add 8” EMA tank isolation valves (TIV’s) at the LO2 tank outlet. As part of the LO2 tank assembly, the LO2 tank contoured outlets, screens and anti-vortex baffles were designed, fabricated and successfully installed in the tank. 4” and 8” Ball Strut Tie Rod Assemblies (BSTRA’s) have been fabricated and are in the process of being qualified. The external 8" gimbal has also been fabricated and is in the process of being qualified.

LH2 Feed Fill and Drain

100% of the drawings have been released for this sub-system. This included the system change to add 8" EMA tank isolation valves (TIV's) to the LH2 feedlines. CFD analysis indicated that as a result of this change the flowfield would not satisfy the engine pump inlet requirements. A redesign of the feedline was made which incorporated 4 vanes to straighten the flow as well as a variable cross-section. As part of the risk mitigation a series of waterflow tests were performed at MSFC to verify the CFD analysis. The results indicated that the flowfield was acceptable to proceed to engine powerpack testing. The first flight type line has been fabricated and is being instrumented and insulated for test later this year.

GO2 Press, Vent and Relief

100% of the drawings have been released for this sub-system. The integration of the vehicle helium requirements into this system led to the integrated helium system (IHS) design. Also a change to add a propellant utilization system was approved and has been integrated with the helium system. The -320 deg F solenoid valve for the helium inject system is available and fabrication of the small tubing system is in process. The -423 deg F solenoid has experienced several problems. However, cryo testing has indicated potential changes that may provide a suitable solution.

As part of the LO2 tank assembly, the GO2 cover plate was designed and fabricated. The GO2 relief valve and diffuser assembly were integrated with the cover plate and were successfully installed in the LO2 tank. Two sections of the 2" pressurization system have been fabricated and are available for integration into the LO2 and LH2 tanks.

GH2 Press, Vent and Relief

95% of the drawings have been released for this subsystem. The -320 deg F solenoid valve for this system has been qualified and the four flight valves have been delivered and are being integrated into the small tubing system. The diffuser assemblies and relief valve for the LH2 tank has been fabricated and are available for integration with the LH2 tanks. Also, sections of the 2" pressurization lines have been produced and are available for integration with the vehicle.

Electrical Systems

95% of the drawings have been released for this subsystem. For the LO2 tank, the capacitance probes that will sense liquid level were qualified, fabricated and installed within the LO2 tank. Several pressure and temperature sensors have been through qualification and will be installed in various locations throughout the MPS systems.

X-33 OPERATIONS - CRYOGENIC SYSTEMS

LMMSS Cryogenic Systems Operations Team continues to provide the program technical lead and direction for the X-33 flight and ground cryogenic MPS systems operation definition activities. We completed operability, operations and maintenance assessments for our Reusable Cryogenic Insulation (RCI) and Vehicle Health Management (VHM) designs and participated in the design activities and Critical Design Reviews.

In the area of assembly, test and launch operations requirements definition, we completed 3 review cycles of 5 volumes of the Test, Operations and Maintenance Requirements, Specifications and Criteria (TOMRSC) documentation. These volumes detail the launch site activation and flight test operations required to be performed to support the LO2 MPS, LH2 MPS, IHSDS, RCI and FTI/VHM. The LO2, LH2 and IHSDS data is the core data included in the MPS Subsystem Control ICD which also completed 3 review cycles and baseline release. We also prepared and completed 2 review cycles of the MPS Assembly Test and Checkout requirements document, and provided drafts of the MPS System Checkout requirements and the MPS Ground Vibration Test requirements documents.

In the area of assembly, test and launch operations procedures and software development, we completed procedure identification. We have also completed the reparation of draft procedures for launch site ground system activation and

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checkout. In addition to outlines of all other procedures required to prepare the X-33 ground and vehicle MPS, RCI and FTI/VHM systems for launch, support landing, and post landing, and vehicle turnaround. We are supporting the ground and flight software development activities through specification and code review participation.

We are 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.

X-33/RLV REUSABLE CRYOGENIC INSULATION (RCI) AND VEHICLE HEALTH MONITORING

The reusable cryo 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 the handspray process for SS-1171, a 2.5 pcf polyurethane spray foam, application on the LO2 tank, cyclic testing of the SS-1171 foam, and an Electrostatic Dissipative Coating. The details of each of these development areas are given in the following paragraphs.

RCI DEVELOPMENT PROGRESS PERFORMANCE:

SS-1171 Spray Foam

The handspray process for applying the SS-1171, polyurethane foam, to the X-33 LO2 tank was developed and tested through approximately 60 mock-up sprays. Three different types of spray guns were used with various modules for each gun.

Cyclic testing of SS-1171, cryogenic and elevated temperature, was completed. Part of the cryoflex testing was conducted over an anvil with a 25" radius with no anomalies.

LO2 Tank Insulated

The LO2 tank was cleaned, primed, and insulated within budget using SS-1171 as the reusable cryogenic insulation for acreage, ring frames, and longerons. PDL-1034, a pourable polyurethane foam, was used as the close-out insulation.

Electrostatic Dissipative Coating

Several coatings were evaluated to aid in dissipating any static charge build-up in the RCI. Through cyclic testing and ohms testing at KSC, Sandstrom Silver Lining was selected to be applied, spray and brush applications, to the surface of the RCI.

Materials Evaluated:

Cappcoat	AZ Technologies, Inc.	Belland (2 different coatings)	Sandstrom Silver Lining
System used MEK and test samples had visible deterioration after application. Did not meet static dissipation rate.	Did not meet static dissipation rate. Only in development stage.	Coatings disappeared during the initial heat test. Did not meet static dissipation rate.	**Water base. Met static dissipation rate requirements. Commercially available. No degradation of material after (25) +350°F cycles.**

Task Agreement Summary

Lewis Research Center - LeRC-01 Atmospheric Pressure Testing

A calorimeter provided by LeRC was insulated with Airex R82.60 and closed out with SS-1171 foam. The insulation was subjected to LH2 backface temperatures, surface temperatures up to +350°F, and vacuum. 60 cycles were completed with no anomalies to the Airex R82.60 insulation.

LaRC-08 Thermal Mechanical Testing

Completed a composite thermal mechanical panel insulated with Airex R82.60 polyetherimide and CryoCoat UL-79, epoxy close-out insulation. An aluminum, Al-2219, panel with SS-1171 and PDL-1034 polyurethane foams was also tested for 50 cycles. The fifty cycles consisted of 25 pre-launch/abort cycles and 25 pre-launch/launch cycles. Those cycles take into account 15 flights, scrubs/aborts, tanking/detanking, flight readiness, proof pressure test, and some margin.

The last panels have the electrostatic dissipative coating added to the configuration to complete the test matrix.

SSC-01 10 ft. Composite Tank RCI Support

Reusable Cryogenic Insulation (RCI) was bonded in selected areas of the 10 ft. composite tank tested at Stennis Space Center. Both Airex R82.60 and CryoCoat™ UL-79, applied with standard processes, were successfully demonstrated.

The number of cycles conducted on the tank were seventeen at 36 psi, one at 55 psi, nine at 75 psi, and three at 100 psi for a total of 30 cryogenic cycles.

VHM DEVELOPMENT PROGRESS PERFORMANCE

Distributed Temperature Sensor (DTS)

Seven optical fibers were installed on the Dual Lobe tank and used as Distributed Temperature Sensors (DTS). Temperature was measured along each fiber and averaged over meter length zones with the help of the York™ DTS system. Approximately 700 feet of DTS fibers were installed on top of the insulation at various phases of the Dual Lobe Tank testing.

The DTS fibers performed nominally during all the tests conducted at ambient conditions and during the first few cryogenic tests. However during the course of cryogenic testing, cracks opened in the SS1171 portions of the foam insulation on which the DTS fibers were bonded. Also, after each cryo test, during the low-flow portions of the tank warm-up, cold gases were vented out of some of these cracks and caused them to open wider. The combination of increased strain on the DTS fibers from the widened cracks and the cold gas venting from these cracks during low-flow caused erroneous temperature readings and damaged DTS fibers. It was found that the baseline EA 9394 adhesive was too stiff an adhesive for the DTS system.

Further environmental testing of the DTS was required beyond the Dual Lobe tank tests as a result of the LOX tank foam baseline change to SS-1171, resulting in a significant improvement in DTS performance and durability. The adhesive was changed from EA9394 to RTV 106, and tests were run for the expected full temperature range of the foam surface (-65 to +350°F). In addition to improved survivability, the RTV also imparted much less light loss to the fiber, resulting in improved sensor performance. The DTS temperature readings correlated closely with thermocouple measurements. A repair technique for DTS was also developed and successfully tested.

This development work has led to released engineering and successful installation of the flight DTS system on the LOX tank. The flight system consists of 2 DTS fibers, primary and redundant, each about 290 feet in length. Each fiber is equivalent to 90 thermocouple measurements for a fraction of the weight.

Distributed Strain Sensor (DSS)

Five separate optical fibers containing a total of 60 Distributed Strain Sensors (DSS) were installed on various areas of the dual lobe tank. DSS fibers measure strain at specific points along the fiber. The DSS fibers were bonded to the external skin of the composite structure under the insulation. The four initial DSS fibers were bonded to the tank using a "thick bondline" method. The final fiber was bonded using the "thin bonding" method which greatly decreased the light loss along the fiber due to the adhesive. Strain data from the DSS fibers was read by DSS hardware and software furnished by NASA Langley Research Center.

Overall the DSS system matched the objectives for the test, namely survivability - no fibers were permanently lost when exercising the DSS system in a non-lab environment. The performance of the DSS system was inconsistent in that some DSS sensors compared well with conventional strain gages and others

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gave erroneous readings, especially at cry. These inconsistencies are caused by known limitations in the DSS hardware device which was employed. NASA Langley is already in the process of correcting these limitations for later versions of the DSS system.

Distributed Hydrogen Sensor (DHS)

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 will finalize the sensor configuration.

One of the challenges with the DHS system is isolating mechanical strain from strain induced by hydrogen absorption. Several strain isolation concepts have been formulated and testing is planned.

Acoustic Emission (AE)

- Performed a downselect from four different AE vendors for flight type sensors and preamplifiers. This involved developing a cryogenic sensor/preamp design, contracting vendors to manufacture to the design, receive and test (cryo and room temperature) the designs, downselect and order the flight sensors.
- Developed a thermoforming technique for application of Airex to small diameter tubing or pressure vessels. Implemented this technique on a selection of small pressure vessels which were subsequently AE tested to determine whether AE could discriminate between damaged and undamaged pressure vessels when they are covered with Airex. The test provided valuable data for sensor selection and spacing for LH2 tank. Damaged tanks could be discerned from undamaged tanks.
- Co-authored a paper on the AE signatures generated from low and high velocity impacts on composites. This work showed that AE is a very viable technique for detecting micrometeoroid impact on space vehicles.

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- Developed a system design in which equipment from two different manufacturers, taking different kinds of data can be integrated so that the resultant data contains more information than either system could provide individually.
- Developing a defect location algorithm tailored specifically to the LH2 aft bulkhead joint. The result will be an accurate determination of the locations of defects in the joint region.
- Performed adhesive bonding tests to simulate the bond between the LH2 composite surface and the ceramic face plate contained on the AE sensors. Downselected to one adhesive for flight based on these test results.

Attached two different AE sensors to the composite 10' tank. These sensors were to test bonding and sensor performance on large composite cryogenic pressure vessels. Results showed that one particular adhesive was unacceptable. The other sensor survived repeated exposure to cryogenics and performed nominally throughout the test.

- Currently testing large composite test panels bonded together with AF-191 film adhesive which simulates the LH2 tank aft bulkhead configuration. AE data is planned to be taken from these panels while they are destructively tested in a tensile machine. The results from this test should be directly applicable to the LH2 tank.
- Developed (~90% complete) AE installation drawings for LH2 tank.

X-33/RLV COMPOSITES

Team 3 has made progress developing technology for composite cryotanks and propulsion system components in the following areas:

X-33

Cryogenic Helium Tank - Completed cryogenic qualification testing for the titanium lined composite overwrapped helium tank for the X-33 LOX Tank Pressurization System. Completed fabrication of 5 Titanium Liners for fabrication and room temperature proof test for 4 of the flight tanks.

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Pressure Box - Designed, analyzed and fabricated biaxial test panel replicating the X-33 LH2 Tank design to be tested in June 98 under combined environments pressure, axial load, radiant heat and cryo.

Composite Coverplate - Completed part design, tooling design, and issued fabrication contract for composite coverplates for X-33 LH2 Tanks.

RLV

LOX Compatibility - Phase II testing was completed for four material systems having promising levels of LOX compatibility suitable for use in tank applications.

Semiconformal Minitank - A 2' x 4' x 4' tank was designed and partially fabricated using a variety of new technologies. The tank uses a conferral design concept, LOX-compatible resin system, and inert technology developed under IRAD. In addition, the tank uses cryo-insulated (foam filled) sandwich core construction, two new low-cost 3D composite architectures for bosses, developed under LMMSS IRAD and straps with sealed through-bolts for lightweight shape control. Low cost mandrel and cure process improvements were also implemented.

RLV Trade Studies - Six tank concepts for LH2 and LOX tanks were developed and traded for weight sensitivity using both multilobed and semiconformal concepts. Trades were carried out to determine optimum stiffener layout to accommodate BFG external TPS attachment, and these results were used to account for total system weights of tank configurations accounting for TPS attachment, pressure loads, and vehicle structural loads from thrust and landing gear attachment.

SYSTEMS ENGINEERING AND ANALYSIS

Systems Engineering:
- Requirements
- ICDs
- Design Reviews
- Engineering Changes
- Nonconformance

Verification / Certification

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

The Systems Engineering effort for Lockheed Martin Michoud Space Systems (LMMSS) has been integrally involved in the design of four major 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 verification plans in place and implementation activities in work. The Interface Control Documents continue to be adjusted and verified as interfacing subsystems are changed to reflect these subsystems maturing engineering design definition. Design reviews are complete and final hardware design certification (both analysis and test) is the primary focus of the Systems Engineering and Analysis group. As the hardware build nears completion, Systems Engineering has managed the nonconformance disposition process ensuring that LMMSS maintain the same high quality of hardware and traceability as our other programs with regard to as-built versus as-designed configuration verification.

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LOCKHEED MARTIN SPACE MISSION SYSTEMS & SERVICES

TAEM AND A/L GUIDANCE AND FLIGHT CONTROL DESIGN

LMSMSS/Houston's prime responsibility is the design of the Terminal Area Energy Management (TAEM) and Approach/Land (A/L) guidance and flight control for the X-33. We have supported the vehicle development process with the following major documentation items:

- Delivered Revision D inputs to the Detailed Design Description (DDD) document on 9/26/97.
- Presented summary of TAEM and A/L guidance and control design and performance at the X-33 Critical Design Review on 10/27/97.
- Delivered Revision F inputs to the DDD on 11/13/97.
- Delivered Inputs to the Analysis and Simulation Document on 12/12/97. These data reflect the design configuration summarized at the Critical Design Review in October.
- Delivered FORTRAN implementation of guidance and flight control requirements to the Skunk Works and to NASA/Dryden on 10/1/97 and on 2/25/98.

In addition, LMSMSS has assisted in defining the requirements for the navigation processing function, and provided unit test cases for validation of flight software, and responded to numerous requests for trajectory and vehicle performance information to members of the development team.

EVALUATION OF VEHICLE CONFIGURATION

LMSMSS/Houston has played a critical role in developing and evaluating changes to the vehicle configuration and reference trajectory, including:

- Change in the wing dihedral to 20 degrees
- Increased vertical tail area
- Canard and upper flap deletions
- Change in elevon split line
- Vertical rudder actuator rigging (15 deg outboard)

- Wing tip/elevon reconfiguration
- Inboard elevon actuator crank arm
- Body Flap deflection capability
- Addition of differential braking as an assist for nosewheel steering
- Trajectory adjustment transonically for pitch trim/hinge moment balance
- Development of requirements and candidate sites for Intentional Controlled Flight into Terrain (ICFIT) abort mode

LMSMSS has responded very quickly to these changes, typically providing a preliminary evaluation within days of receiving updated aero data sets. LMSMSS has helped to identify and address the issues that have driven these configuration changes, especially the pitch trim requirement at mach 1.15 and the elevon hinge moment saturation encountered near maximum upward deflection.

TAEM and A/L Dispersion Analysis

As the vehicle configuration has matured, we have performed numerous studies to characterize vehicle performance and robustness with respect to system and environmental dispersions. These analyses have typically been updated with configuration changes and as model information has matured. The following are typical of the analyses performed:

- TAEM interface dispersion capability
- Sensitivity to aerodynamic and environmental dispersions
- Rollout vs. brake energy tradeoff
- Lateral runway excursions in rollout

Modeling and Simulations

The SES 6-DOF simulation has been the basis for development and validation of vehicle and trajectory modifications in the TAEM and A/L phases of flight. The SES has been installed at the Skunk Works, the ITF at NASA/Dryden, and at AlliedSignal/Teterboro in order to provide the development and verification community with simulation capability. The major releases are summarized below:

- Released SES V1.4 on 10/1/97. Highlights of this release included implementation of the Dryden aerosurface actuator model, aero dispersion capability, aero data model standardized to MSFC format, and tailscrape test logic.
- Released SES V1.5 on 2/25/98. Major updates included flight control design changes, code modification to facilitate porting the G&C modules into the ITF, and capability to produce multiple runs via a script file of input directives.

LMSMSS also provided on-site support at the Integrated Test Facility to accomplish integration of the SES to provide an end-to-end (launch to landing) simulation capability. Common block structures and interface definitions were modified to allow compatibility with the ITF simulation operating system. Interfaces to the navigation processing function were defined and coded. The root simulation in Houston was updated accordingly to streamline installation of future versions at the remote sites.

Unit Test Cases

Unit test cases for the TAEM and A/L guidance and control have been delivered. These provide a means for verifying implementation of the flight software at the module level. The guidance and flight control modules from the SES simulation have also been delivered in "wrapper" form which is a stand-alone unit program that allows the software implementer to run unit test cases other than those provided. The delivered products are summarized as follows:

- X-33 TAEM and A/L Unit Test Cases, Revision A, 2/13/98. This version is consistent with Revision F of the X-33 DDD.
- X-33 TAEM and A/L Unit Test Cases, Revision B, 3/31/98. This version included some changes to the code structure and updated i-load values, all of which are documented in Revision G of the DDD.
- Dispersion analyses were performed on the Rev B design and the results are documented in Revision A of the X-33 GN&C Analysis and Simulation Document (604D0041A).

Ancillary Support

Routine support to the GN&C development activity included:

- Participation in weekly Flight Sciences telecons
- Support to the periodic Flight Sciences TIMs with analysis and development results
- Review and redlines to the associated requirements and interface control documents

LOCKHEED MARTIN - SANDERS

This progress report is focused on Sanders' contribution to the X-33 vehicle and ground system development. Sanders is developing a Vehicle Health Management (VHM) system for on-board X-33 with three major constituents: the Vehicle Health Monitoring Computer (VHMC) LRUs (2 units), the Remote Health Node (RHN) data acquisition LRUs (50 units), and the fiber optic bus networks. Sanders is responsible for the acquisition and development of the LMCMS Core System. The LMCMS Core System consists of Ground Interface Modules, Telemetry and Range Interface Processors, Storage and Retrieval System, Database Server, Command and Data Processors, Operator Consoles and LMCMS System Software. Four adaptations of the LMCMS Core System will be provided: Operational Control Center (OCC), Mobile OCC (MOCC) , Portable and ITF adaptations. Additionally, Sanders is providing an on-site team supporting the development of LMCMS application software, and overall LMCMS integration and test.

VHM PROGRESS SINCE JULY 8, 1997 PROGRESS REPORT:

- Completed vehicle CDR in October, 1997
- Shipped Brassboard update with 1553 functionality, January, 1998
- Shipped RHN mock-up April, 1998
- VHM mock-up in process to meet June, 1998 requirement
- Completed VHM processor upgrade from STAR 2 to STAR 4 for CPU utilization
- Completed redesign of hard disk drive (HDD) to meet environmental requirements
- Completed HDD life testing successfully, no impact to design
- Completed optical fiber routing and ordered cables for delivery starting May, 1998
- Completed mechanical and thermal analysis of VHMC and RHN
- Completed test of power supply and digital RHN design prototype
- Testing in process on analogue flight electronics RHN design prototype
- Multi-Chip-Module designs successfully passed room temperature tests, first pass

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- Software development on schedule for completion May, 1998
- Test stands and test procedures on schedule for completion May, 1998

GSS PROGRESS SINCE JULY 8, 1997 PROGRESS REPORT:

- Participated in the successful X-33 CDR in October, 1997.
- Installed LMCMS Test System at Sanders Lab in October, 1997.
- Installed LMCMS Test System at LMSW Lab in November, 1997.
- Installed LMCMS Core System adaptation at ITF in January, 1998.
- X-33 VHM/GSS Progress Report
- Procured LMCMS equipment required for the OCC and MOCC LMCMS Core System adaptations. Hardware acquisition and integration is on schedule to support LMCMS Build 5 and Build 6 shipment internal milestones.
- Completed delivery of LMCMS Build 3 in March, 1998.
- Completed software development of LMCMS Build 4 in April, 1998. 48,000 SLOC out of a projected 63,000 for the LMCMS System Software SLOC has been completed through April 1998.
- Integration of LMCMS Build 4 is on schedule for April 17, 1998 shipment.

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LOCKHEED MARTIN TECHNICAL OPERATIONS

Over the previous 12 months significant contributions have been made to the development of the X-33/RLV Phase II Program by the LM Technical Operations Company team. The following are a summary of those efforts:

X-33

- Developed console displays and ground software requirements for ground and vehicle subsystems
- Developed the integrated launch site activation plan
- Developed launch sequence and first drafts of launch sequence document and launch commit criteria document
- Developed first drafts of launch site systems checkout procedures
- Initiated development and coordination of vehicle systems checkout procedures for manufacturing checkout
- Developed draft launch and landing operations safety plan
- Developed draft X-33 emergency response plan and successful coordination with government agencies
- Considerable progress made in landing sites coordination and developed/released Program Introduction Documents
- Completed range population overflight risk analysis in support of EIS approval
- Coordinated launch site construction permits
- Completed detail designs of the LMCMS Independent Safing System, Vehicle Positioning System, laser initiated Holddown/Release System, Vehicle/GSS T minus Zero Umbilical Systems and vehicle lifting slings
- Completed hardware procurements for the Independent Safing System and Vehicle Positioning System. Hardware procurements for all other LMTO responsible hardware nearly complete less vehicle lifting slings
- First vehicle qualification titanium holddown bolt fabrication successfully completed
- Assembly initiated for the Independent Safing System and Vehicle Positioning System
- Developed draft of the X-33 Quality Assurance Plan
- Lead the development of the draft X-33 Master Operations Plan

- Identified all required X-33 Ground Support Equipment
- Developed X-33 ground transportation plan as alternate to Shuttle Carrier Aircraft for transportation between factory to launch site and landing sites to launch site. Resulted in $18+ million program cost savings and eliminated major program schedule threat
- Completed overland transportation survey and initial government agencies coordination
- Coordinated the integration, requirements and development of the X-33 Ground Vibration Test
- Lead the X-33 Team Engineering Review Board to provide the most cost effective solutions to system design changes
- Coordinated and lead development testing to resolve issues concerning hydrogen free venting from X-33

RLV/VENTURESTAR

- Provided major contributions to the RLV Systems Requirements Draft Document and review
- 70 Percent complete in developing the SSTO/RLV Operations Functional Analysis
- Established ground operations development team and strategy for achieving necessary RLV Go-Ahead Decision criteria and products
- Performed studies and functional analysis for payload processing and integration including crew accommodations

LOCKHEED MARTIN ASTRONAUTICS-DENVER

RLV/X33 research accomplished by Lockheed Martin Astronautics during the reporting period occurred in four major areas of the cooperative agreement Work Breakdown. Astronautics provided engineering support to the Skunk Works in X-33 Development, RLV Development, Systems Engineering, and Business Development.

BUSINESS OPERATIONS

Astronautics supported business plan development by the Enterprise Development group and provided inputs, updates and analyses of requirements to the mission and market models.

SYSTEMS ENGINEERING

Astronautics has provided systems engineering for X-33 and RLV development, with the level of support appropriate to the respective phases of X-33 and RLV in the system development cycle. The systems engineering effort has been principally in the areas of requirements specification, interface management, configuration management, risk management, test plan development, requirements verification and compliance, technical performance measures, and technical reviews.

RLV DEVELOPMENT

Astronautics has provided primarily systems engineering for RLV development, with major emphasis in the areas of technical planning and control, risk management, requirements specification, and Systems Requirements Review preparation.

X-33 DEVELOPMENT

Astronautics provided direct support to the preparation, conduct, and closure of the X-33 Critical Design Review. In addition to systems engineering for X-33, Astronautics has developed and tested a bonding process for X-33 truss-tubes and has applied the process in the fabrication of X-33 flight hardware. Astronautics also is continuing development of Integrated Health Monitoring (IHM) ground system software for use during X-33 flight tests as part of the Launch and Mission Control Management System (LMCMS). The truss-tube bonding effort adapts a proprietary bonding process developed for satellite fabrication to X-33 composite tube and titanium end-fitting requirements. It is being performed in our composite laboratory.

BOEING – ROCKETDYNE DIVISION

ACRONYMS AND ABBREVIATIONS

C/C	Carbon/Carbon (fiber/matrix)
CDR	Critical Design Review
C/SiC	Carbon/Silicon Carbide (fiber/matrix)
CTTD	Composite Turbine Technology Demonstrator
CWI	Combustion Wave Ignition
EMA	Electro-Mechanical Actuator
EPL	Emergency Power Level
GCH_4	Gaseous Methane
GG	Gas Generator
GO_2	Gaseous Oxygen
HIP	Hot Isostatic Pressure
Isp	Specific Impulse
LaRC	Langley Research Center
LeRC	Lewis Research Center
LH_2	Liquid Hydrogen
LMSW	Lockheed Martin Skunk Works
LOX	Liquid Oxygen
LSTA	Large Scale Test Article

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MSFC	Marshall Space Flight Center
MTD	Manufuacturing Technology Demonstrator
NASP	National Aerospace Plane
RCS	Reaction Control System
RFQ	Request For Quote
RLV	Reuseable Launch Vehicle
RNTF	Rocket Nozzle Test Facility
SSC	Stennis Space Center
SSTO	Single Stage To Orbit

OVERVIEW

Significant propulsion progress was made during the past year in support of the X-33/RLV Program. The majority of the design phase for the X-33 XRS-2200 engines was completed in September with the successful completion of the engine system CDR. Remaining design details are in work with total completion expected in June. Concurrently, the fabrication and engine assembly activity is in process, and the engine assembly team has been co-located adjacent to a new engine assembly area for X-33. Selected component testing including gas generator testing, thrust cell multi-rig testing, and CWI single element and assembly testing were either completed or are currently in process. Flight design single cell testing and powerpack testing are planned to be initiated in June. Engine testing is scheduled to be initiated in the Fall.

Work was also initiated on the RS-2200 Engine in support of the RLV Phase II activity. A point of departure engine design was defined, and program planning activities were started. Design and technology work tasks were identified, and staffing of integrated product teams was initiated. Remaining program planning is expected to be completed by June.

XRS-2200 ACCOMPLISHMENTS

ENGINE SYSTEMS DEVELOPMENT

Significant XRS-2200 engine system development progress was made. Activity included engine control system design, engine control software development, and test facilities preparation.

Control software development included completion of the coding of the OI-1 software release. This release includes the control laws which will be used in powerpack testing and is currently in verification and validation testing at the Huntsville Simulation Lab. The control system design effort was also completed including the release of all harness drawings. Fabrication of the first set of harnesses was completed in support of powerpack #1.

Major powerpack and engine testing progress was made on the A-1 test stand at SSC. The engine deck was cleared, and the thrust platen was template drilled to attach the thrust adapter. The powerpack discharge system was installed including back pressure control valves, ducting, and burn stacks. Cold shock of the LOX and hydrogen discharge systems was completed, and flowmeter calibration was initiated.

POWERPACK AND VALVES

Gas Generator and Heat Exchanger

Gas generator testing was conducted at MSFC to demonstrate ignition robustness and steady state operation over the required mixture ratio and flowrate conditions. Testing of the gas generator (modified J-2 design) was successfully completed and consisted of 38 tests including 20 steady state tests and 11 ignition tests. The steady state tests demonstrated safe operation in excess of the required power level operating range from 57% power level to the emergency power level (EPL) at mixture ratios from 0.80 to 0.95. The ignition tests demonstrated ignition robustness at low mixture ratios and high chamber pressure in excess of 300 psia.

For the heat exchanger, five units were refurbished, and proof-pressure testing was conducted based on the XRS-2200 operating requirements. The five units were stocked for engine use.

Fuel and Oxidizer Turbopumps

The fuel and oxidizer turbopumps activity consisted of design analyses and hardware fabrication and assembly. The turbopump designs (upgraded J-2S designs) were analyzed for the XRS-2200 operating environments and flow conditions. For operation outside of the historical operating experience database, mitigation measures were identified to insure robust operation. Fabrication of all of the turbopumps hardware is either complete or in process, and rotor balancing was initiated for the first units. Figure 1 shows a fuel pump rotor balance assembly.

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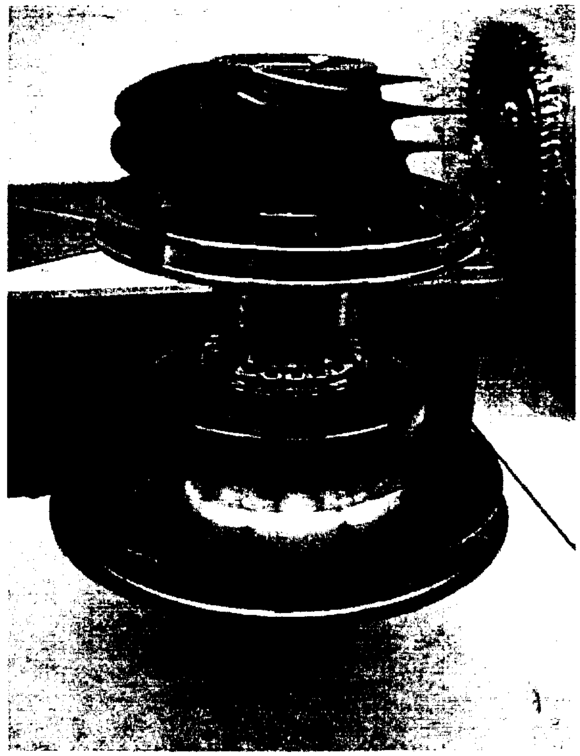

Figure 1. Fuel Pump Rotor Balance Assembly

Valves

Significant progress was made for the gas generator fuel and oxidizer valves. The detail parts shown in Figure 2 were completed for each valve, and the first two development valves were assembled. In addition, water flow testing was conducted to verify engine resistance requirements. Both valves were then assembled with an Allied Signal supplied EMA actuator as shown in Figure 3 and tested at ambient and cryogenic conditions for leakage and response. Both valves met their functional requirements and were shipped to MSFC for continued development testing. Tests planned include propellant flow, cryogenic cycle, and vibration endurance tests.

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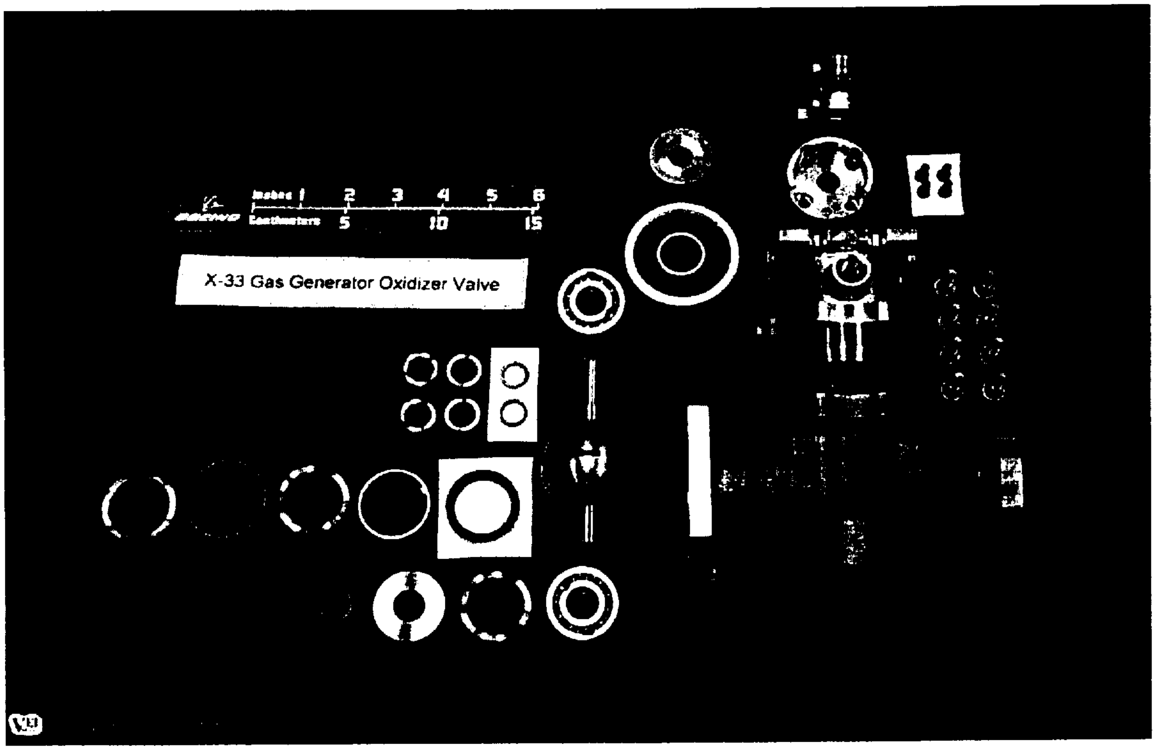

Figure 2. GG Valve Parts

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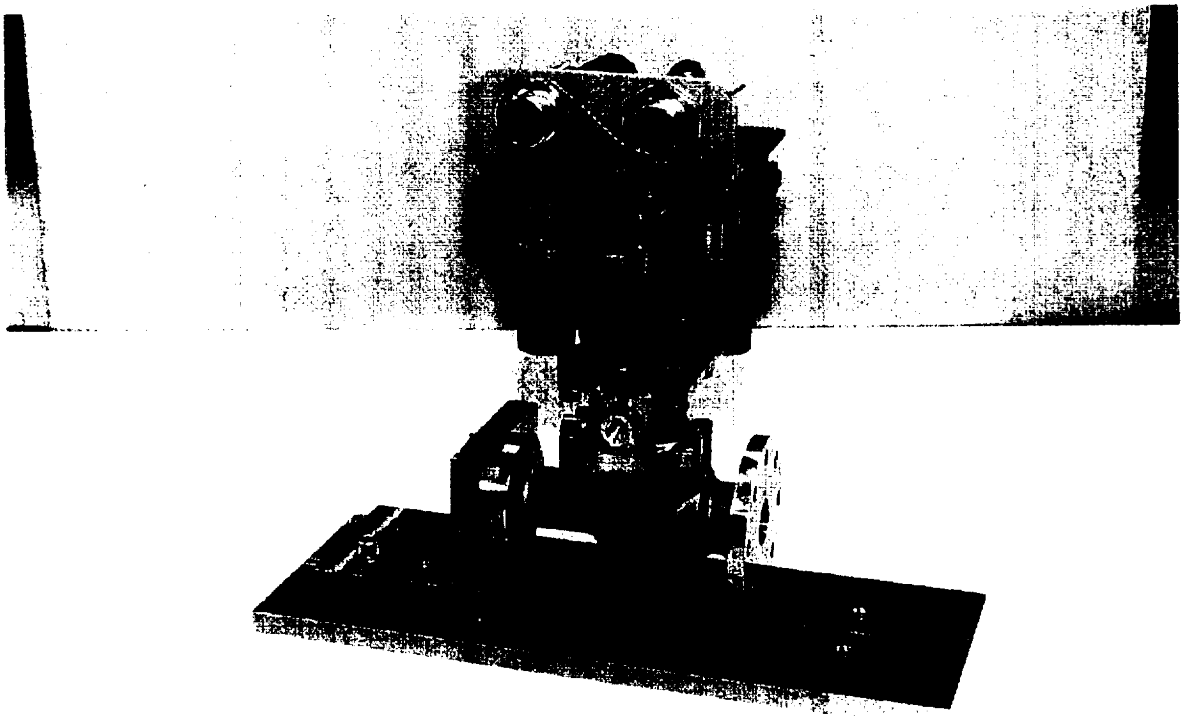

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Figure 3. EMA Actuator

THRUST CHAMBER ASSEMBLY

Thrust Cell Fabrication

The thrust chamber and injector design activity was completed, and production operations were initiated. Detail machined parts were fabricated by Rocketdyne and suppliers, and the first injector was assembled with piece parts for 60 units in stock. For the thrust chamber, the most critical assembly operation, HIP brazing, was completed for the first unit. This operation joins the liner to the jacket. Jackets and liners for over 20 units are nearly complete, and six chambers have been HIP brazed and are ready for final machining. Figure 4 shows the thrust cell components including a completed injector and thrust chamber which are on the right.

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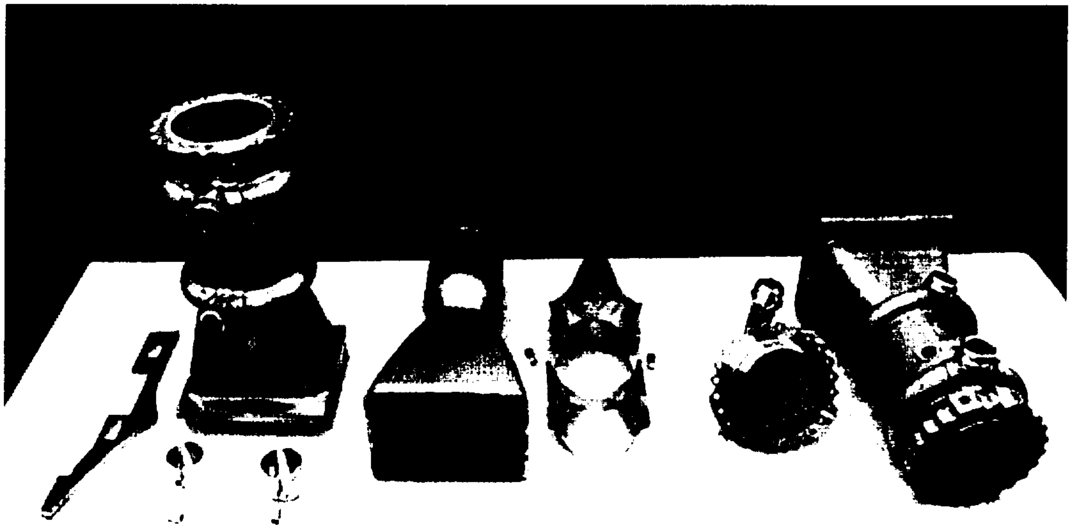

Figure 4. Thrust Cell Components

Combustion Wave Ignition Testing

Significant combustion wave ignition (CWI) system activities were accomplished. Single element CWI testing was successfully completed, and a test rig (spider rig) simulating the full scale engine ignition system was assembled and delivered to LeRC. The spider rig is shown in Figure 5. Ignition tests on this full-scale rig were initiated to determine ignition margins at cryogenic engine start conditions. Fabrication and assembly of the spider rig validated the automated bending of small tubes direct from Pro-E drawing models. This manufacturing process will result in significant cost savings for the program.

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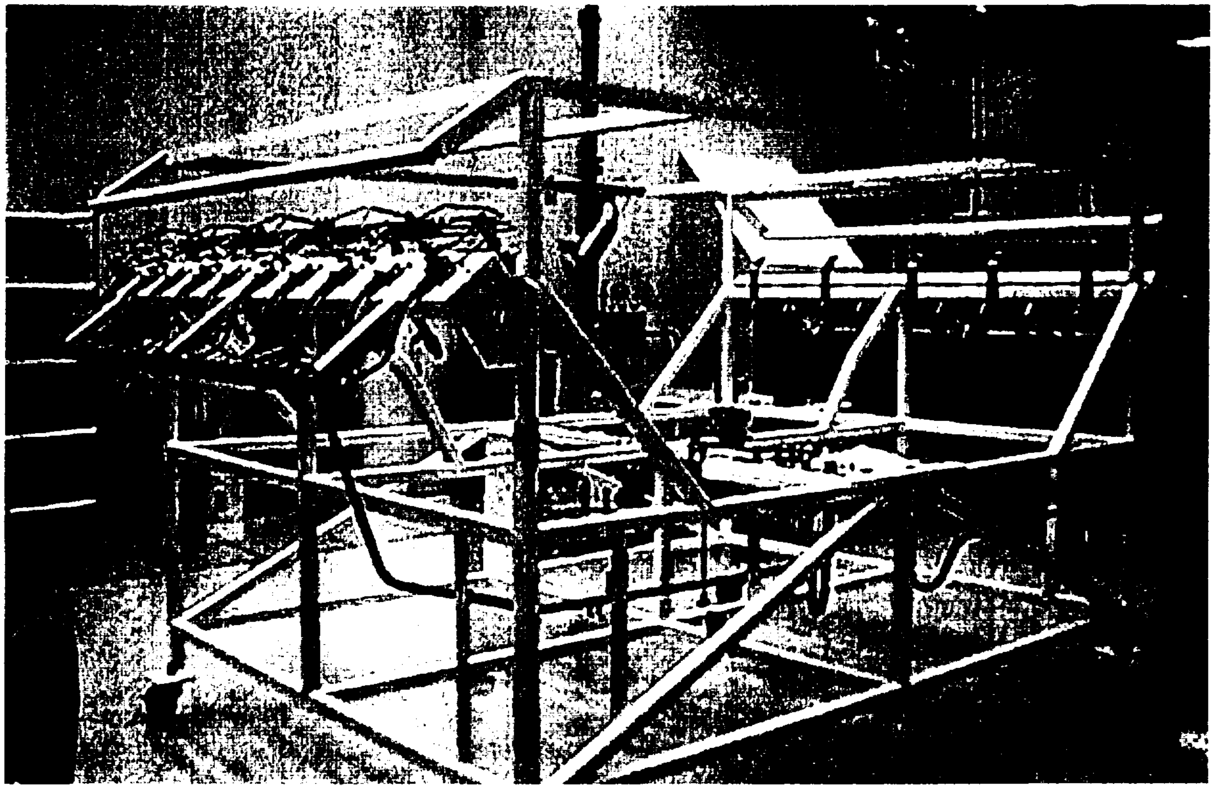

Figure 5. CWI System Spider Rig

NOZZLE

Manufacturing Technology Demonstration Hardware

Manufacturing technology demonstrator (MTD) hardware was developed to validate unique assembly tooling and processing techniques for the nozzle ramp assembly production hardware. Representative of actively cooled and internally pressurized production thrust ramp structures, three key thrust ramp MTD subassemblies were completed through braze. Shown in Figures 6, 7, and 8, these consisted of the inboard edge assembly, outboard edge assembly, and ramp. Each of the three MTD's successfully demonstrated many of the large scale machining, plating, and brazing processes that are critical to the production ramp program.

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LOCKHEED MARTIN AlliedSignal AEROSPACE BFGoodrich Aerospace BOEING Rocketdyne Division Sverdrup NASA

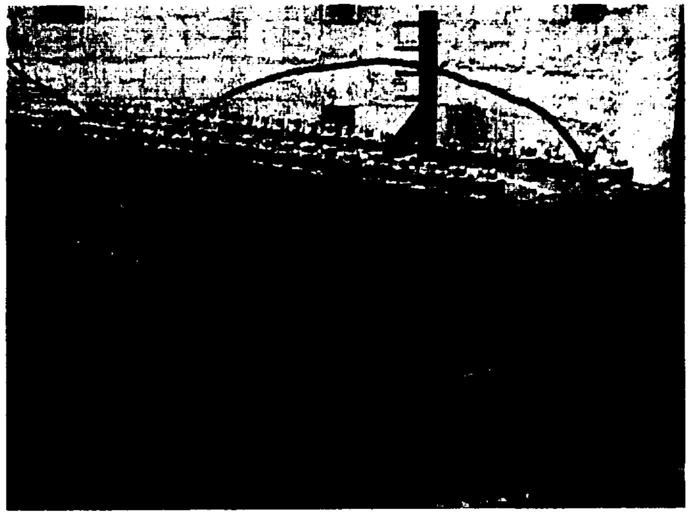

Figure 6. Inboard Edge MTD in Braze Furnace

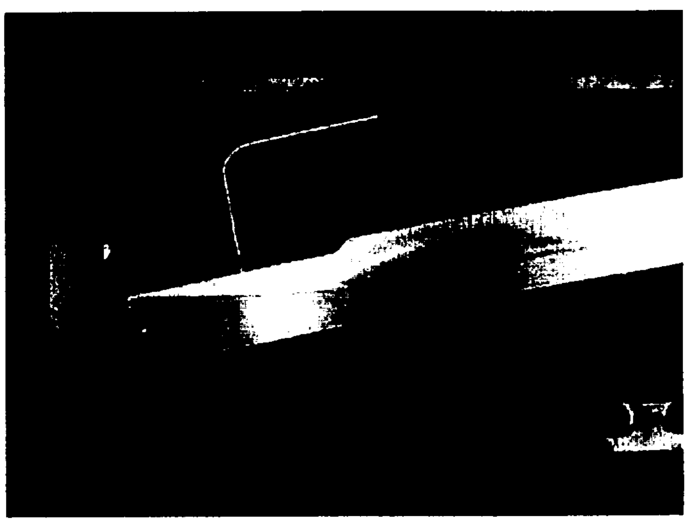

Figure 7. Outboard Edge MTD

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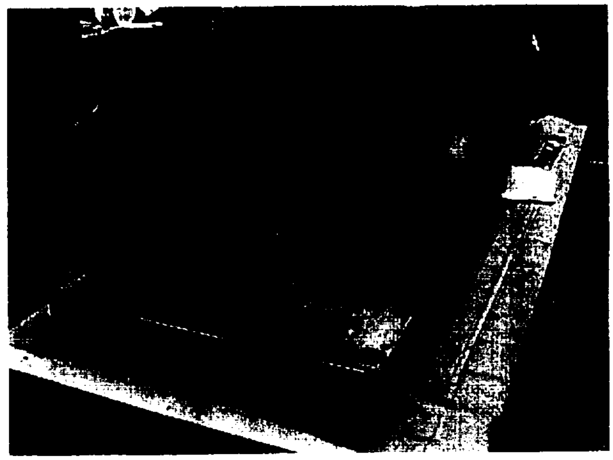

Figure 8. Thrust Ramp MTD

Production Hardware

Significant progress was made on the thrust ramp production hardware. The slotting of four thrust ramp liners was completed. Shown in Figure 9, each liner is a precision-machined NARloy-Z plate with 682 individual cooling channels which are efficiently cut in a single tooling setup. Following machining, each liner is gold plated as a final preparation for brazing. The plating of the first liner, shown in Figure 10, was completed, and a second liner is currently being readied for plating. The next assembly step is the brazing of the plated liner to a closeout assembly. Shown in Figure 11, the closeout assembly consists of inlet and outlet manifolds and a thin close-out sheet. When brazed together, the liner and close-out assembly form the actively cooled portion of the thrust ramp.

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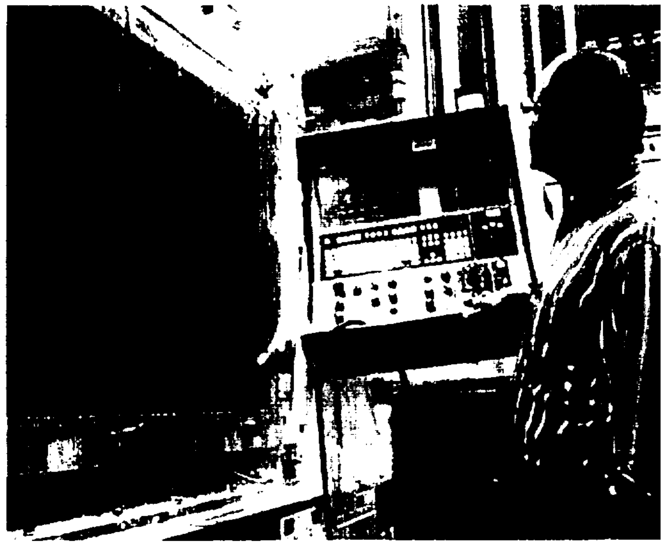

Figure 9. Thrust Ramp Liner Slotting

Figure 10. Thrust Ramp Liner Gold Plating

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Figure 11. Thrust Ramp Closeout Assembly

ENGINE DESIGN AND ASSEMBLY TEAM

Design and Assembly

Detail design of all powerpack structure, duct, and line assemblies was completed and drawings were released for hardware fabrication. Rocketdyne and supplier manufacturing operations commenced, and powerpack hardware and associated tooling were either completed or are nearing completion. The team also conducted a detailed powerpack build simulation to establish a build sequence and verify that all hardware and support equipment is accounted for prior to assembly. In addition, the XRS-2200 engine final assembly area was established, and all necessary modifications to the facilities were completed including co-location of all supporting team members.

Fabrication of the engine test stand adapter was also accomplished. The adapter attaches the SSC A-1 test stand platen and has attachment provisions for the powerpack test fixture and XRS-2200 engine. Installation and removal of

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the engine test stand adapter will be accomplished utilizing the vertical engine installer adapter attached to the space shuttle main engine installer. This will also be used to install and remove the engine master interface tool, powerpack assembly test fixture, and XRS-2200 engine into the test stand.

Scale Model Aerospike Cold Flow Testing

Simulated altitude testing was performed on a 1/26 scale model of the XRS-2200 aerospike engine at the Rocketdyne Rocket Nozzle Test Facility (RNTF) to assess nozzle performance characteristics. The model incorporated twenty scaled thrusters and a scaled aerospike nozzle ramp identical to the XRS-2200 Engine. Nozzle tests were conducted over a range of nozzle pressure ratios (chamber pressure/ambient pressure) from 5% to 120% of the nozzle design pressure to simulate moderate altitude conditions. Parametrics were performed on various nozzle fence design configurations to evaluate improvements required for the X-33 Malmstrom mission. Other parametric tests were conducted to assess the effects of nozzle base bleed flow on nozzle performance.

In total, thirty three tests were conducted for a total test time of 275 minutes. Measurements included thrust, flowrates, chamber pressure and temperature, wall pressures (static and high frequency), wall temperatures, and flow visualization using shadow graph images. Figure 12 shows a shadow graph image for the baseline engine configuration with no performance fences operating at a pressure ratio of 600. The flow is from the right to left and the shock structure resulting from the thruster to thruster interactions are clearly seen. Ramp flow spillage is evident on the lower no fence side of the ramp.

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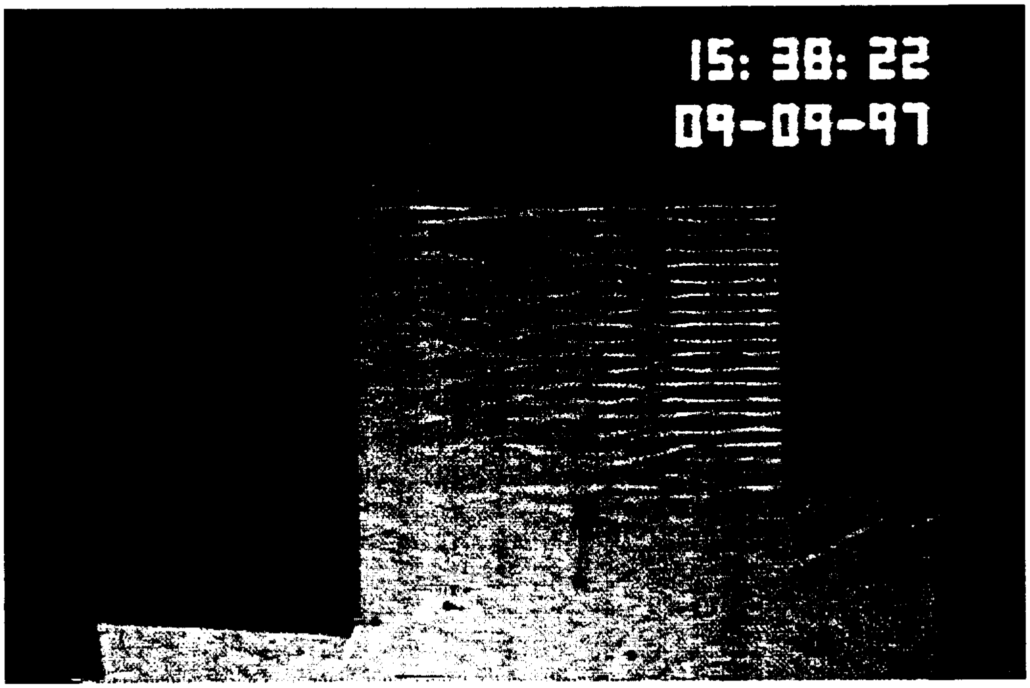

Figure 12. XRS-2200 Subscale Nozzle Test Shadowgraph

AEROJET X-33 RCS SYSTEM

The Aerojet X-33 RCS system underwent a major redesign within the past year. As a result of weight concerns, the system design was changed from a GO_2/LH_2 system with active hydrogen gasification to a compressed GO_2/GCH_4 system. This change greatly simplified the system configuration, improved the reliability and operability, and reduced the system weight by over 1500 lbs. The GO_2 storage tanks and several of the system valves were unchanged; however, the thrusters required modification for GCH_4 operation, and GCH_4 tanks were developed. Also, the gasification pallet was reconfigured to mount the propellant supply system control components.

Significant design, development, and fabrication activity for the RCS thrusters, propellant tanks, and flow control components was completed. Design and preliminary qualification testing of the GO_2/GCH_4 thrusters was completed, and formal qualification testing is scheduled to begin this month. Figure 13 shows prequalification testing of a GO_2/GCH_4 thruster. Fabrication of the flight units is on-going. Design and qualification testing of the GO_2 storage tank, shown in

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Figure 14, was completed, and the flight units are in final inspection and are scheduled for delivery to the vehicle this month. Design of the GCH_4 tank was also completed and is based on an enlarged GO_2 tank design. Fabrication of the qualification unit is in progress, and qualification testing is scheduled to begin in May. Design and fabrication of the propellant supply system valve trays was also completed, and final assembly is in progress. System valves were delivered, and the pressure regulator completed qualification testing and is scheduled for delivery in May. Lastly, build-up of the test facility is underway, and a system verification test is planned for July.

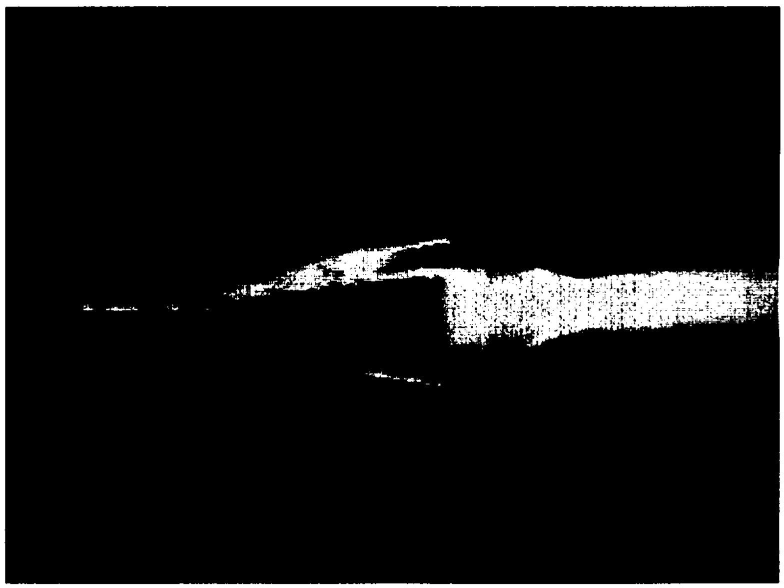

Figure 13. Prequalification Testing of GO_2/GCH_4 Thruster

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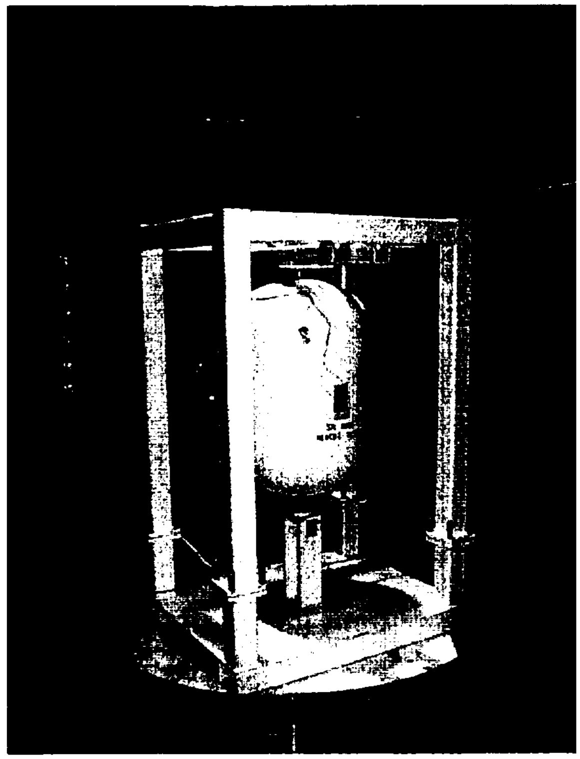

Figure 14. GO_2 Tank During Qualification Testing

RS-2200 ACCOMPLISHMENTS

The Phase II RLV engine system design and technology development effort was initiated in October. RS-2200 engine efforts have been focused on establishing plans to support the RLV Phase II, defining point of departure requirements and engine designs, and supporting ongoing vehicle architecture studies at LMSW. Plans established entail design and technology activities which will result in a preliminary engine design and in the selection of technologies critical to achieving engine performance and weight goals. For the initial part of the program, engine system and powerpack teams were formed and are currently in the process of being staffed up.

As a part of the planning effort, a propulsion review was conducted in November with MSFC and LMSW representatives. During the review, a new technology development roadmap was generated and agreed to, and program risks were

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identified and assessed. As a result of the review, the program plan and funding allocations were revised.

NOZZLE RAMP TECHNOLOGY

The nozzle ramp technology development effort was initiated in October to investigate composite materials. A planning meeting was held which included representatives from MSFC, LeRC, LaRC, and Lockheed Martin/General Dynamics (Fort Worth, TX). As a result, a fast track NASP panel architecture was selected as the point of departure design for the development of a Large Scale Test Article (LSTA) to be used in subsequent multicell testing planned for the spring and summer of 1999 at MSFC. In addition, it was decided to pursue other more advanced panel architectures due to the fact that the NASP panel architecture appeared marginal for surviving the MSFC multicell test environment.

In support of these activities, a flysheet specification (RD97-101) for the MSFC multicell ramp test was written along with a derived "white paper" describing the thermal-stress environment of subscale coupon test samples. The white paper was subsequently sent to 25 potential suppliers to determine their interest in participating in the advanced panel development effort. Nearly 20 vendors responded, and a series of vendor review meetings was held at MSFC in December and at Rocketdyne in January to review initial vendor concepts. Based upon the most promising concepts, formal RFQ's were expected to be released to approximately eight of these vendors in February.

Concurrently, aerothermal/stress analyses were performed on the NASP panel LSTA design based on the multicell flysheet specification. These analyses showed that the current NASP panel geometry could not survive the multicell test environment. As a result, a number of required modifications were identified, and a development effort for making these modifications was initiated with the NASP panel manufacturing team.

POWERPACK

Powerpack efforts have been focused on ceramic component vendor evaluations, gas generator (GG) conceptual designs, and ceramic turbine technology development. In addition, evaluation of a backup metalic turbine was initiated.

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Supplier visits were conducted with three potential ceramic component vendors to assess their current and projected capabilities and limitations. In addition, teleconferences were held with three other suppliers with substantial ceramic component experience to gain their feedback on experiences and lessons learned with the integration of ceramics into high temperature turbines. The information gained enabled an accurate assessment of the current state-of-the-art technology in ceramic turbine component fabrication and operational limitations.

GG conceptual design activities were initiated and continue. Development of power balances for a prototype powerpack and a ceramic turbine technology demonstrator (CTTD) test article are in process. Conceptual design efforts have been initiated and are currently focused on accommodating the required throttling range.

Other effort has focused on the evaluation of a back-up metallic turbine concept. High temperature capability superalloys are being investigated to allow higher operating temperatures; however, concerns with I_{SP} may push the turbine temperatures back up into the range where a metallic design is no longer feasible. Trades will be made to evaluate actively cooled metallic designs and uncooled ceramic designs to derive a balance that meets I_{SP} requirements.

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ALLIEDSIGNAL AEROSPACE ELECTRONIC SYSTEMS

LANDING SYSTEMS

Component deliveries to LMSW continues on schedule. Seventy percent (70%) of hydraulic system components have been delivered to LMSW ahead of schedule. Design changes late in the cycle will require landing gear and door component delivery to slip from the original plan; but, the component delivery will satisfy LMSW's current manufacturing need dates. Integration tests of the Nose Wheel Steering unit and DIU cards has been successfully completed. Brake Control tuning is progressing at the supplier and dynamometer test setup is in final stages of completion. Requirements tracking, V&V and MDL matrix tracking processes are all in place and in use.

FLUSH AIR DATA SYSTEM (FADS)

The X-33 air data system was redirected to a Flush Port System with Remote Pressure Transducers (RPS) in May 1997. Aerospace Equipment Systems - ESA is providing the RPS and Electronic & Avionic Systems is integrating the flush air data algorithms in the Vehicle Management Computer. RPS PDR and CDR were completed in 1997. The ITF prototype RPS has been shipped to LMSW, with delivery of the flightworthy RPS' scheduled for June and July 1998. Safety of Flight testing will begin in April 1998 with completion prior to shipment of the flightworthy RPS'.

COMMUNICATION SYSTEMS

Radar altimeter shipset no. 1 was delivered to LMSW on time, in January 1998. The Communication Systems' frequencies are approved.

ENVIRONMENTAL CONTROL SYSTEMS

Active Thermal Control System (ATCS)

Work continues on or ahead of schedule for all aspects of this system. Six (6)

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fully qualified flight coldplates and three (3) spare coldplates were delivered to LMSW ahead of schedule. Qualification-tested flight and spare heat exchangers and all temperature sensors were delivered ahead of schedule. The pump package assembly and controller deliveries continue on schedule with no development issues. Qualification Test Procedures were completed for the pump package assembly, controllers, temperature sensors, coldplates, and the EGW heat exchanger. Qualification Test Reports were completed for the coldplates and the EGW heat exchanger.

ENVIRONMENTAL CONTROL SYSTEMS

As part of the weight reduction effort in mid 1997, the RCS hydrogen system was removed from the vehicle thereby eliminating the ATCS hydrogen heat sink. At the same time, LMMSS was searching for a heating source for the main-engine buffer seal. A helium heat sink was selected for the ATCS to help satisfy LMMSS' requirement to supply warmed helium to the main engines and to maintain a low target ATCS weight. As a result, a heat exchanger development was initiated in August, 1997, and two cryogenic solenoid valves were added to the system. The pump package material was changed to titanium; one flow sensor and five temperature sensors were eliminated in the effort to reduce weight.

Risk-reducing research tests were completed for the helium heat exchanger to eliminate concerns of icing within the ATCS cooling loop. Full-scale configuration performance tests are on schedule to be performed prior to the release of the helium heat exchanger drawings.

Purge And Vent System

The system design review was held in September 1997. Development testing of the Vent Door Assembly was completed. Approximately 50 percent of the components are in the procurement cycle; all other AlliedSignal hardware fabrication was completed. BF Goodrich is scheduled to deliver the door frames and panels to AlliedSignal in mid May 1998. The Acceptance Test Procedure and Qualification Test Procedure were completed. The flight Pressure Sensors were delivered to LMSW ahead of schedule.

One brassboard VME was delivered to AlliedSignal Teterboro for integration testing. The qualification and flight VME fabrication is progressing.

The Purge Ducting design was finalized for three (3) of the four (4) packages. The Ducting has been ordered for all four (4) packages; however, package no. four (4) is currently on hold due to vehicle changes. The tooling for package no. one (1) is complete and fabrication is in process. The tooling for packages two and three is being fabricated.

Leak Detection System

Design and fabrication of the Hydrogen Detection System is progressing as planned. Demonstration testing of the flight prototype hardware was successfully completed. The system design review was held in September 1997.

ENVIRONMENTAL CONTROL SYSTEMS

Two flight-prototype-VME-controller cards were completed; one was shipped to AlliedSignal Teterboro for integration testing. Four (4) development-grade-VME cards were delivered to AlliedSignal Teterboro to be used in the simulation laboratory. The qualification VME cards are currently being fabricated. The Qualification Test Procedure for the sensors was completed. Qualification testing is in progress.

Environmental qualification testing of the VME Cards is proceeding. Circuit reprogramming (software) capabilities were added to the VME Cards to increase system flexibility. A second DIU simulator was ordered.

Avionics Bay Inerting System

An Avionics Bay Inerting System was ordered by LMSW on November 18, 1997. The system and component designs were completed; all hardware orders were placed except for the check valve which is in the final design phase. The nitrogen pressure vessel and check valve are the same as those used on the X-33 PLAD system to reduce schedule risk. All interface parameters were defined.

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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 continues to make significant milestones and has been expanded to include the following system configurations:

- Triplex VMC with Commercial Cross Channel Data Links (CCDLs):
  - Three (3) VMC racks, each rack containing the following minimum set of components:
    Three (3) DY4 CPU cards using Power-PC 603e microprocessors
    Two (2) 1553 Cards
    One (1) Comm Card
  - PC-based Tornado Server designated as "Triplex".
  - In addition to this minimum configuration, the following additional test/analysis tools are installed on the following VMC racks (VMC0 = top, VMC1 = middle, VMC2 = bottom chassis):
    Vmetro Card (VME-embedded VBT-325 VME Bus Analyzer) - located in VMC1.
    CodeTest Card (Applied Microsystems Corporation) - located in VMC0.

Systems Integration Laboratory (SIL)

- Simplex VMC with no CCDL Present
  - One VMC rack containing the following minimum set of components:
    Three (3) DY4 CPU cards using Power-PC 603e microprocessors
    Two (2) 1553 Cards
    One (1) Comm Card
  - PC-based Tornado Server designated as "Simplex".

- The SIL integration/test environment also includes:
  - Application Server: Compaq Pentium 233 Mhz/128 Mbytes RAM
  - Clients: Various Compaq Pentium 233 Mhz/32 Mbytes RAM Workstations

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Simulation models for AlliedSignal subsystems have been developed for integration with the ITF simulator. Several versions of the ITF simulator have been transferred and hosted on the SIL Onyx computer for use during software testing. The Flight Manager software has been tested in the SIL using reflective memory for high-speed transfer of data to and from the Onyx. Part of the integration and testing of the VSM software has utilized the 1553 communications bus between the VMCs and the Onyx. A sockets-based Ethernet communications channel has been used to pass data to and from the Onyx as part of the automation of the testing. ETS/Onyx integration has been started, with the Onyx generating the Reflective Memory interrupts, which will drive the ETS software.

In order to perform Simulation with the DIUs, AlliedSignal is designing one (1) Engineering Test Stand (ETS) for each DIU. Each ETS contains a full set of complementary CCAs to interface to the DIU I/O signals.

- The design of the Engine ETS is complete and the hardware is presently interfacing with the Engine DIUs.
- The Design of the Forward and Rear ETS hardware is nearing completion and 40% of the hardware is in house.

POWER MANAGEMENT AND GENERATION SYSTEMS

Electric Power & Actuation System (EPAS) System Engineering

The EPAS system team and the system engineering elements of each subsystem actively supported the LMSW vehicle level CDR in October 97. The EPAS design change replacing the Turbo Alternator with the Battery Power System started in July 97 and was completed in September 97. The EPAS CDR incorporating the BPS was held in October 97. The EPAS "A" Spec, Failure Modes Effects and Criticality Analysis, FMECA, and Verification Plan for Task Agreement EP-02 were updated in October 97, December 97 and March 98 respectively to reflect the BPS change.

POWER MANAGEMENT AND GENERATION SYSTEMS

The EPAS dynamic simulation model was modified in December 97 and January 98 to the incorporate the BPS changes and used to assess system performance and to define subsystem requirements. An analysis of the impact of regenerated current on the batteries and power quality was completed in February 98.

Flight Control Actuation System (FCAS)

The Pneumatic Load Assist Device (PLAD) design was completed, enabling increased body-flap loads and weight savings. An FCAS design review incorporating the PLAD was held in October 97 prior to the vehicle-level CDR. The PLAD PDR was held in April 98.

Procurement for development and flight controllers was initiated in July 97. Manufacturing and checkout of the first development controller chassis and circuit card assemblies were completed in April 98. Assembly of the first development controller was completed in April 98. FCAS Qual. Test Procedures were completed in April 98.

A proposed actuation mechanism for the Flight Termination System based on the PLAD concept was completed in March 98 and was submitted to CCB for LMSW approval in April 98.

ELECTRIC POWER CONTROL & DISTRIBUTION SYSTEM (EPCDS)

Since the initial design review in February 97, changes in the user requirements increased the number of electrical loads, and the avionics bay redesign restricted the EPCDS LRU volumes. The Power Converter Assembly, PCA, load and volume changes were approved by the CCB in July 97. The EPCDS hardware PDR (IR #3) was also completed in July 97. The EPCDS ICD was completed in August 97. Changes resulting from the Turbo Alternator replacement by the BPS were approved by the CCB in September 97. A Technical Coordination

Meeting was held in October 97 prior to the vehicle-level CDR with LMSW and NASA, to approve the design incorporating the PCA and BPS changes.

Procurement of long-lead items was started in November 97. The EPCDS LRU Circuit Card Assembly, CCA, detailed design review (IR#4) was completed in December 97. The EPCDS Low Voltage Power Conversion Assembly, LVPCA, mechanical chassis mockup was completed in December 97.

POWER MANAGEMENT AND GENERATION SYSTEMS

Layout drawings commenced in February 98. The EPCDS Verification Plan was also completed in February 98. In April 98, the DC/DC converter PDR was held with the supplier, EPCDS Qual. Test Procedures were completed, and the EPCDS High Voltage Power Conversion Assembly (HVPCA) mechanical chassis mockup was completed.

Electric Power Generation System, EPGS

The Turbo Alternator program was formally terminated in September 97 to accommodate an 1800 pound vehicle weight reduction achieved by eliminating the Aerojet RCS gasifier. It is replaced by the BPS.

Battery Power System, BPS

The PCA changes resulting from the Turbo Alternator replacement by the BPS was approved by the CCB in September 97. A Technical Coordination Meeting to review the BPS design was held jointly with the EPCDS review in October 97, prior to the vehicle-level CDR. The BPS ICD Rev N/C was completed in November 97 and the BPS Verification Plan was completed in December 97.

The procurement of batteries commenced in December 97. Testing to characterize cell and battery performance was conducted in January and February 98. In April 98 a PDR was held with the Battery supplier. BPS Qual. Test Procedures were also completed in April 98.

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BF GOODRICH

X-33 THERMAL PROTECTION SYSTEM DEVELOPMENT

Introduction

This report is a summary of the achievements and progress to date of the BFGoodrich Aerospace (BFG) X-33 Thermal Protection System (TPS) team for the year dating from 1 July 1997 to 17 April 1998. Phase II of the overall Venture Star program commenced on 2 July 1996 and extends until 31 December 2000. BFGoodrich Aerospace, Aerostructures Group, under the Recipient Team Member Cooperative Agreement (RTMCA) No. 96-RHR-0001, is responsible for the design, development, qualification and build of the Thermal Protection System 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, BFG has formed three Product Development Teams (PDT) to effect the design and build of TPS components. The TPS has been divided into the following PDT's: a) the Refractory Composites team responsible for the Nose Cap, Chin Panels, Skirt Panels, Elevons, Canted Fin Leading Edges and Canted Fin Forward Fillets; 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; and c) the Leeward Aeroshell Team responsible for the Leeward Aeroshell, Avionics Bay Door and Payload Bay Door.

BFG presented the TPS at the September 1997 TPS Critical Design Review (CDR) and successfully met all CDR criteria for the TPS design. The presentation was electronically delivered to Palmdale as a milestone deliverable.

VEHICLE CONFIGURATION (DESIGN AND ANALYSIS)

Structural Advancements

Metallic TPS Structural Analysis

The body Inconel 617 TPS panel skins, core and standoffs have been sized to the liftoff, ascent and reentry acoustic loads with preliminary fatigue data. BFG has completed the sizing of the Inco 617 panel's skins and core for aerodynamic and thermal loads with preliminary stiffness and strength finite element (*FE*) models. The first detailed *FE* strength analysis iteration of the nominal Malmstrom 4 trajectory for a highly loaded flat Inco 617 panel assembly with preliminary stiffness, strength and creep models has been completed.

The MA-754 Isogrid TPS panel skin thickness, rib thickness, rib pitch and standoffs have been sized to the liftoff, ascent and reentry acoustic loads with preliminary fatigue data. Selected Isogrid assemblies preliminary strength analysis has been completed for aerodynamic and thermal loads with *FE* models. Detailed structural and thermal analysis iteration of the nominal Malmstrom 4 trajectory for a highly curved Isogrid panel assembly is in work.

The FE models are unique in that they include time, temperature and load dependent material response. This analysis is performed with MARC non-linear structural response software. It should also be noted that BFG is incorporating MARC in performing combined thermal and structural analyses for metallic TPS evaluation.

Flight test instrumentation defined. Structural materials data and component and assembly tests have been designed and scheduled. Progressive wave tube testing of a 3 panel array was completed. The HTT assembly test is underway at NASA LaRC. High temperature 4 point bend tests for strength and creep have been performed at 1600F for Inco-617 panel sections. Most of the tensile creep data has been received for Inco-617 panel skins.

Structural indicator algorithm developed for rapid trajectory evaluation at 14 body points and for the full vehicle when coupled with the HAVOC code output.

Leeward Aeroshell TPS Structural/Dynamic Analysis

Material and configuration options have been evaluated and a final selection was made prior to CDR. 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 and weight savings studies have been completed. Flutter analysis for Avionics and Payload Doors has been completed and report delivered to LMSW. Structural component tests have been designed, scheduled or in progress. Materials static and fatigue strength tests were completed. Flight test instrumentation defined. The final strength and durability substantiation documentation is underway, without a vibration specification that is still in work at MSFC.

Flutter analysis completed for Avionics and Payload Doors. Structural tests designed, scheduled or in progress. Materials testing completed. Flight test instrumentation defined. Weight savings studies have been completed.

THERMODYNAMICS ADVANCEMENTS

Panel Bowing Analysis

The algorithms for predicting the metallic panel bowing height are being integrated into the acreage thermal analysis models such that predictions of the bow height and the local heating augmentation can be made for every metallic panel on the body and the windward canted fin. The bowing height model will be correlated with panel bowing radiant heat tests being conducted at NASA-JSC in April 1998. The heating augmentation factors have been provided by NASA-ARC based upon deflection height.

Tests in the NASA-LaRC High Temperature Tunnel (HTT) showed no detrimental effects of panel bowing induced by a temperature differential between panel face sheets of ~300 F.

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.

Sizing of the insulation beneath the metallic panels has been completed. The Malmstrom-4 trajectory was used as the TPS design trajectory to size the insulation. Insulation sizes vary from 0.75 inches to 2.00 inches. Insulation sizing beneath the Carbon-Carbon components is nearly complete.

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.

All vehicle splitlines have been defined including the leeward aeroshell.

AEROTHERMODYNAMICS ADVANCEMENTS

Aerothermal Environments

After the vehicle configuration changes and the final release of the new loft lines in August 1997, the revised design aerodynamic heating database was developed by NASA-ARC and provided in Oct. 1997 for the original Malmstrom-4 trajectory. This database became the standard for all thermal protection system thermal design. An itemized list of the detailed heating environments needed for areas such as deflected control surfaces acreage, gaps, and hinge areas were requested from LMSW. Estimates for the control surface heating were received.

Boundary-Layer Transition

With coordination provided by BFG, NASA-LaRC conducted boundary-layer transition wind tunnel tests with simulated bowed panels on the fuselage. The results showed that for panel deflection heights up to the largest tested (0.45 inch), panel bowing had little effect on the boundary-layer transition criteria presently being used. Discrete roughness testing shall continue to help better define the allowable steps and gaps on the vehicle. BFG provided NASA-LaRC direction for testing the effects of large steps and gaps on boundary-layer transition in the canted-fin fillet/leading region. The large gaps exist due to the flexibility and thermal growth of the canted-fin structure.

Material Splitlines

Based upon the Oct. 1997 aerodynamic heating database, the splitlines between material systems - refractory composites, metallic panels, and blanket insulation - were finalized. Based upon cost and schedule constraints, it was also decided to use ceramic tile on the base region, the body flap, and the elevons.

BFG developed a computer process to rapidly evaluate the thermal/structural capability for every metallic panel on the X-33 for a given trajectory aeroheating database. This tool is being used to fine tune the type of metallic panels used in specific locations on the fuselage.

Trajectory Constraints

BFG developed algorithms for estimating the thermal/structural stress in the different types of metallic panels and the long-term creep in the panels as a function of temperature and pressure histories. These algorithms and constraint values were provided to LMSW for assistance in designing X-33 trajectories within the capabilities of the metallic TPS.

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 a 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 splitline 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 stand-off fittings will have to span across tank frames. This resulted in a new "diamond" pattern over the entire fuselage of the vehicle. Additionally, this pattern improved seal orientation to airflow. This new pattern was released on 3/13/97.

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. This has been defined and BFG has reviewed the loft and made minor modifications in order to enable efficient downstream usage. The BFG 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

Since July 1997, the Leeward Aeroshell design team has continued to refine the panel design, seal designs, and interfaces with mating components. Manufacturing has successfully built two panels and is working on the third and fourth panel. Hole locations and fastener sizes have been fully defined for the entire leeward surface. The carrier plates with bulb seals has been fully modeled and testing is showing positive results.

Leeward Aeroshell Penetrations

All of the penetrations have been fully modeled (except the RCS thruster) and engineering is either under final review or has been released for all antenna brackets, access panels, ECS vent panels and doors, and exhaust vents. The ECS vent panels and doors, the hydrogen exhaust vent plate, and the oxygen exhaust plate underwent a redesign to better accommodate the applied loads. One configuration of the ECS vent panel and door (used 8 locations) has been machined and is ready for assembly.

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 made with Inconel 617 material 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.

Refractory Composite Basic Design

Final engineering has been completed on the nose cap, skirt, and chin panel assemblies. Since ballast is added to the nose of the X-33, the nose cap design was optimized to reduce fabrication risk and cost. The design of the leading edge has been finalized and the Carbon/Carbon details have all been released. The final concept allows the outboard panels and the inboard panels to be installed independently with panel number six acting as a keystone. The access panel at location six is comprised of oxidation resistant Carbon/Carbon (ORCC) for traceability to the RLV. In all, the leading edge is comprised of 16 separate Carbon/Carbon panels per fin. The design of the fillet fairing has been finalized. Increased fin rotational deflections, determined in January, have been accommodated with an increase in the interface gap between fin mounted and body mounted structures. The gap will be filled with an insulation blanket thermal barrier. The fin tip has been reduced in size and the engineering is off-board for the one piece Carbon/Carbon component. Trimming off the cantilevered portion of the fin tip trailing edge, greatly reduced the loads and simplified the design.

SYSTEM OPTIMIZATION / TRADE STUDIES

Elevon Trade Studies

Trade studies continued on the elevons as the vehicle control philosophy matured. A final configuration was chosen with the outboard elevon enlarged to include a portion of the inboard elevon, and extending outboard to include a portion of the fin tip. The inboard elevon was reduced in size. The resulting configuration yields elevons of approximate equal surface area. The structural configuration matured as well. A configuration trade study compared integral C/Sic hot structure, C/SiC hybrid design, and ceramic tile hybrid designs. The weight of the tile design showed it to be only slightly greater than the all Carbon/SiC design, so it was selected based on X-33 schedule feasibility. Design responsibility for the elevon structure and ceramic tiles has been transferred back to LMSW. BFGoodrich will fabricate the elevon structures.

Elevon Seal Trade Studies

Initiated in December, several elevon seal candidates were proposed and evaluated to meet sealing requirements for the span between elevons. A final seal candidate will be selected pending analysis and screening tests after the elevon structure matures. Along the span between hinges, a wiper seal is being considered at the centerline of the rotation axis. This seal will wipe along a circular seal land built into the leading edge of the elevon structure. Across the hinges, a machined trough spans across two bulkheads and incorporates a captured wiper seal making a continuous seal past the hinge. Concepts for sealing between elevons are being evaluated. Different methods of sealing at the ends of the elevons are also under consideration. Seal details are in work and test requirements have been defined.

Inboard Fixed Fairing Trade Study

A region of fixed canted fin structure of the inboard elevon was identified as exceeding the temperature capability of the baseline canted fin TPS. This component, identified as the inboard fixed fairing, was selected to be refractory composite due to the temperature. As the elevon design continued to mature, the fixed faring design also went through several design iterations with the final design selected to incorporate a 20 degree beveled side wall to reduce gap heating on the tile elevon. Due to the late incorporation of this structure on to the vehicle, a trade study conducted against a ceramic tile design showed no weight increase from the all Carbon structure. The tile design was selected to reduce schedule risk. LMSW will design the substructure and BFGoodrich will design the tile TPS and fabricate the structure.

Base Region Trade Study

Trade studies continued on the base region after an initial test of the ablator material indicated that extensive refurbishment would be required after every flight. The titanium substructure with MI-15 ablator and PowerScrub coating was traded against a Graphite/BMI substructure with ceramic tile. The weights were similar, and with potential reduced post flight maintenance, the composite and tile base was selected. Design of the base and ceramic tiles has been transferred back to LMSW and BFGoodrich will fabricate the Graphite/BMI base panels.

Nickel vs. Iron ODS Material Usage Trade Studies

Trade off studies have been performed in order to down select the high temp alloy and forms that will be used on the X-33 Metallic TPS. Nickel ODS material has been selected over Iron ODS material because of its better material strength at temperature, ductility, fracture toughness and braze characteristics.

MA-754 Nickel ODS plate material was down selected for usage in isogrid configuration TPS panels from five candidate configurations. This configuration was selected to meet the vehicle build schedule, due to problems obtaining the required minimum gauges and joining development work required for the honeycomb sandwich panel configuration.

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RLV METHODOLOGY / APPLICATION

RLV Definition Studies

Tradeoff studies on TPS to tank/substructure integration are underway to obtain the most beneficial vehicle/system weight balance. These studies are concentrating on TPS attachment concepts to tank/substructure. Panel size optimization, for both leeward and windward aeroshell, including combinations of different panel sizes, is dependent on vehicle loft placement. Additional trade studies are being pursued regarding seal configurations (primary & secondary), focusing in the areas of reliability and safety.

Weight Tradeoff Studies

Preliminary weight tradeoff studies have been completed on TPS configurations, and this information has been incorporated in the stretch goal vehicle concept for RLV.

RLV Cost Estimate

ROM cost for the RLV was submitted to Lockheed Martin based on an X-33 baseline configuration resized to RLV proportions.

RLV Weight Comparisons with X-33

The X-33 weights were used as a baseline for calculations to determine how much weight the X-33 could be reduced by if additional time and funds were available. 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 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 have been characterized in an arc jet for thermal/optical properties. Mechanical testing has begun to develop the necessary structural design data. The TPS seals are being tested in the Hot Gas Facility at NASA Marshall to quantify leakage rates for different portions of the X-33 flight trajectory. Aerothermal performance testing of TPS panels and subcomponents is being conducted in arc jets at the NASA-ARC and -JSC centers. Thermal characterization of TPS panels and Sub-Elements 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 BFG and Wright Patterson Air Force Base. The ability of the TPS to withstand the rapid de-pressurization during vehicle ascent has been demonstrated during tests at NASA-JSC in a thermal-vacuum chamber.

Testing is currently underway in the NASA LaRC 8 ft High Temperature Tunnel 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 to verify the ability of the TPS and supporting structure to survive combined loading effects.

Metallic Panel Emissivity Coating Test

Paints and coatings were evaluated for emissivity and catalysis through

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exposure to arc-jet conditions. Substrates tested were Inco 617, PM 2000 and PM 1000. Coatings included several paints and a two-phase glass (Sol-Gel), compared to a pre-oxidized surface. Results show that Pyromark 2500 has adequate emissivity (0.8 or greater), is easily applied and cured. Catalysis tests show that the oxidized base materials, Inconel 617, MA 754 (equivalent to PM 1000), as well as Pyromark 2500, all have Relative Catalytic Efficiencies (RCE) of 1.80 to 1.99 (2.0 is considered fully catalytic). Several lower RCE values were noted in a Cetek coating (1.4 - 1.6) and in a Sol-Gel coating (1.4 before burning off the test specimen). These materials may be developed and utilized in RLV applications in which low catalysis is required.

Combined Environments Test

The test objectives have been determined and agreed to by all parties. The test plan for Phase A (Metallic to Metallic panel) has been written and released. At suggestion of LMSW and LMMSS the cryogenic and bi-axial loading have been eliminated to reduce scope to control costs. The schedules for Phase A now shows a test date of May 98. Phase A model build is near completion. LMMSS has completed work on Simulated LOX Tank. Phase B (Leeward to Leeward panel) has been canceled. Phase C (Leeward to Metallic panels) electronic models have been completed and hardware build is soon to begin. Phase C Substructure build is underway. Phase C Simulated LOX Tank changes are minimal and not expected to effect Phase C build. Instrumentation requirements for each facility involved are being discussed.

Thermo-Vibro-Acoustic (TVA) Test

The TVA test plan was released in January 1997 and revised in September 1997. Minor 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. C.

Refractory Composite TPS Material Systems

Thermo-vibro-acoustic testing at the BFG test facility and at Wright Labs 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. BFG'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 *OASPL* levels of 170dB and temperatures of 2500°F. Nose cap subelements are planned for these types of tests.

Metallic Panel TPS Material Systems

Thermo-vibro-acoustic testing at the BFG test facility consists of 2 panels, one Inco 617 square and one MA 754 Isogrid. TVA testing of Inco 617 panels at Wright Labs consists of two diamond shaped panels (one intact, one with impact damage), one multi-panel array (five panel mixture of flat and curved) and one curved canted fin specimen. Test definition, specimen and fixture design are scheduled to support completion of testing by September 1998.

Leeward Aeroshell TPS Material Systems

Two single panel PWT tests were conducted at BFG. Prior to PWT tests, the models were exposed to radiant heat at JSC. The PWT testing included exposure to sound pressure levels that represent ascent, oscillating shock, and re-entry conditions of the X-33 trajectory. Both models were tested to four lifetimes.

Leeward Aeroshell Acoustic Test

An assembly of a Leeward Aeroshell Payload Door Graphite/Epoxy production panel with insulation and its representative substructure will be subject to reverberant acoustic environments at MSFC in July 1998. This is in accordance with LMSW ETR 39.

Subelement Shaker Testing

Design verification shaker testing will evaluate seal and panel attachment concepts.

Windward Aeroshell Metallic Seal Durability Shaker Test

Representative panels were tested to the specified random vibration loads and damping measured. This was performed for in-plane and out off-plane loadings. The response of the panel was characterized. This testing included a .006 skin production panel, production MBF-50 braze, Inconel 617 close-outs, Q-fiber insulation and production rosettes.

Sub-Element testing was carried out on production rosettes to verify the heat treat and stress relief of the parts. Based on this testing the production heat treatment of the parts was optimized for minimum residual stress.

Shaker testing of the panels with inserts has been started to verify the analytical strength predictions for the inserts.

Leeward Aeroshell Carrier Plate Durability Shaker Test

A representative carrier plate attachment joint was successfully tested for panel durability, wear and attachment design feasibility. Testing was conducted at room temperature and at 250 °F.

Fatigue strength verification testing of pre-cured and co-cured sandwich specimens is complete.

Arc Jet Testing

FRSI Blanket Arc Jet Testing

FRSI blankets were arc jet tested at NASA JSC. The FRSI was tested on aluminum and composite substrates to surface temperatures of 750 °F.

AFRSI Blanket Arc Jet Testing

AFRSI blankets were arc jet tested at NASA Ames. The AFRSI was tested on aluminum and composite substrates to surface temperatures of 1500 °F. Low speed impact testing was performed on AFRSI blanket models subjected to two arc jet cycles.

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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.

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°F limit. Backside air temperatures near the seals did not indicate a gross leakage problem. No structural anomalies or failures occurred.

This model was then modified, with 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 were added to the backside of the array so these measurements could be made.

Arc Jet Testing of a Metallic Honeycomb TPS Panel

Testing of a metallic honeycomb TPS panel in the Arc-Jet has been performed at ARC in September 1997, to validate thermal models and qualitatively assess panel performance. The results of the tests were encouraging. There were two areas of simulated repairs, where a doubler of inconel had been welded to the panel surface; and there was another area where the Pyromark 2500 paint had been removed, exposing bare metal to the arc jet stream. Both of these areas survived the test, exhibiting no degradation. During the test, it was possible to witness the panel bowing with amplitude proportional to the heating rate.

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.

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Additional Near Term Arc Jet Testing

An Arc jet test plan has been issued and the following tests are scheduled in the near term: a) Additional Metallic Inconel honeycomb 4 panel array arc jet tests at NASA JSC; b) an extensive series of arc jet tests of flat and curved metallic TPS panels at Ames, June-September, which will measure leakage past the metallic seals: c) arc jet tests of a transition seal between AFRSI and a metallic TPS panel at Ames, June-September, which will also measure leakage past seal; and d) a series of "flyable damage" tests, at ARC.

Radiant Heat Testing

Panel Bowing Tests

A test plan was written and approved for Radiant Heat tests 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 sub-scale piece of metallic honeycomb panel was performed at JSC in June 1997. In this test, the surface of a honeycomb panel was 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.

Since the test method was verified by the sub-scale test, a full-sized diamond shaped honeycomb panel and an Inconel isogrid panel were instrumented for measuring bowing. These panels will be tested in April-May 1998.

Radiant Heat Venting Test

A full-sized diamond shaped honeycomb panel was instrumented for measuring the venting behavior of the insulation pan assembly, which is attached to the rear of the honeycomb. In these tests, which were also performed at JSC, both a thermal and pressure (time-varying) profile are provided to simulate the flight conditions of the X-33. Initial results of these tests were not satisfactory, and led to a redesign of the vent assembly. A retest demonstrated acceptable performance, and the test was repeated 20 times to demonstrate lifetime survivability.

Radiant Heat FRSI and AFRSI Testing

Both FRSI and AFRSI test models were radiant heat tested at JSC. The blankets were bonded to sandwich panel substrates that represent minimum thermal capacity for the leeward composite structure. Heat input that represents the Malmstrom 4 vehicle heat load were used. The temperature response of the RTV bond line and the composite sandwich panel verified the thermal performance for these two blanket systems.

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.

Several seal configurations have been tested. These configurations include the Metallic primary seal concepts, secondary seal concepts, landing gear door seal concepts; the Carbon-Carbon Nextel/Cerachrome and Nextel/Saffil seal concepts; and the Leeward Aeroshell AFRSI blanket with Saffil/Quartz fabric

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seal concepts, and Nextel/Satin fabric seal concepts.

Approximately 90% of the Leeward Aeroshell required tests are completed; with 75% completion for the Metallic; and 60% completion for the Carbon Carbon.

The effective leakage areas measured during these tests have been less than 0.015 in^2 per linear foot of seal. These test results are in correlation with the analytical estimates.

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.

Metallic Panels

Approximately 35 Inconel 617 panels (1.5 mil core type) have been fabricated for producibility trials plus additional production configuration panels have been utilized for producibility development. These trials are aimed at proving different panel detail features, curvature configurations, and process modifications for subsequent verification testing.

Metallic Seal Configurations

Several iterations of the shingle seal & edge closures have been developed, which improve manufacture and durability of the shingle seal as the result of Producibility & test results.

MATERIALS AND PROCESSES

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

BFG has examined several Oxide Dispersion Strengthened (ODS) alloys MA 754 (PM 1000), and MA 956 (PM 2000) for use in high-temperature metallic panels. PM 2000 was dropped from consideration due to embrittlement by the selected braze alloy (MBF-100). Further investigation into alternative brazing alloys may make this material useful for RLV. Brazes for MA 754 (PM 1000) were developed, however the material could not be rolled to foil thickness (0.007" and below) with the proper coarse-grain material texture necessary for high temperature creep resistance.

To retain creep strength, coarse-grained MA 754 sheets of 0.056" and 0.020" were belt-ground to 0.010". Elevated temperature mechanical test results showed acceptable properties. But further work on brazing of MA 754 was suspended when the total number of panels needed dropped due to revised thermal models. The low number justified a change in panel construction from brazed honeycomb to machined isogrid. Development of a coarse-grained texture in MA 754 foil would be most desirable in future aerospace applications such as the RLV.

MANUFACTURING PROCESSES

Inconel 617 Metallic Panel Brazing Process Definition

Several brazing alloys foils were evaluated with Inco 617 face sheets and core to replace the salt-and-pepper shaker method used in Phase One of the program. MBF-80 foil was selected, and a robust braze cycle was developed. For possible weight savings a 1.0 mil braze foil was evaluated, however the tolerance of the foil thickness overlapped the baseline 1.5 mil foil to a large extent, making any foil replacement questionable. Although the basic braze cycle has been set, slight adjustments may be made to better accommodate the conditions existing within the braze furnaces due to thermal mass and furnace heat-up rate capability.

Inconel 617 Brazing Furnace Cycle Time

Furnace cycle times have been reduced by applying metallic and graphite tool concepts in the panel bond cycle, reducing cost and schedule hazards.

Metallic tool concepts were considered for panel brazing, however problems with residual stresses, thermal capacity and long furnace cycles caused this concept to be abandoned in favor of graphite tooling. Present cycle times are within the ranges considered during braze cycle development.

Inconel 617 Core Fabrication Process Improvements

The Metallics team has developed core tooling dies required for fabricating the 1.5 mil. and 3.5 mil. Inco 617 net core manufacturing process in conjunction with our HTA facility in San Marcos TX. The HTA facility is producing the 1.5 mil. core blankets at a rate necessary to sustain panel production rates.

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 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

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CIL.

Preliminary Hazard Analysis (PHA)

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

Subsystem Hazard Analysis (SSHA)

The SSHA expands the PHA and the analysis continues until all actions required on the identified hazards have been completed. Mitigation of the identified hazards is documented on a bi-monthly basis through a LMSW Microsoft ACCESS database. Each hazard is documented as; Transfer, Open, Monitored, Closed. All Transfer, Open, and Monitor items must be Closed before System Hazard Review prior to first flight.

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

BFG 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 subsystems are located underneath the TPS panels there will be additional close out activities on the TPS during flight test operations.

Fault Detection Methods

BFG 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)

BFG 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.

Logistics Engineering Documentation

BFG has provided the preliminary Processing and Maintenance Activity Procedures for the TPS. The maintenance data is comprised of handling, inspection, repair, removal, installation and testing procedures to support the scheduled and unscheduled maintenance tasks. The procedures include special tools, consumables, storage, safety requirements, set up procedures and prerequisites as required. These procedures reference existing drawings, documentation and analysis as required. These procedures are provided for all line replaceable units for the BFG provided TPS. Methods for procuring, maintaining and replacing each line replaceable unit will be based on these procedures.

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Quality Assurance

Quality Assurance Plan

A Quality Assurance Plan based on ISO 9001 was written and will 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 BFG'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. BFG will not be providing any flight software for the X-33 vehicle.

X-33 Material Review Board Procedures

Procedures specific to non-conformances occurring during performance of the X-33 hardware manufacturing were written. Two Quality Instructions were written: 1) For the control of non-conforming 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 non-conforming flight hardware. This procedure is designed to provide the control of flight hardware manufactured in a product development environment and will provide the visibility of quality costs (scrap, rework, repair).

Quality System Surveys of Suppliers

Quality system and process surveys were performed at suppliers that possess 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

Evaluation studies have been completed and Pulsed Infrared Thermography was selected as the primary nondestructive testing method for post-braze metallic TPS. Ultrasonic pulse echo and through transmission inspection techniques are the secondary or back up method. A Level III and two Level I personnel at our facility are certified in Thermography to perform these inspections. A BFG Process Specification and a Quality Instruction are in place to control this method of inspection.

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 (BFG'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 Thermography method has an equivalent POD to the Ultrasonic method and is by far the preferred system from a cost and operation stand point.

SVERDRUP TECHNOLOGY, INC.

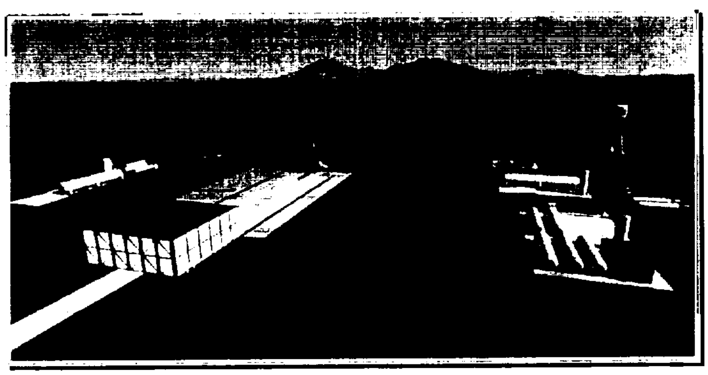
X-33 LAUNCH AND LANDING FACILITIES

Responsibilities

Sverdrup is responsible for the design, construction and activation of the X-33 Launch Site at Edwards Air Force Base and for providing assistance in activating the X-33 Landing Sites.

Progress

Progress throughout the past year has been excellent with design of the Launch Site being completed and construction nearly complete. All equipment is under contract, much of which is on-site at the launch site. All construction contracts are in place and much of the construction is complete.



Approximately 50% of the companies invited to bid on construction contracts were of the small business, small disadvantaged business (SDB), or woman-owned business (WOSB). While the response from SDB and WOSB concerns have been disappointing, the small business awards are meeting the target goals. Through the use of the $1 million Highway-to-Space Grant from the State of California and use of GFE and "loaner" equipment (a savings to the program of about $1.4 million), the cost of the launch facility is being kept within the budget.

Development of the landing sites is progressing with many of the modifications necessary underway. GSE commitments are in place.

The E.I.S. Record of Decision, Biological Opinion, and other permits were received on November 4, 1997 and the formal groundbreaking ceremony was held on November 27th. Prior to the formal ground breaking, a number of pre-construction activities were completed, including surveying, electrical utilities connections and environmental surveys.

Included in the environmental surveys, was the assessment of the launch site for Desert Tortoise (an endangered species) populations. Prior to grading the Launch Site area, a sweep was made to ensure that no tortoises were in harm's way. A certified biologist observed all earth moving operations. Once the site was assured to be clear of Desert Tortoises, a tortoise exclusionary fence was constructed to prevent re-entry of tortoises. In addition, during this time, all Joshua trees in the area that were deemed transplantable were relocated to another area on Edwards AFB to facilitate a revegetation program.

A personnel training program was developed by Sverdrup for all persons entering the launch site construction areas to maximize safety and minimize intrusion upon the environment. This training program included construction and Air Force Research Laboratory safety, environmental training with emphasis on protection of the Desert Tortoise, and EAFB and AFRL security training. Paramount to the success of this program was the development of an access security plan that was acceptable to the AFRL security forces.

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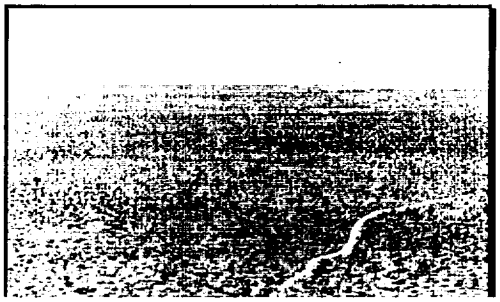
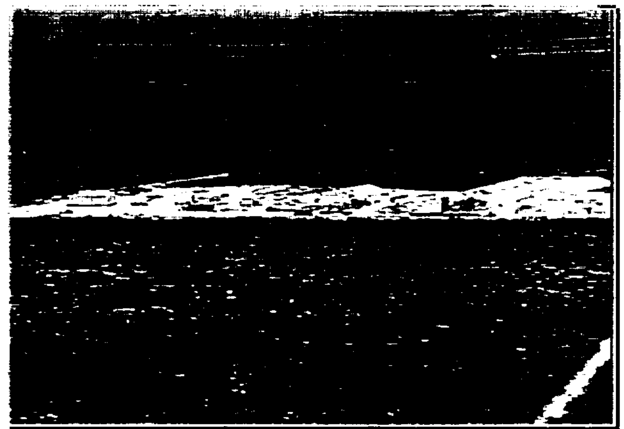


Before Clearing



Current Condition

Site clearing and construction of the X-33 Launch Site began in earnest at the end of November, and were completed by mid-December. Close cooperation between Sverdrup, the construction workers, and the environmental biologist permitted site clearing and grading to proceed in a timely fashion without harm to the wildlife, in particular, the Desert Tortoise. Although the entire X-33 site encompasses approximately 50 acres including a new access road, only the areas directly impacted by the construction were cleared to minimize the impact on the environment. A total of about 30 acres was actually disturbed.

A new site access road was cut through the desert and paved in late December to provide good access to the construction site for trucks and cars. This road will serve as the X-33 towway, delivery of propellants and other supplies, as well as providing for personnel access, when the construction is complete.

VentureStar Way Before Paving

VentureStar Way After Paving

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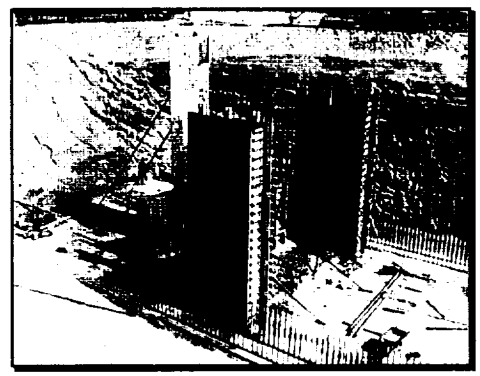
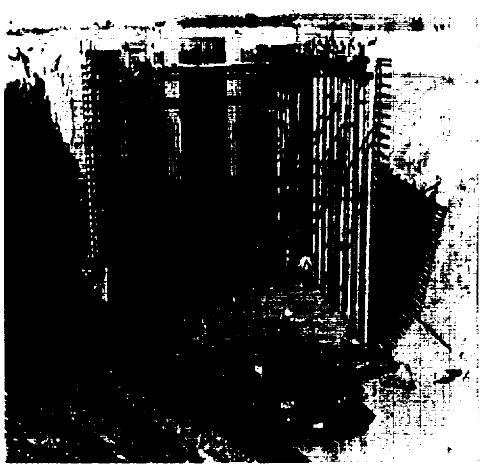
In early November, electrical conduits were installed from the Operations Control Center (OCC) on Haystack Butte to the desert floor to accommodate the installation of fiber optic and telephone cables. As part of a cost reduction effort, the services of Air Force construction groups from Tinker AFB were utilized to install the X-33 system at the same time as another communications project was being installed for the Air Force Research Laboratory. The installation of the fiber optics and the telephone system is in the final stages of completion.

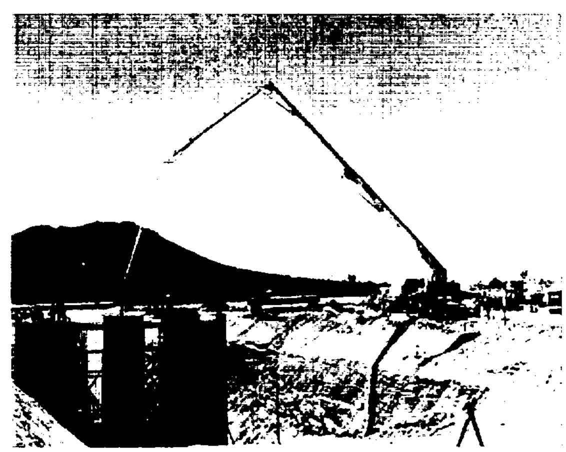
Mass Excavation of Flame Trench



Initial Forms for Flame Trench



Forms Ready for Concrete



Placing of First Pour of Concrete

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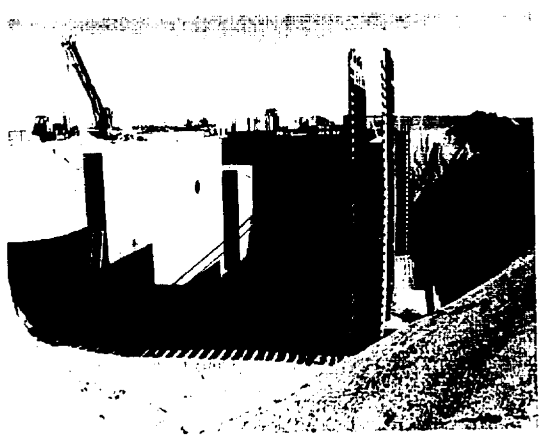
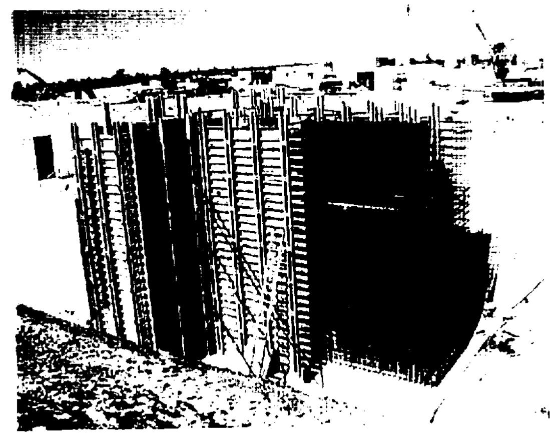
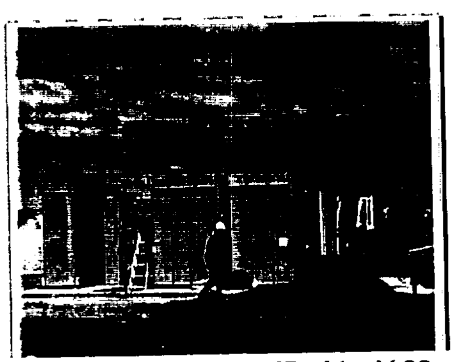
The month of December also saw the mass excavation of the flame trench -- an excavation approximately 40 feet deep, 100 feet wide, and 30 feet long -- completed and made ready for the erection of the forming for the concrete flame trench walls. After the mass excavation, a concrete base mat 4 feet thick was constructed at the bottom of the excavation for supporting the flame trench sidewalls. After curing, the forming for the sidewalls was erected and approximately 400 cubic yards of concrete were placed in one day. The major portion of the sidewalls are complete, ready for the installation of the contoured bottom.



After Removal of Forms



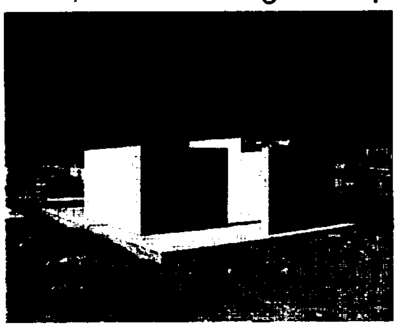
Hydraulic Cylinder Pit Forms

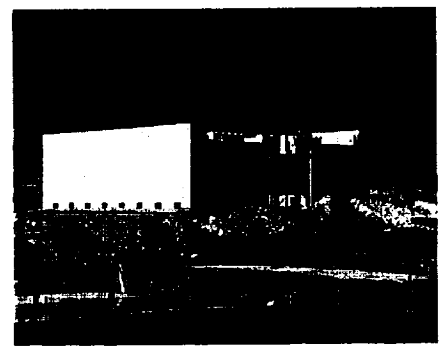


All site utilities (water and electric power) have been extended to the site with the main electrical substation and switchgear active and supplying power to the site. The erection of the Sound Suppression Water system elevated water tank has begun; the 48 inch underground SSW pipeline has been completed.

The performance of the Ground Vibration Test (GVT) of the X-33 which was intended to be performed in an existing off-site building using water, has been relocated to the launch site to take advantage of the existing infrastructure and to allow the use of liquid nitrogen instead of water in the LOX tank. This will require the construction of a temporary shelter to protect the vehicle from the sun and wind during the testing periods, and a redesign of the rotating launch mount. It is expected that these changes will enhance the overall program schedule, although the completion of the launch site will be delayed a couple of months.

All major foundations are complete and equipment is being installed. Most of the underground piping and electrical systems are in place, with above ground piping and electrical work beginning. Construction of the GIM Shelter and Electric Shelter is complete and ready for installation of equipment. The erection of the Translating Shelter has begun.





The construction of the X-33 Launch Complex has been performed within the Edwards AFB system with no substantial interference to either parties. A high level of cooperation exists between Sverdrup, Edwards AFB, and the Air Force Research Laboratory in the areas of access, training, security, and operations. There have been no conflicts between programs that have not been accommodated. For instance the X-33 construction "stood-down" to accommodate a test of the X-38.

The X-33 Launch Complex is on-track for an end of 1998 completion and will be ready for the integration of the LMCMS components and systems.

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

MARSHALL SPACE FLIGHT CENTER

X-33 SAFETY, RELIABILITY, MAINTAINABILITY, AND MISSION ASSURANCE

The Marshall Space Flight Center (MSFC) Safety and Mission Assurance (S&MA) Office continued the effort to complete the failure modes and effects analysis (FMEA) on both the linear aerospike engine and the main propulsion system (MPS), including a detailed FMEA on the engine controller data interface unit. The quantitative reliability predictions for the linear aerospike engine and the MPS were also finalized. Using fault tree analysis and sensitivity analysis, trade studies were performed for the engine components which drive the engine reliability. The fault tree for the linear aerospike engine was completed, including quantification of basic events. There were significant contributions to the X-33 reliability, maintainability/testability, supportability, and population hazard analysis team effort. Since Congress is considering indemnification and cross-waiver authority for the "X" programs, MSFC actively participated in NASA's S&MA Review of the X-33 Program to ensure that appropriate risk management practices are in place for the X-33 Program.

X-33 Natural Terrestrial Environment

The "beta test" version of the GRAM-97 has been successfully formulated and provided to users for the high altitude portion of X-33 simulations for determination of aerodynamic heating effects, vehicle control analysis, and terminal area energy management (TAEM) operations. Statistical analysis of surface wind speed was completed and provided as input to the go-no-go assessments for engine static firing tests or launch for a specified wind speed criteria. The analysis strongly supports test and operations during the early morning hours. Analyses have been completed supporting the implementation of a new method to transition from a measured (rawinsonde) profile to a GRAM wind profile. Weekly archiving, distribution, and analysis of rawinsonde wind profile pairs for Edwards Air Force Base (EAFB) to provide a launch system data base have continued.

Radio Frequency (RF) Communication System Design and Coverage Analysis

The Stage 2 Spectrum Allocation Request Package was submitted to the National Telecommunications and Information Administration (NTIA) in early 1997 seeking approval for use of the telecommunications systems planned for X-33. Only after assuring the NTIA that the frequencies would only be used during experimental testing of the reusable launch vehicle (RLV) concept and not used for any follow-on operational system; approval was granted in December 1997. Due to the nature of the X-33 Program being a non-orbital test vehicle, no additional stage request (out of normally a four stage process) is required by the NTIA. Updates to the stage 2 will be required as flight trajectories, hardware, etc. change. MSFC continued updating communication link information from the MSFC developed computer simulation that utilizes both program trajectory and altitude data developed by MSFC for the X-33 Program providing AlliedSignal Aerospace (ASA) with the results.

X-33 Actuator and Controller Electromagnetic Interference (EMI) Testing:

Preparations are in process to perform EMI testing of an X-33 development actuator and controller in concert with our industry partner, ASA. Procurements have been initiated and software development is in process and should be finished by 06/01/98. Testing will be performed beginning mid-July 1998.

X-33 Antenna Patterns

Performed gain, circularity, and principal plane patterns on a Hurley-Vega 815S-3 antenna supplied by ASA. Twenty-eight patterns were taken in the anechoic test chamber on an aluminum ground plane. Test procedures for the X-33 flight antenna tests were generated and the test equipment in the anechoic test chamber that will be used to measure the antenna patterns was calibrated. All preparations for the flight antenna tests were completed. Testing is scheduled to begin upon ASA delivery.

X-33 Communications

The Critical Design Review (CDR) data package evaluation and review were provided for the X-33 Communications Subsystem CDR at ASA/Towson, the RF combiner unit CDR at SAGE microwave and the extended test range CDR at Dryden Flight Research Center. Command receiver and bit error rate characterization testing was performed for ASA/Towson along with telemetry transmitter characterization testing. Test plans were developed and communication subsystem phase cancellation analysis, tests, and measurements performed and documented in a final test report. Test plans were reviewed and support provided for command receiver and telemetry transmitter acceptance test procedures at Aydin Telemetry.

Electrical Power Systems

Engineering support was provided to ASA/Toronto in the area of electrical power systems. Design review support was given to the Turbo-Alternator Ground Development Program, and then to the battery power system once the turbo-alternator was removed from the baseline design. A newly designed piece of hardware, the battery contactor unit, has also been reviewed. A 3-month aluminum wire development test program was conducted. A series of mechanical (thermal, vibration, corrosion, tensile strength) and electrical (insulation resistance, dielectric withstanding voltage, DC resistance) tests were conducted to compare performance to an equivalent copper wire. Results were encouraging, but due to schedule constraints the aluminum conductor wire will not be used for the initial flights of X-33. There are plans to change out some of the power feeders on later flights to test the aluminum wire. Also, a more in-depth test program has been proposed for the RLV Program. The loads analysis report was reviewed on a monthly basis for compatibility with the distribution system and the capabilities of the battery power system. Technical advice and recommendations were also given for system integration issues. EMI/EMC issues were also addressed and test planning for the flight control electric actuators and integrated electrical power system was supported.

INU/GPS Hardware in the Loop Simulation

The X33 INU/GPS hardware-in-loop simulation was developed within the MSFC Avionics Systems Testbed (MAST). Capabilities include provisions for both open and closed loop testing of the X33 INS/GPS supplied by Litton. Hardware will be delivered to the MAST for testing beginning in May 1998.

Propulsion System Testing

The second phase of J2 GG hot-fire testing took place in August 1997 (testing with spark ignition system). It successfully demonstrated ignition with the spark igniters over a range of propellant mixture ratios. Nine ignition tests with spark plug ignition systems were conducted. Six mainstage tests with the pyro ignition system were conducted. Two spark ignition and two mainstage tests were conducted and terminated due to erosion of J2 GG LOX poppet. Four hot-fire tests were completed. A total of 38 test have been completed with this phase of testing and the hardware has remains in excellent condition.

All mechanical items (purge and burnstack) were installed for the injector ignitor tests. Two ignition and three bomb stability test have been completed and pressures are stable and the damping was excellent. Task Agreement (TA) Change Request (EP04 R3) was submitted to change completion date for thrust chamber testing from 11/30/97-4/1/98. The thrust chamber test hardware delivery to MSFC for thrust cell test has been delayed until mid April 1998.

With facility piping complete and facility instrumentation installed, Test Stand 500 facility buildup for the X-33 valve flow tests at MSFC has progressed as far as possible. TA changes due to hardware delivery delays and requirements changes are being processed. As of today, the facility is still waiting on final test requirements from Rocketdyne. Vibration testing of the valves has been halted due to requested changes in fixture stiffness and engine mounting simulation requirements. MSFC activities have continued as much as possible considering the changes that have occurred.

X-33 Power System/Actuator Simulation and Integrated Test

Since a vehicle weight reduction exercise resulted in a change from a turboalternator to batteries for system electrical power, the test was revised/planned to incorporate the changes and a TA submitted to ASA.

Flight Control Actuator Model Development and Test

Due to program realignments and changing requirements a TA Change Request was submitted to extend task completion to June 26, 1998. The inertia simulators were delivered to MSFC in February 1998. MSFC has started lab prep work for a late May delivery of test hardware. Interlabs are being reworked to assemble and charge new battery, prepare the EMI floor, and bolt simulators to the building floor. ASA, Tempe, will sign the test procedure when they visit MSFC in November and a fit check actuator will also be delivered for fit checks at that time.

Helium Storage Subsystem Test

After arrangements were made to move the A2100 helium bottle testing to another location at the Army test facilities which is designed to accommodate detonations, a capability/burst test of A2100 helium bottle when exposed to X-33 thermal/pressure environment was performed. The first test was successfully completed with no rupture at 6,500. Phase 4 stratification testing was completed in February 1998, which consisted of two cryogenic cycles replacing the original request of ten. In April 1998, Phase 5 of the updated TA will begin with the arrival of flight tanks 2 and 3. Each of these 8 tanks will be cryoproofed to 4,000 psig.

LH2 Double Cylinder w/Woven Cylinder Joints Test

Test planning and requirements definition were completed and Test Stand 500 facility modification design/fab begun. A tooling failure delayed delivery of the test article until February 1998. After the instrumentation installation and check-out the test article was moved to building 4708 for priming and foaming. A blast analysis was conducted by Bill Riehl and presented to a Pre-TRR Board with no apparent issues that would preclude testing at Test Stand 500. As of March 1998 test facility build up was completed and testing initiated.

Propulsion System Design Reliability and Operability Modeling

Applicable STS OMRSD's to the X-33 engine (X-33 OMRSD development support) were identified/worked and task planning and support for the Engine IDR was provided. The Engine Operation Model Update was completed and provided to Lockheed Martin Skunkworks (LMSW) via telecon in October 1997. MSFC test analysis (multicell) was completed and provided to LMSW via telecon in October 1997. In addition, MSFC provided vehicle CDR support, planned for RLV and post CDR X-33 tasks.

Propulsion Health Management System Development

In July 1997, the final engine integrated diagnostics/testability matrix analysis was provided to Rocketdyne and LMSW and task planning and support for Engine IDR was provided. The Engine Operation Model Update was completed and provided to LMSW via telecon in October, 1997 and Vehicle CDR Support was provided.

In March 1998, funding was approved for the real time vibration monitoring system (RTVMS). The phase for the RTVMS hardware could be completed between 1-3 months. The high speed observation (HSO) has been completed at MSFC and is being benchmarked. MSFC and Rocketdyne are currently working software problems with the vendor. However, it is projected that HSO will meet the schedule. Also, the Integrated Health Management (IHM) Workstation hosting labviews and another server workstation has been verified and tested in the labviews environment. Ethernet communication options are still being discussed between Stennis Space Center (SSC), RTVMS, and HSO. Local communication with HSO will be verified once their software problems are resolved. It is projected that IHM readiness will meet the schedule.

Ascent, Entry, Abort Trajectories, and Guidance

Numerous X-33 nominal and abort trajectories, designed to fulfill the various X-33 mission objectives, were generated along with the X-33 reference trajectories used by the rest of the program. Guidance algorithms that successfully fly these trajectories in the presence of vehicle and environmental dispersions were fine-tuned and documented in detail in the GN&C Design Description Document. Test cases were provided to verify that the flight software is equivalent in function to the algorithm design. Refinements were made to the logic of the mission manager, the system that simulates the remainder of the flight on-board the vehicle and, if necessary, reshapes the trajectory as needed to reach the landing site safely. This logic, which is new technology, was also documented in detail. Support was provided to assist in incorporating and verifying the algorithms in the X-33 Integrated Test Facility.

Numerous LMSW documents were reviewed and comments provided. GN&C integration was supported through continual trajectory/guidance personnel co-location in Palmdale. Data requirements and implementation plans were developed for post-flight trajectory reconstruction. This effort will involve estimation of actual in-flight engine parameters from the navigation data. Trajectories were generated and GPS coverage analysis performed to support X-33 GPS/INS hardware testing. VentureStar trajectories were generated to support early vehicle design and work progressed on a simulation of the VentureStar flight.

Ascent and Entry Flight Control

The Ascent and Entry Flight Control System was incrementally updated in the X-33 GN&C Design Description Document (DDD). Incremental updates were provided in November 1997, January 1998, and April 1998 that kept the DDD up-to-date with the flight control design process. Flight software test cases were provided with the incremental DDD updates to support system level testing of the flight software design. Updates were made to the GN&C Analysis and Simulation Document that also tracked the incremental design process of the Ascent and Entry Flight Control System Design. The maveric six-degree-of-freedom (6-dof) simulation was kept up-to-date by implementing model modifications and guidance and control modifications. Maveric was released to, and was heavily used, by LMSW, ASA, and the Integrated Test Facility numerous times during the year. Maveric was also placed under revision control to enhance traceability of modifications to released versions. Maveric was used to analyze system dispersions via monte carlo analysis for the 7a_2 X-33 mission. This analysis was performed two times with the latter analysis consisting of 518 simulation runs. This number of simulation runs provided 2-sigma envelopes for 6-dof parameters of interest and indicated a degree of flight control system robustness in that only three of the 518 runs had poor terminal area energy management (TAEM) interface conditions. Major test plan and preliminary requirements generation support was provided for the ground vibration test, main engine tests, and inertial navigation system (INS) testing.

Structural Loads & Dynamics

Vehicle loads for three load cycles were provided to LMSW for each load cycle which included the flight events of prelaunch, liftoff, ascent, reentry, landing, shuttle carrier (when it was applicable), and maximum thermal loading events. This was done with support personnel co-located in Palmdale for the majority of the reporting period. The analyses for the ascent and reentry loads used external pressures supplied by MSFC and Langley Research Center (LaRC) computational fluid dynamics (CFD) groups. The critical load events of ascent and reentry were determined in association with LMSW and the ascent and entry flight trajectory data provided by MSFC. The loads data is part of the input into the X-33 Structural Design Criteria and Design Loads Document (604D0011).

MSFC provided individual finite element models (FEM) of the launch platform, vehicle aeroshell, and aero surfaces for the three load cycles. An integrated X-33 FEM of the other partner's FEM's and MSFC FEM's was also provided for the three load cycles by MSFC. Using the integrated FEM, the dynamic characteristic analyses of the FEM in the critical flight configurations was performed for control stability and POGO analyses. This included three different dynamic analysis cycles corresponding to the three load cycle FEM's and numerous tank fill levels.

A ground vibration test (GVT) plan was co-authored with LMSW. GVT pretest analyses were performed on two of the load cycle FEM's to help predict sensor and shaker locations for the GVT. This data has be provided to LMSW as it has become available.

X-33 fuel tank slosh testing was completed in May 1997, but data analysis and evaluation continued into September. Using the slosh data from the numerous testing, damping values were computed based on slosh amplitude and frequency and provided to the baffle design engineers at LMSW Michoud.

Additional vibration criteria for various locations around the X-33 were calculated and provided to LMSW and the subcontractors. Pyrotechnic shock criteria for the holddown bolt area were also provided to LMSW.

Induced Environments

The MSFC 14-inch trisonic wind has been extensively involved in Phase II X-33 Vehicle Development Program. The majority of tunnel time during 1997 and 1998 has been spent in support of the X-33 Program. Extensive parametric testing was done to determine configuration modifications to solve the aerodynamic stability problems discovered in earlier testing at MSFC. Over 20 configurations were tested during the middle of 1997 involving over a 1000 runs and extended tunnel operation to solve these stability problems. Upon the selection of a new configuration, Wind Tunnel testing was conducted to support a new aerodynamic database. During this 3 month period the Wind Tunnel Facility was operated on an extended operating schedule to meet the program's critical need for the new configuration's aerodynamic characteristics. This testing provided total vehicle aerodynamic data along with multiple control surface effects and control surface interactions. Additionally, in 1998 a loads test was run in the 14-inch trisonic Wind Tunnel to determine the aerodynamic loading on both the fins and vertical tails along with the vehicles aerodynamic characteristics. This test was run from 3/98 to 5/98 and provided data for structural loads analysis of the vehicle.

Plume induced design environments were updated as the vehicle and its flight profiles were matured. Cycle 3.0 ascent plume induced thermal design environments for the X-33 CDR were published in October 1997 and post CDR X-33 cycle 3.1 ascent plume induced thermal design environments in March 1998. Three-dimensional ascent base flowfield CFD solutions were completed at four altitude points which included the linear aerospike plug "pillow region" and incorporated the hydrogen rich base bleed flow. These results were published in AIAA 98-2469. These CFD convective and radiative heating solutions will form the basis for generating the next Cycle 4.0 ascent base thermal environments update in June 1998. Cycle 1.0 X-33 reaction control system (RCS) plume impingement heating and pressure environments were generated and published for the CDR in August 1997.

CFD analysis to correlate the jet effects II test and expected flight data is nearing completion. Analysis of the X-33 at flight conditions indicate an increase in vehicle base pressure over the same trajectory point in the test data. This is consistent with past experience that vehicles at flight conditions with hot plumes experience higher base pressures than cold (or even hot) test data. The accuracy of the X-33 in flight CFD solution is currently being assessed.

Transonic, supersonic, and hypersonic inviscid CFD analyses were performed to define aerodynamic loads acting on the F-loft revision F X-33 vehicle surface elements. This data was used by MSFC, LMSW, and B.F. Goodrich in various structural analyses.

Updates for ascent and reentry acoustic environments were generated due to configuration and trajectory changes. Farfield acoustic environments for liftoff and sonic boom environments were generated for the Environmental Impact Statement. Test support and data analysis was provided for the jet effects II Wind Tunnel test at Arnold Engineering Development Center. Planning and support for upcoming Wind Tunnel tests at LaRC and static engine tests at SSC is underway. As the vehicle and launch pad have matured, ignition overpressure prediction updates have been generated for the cases of "water in the trench" and a "softer start transient."

X-33 venting analyses were performed updating the database for vehicle compartments using the most current trajectories and surface pressure data. Recommendations were made for the number and location of active vent doors required during ascent and entry.

Testing at the Improved Hot Gas Facility (IHGF) to determine leakage past various seal configurations in support of the X-33 Program continued. To date, approximately half of the 200 runs proposed in FY98 have been completed in addition to the 250 runs completed for FY97. The seal configurations tested to date in FY98 consist of primary seals, primary with secondary metalic seals, primary with nonmetalic secondary seals, landing gear door seals, and AFRSI blanket candidates. The planned tests for the eleven/body flap seals have not taken place at this time.

The X-33 LH2 feedline design requirements for inlet distortion at the turbopump inlet were verified through water flow testing at MSFC. The SSC powerpack feedline configuration was analytically assessed. Based on the X-33 feedline results, Rocketdyne and LMSW verified the SSC powerpack feedline by analysis only. Work was also initiated on the "Wide Flow Range Pump Components" task. Code validation for a diffuser with large diffusion ratios is in progress.

Thermal Assessment and Thermal Control

The internal compartment environments of the X-33 during ground purging, flight, and post landing operations have been determined for various Malmstrom and Michael trajectories. The affects of air leakage through the TPS seals, venting, cryogenic tanks, aeroheating and radiative effects of the seals due to a TPS redesign were included. Additional efforts were expended to determine the effects of the TPS support structures on internal temperatures. The ATCS performance was predicted for the redesigned system considering the new coolant sink helium. Avionics temperatures were determined for the normal ATCS operation and also for failed cases. The aerothermal TPS sizing has been updated based on revised aerothermal environments. Base TPS sizing was done using both metallic TPS and ablative TPS configurations. Detailed thermal analyses has also been accomplished on the redesigned TPS seals for various areas of the vehicle. Various thermal models of the TPS support structures, intertank, LH2 thrust structure, body flaps were developed and analyzed for prelaunch and flight conditions. Separate thermal analyses were also accomplished to determine internal environments for the remote health nodes and vehicle cabling. Studies have been issued addressing the internal compartment convective heat transfer coefficient to use in the various thermal models developed by the partners. A thermal model was developed of the battery compartment in the nose section. All models are used to redo analyses as required when updated aerothermal environments are issued. Numerous small separate studies to address LMSW thermal issues in addition to the above large efforts have also been performed.

LH2 Flight Tank and LO2 STA Tank Static Load and Cryogenic Testing

Progress was made in the development of ground test facility and support systems for combined mechanical load and cryogenic tests of the flight LH_2 and LO_2 STA tanks. A weekly telecon between all partners of interest was instituted to facilitate the test planning and establishment of test requirements for the flight LH2 tanks and the LO2 STA tank. Baseline test systems for both tanks were planned and conceptually designed including test hardware and software, test operational programs for load control and data processing functions, and test infrastructure support. Detailed designs for the LH2 tank tests' systems are well underway based on current LMSW LH2 test requirements. Optional test sites to allow parallel test operations of the LH_2 and LO_2 tanks were evaluated including cost data and projected schedules.

Since the decision by project management to perform pre- and post-test assembly operations of the LH2 flight tanks at MSFC, a TA between MSFC and

LMSW has been in development detailing the responsibilities and requirements for preparations to support these activities. Requirements were identified by both LMSW and LMMSS, with designs and modifications implemented through MSFC's Facility Office and its support contractors. Significant program cost savings are anticipated as a result of performing these activities at the test location, modifying an existing clean room available at MSFC, as well as sharing NASA's super guppy transport aircraft for transporting the tanks from California to Huntsville, AL, and return. The 100% design review for modifications at building 4650 is scheduled for the end of April with all planned preparations complete by the end of June.

X-33 Dynamic Testing

X-33 fuel tank slosh testing was completed in May of 1997 but data analysis and evaluation continued into September. The slosh testing was conducted on three plexiglas models, one representative of the LH2 tank with septums, one representative of a quarter of the LH2 tank, and one representative of a half of the LOX tank. Various tests were conducted to identify slosh modes and the associated damping. A series of tests were also conducted to evaluate various ring baffle designs for the LOX tank. Data from the LOX tests was electronically filtered using MATLAB to provide the analyst with cleaner data for his analysis.

Planning for the X-33 vehicle ground vibration test (GVT) has continued, including discussions at the CDR in October 1997 and Technical Interchange Meetings in July, September, and November 1997 and January and February, 1998. MSFC is tasked with conducting the GVT in Palmdale. Major issues have been resolved, although the GVT has slipped from the planned dates of October-December 1998 to the June 1999 time frame. Significant contributions have been made in support of the decision to move the test site from the manufacturing facility at LMSW to the launch site at EAFB. Consultation, based on past experiences, was provided relative to modifications to the launch mount to accommodate the GVT suspension system, plans for a temporary shelter to protect test personnel, instrumentation, and equipment and the decision to test with liquid nitrogen to simulate the LOX during the GVT. The LH2 tank will be pressurized with helium. Modifications to the original TA to accommodate additional testing, including tests of the rotating launch mount (RLM), the GVT suspension system, the thermal protection system, and three configurations of the integrated vehicle as requested by LMSW has been initiated.

Only one test configuration was planned in the original TA. The initial version of the test plan was released in March 1998. Issues relating to instrumentation, excitation, operational, safety, and schedule issues are being worked regularly.

LO2 Composites Component Fabrication

During phase 2, LMMSS was involved in composite LO2 tank development and LO2 tank shape trade studies. In support of this effort, fabrication development for the LO2 semi-conformal mini tank (SCMT) consisted of three proof-of-concept demonstration cylinders fabricated to establish a baseline for assessing any design, material, manufacturing or processing anomalies prior to fiber placement of the actual 4ft. SCMT. Each cylinder was validated through subcomponent testing and finite element modeling. Additional flat panels were fabricated for material property testing for development of a mechanical property database, and for verification of the proprietary material system selected for the SCMT. A manufacturing process plan was developed and used extensively during MSFC's ISO 9000 Certification Audit. The SCMT will be 4 ft. in length, 2ft. in diameter at the forward end, and have an aft dome which is 2 ft. by 3 ft. and 12 inches deep. As a result, fabrication and assembly efforts are currently on-going in MSFC's productivity enhancement complex. The overall objective is to expand and demonstrate advanced composite cryogenic tankage technologies of a pressure vessel with a semi-conformal shape. The SCMT will demonstrate the fiber placement and sandwich laminate technologies associated with oxygen compatibility of composite materials.

LOX COMPATIBILITY PROGRAM

Testing to determine the oxygen compatibility of composite materials in a liquid oxygen tank structural application was conducted and a down select to five composite material systems made. Phase II of this test plan, which consisted of a variety of ignition and flammability tests on these five material systems, has been completed. This test series included puncture, spark, pyrotechnic shock, and friction tests. A delta LOX hazard analysis has been performed on the X-33 LOX tank which has allowed the generation and initiation of phase III test plans. Phase III testing will consist of a move from coupon testing to bottle testing in LOX.

PROTECTIVE SERVICES AND SECURITY

Security support was provided on-site during the Environmental Impact Study (EIS) Public Scoping process and an ongoing liaison was established with state and federal Law Enforcement and military agencies. Significant inputs to the Launch Site Security Plan were provided. Physical security surveys of Launch/Landing Sites, Operations Control Center (OCC), equipment storage areas were conducted and initial recommendations submitted for enhancing asset protection. Detailed coordinatation and assessment of security controls with state and local law enforcement agencies from five states, development of a cost impact assessment, and a risk analysis was performed for the X-33 Overland Transportation Study. Additionally, significant coordination was conducted with the Defense Intelligence Agency for national-level counterintelligence analytical support for RLV/X-33.

X-33 RESIDENT OFFICE SUPPORT

Mr. Frank Key (EH01), Andy Hodge (EH32), and Seth Lawson (EH33) served in the resident office in Palmdale to support the development of the composite LH2 tank providing significant and relevant engineering input to the program while in residence.

STENNIS SPACE CENTER

In October 1997, work was initiated to modify the A-1 Test Stand from it's Space Shuttle Main Engine (SSME) test configuration to test the XRS-2200 Power Pack Assembly (PPA) and single engine and dual engine configuration. Design, procurement, fabrication and installation of the PPA Oxygen and Hydrogen discharge systems have been completed. Approximately 875 feet of Liquid Hydrogen and Liquid Oxygen PPA Discharge, Hot Gas Turbine Discharge, Cold Helium (oxygen tank pressurant) and Helium Spin Start piping and pipe supports was fabricated and installed. Approximately 100 feet of Special Test Equipment piping was fabricated and is ready for use in the test program. A 3-foot diameter flare stack was fabricated and installed and approximately 4 acres of land was cleared for the flare stack heat affected zone. Two cold helium heat exchangers were fabricated and one was installed on the test stand while using one as a spare. 270/28 VDC Power Systems were installed at Building 3202 and A-1 Test Stand. The design of the 270/28 VDC is completed for B-1 Test Stand. Installation of the Cold Helium System, Helium Spin Start, Turbine Discharge, 270 / 28 VDC EMA and Controller Power Systems are in progress and are currently on schedule to support the X-33 test program. The A-1 Test Stand Control System has been upgraded to provide a Computer/PLC (Programmable Logic Controller) based graphical user interface. Control of all new facility systems is via Computer/PLC's. The A-1 Data Acquisition Systems have been upgraded to support the X-33 test program with improved turnaround times and greater flexibility in data recording and processing. Activation of the new facility systems is ongoing. Activation testing to date includes Cold-shock (with liquid nitrogen) of the PPA Propellant Discharge Systems, in-place Calibration Flow Testing (with liquid oxygen) of the Facility LOX Flow Meter and ignition of the PPA Hydrogen Discharge Flarestack.

Also, work is in progress to support the Lewis Research Center during the testing of the Multi-Lobe Tank (MLT), which is a prototype Liquid Hydrogen Tank for determination of an acceptable tank design for the X-33 Vehicle. Currently, we are in the process of providing equipment, technical support, and training to the Lewis Research Center test crew for MLT testing. The equipment shall include the gaseous hydrogen (GH_2) Leak Detection System hardware and software and a support structure for the MLT. The technical support to be provided shall consist of assistance in activation and checkout of the GH_2 Leak Detection System. The training to be provided shall consist of training Lewis Research Center personnel on the operation of the GH_2 Leak Detection System.

This data was generated by Lockheed Martin Skunk Works, AlliedSignal Aerospace, Rocketdyne-A Division of Boeing North American Rockwell, B.F. Goodrich Aerospace - Sverdrup Corporation under NASA Cooperative Agreement No. NCC8-115, dated 2 July 1996

DRYDEN FLIGHT RESEARCH CENTER

X-33 PILOTED SIMULATION (TASK DFRC-19):

The X-33 Piloted Simulation became fully functional and fully funded under the rebaselining effort. Piloted evaluations were performed on this simulation with new aerodynamic databases this past year.

The databases evaluated were the 16 May '97 or 516 release; the August 8, '97 or 808; and the Feb. 16 '98 release known as the 216 release. Several versions of the engine model were also evaluated. An aerothermal model was incorporated so that realistic heating effects could be documented during reentry.

The most recent aerodynamic databases along the mass properties utilizing a 79,000 LB empty weight have produced satisfactory flight operation during the Michael trajectories.

The Piloted Simulation continues to be an excellent engineering tool for providing data for rapid decisions on various external configurations.

X-33 ITF SOFTWARE LAB (TASK DFRC-06):

The X-33 Integration Facilities located at Dryden became fully functional this past year. The lab floor space was essentially doubled under the Rebaselining effort to satisfy new software integration requirements.

Two major software builds were integrated, verified correct and then released to AlliedSignal during the past year. The first was software build no. 2 which was released to AlliedSignal on 29 Sept. 1997. Build no. 3 was then released to AlliedSignal on 1 April 1998.

The labís primary hardware consisted of (2) Onyx computer systems and Brassboard Vehicle Management Computers (VMC). A Flush Air Data remote pressure sensor was received in March, to be part of the integration effort. A data recording system was procured and installed in the lab. This capability is expected to be fully functional by May 1998.

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

The autonomous software simulator was established in March '98 using databases from late 1997. This software automatically flies the vehicle from liftoff to touchdown.

Extended Range Design and Operations (Task DFRC-09)

The last year has resulted in many significant accomplishments for the range task. First was the completion of the Preliminary Design Review in May 97. Next the range design was completed and a Critical Design Review held in December 97. Equipment purchases are nearly complete, and integration and test of subsystems has begun. A major task realignment was completed to cover changes in requirements. The task realignment solved several major range issues, including range communications at the launch site, microwave systems for redundant data communications at the landing sites, and funding to complete the range systems required for the Integration and Test Facility.

The Extended Test Range Alliance (ExTRA) consisting of NASA Dryden, the Air Force Flight Test Center, Goddard Space Flight Center, and Wallops Flight Facility continues to work extremely well. Some of the advantages include

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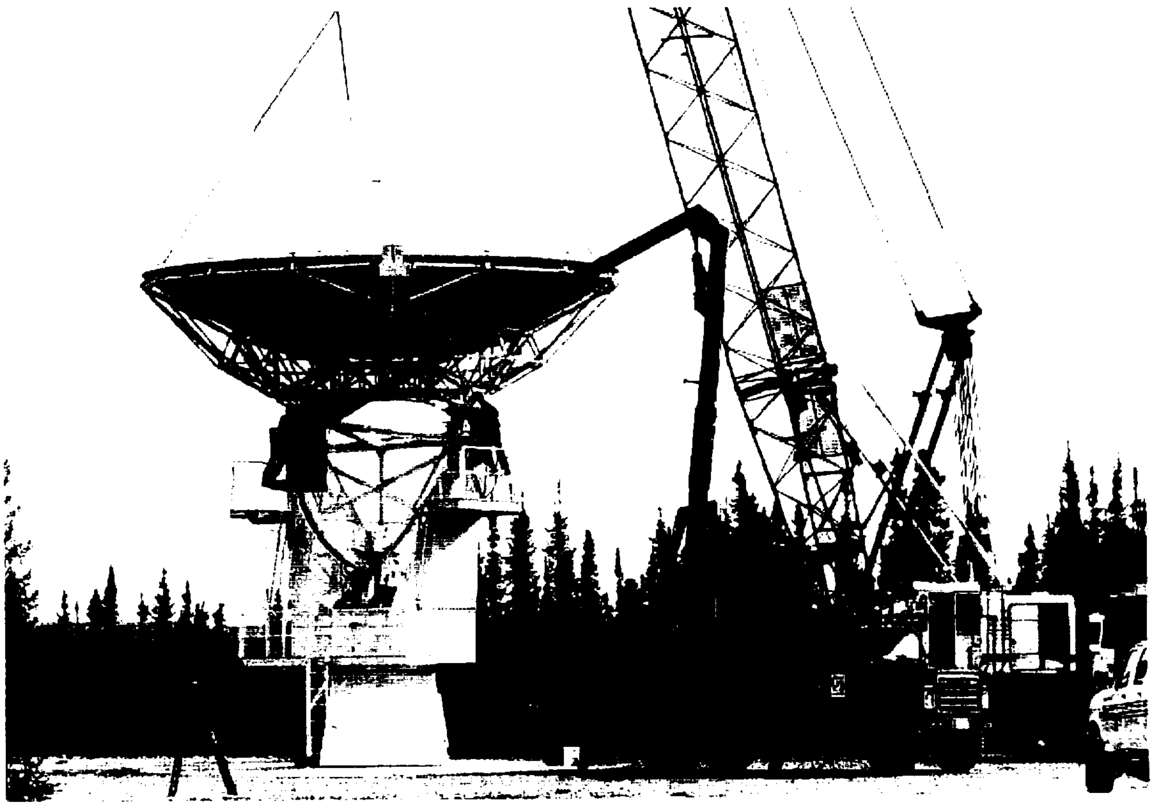
sharing of existing contracts to reduce delivery time, large cross section of knowledge, and the analysis of reentry plasma fields to determine communication blackout periods.



Installation in Alaska of an identical 9 meter telemetry and uplink system soon to be installed at Dugway.

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JOHN F. KENNEDY SPACE CENTER

TASK AGREEMENT NUMBER - TASK TITLE

KSC-02 Holddown Post Testing

1. Fabricated parts to support testing.
2. Revised the testing schedule to reflect the current scope of anticipated testing in FY98

KSC-03 Umbilical Plate Testing

1. Revised the testing schedule to reflect the current scope of anticipated testing in FY98.
2. All testing is anticipated to be accomplished in FY98

KSC-04 Programmatic Support

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

KSC-05 Support to IHM Development

1. All work was stopped on this Task Agreement at the direction of the X-33 Program Office.

KSC-06 Phase II EA/EIS Support

1. Supported preparation of Final Environmental Impact Statement and Record of Decision (ROD). Final was published in the fall of 1997.
2. Provided support to MSFC on supplemental Environmental Assessments being prepared to address program changes including the overland transport of the X-33 vehicle back to the launch site and the extension of the runway at Dugway.

KSC-07 Ground Interface Modules (GIM)

1. Storing and maintaining GIM racks at KSC until installation, technical support, and troubleshooting are required in Palmdale.

KSC-08 GSE Design Support

1. Performed umbilical system and vehicle positioning system (VPS) trade studies.
2. Furnished a design concept of a Holddown post blast shield.
3. Supported the X-33 Program CDR.
4. Provided complete design package including models on a Vehicle Positioning System.
5. Provided the following design drawings for the umbilical system: collet lock receptacle for assembly, housing, pin, and sleeve; receptacles for shear pin and alignment pin; collet lock assembly; shear pin, level strut assembly, retractable latch assemblies; collet lanyard assembly; and center strut assemblies.

KSC-09 Weight and Center of Gravity Simulator

1. Performed analyses and furnished drawings.

KSC-10 Fault Tree Analysis

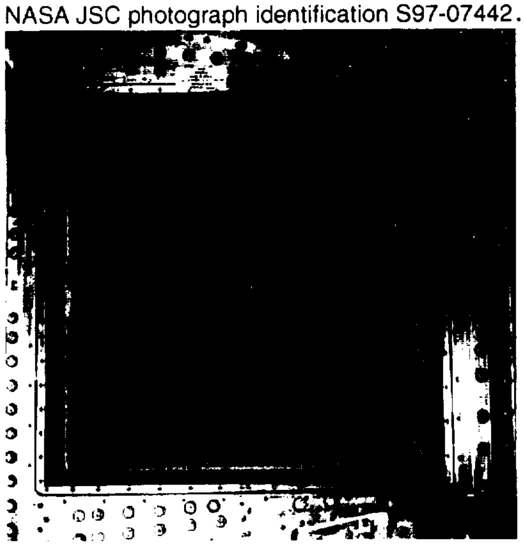
1. Performed fault tree analyses for X-33 program.

KSC-11 Hazardous Gas Detection Equipment

2. Analyzed requirements and ordered the hazardous gas detection equipment.

JOHNSON SPACE CENTER

NASA JSC photograph identification S97-07442.



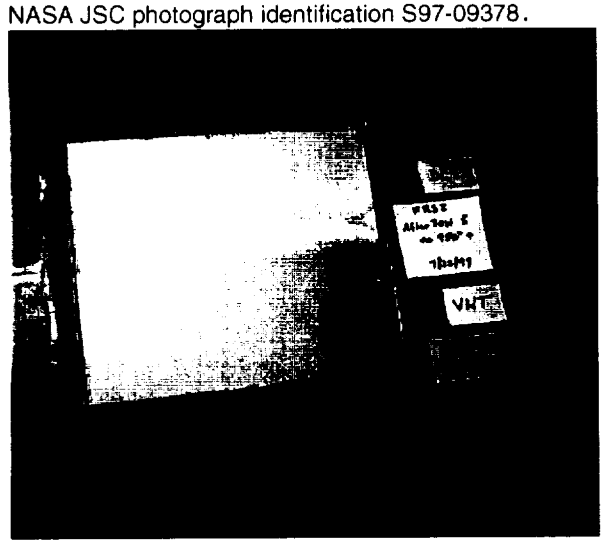
X-33 FOUR PANEL ARRAY METALLIC HEAT SHIELD SEAL LEAKAGE

Arc jet testing of the four-panel array metallic heat shield was conducted to determine the severity of the hot gas leakage by acquiring temperature response data with and without a secondary seal while simulating the predicted flight surface temperatures. The tests were performed with three flow orientations that showed surprisingly modest increases in internal temperatures for the reversed flow orientation. The measured leakage rates were found to be a linear function of the surface pressure for various gas enthalpies.

AEROTHERMAL EVALUATION AND QUALIFICATION TESTING OF FELT REUSABLE SURFACE INSULATION (FRSI) FOR X-33

Aerothermal testing of Felt Reusable Surface Insulation (FRSI) for X-33 with two candidate surface coatings was conducted in Johnson Space Center's (JSC) Atmospheric Reentry Materials and Structures Evaluation Facility (ARMSEF). The primary objectives of selecting either the Dow Corning (DC) 92-007 coating or

NASA JSC photograph identification S97-09378.



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the Very High Temperature (VHT) coating and then qualifying the selected coating for X-33 flight were achieved through a series of tests completed from July 21 - August 2, 1997. The results of side-by-side testing of the DC 92-007 and VHT coatings led to downselecting DC 92-007 as the coating to be qualified for X-33 flight. A FRSI test specimen coated with DC 92-007 was then subjected to twenty simulated mission cycles at 700° F to represent the anticipated X-33 flight lifetime. No anomalies on the FRSI or the coating were identified.

THERMAL EVALUATION OF FRSI MATERIAL FOR X-33

Thermal conditioning of a Flexible Reusable Surface Insulation (FRSI) blanket/graphite epoxy-aluminum honeycomb panel has been performed for BFG. in the Radiant Heat Test Facility (RHTF) in support of the X-33 Single Stage To Orbit (SSTO) program. The thermal conditioning consisted of multiple exposures to a temperature profile which represented both the ascent and entry portions of the X-33's flight. The peak temperature in the areas where FRSI will be used is about 700° F. The purpose of the conditioning was to prepare the panel for thermo-vibro-acoustic testing in a progressive wave tube (PWT) test facility. In addition to the preconditioning, the data collected in the thermal tests will be used to validate thermophysical properties of the FRSI and to verify the thermal performance of the material. Post-test inspections of the panel revealed no significant material degradation

THERMAL EVALUATION OF AFRSI MATERIAL FOR X-33

Thermal conditioning of an Advanced Flexible Reusable Surface Insulation (AFRSI) blanket/graphite epoxy-aluminum honeycomb panel has been performed for BFG. in the Radiant Heat Test Facility (RHTF) in support of the X-33 Single Stage To Orbit (SSTO) program. The thermal conditioning consisted of multiple exposures to a temperature profile which represented both the ascent and entry portions of the X-33's flight. The peak temperature in the areas where AFRSI will be used is around 1200° F; however, the test specimens were taken to 1500° F to collect data on the material at a higher possible use temperature. The purpose of the conditioning was to prepare the panel for thermo-vibro-acoustic testing in a progressive wave tube (PWT) test facility. In addition to the preconditioning, the data collected in the thermal tests will be used to validate thermophysical properties of the AFRSI and to verify the thermal performance of the material. Post-test inspections of the panel revealed no significant material degradation.

THERMAL EVALUATION OF AFRSI SEAL CONCEPT FOR X-33

Similar to the test stated above, these tests were performed to evaluate a seal concept proposed for use at the joint between blankets. The test articles were exposed to the same thermal environment multiple times in preparation for a PWT exposure. Post-test examination of the seal area revealed discoloration of the metallic sheath. The seal design is currently being reworked and another test is scheduled for the future.

THERMALLY INDUCED BOWING OF METALLIC TPS MATERIAL FOR X-33

Thermal evaluation of a metallic Thermal Protection System (TPS) Inconel honeycomb panel was performed in an effort to assess and quantify the deformations experienced by the honeycomb panel when it is subjected to thermal gradients across its thickness. This was achieved by incorporating seven linear variable displacement transducers (LVDT) in the 17-inch-by-4-inch test article. These LVDTs measured the out-of-plane linear displacement of the flat panel during and after the heating cycle.

The test article was exposed to thermal environments which produced surface temperatures up to 1625° F and thermal gradient as high as 370° F. This thermal environment, which was specified by the test requester, produced displacements of 0.0664 inches at the ends of the panel and a maximum displacement of 0.1412 inches at the center of the panel. The difference between these two measurements, 0.0748 inches, represents the actual deflection the panel experienced. This value compares well with analytical predictions. The exposures were performed several times to assure repeatability.

LEWIS RESEARCH CENTER

TASK NO. LeRC-10: MULTI-ELEMENT COMBUSTION WAVE IGNITION TESTS

Following the successful completion in the first half of 1997 of the single element combustion wave ignition tests, LeRC began testing, in March 1998, the flight prototype, multi-element combustion wave ignition system for the X-33 aerospike engine. The combustion wave ignition concept enables multiple combustion chambers (thrust cells) to be ignited from a single ignition source. Testing, although just underway, has demonstrated that the concept works. The objectives of the tests are to verify the operating envelop of the ignition system, optimize valve timing for the start sequence, and gain a better understanding of the hardware characteristics.

TASK NO. LeRC-2: X-33 CRYOGENIC INSULATION TEST

LeRC completed thermal vacuum tests on the airex cryogenic insulation system being used on the X-33 propellant tanks. Tests at LeRC's Supplemental Multilayer Insulation Research Facility with liquid hydrogen provided a mission duty simulation for this reusable insulation to verify thermodynamic and durability properties. LeRC successfully subjected the airex insulation to 60 thermal cycles. The airex did not show any evidence of debonding , delamination, or degradation of thermal performance after repeated thermal cycles. A secondary objective of this test was to evaluate the performance of the fiber optic cable in the insulation. The fiber optic cable did not exhibit any decrease in light transmission after repeated thermal cycles.

TASK NO. LeRC-4: HEALTH MANAGEMENT FOR THE X-33 AEROSPIKE ENGINE

LeRC is developing the Post Test Diagnostic System (PTDS) for the X-33 aerospike engine. This software system will automatically analyze the data from every engine test firing and flight of the X-33. During this period, the system specifications were defined and a prototype graphical user interface was developed and demonstrated. The first use of the PTDS system will be in support of the engine power pack testing later in 1998.

LANGLEY RESEARCH CENTER

SYSTEMS ANALYSIS

Task 5 - RLV System Concept Evolution and Trades

- Completed transonic aerodynamic analyses of configurations 0002A and 0003C
- Performed configuration parameterization, structure, mass properties, aero and aerothermal performance, and aerospike engine performance sensitivity studies for 0002A and 0003C configurations.
- Completed Mach 20 He experimental aerodynamic testing on 0002A and 0003C configurations.
- Completed weight and center-of-gravity sensitivity studies on configurations 0002A and 0003C.
- Completed hypersonic aerodynamic trim assessments for 0003C configuration.
- Determined thrust-vector-control (TVC) trim capability of L1M configuration. Developed comparative TVC-trimmed versus untrimmed ascent trajectories.
- Developed entry trajectories for 0003C configuration which did not violate heating constraints.
- Performed sensitivity study of payload mass to lift-off thrust-to-weight ratio.
- Performed TPS / TPS Support Structure concept trade.
- Performed sensitivity study of vehicle dry weight to TPS / tank stand-off distance.
- Developed high fineness-ratio LL201 configuration mass properties and preliminary aerodynamics.

AEROTHERMODYNAMICS

Task 1 - Aerodynamics

- Performing assessment of hypersonic aerodynamic data from multiple facilities to establish understanding of apparent inconsistencies. Effort includes additional wind tunnel testing, complemented by extensive

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computational fluid dynamic analyses, to determine fluid dynamic phenomena which are affecting wind tunnel results.

- Performing extrapolation of wind tunnel and CFD results to flight environment to establish valid flight aerodynamic database.

Task 2 - Thermodynamics

- Performed CFD computations of heat-transfer levels to deflected body flaps at multiple trajectory conditions for both laminar and turbulent flow.
- Provided predictions of flight aerodynamic heating environments for both laminar and turbulent flow in support of the X-33 Critical Design Review.
- Developed boundary-layer transition criteria for smooth body transition.
- Developed methodology for inclusion of boundary-layer transition methodology into trajectory studies.
- Performed extensive program of testing and analysis to determine the possible effects of surface roughness on vehicle heat transfer and boundary-layer transition. Discrete roughness elements and "bowed" TPS panel simulations addressed experimentally. Results support development of "roughness-induced" boundary-layer transition criteria.

Task 3 - Wind Tunnel Model Fabrication

- Fabricated aerodynamic force and moment, aerodynamic loads, dynamic stability, and aerodynamic heat-transfer models per Task Agreement.

Task 4 - Wind Tunnel Testing

- Completed aerodynamic force and moment testing in the following NASA Langley facilities:

Low Turbulence Pressure Tunnel	Subsonic
14-Foot x 22-Foot Subsonic Tunnel	Subsonic and in-ground-effect
Unitary Plan Wind Tunnel	Supersonic
20-Inch Mach 6 Tunnel	Mach 6
31-Inch Mach 10 Tunnel	Mach 10
20-Inch Mach 6 CF4 Tunnel	Mach 20 Simulation

- Completed dynamic stability testing in the following facilities:

16-Foot Transonic Tunnel	Transonic
Unitary Plan Wind Tunnel	Supersonic

- Completed aerodynamic loads testing in the 16-Foot Transonic Tunnel
- Performed aerodynamic heat-transfer testing in the following facilities:

20-Inch Mach 6 Tunnel	Mach 6
31-Inch Mach 10 Tunnel	Mach 10

Task 28 - X-33 Aerothermodynamic Database Development / Validation

- Assessed effects of change in canted fin dihedral from 37-deg. to 20-deg. on fin heat transfer.
- Developed flight-test trajectories which delay boundary-layer transition until well after peak heating.

VEHICLE HEALTH MANAGEMENT / NON-DESTRUCTIVE EVALUATION

Task 10 - Sub-Scale Composite Health Monitoring Evaluation

- Evaluations Completed.

Task 11 - Flight-Quality Fiber Optic Temperature Sensor System

- Evaluations Completed.

Task 12 - X-33 Reusable Cryogenic Tank System VHM Sensor Suite

- Fiber-optic Distributed Temperature Sensor system flight boards successfully vibration tested.

Task 13 - Dual-Lobe LH2 Ground Test VHM Sensor System

- Acoustic Emission (AE) ground test interface hardware designed and awaiting fabrication.
- AE flight pre-amplifiers successfully vibration tested.

Task 23 - X-33 Flight LO2 Tank Distributed Temperature Sensor System

- Fiber-optic Distributed Temperature Sensor system installed on X-33 liquid oxygen tank at Palmdale.

Task 24 - X-33 Flight LH2 Tank Distributed Sensor System

- Fiber-optic Bragg grating sensors delivered to Lockheed Sanders for prototype testing of the flight Distributed Strain Sensor system.

Task 25 - Integrated LO2 Ground-Test Panel VHM Sensor System

- Hardware procured for Distributed Strain Sensor and Distributed Temperature Sensor systems for cryogenic pressure box test panel (see Task 9)

STRUCTURES AND MATERIALS

Task 8 - Thermomechanical Testing of Cryogenic Insulation

- Completed testing of second set Al-2219-T87 panels with Spray-on Foam Insulation (SOFI) and Poured-in-Place (PIP) Insulation. (-320F to 350F)
- Completed testing of Gr-Ep panel with Airex LMMSS cryocoat insulations (-423F to 350F). Cryocoat cracked during thermal/mechanical cycling.

Task 9 - Pressure Box Test of LH2 Tank Segment

- Cryogenic Pressure Box Facility passed Langley Systems Operations Committee Review in preparation for initial operation.
- Facility in final facility systems readiness process prior to installation and testing of "check-out" panel.
- Test panel in fabrication by Alliant TechSystems

Task 15 - Metallic TPS Thermal and Structural Analysis and Design

- Performed parametric studies of X-33 metallic TPS design which identified key thermal performance issues (gap radiation at panel-panel interfaces, heat-shorts through rosettes).
- Performed thermal analyses of JSC arcjet test specimens.
- Performed flutter analyses of cargo-bay doors and metallic TPS panels in flight, and metallic panel-to-panel seals at ground-test facilities.

Task 16 - TPS Materials Thermal Characterization Tests

- Completed all thermal conductivity testing of fibrous insulations, as function of temperature and pressure. Final report in process.
- 4-point bend tests at room temperature conducted for face-sheet ultimate strength.
- Heater box (for high-temperature testing) check-out in progress.

Task 17 - Metallic and Carbon-Carbon TPS Material Property Testing

- Developed test plan and matrix, in consultation with BF Goodrich, for evaluation of metallic TPS sandwich structure.
- Initiated testing of face-sheet material and TPS sandwich structure over temperature range from ambient to 1800F.

Task 18 - TPS Testing in 8-Foot High Temperature Tunnel

- Five (5) successful tests of metallic panel array complete. TPS panel thermal performance verified at flight conditions. Seals between panels performed as expected.
- Metallic panel array failure during sixth run (a severe out-of-tolerance test simulation) under investigation.
- Three (3) successful runs on Single-Blanket leeside TPS panel.
- Initiated testing of 3-Blanket with Seals panel.

Task 20 - Actively-Cooled Nozzle for Linear Aerospike Engine (RLV)

- Developed test plans for coupon thermal tests.
- Initiated modifications to LaRC vortek facility for thermal tests.
- Developed design code for ramp heat exchanger.
- Initiated finite element analysis of ramp heat exchanger.

Task 26 - Cryogenic Insulation Development (RLV)

- New polyimide foams developed using NASA resin systems. Foams have physical properties equivalent to commercially available foams.
- Developed new Hollow Polyimide Microspheres which allow for syntactic foam fabrication and repair.

Task 29 - Improved Metallic TPS (RLV)

- Task "kick-off" and "brainstorming" meetings held.

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USAF ORGANIZATION: EDWARDS AIR FORCE BASE (AFFTC)

With Edwards AFB being selected as the launch site for the X-33, one of the Air Force Flight Test Center's main contributions to the program this past year has been providing support to insure the timely construction of the launch site and related ground support systems. It was established that the AFFTC Commander, acting in his capacity as the test range commander, is responsible for range safety of each X-33 flight. Significant progress has been made in preparing the necessary range safety documentation; the range safety requirements have impacted the vehicle design and its operating concepts. AFFTC personnel, with considerable engineering experience in flight testing hypersonic and lifting body vehicles, contributed to the X-33 design and associated flight test plans.

The AFFTC Environmental Management Office made major contributions to support the accelerated Environmental Assessment that allowed construction of the launch complex to begin on schedule. These contributions included performing the required local environmental studies, obtaining the required permits from the appropriate environmental organizations, and conducting the required training for personnel who may come in contact with the local endangered species (desert tortoise). They also coordinated the Air Force Record of Decision for the X-33 Environmental Impact Statement (EIS) prepared by NASA.

The AFFTC engaged in a very pro-active effort to finalize the Cooperative Research and Development Agreement (CRDA) between the AFFTC and LMSW that made the selected real estate on Edwards AFB available to begin construction of the launch site on schedule. Very effective cost sharing concepts were conceived and implemented in the communications area for such items as the fiber optic communication lines, power transformers, etc. Also, a focus was placed on obtaining the required permits and plans for launch site construction to include approval by the AFFTC Planning and Zoning Committee, development of an explosive site plan and biological opinion, removal of the X-33 launch site area from the official East Precision Impact Range airspace, and a Memorandum of Agreement between Air Force Research Laboratory and AFFTC to support the planned construction schedule.

A very comprehensive X-33 Range Safety Requirements Document was developed and provided to LMSW for implementation. The required range safety hardware and software were defined, and action was taken to acquire this equipment.

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The requirements for range operations from launch to landing were developed as part of a joint NASA DFRC/AFFTC Extended Test Range Alliance (EXTRA). In addition to an enlarged range airspace, the required features of EXTRA include interfaces to operational intercom and television systems, ground support systems automation and integration, weather support, ground and range safety, and flight assurance operations. All proposed landing and range overflight sites were visited. Requirements were developed and range business documentation was accomplished. Possible contingency sites were determined. Likewise, airspace requirements were identified. Also, interface with the FAA was planned, launch commit criteria were developed, and the Operations Directive was begun.

At the request of LMSW, the AFFTC conducted an extensive study of the winds at altitude in the launch area by providing Rawinsonde measured atmospheric data for approximately 140 pairs of balloons released 3 hours apart.

AFFTC engineering successfully advocated the development of Automated Programmed Test Input data maneuvers (PTI) that will be used during the flight tests to obtain aerodynamic coefficients. These coefficients will allow comparison between test and predicted data to validate the characteristic of the configuration in support of the X-33 envelope expansion flight tests and to validate the VentureStar configuration. A draft description of a longitudinal PTI and the control logic associated with that maneuver were prepared for the avionics software Design Description Document. Assistance was provided in the development of many of the test planning documents (flight test profiles, master measurement list, flight test objectives, etc). Engineering personnel participated in the many design reviews and test planning meetings. An improved method of interpolating and extrapolating engine performance data was developed, and this technique with improved accuracy was provided to Boeing Rocketdyne for implementation in their updated (Revision 5.0) model of the linear aerospike engine used in the X-33.

AFFTC prepared a Contingency Plan to define the required reaction in case the vehicle does not complete its flight to the planned landing site. Appropriate candidate contingency reaction forces, both government and civilian, along the flight path were contacted and identified in the plan.

AFFTC was responsive to the California Red Team and the City of Lancaster in their definition of the California proposal for candidate launch sites for the VentureStar.

AMES RESEARCH CENTER

X-33 SUPPORT

- Supported the TPS and Vehicle System CDRs in the areas of Aerothermodynamics, Thermodynamics, and TPS.

AEROTHERMODYNAMICS AND VERIFICATION

- Developed efficient process for generating accurate aerothermal environment databases which includes application of the high fidelity 3-D, real gas GASP CFD code and of the HAVOC engineering code. The demonstrated process is directly traceable to the RLV design process.

- Provided 40 additional GASP CFD solutions for the Rev F Loft vehicle configuration that cover the X-33 design and flight test range of Mach No., Reynolds No., angles of attack and yaw, and both fully laminar and turbulent flow. Surface heating of one of these solutions is shown in Figure 1, and is compared with a preliminary RLV solution to show quantitative level of traceability.

  The solutions are post processed to provide design and pre-flight data for TPS design, trajectory analysis, structural loads, and aerodynamics (Mach 2-15).

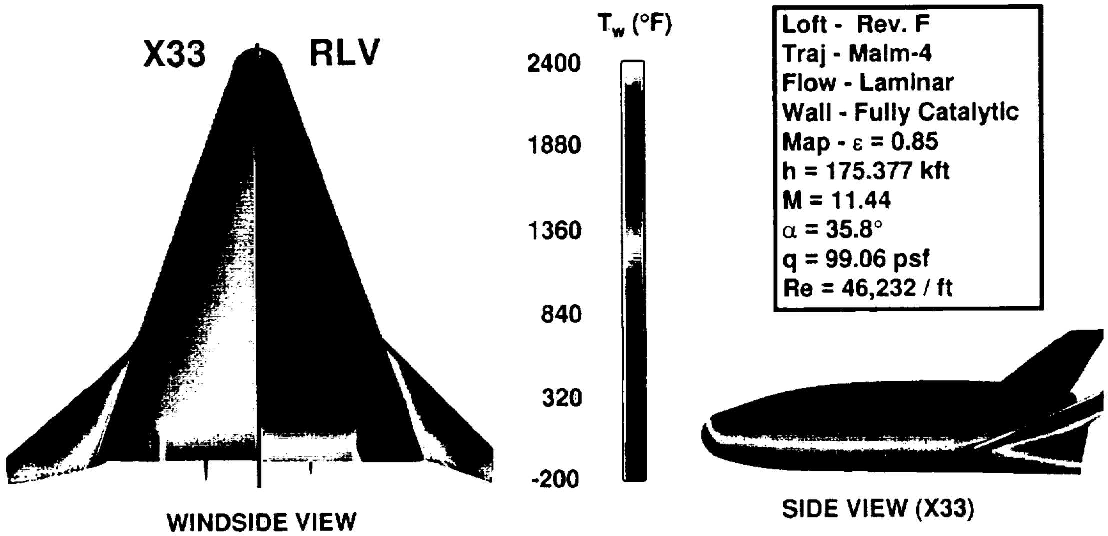


Figure 1

- Provided HAVOC generated aerothermal databases for design and all released flight test trajectories using GASP solutions as benchmarks.

- From the GASP database, developed approximate correlations to predict surface catalytic heating. The correlations have been incorporated in the analysis tailoring trajectories to meet program Real Gas flight test objectives.

- Assessed, computationally, the local effects of metallic panel bowing by applying coupled CFD aerothermal and FEM thermal response. Results revealed the maximum increase between unbowed and bowed panels is 100°F.

- Also conducted a local parametric study of the effect on heating of shingle and bulb seals. Amplification heating factors have been provided to the TPS team.

- Simulated high-enthalpy arcjet using the GASP CFD methodology (with some changes in the chemistry model). A comparison with experimental data for a typical metallic TPS panel test condition is presented in Figure 2. Comparisons like these and those of available ground and flight tests, allow assessing the uncertainty and thus accurately understanding the design margins that enable the RLV design.

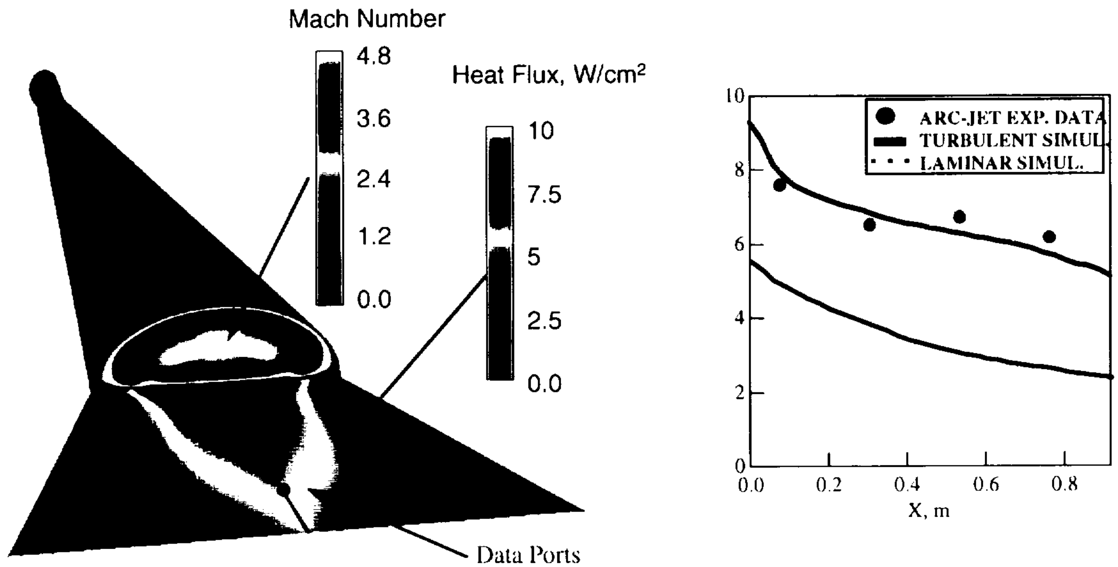


Figure 2

- Documented the aerothermal environment process, for X-33 design in four AIAA papers, which were presented at the session co-chaired by the LMSW Aerothermodynamics Lead.

- Provided an uncertainty analysis of the current aerothermal methodology. Figure 3 compares surface heating from the high fidelity GASP CFD solution with that from the fast HAVOC engineering, at peak TPS design heating. The maximum difference is 35°F.

Loft: Rev.F
Trajectory: Malm-4
Time: 353 sec
Altitude: 175,377 ft
Mach #: 11.44
Attitude: 35.8°
Reynolds #: 46,232/ft
Dyn.Pressure: 99 psf

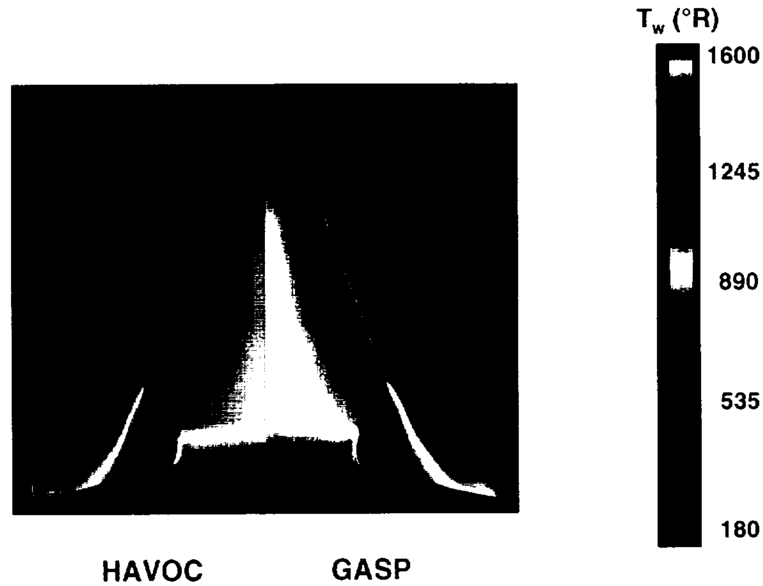


Figure 3

TPS ANALYSIS AND VERIFICATION

- Completed detailed 3-D FEM analysis of local regions near the LOX and LH_2 tanks. See Figure 4.

Finite Element Model of TPS and Support Structure Detailed Model of Rene 41 Rosette

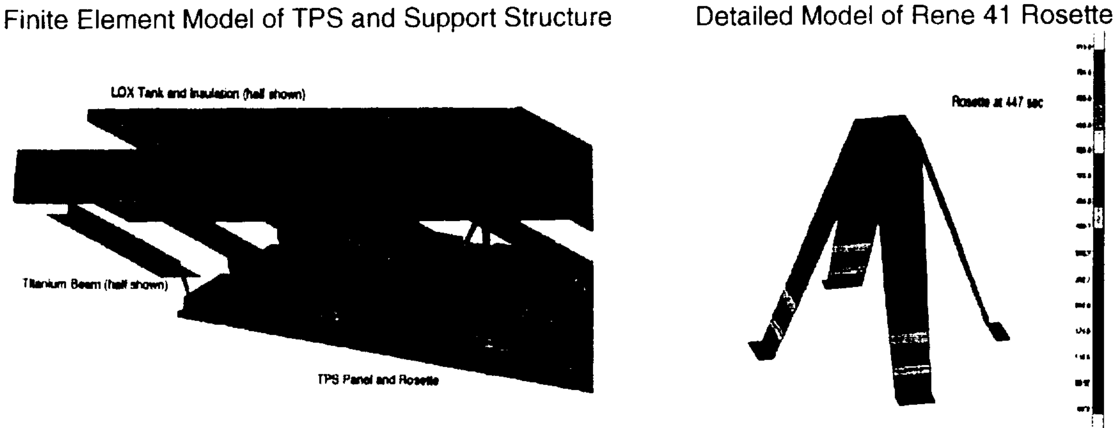


Figure 4

- Completed pre-test FEM analysis of Combined Environments Test. The tests are scheduled to begin at MSFC in April.
- Provided independent HAVOC TPS sizing, including detailed analysis of canted fin.
- Maintained/updated web-based X-33 Thermal Database.
- Provided refined design environments for leeward TPS qual testing.

TPS DESIGN AND QUAL TESTING

- Supported BF Goodrich/Riverside's realignment by adding design and qual responsibilities for three TPS areas

  1) AFRSI-2500 blanket on leeward canted fin. Figure 5 shows a photograph of the test article.
    - Demonstrated by analysis that baseline design still acceptable for Rev F loft
    - Defined qual environments/tests/conditions
    - Completed arcjet testing
    - F-15 tests scheduled for early May
    - Progressive Wave Tube (PWT) vibro-acoustic test in May

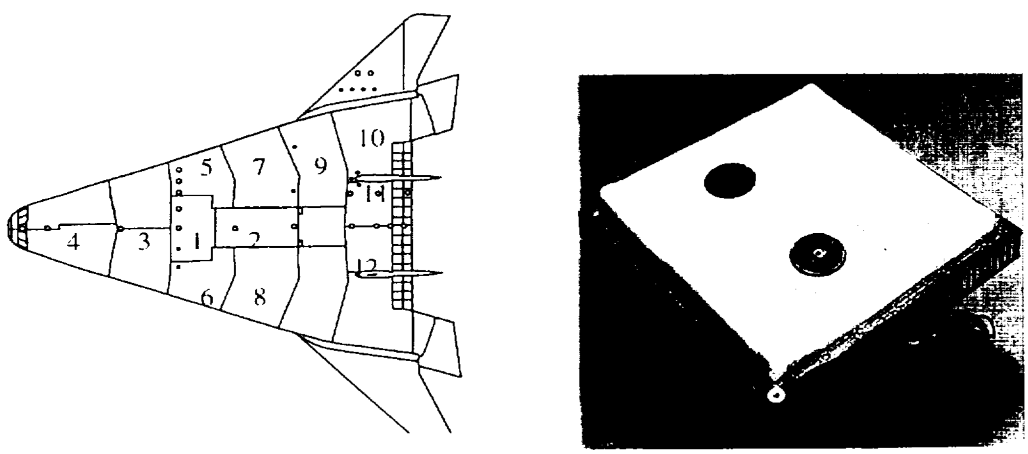


Figure 5

2) Flight Test Instrumentation (FTI) Islands for blanket TPS. Also shown in Figure 5 are two FTI islands.
- Completed design/downselect with developmental arcjet and PWT tests
- F-15 tests scheduled for early May
- PWT vibro-acoustic test in May
- Fabrication to begin in May
- Initiate delivery to BFG in July

3) DurAFRSI as potential TPS transition seal
- Completed arcjet testing
- F-15 tests scheduled for early May
- PWT tests scheduled in May
- High Temperature Tunnel tests scheduled in May

TPS SURFACE CHARACTERIZATION

- Characterized/documented 20 X-33 TPS/coatings
- Developed plan for Surface Catalysis Flight Experiment as part of Real Gas Flight test objective
- Completed pre-flight GASP CFD predictions, such as the one presented in Figure 6
- Beginning ground test characterization of potential RLV coatings

WINDWARD CENTERLINE TEMPERATURE
DISTRIBUTION
X33 (Rev.F) Peak Heating Malmstrom-4 Trajectory

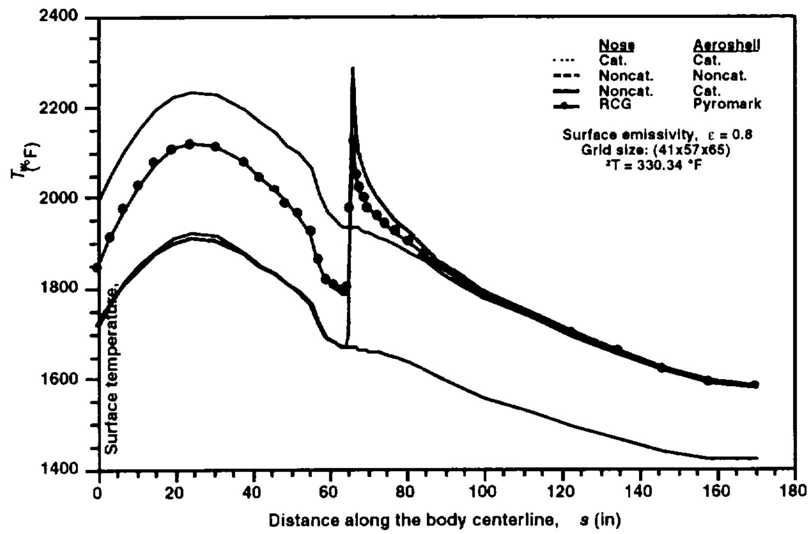
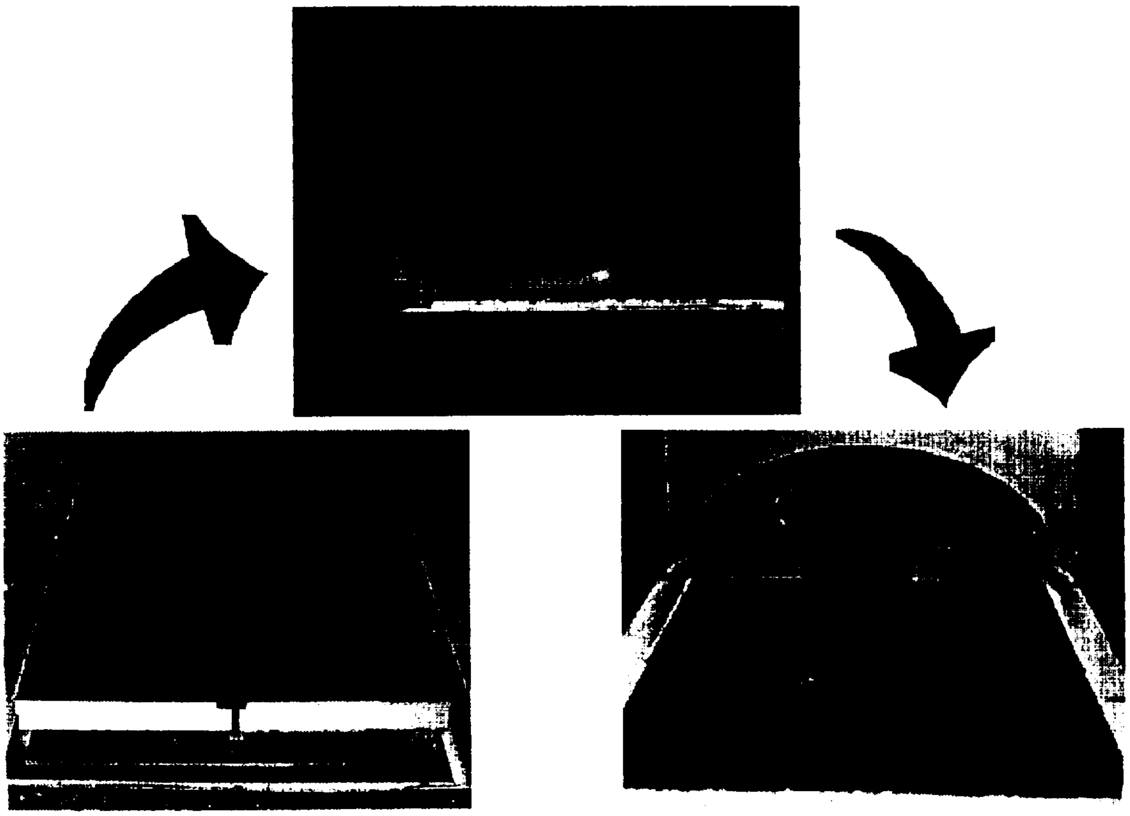


Figure 6

TPS ARCJET TESTING

- Completed 45 weeks of Arcjet Testing. Figure 7 shows the hot plasma simulating reentry heating over a metallic TPS panel coated with PyroMark 2500
- Completed design of special plenum box to support metallic seal leakage measurements; fab-checkout to be completed in June

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



Pre-Test **Post-Test**

Ames IHF Arcjet test of a production Inco 617 metallic panel with Pyromark-2500 coating.

Conditions: $T_w \approx 1650°F$, $q_w \approx 10$ Btu/ft^{2}sec, Pt = 49 psia, Duration = 150 sec

Figure 7. TPS Design Verification Test

FLIGHT SOFTWARE INDEPENDENT VERIFICATION

- Reviewed GN&C Design Description Document (Rev G) and identified 182 issues that are being resolved
- Provided preliminary version of Build 3 requirements traceability matrix to V&V team
- Developed Access Database tool that facilitates software design interface analysis

RLV SUPPORT

Aerothermodynamics and TPS Analysis

- Delivered a preliminary HAVOC aerothermal database for 3C VentureStar preliminary design

WIND TUNNEL TESTING

- Met with LMSW Aero Lead and secured 7'x10' test window in November