



X-33 Flight Operations Center

p287



ANNUAL PERFORMANCE REPORT

April 1, 1998 - March 31, 1999

Lockheed Martin Skunk Works
Cooperative Agreement NCC8-115





Forward

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.

With the dedication of the launch site, and continuing excellence in technological achievement, the third year of the Cooperative Agreement has been one of outstanding accomplishment and excitement.

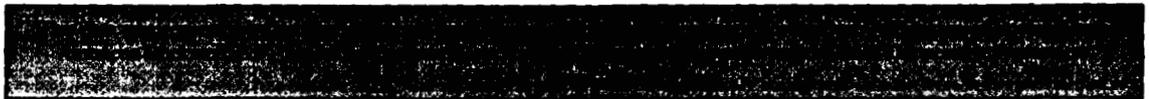
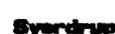




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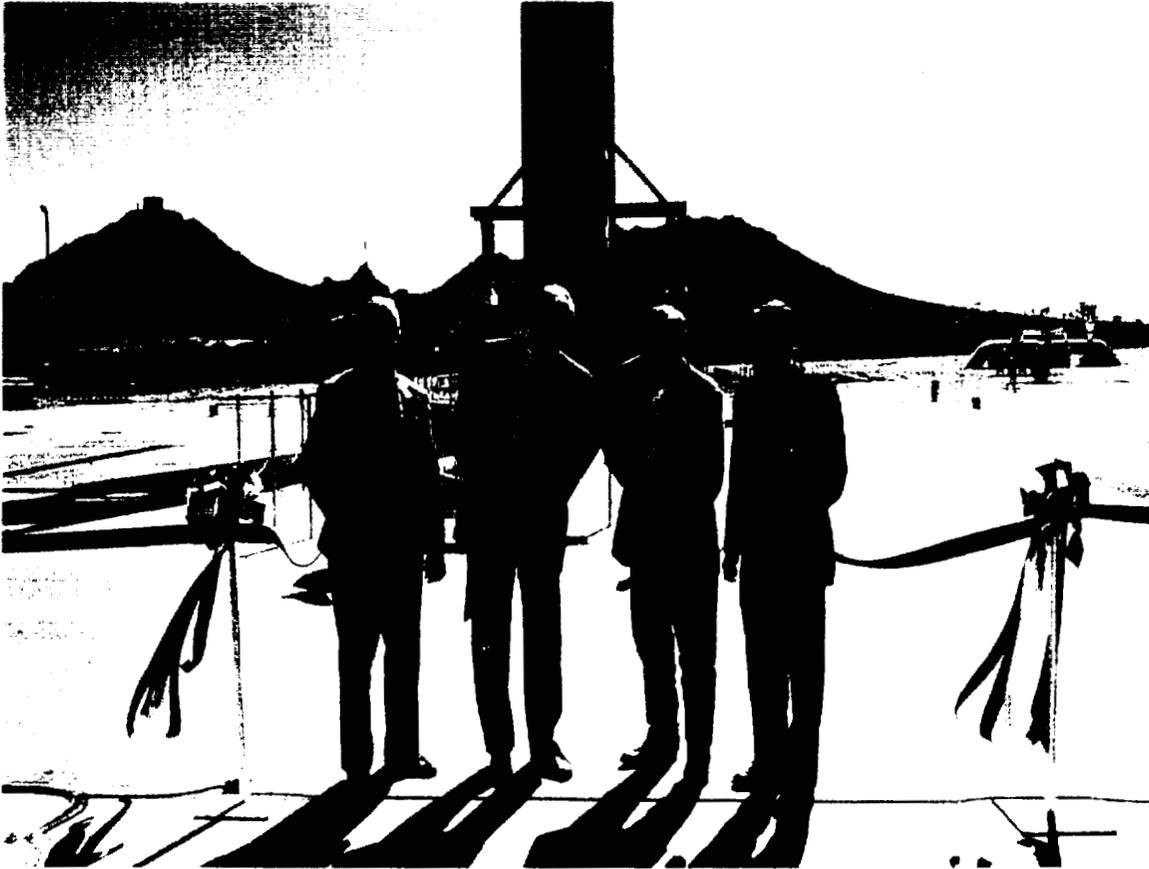




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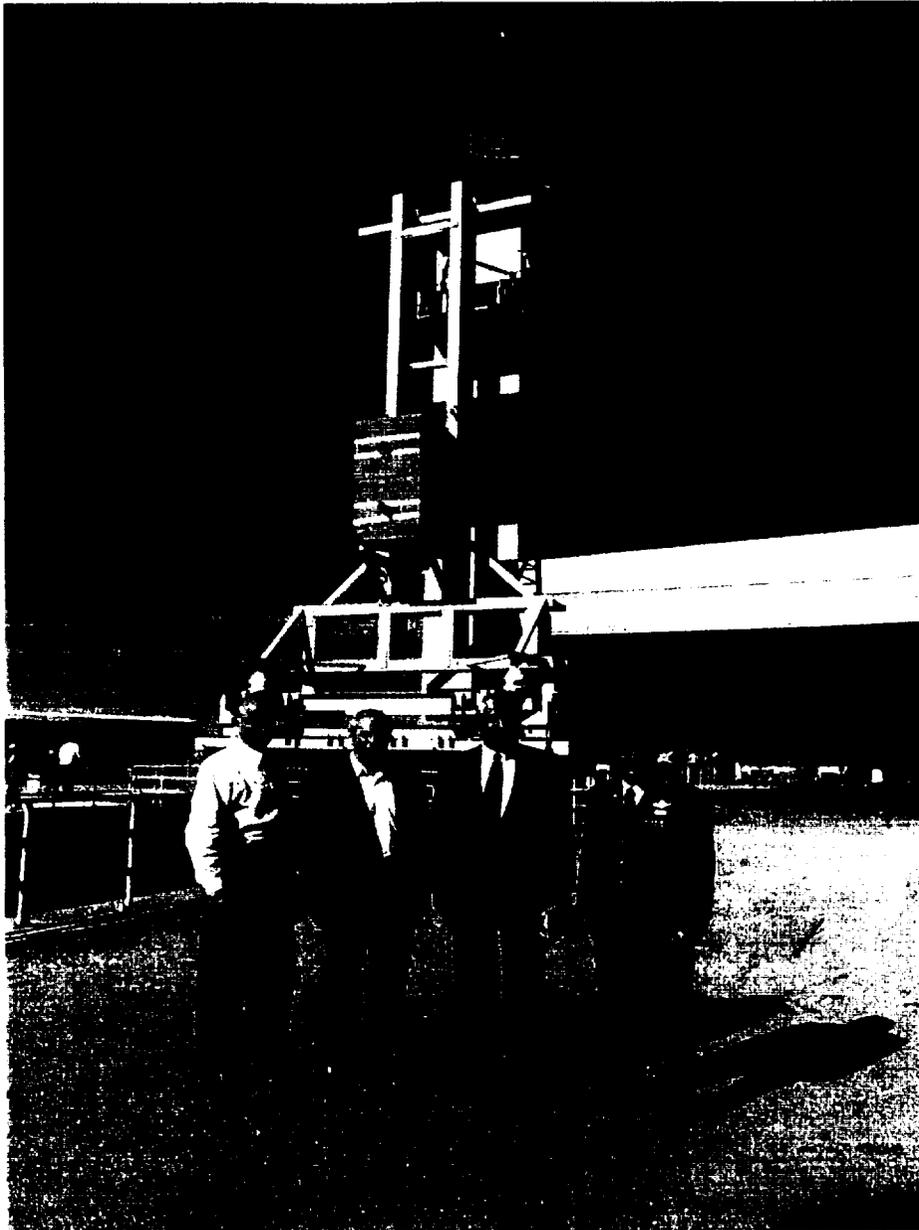
X-33 Flight Operations Center Dedication



Pictured from left: Jerry Rising, President of VentureStar™ LLC (A Lockheed Martin Company), Jack Gordon, President of Lockheed Martin Skunk Works, Daniel Goldin, NASA Administrator, Major General Richard V. Reynolds, Commander of Air Force Flight Test Center.



X-33 Flight Operations Center Dedication



Pictured from left: Congressman Buck McKeon, California 25th District Representative, Dan Goldin, NASA Administrator, Jack Gordon, President of Lockheed Martin Skunk Works, Major General Richard V. Reynolds, Commander of Air Force Flight Test Center.





Lockheed Martin Skunk Works

Single Stage to Orbit / Reusable Launch Vehicle

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Vehicle Development

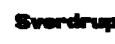
Design

Configuration optimization completed this year as LMSW demonstrated the benefit of a partially protruding faired payload to produce a vehicle with higher propellant mass fraction. To validate the parametric database used in developing this configuration, a comprehensive structural and systems design and analysis was completed. The lessons learned from the X-33 Technology Demonstrator program have been incorporated into the latest RLV design, including a uniform TPS interface to the airframe, elimination of honeycomb core from cryogenic tanks, and dual purpose/redundant structural load paths throughout.

Detail structural design and analyses completed on this configuration demonstrated a 10.7% improvement in vehicle propellant packing efficiency. A fully modular wind tunnel test program is now underway to validate the flying qualities of this vehicle.

Graphite composite structure is essential to achieving the high propellant mass fraction required for a single-stage-to-orbit vehicle. All but the aerosurfaces (canted fin/vertical fin/body flap) have been configured using graphite composites, and reflect structural optimization studies from NASA Langley Research Center, and LMSW's own optimization work. The aerosurfaces were optimized as titanium hot structures. Over 25 separate trade studies were completed to verify the optimum load path and lightweight structure used in the current baseline RLV design.

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Propulsion

Design and flight sciences work closely with Rocketdyne to develop the propulsion system design for the RLV. Rocketdyne delivered an engine deck to model the RLV propulsion system performance. The model was used to support trajectory analysis in optimizing the vehicle performance, as well as Trade studies on engine area ratio, nozzle length, mixture ratio, number of engines, and inlet pressure to the pumps were performed on the main propulsion system.

Orbital maneuvering and reaction control systems were analyzed to select an optimum propellant combination. The baseline approach of performing orbital maneuvers using the main propulsion system was replaced with a separate orbital maneuvering system using liquid hydrogen and liquid oxygen. The baseline reaction control system was changed from a gas blowdown hydrogen and oxygen system to a liquid oxygen and ethanol system.

Flight Sciences

Several candidate trajectories were analyzed to define RLV external heating characteristics. Rapid temperature transients are experienced early in reentry and ascent. TPS stress indicators are driven by the time derivatives of dynamic pressure and heating rate. Trajectory and atmospheric dispersions appear to have a greater impact than boundary layer transition dispersions. Non-continuum heating effects are significant for TPS and trajectory design.

Results of the external heating studies were used to assess internal heating characteristics. A hot structure approach can be used for the leeward side of the canted fins. The impact of plume radiation heating in the base region is mitigated with low absorptivity coatings. Heat flux into vehicle structure after landing is not significant. The initial temperature gradient experienced by the TPS is high due to on-orbit environment. TPS stress and creep indicators were incorporated into the trajectory design process. A strategy for minimizing the integrated product of dynamic pressure and heat rate was

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developed to keep TPS stress indicators within an acceptable range. These trajectories keep the vehicle higher in the atmosphere during the early reentry phase.

Vehicle configurations and were analyzed for control characteristics along candidate trajectories. Landing studies indicate vehicle drag to weight ratio should be no larger than 0.5 for landing. Control analysis indicates aerodynamic instability levels greater than 2% will be difficult to accommodate during any phase of flight.

Several candidate vehicle configurations were analyzed for aerodynamic and stability characteristics. Semi-submerged payloads can be incorporated without introducing large drag penalties. Additional vertical tail volume is required for semi-submerged payload configurations. Additional canted fin incidence is required for semi-submerged payload configurations during transonic flight. Canted fin position and orientation is significant to hypersonic lateral-directional stability. Body shape provides a substantial contribution to hypersonic longitudinal and lateral-directional stability.

Avionics

During the past year, the avionics effort concentrated on refinement of the system requirements and the allocation of these requirements to the avionics, software and health management elements. Additional effort was directed toward the development of candidate avionics system architectures and the development of an accurate baseline for evaluating changes to the configuration (weight, power, cooling, performance and cost). Lessons learned from the X-33 as well as technical discussions with the supporting NASA Centers helped to define and refine this baseline.

The RLV baseline architecture was established and submitted for review. Primary areas of concern included the operational costs associated with the communications functions, operations around the International Space Station (ISS) and the weight and complexity penalties associated with vehicle health management.



An evaluation of communication requirements and commercially available capabilities was completed. Although there are several emerging communications capabilities that might meet the needs of the program, only TDRSS meets all of the VentureStar™ requirements. Primarily used to support Government programs, TDRSS can also be used to support commercial launches. Availability, technical support, experience with the commercial launch market and use by the ISS all favor VentureStar™'s use of this capability. Additionally, the availability of NASA certified vehicle communications equipment from multiple sources further support the use of TDRSS.

Early technical interface meetings with the Network Support Group (NSG) by monitoring the communications efforts for the European Autonomous Transfer Vehicle and Japanese HTV programs began. This early effort will minimize communications interface issues for the RLV when performing space station support in conjunction with these vehicles.

Initial discussions with ISS Program personnel related to rendezvous and docking started. These discussions in turn led to the first RLV/ISS Technical Interchange Meeting (TIM) at JSC. Primary emphasis of these early meetings and the RLV/ISS TIM was to ensure that VentureStar™ development and planning incorporated the necessary technical capabilities and interfaces for ISS integration. To date, discussions have resulted in an avionics configuration that is compatible with ISS rendezvous and docking requirements.

Vehicle health management data collection and processing requirements were integrated into the avionics architecture to help minimize the weight and cost impacts. Began Working group meetings and technical discussions with both system developers and NASA health management specialists are under way to refine requirements and capabilities for incorporation into the vehicle. Initial health monitoring databases for the engines, thermal protection system, propellant tanks and vehicle structure were defined.

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Subsystems

A baseline system architecture was defined for the RLV vehicle subsystems. A preliminary vehicle subsystem layout and integration into the structural arrangement was accomplished. The layouts defined the vehicle system locations, structural support locations and access requirements. Various trade studies have been completed which aided in the downselect of the system designs.

The vehicle electrical subsystem is based upon a 120Vdc electrical power system with local power conversion to meet various user requirements. Electrical power generation is provided by three fuel cells utilizing hydrogen and oxygen fuel. Each fuel cell will generate 120Vdc power at a maximum output of 15Kw. A backup system with batteries is incorporated to supply power to the essential control systems. The electrical distribution system for RLV is divided into multiple distribution centers to minimize wiring throughout the vehicle. Three primary voltage distribution centers are connected to the fuel cells. Each primary distribution center provides power to multiple secondary distribution centers located throughout the vehicle. Power conversion is accomplished at the secondary distribution centers to power the various subsystems. This approach was chosen to minimize conversion losses and optimize ships wiring to reduce overall system weight.

The flight control actuation system will operate the aerodynamic control surfaces through a single actuator for the rudders and inboard & outboard elevons. The body flaps are operated through a single primary actuator with a secondary actuator to provide load assist during high demand. The FCAS actuators are a linear ballscrew design driven by two motors that are speed summed.

The landing gear system will provide vehicle support, steering and antiskid braking for the RLV. The landing gear configuration is a dual nose wheel assembly and two four wheel bogie main assemblies. Structural loading into the landing gear is based upon a 21/79% weight distribution between the nose and main gear respectively.

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The environmental control system provides the vehicle functions to control and monitor the internal environment of the RLV. The active thermal control system consist of redundant dual loop cooling circuits capable of collecting and rejecting 20kw during ascent and entry and 15kw while on orbit. The purge and vent system provides means to maintain pressure gradients within the aeroshell during vehicle ground processing and flight regimes. The vehicle internal environment is also monitored for hazardous gases, smoke and fire detection.

Operations Development

Vehicle Maintenance & Processing

The Operations Development group completed several critical trade studies this year. Chief among these were the studies on a translating vs. fixed maintenance shelter and horizontal vs. vertical processing / integration of payloads. The translating shelter concept being demonstrated by the X-33 program was verified as the RLV program baseline. As the X-33 program transitions from development to operations, it will provide valuable data to further refine the RLV operations approach. In addition, Spaceport selection and the amount of available infrastructure may cause translating shelter concept refinement because of the potential change in baseline cost assumptions.

Horizontal processing and integration of payloads was found to be superior from an overall perspective. This approach required fewer move operations, had greater accessibility and potentially provided a lower facility cost. The operations recommendation, however, was for horizontal or vertical processing of payloads, because certain payloads (part of the projected market) could only be fueled vertically. The payload processing facility baseline was updated to allow flexibility in payload orientation. All payloads will be integrated with the RLV horizontally. Vertical integration was not selected because it required costly development of specialized launch site equipment.

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Informal interface reviews were held with each of the development elements to define their baseline design and form a path to the System Design Review (SDR). The “wall walks” highlighted interfaces between the vehicle, mission module, and ground elements that required special attention in order to be ready for SDR. A closed loop system was implemented to track issues and regular follow-up activities are ongoing. Many have been closed, some are awaiting X-33 test data for resolution and others are in various stages of study.

The Baseline Operations Analysis Document originally written in 1995 stated that there would be “no planned depot level maintenance for the flight vehicle.” Work continued over the last year to achieve this goal. Depot level maintenance activities have been divided into manageable buckets and are now distributed over the normal maintenance profile. All required maintenance work is still accomplished, but without the vehicle being taken out of service for an extended period. This dramatically improved vehicle availability. Work allocations have been defined for RLV based on allocated and predicted maintenance workloads for X-33. Several items have been extrapolated to the scale and complexity of the RLV. Head count to accomplish the work and job classifications for 47 hands-on technicians were defined.

Operations Development has expanded the RLV functional flow to encompass the complete mission requirements including mission planning, mission module reconfiguration, payload processing, vehicle processing, ground system turnaround and ground tracking / communication. An RLV computer simulation has been expanded to size the payload facility and determine mission module quantity. Based on current assumptions, four non-hazardous payload processing cells, two hazardous cells for fueling and at least four mission modules will be necessary to meet operational requirements.

Ground Data & Control System

The Ground Data and Control System (GDACS) provides the ground based computing resources to complete the RLV mission. System, Ground, Flight

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requirements were analyzed, and requirements that drive the GDCS design were identified. Preliminary analysis indicates five major support services are required:

1. VentureStar™ (Control System - provides real-time display and control of the vehicle, associated ground equipment, mission modules and payloads for all mission phases and provides a control link to external customers
2. Data Analysis and System Health - stores vehicle / ground / payload data, provides near-real-time / archived data access and supports analysis and maintenance action monitoring functions
3. Mission Planning - supports requirements definition, mission buildup, flight planning, unique mission software and vehicle mission contingencies
4. Maintenance and Operations Support Service - provides ground planning, scheduling, logistics, component histories, configuration management and operational procedure controls required for ground and mission operations
5. Process Control Network - provides office and business services including word processing, spreadsheet, requirement tracking, web access tools, data storage and external connectivity, etc.

Although each service can operate independently, the power of the Ground Data and Control System is a direct result of designing the pieces to work with each other. The integration of these services into a single system, along with a robust vehicle and ground system design, enables dramatic processing efficiencies.

GDCS requirements are influenced by the VentureStar™ (System Management and Maintenance Management (SM3) strategy and unified ground-vehicle software architecture goal. The SM3 strategy, drafted in late 1998, allocates roles for system control and maintenance support activities. The strategy shapes the interactions between the control system, maintenance and data analysis services, as well as interaction between ground and vehicle systems. High-level GDCS requirements are being drafted, using the input from all sources (e.g., high-level RLV requirements,



operations concepts / requirements, strategies). The GDCS requirements, under development, do not force a single design solution and define requirements from a customer/user perspective. Considerable effort is being expended to capture the rationale behind each requirement.

Interconnectivity and external interfaces between the services, launch assets (vehicle, payload, mission module), Spaceport and customers/vendors have been identified. Interfaces allow the partitioning of services and enables concurrent development. In addition to interfaces, system level requirements drive the development of two additional functions, the Portable Payload Tester (PPT) and the Site-Based Workstation (SBW). The PPT enables the customer to interface with a simulated vehicle at the customer production plant and the Spaceport payload processing facility. The PPT will be compatible with the VentureStar™ (Control System, enables rapid processing and assists in the identification of payload-vehicle integration issues early. Site-Based Workstations are located at the launch complex, support complex and payload processing areas. The Site-Based Workstations increase workforce efficiency by allowing the control of end-items and subsystems as close to the end-item as possible. Local control capability is common throughout industrial processes, but has been difficult to implement in existing launch control systems.

Certification & Licensing

The RLV will require government licensing in order to operate as a commercial launch vehicle. A certification and licensing working group meets regularly to develop a certification and licensing approach. The working group reviewed the currently available information on FAA launch licensing requirements and defined a program approach for Phase III in the VentureStar Certification and Licensing Approach Document. Both the AIAA and COMSTAC are working with the FAA to develop standards for RLV licensing. The working group is supporting these activities through attendance at AIAA and COMSTAC meetings, with white papers, and through direct briefings to the FAA.

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X-33 and RLV SYSTEM ENGINEERING

This report summarizes the System Engineering activities since the last report in March 1998. System Engineering is responsible for the following areas of the X-33 and RLV programs.

- X-33 Independent Verification and Validation of Flight Software Elements
- X-33 and RLV Requirements, Requirements Traceability, and Requirements Verification
- X-33 and RLV Configuration Management
- X-33 and RLV Master Equipment List
- X-33 and RLV Risk Management
- RLV Customer Technical Point of Contact
- RLV Upper Stage Requirements and Technical Point of Contact

The Independent Verification and Validation of X-33 flight critical software was established under Lockheed Martin Skunk Works System Engineering at NASA's IV&V Center of Excellence in Fairfield, West Virginia. The IV&V team has completed numerous verification analyzes, including a complete review of the Guidance, Navigation and Control (GN&C) Design Description Document (DDD) as well as, an interface verification analysis on Flight Manager (FM) and the Abort Manager/Performance Monitor (AM/PM) portions of Mission Manager (MM). To assist the X-33 Program in the generation of interface design documentation, IV&V generated interface tables for all external FM and AM/PM interfaces, based on the DDD.

During the review of the X-33 documentation and simulation model development, the documentation is graded on its maturity and stability, a risk analysis performed, and problems reported through the X-33 Problem Reporting System. Each problem reported is tracked to closure within this system as well as, the IV&V problem tracking and verification system.

To date, IV&V has identified and verified closure on a majority of the 245 Problem Report Issues in the Mission Manager / Communication Manager, 733 Problem Report Issues in the Flight Manager / GNC Design Description

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Document, and 16 Problem Report Issues in the Engine Controller. IV&V has also completed 4 GNC DDD Maturity Assessments and an Integrated Test Facility (ITF) Assessment. Simulation model validation was completed on the Atmosphere Model. Plans were completed for Flight Software Certification and Post Flight Analysis. IV&V is preparing for build 5 flight software testing on May 5, 1999.

The X-33 Compliance Matrix provides traceability of the X-33 requirements from the System Requirements Document to each major sub-system element. Sub-elements are traced by each team member down to the component level. Verification of each requirement is established by test, demonstration, analysis, or inspection. The method and satisfactory completion of the verified requirement is placed into the Compliance Matrix, thus documenting the verification of the system and each of its sub-elements.

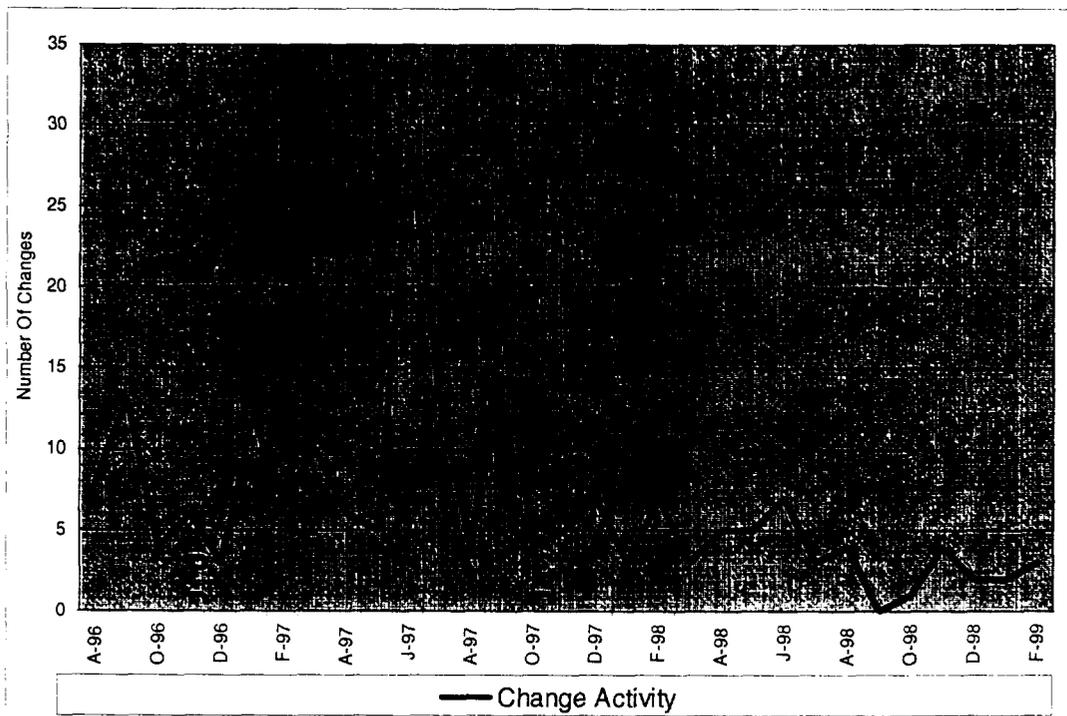
X-33's initial Compliance Matrix was completed in September 1998 and evaluations of requirement revisions are being incorporated at this time.

In addition, the X-33 team members will provide Certificates of Compliance for 27 vehicle hardware configuration items (HWCI), 8 ground support system (GSS) HWCI, and 27 vehicle and GSS software configuration items (SWCI).

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X-33 Configuration Management process has continued to perform as described in last year's report. The number of change requests have been kept to a minimum after the X-33 CDR and additional measures are being taken to reduce the X-33 change activity now that the majority of X-33 components are being fabricated or completing qualification testing. A chart of the X-33 change activity is shown below. Note that each change request processed may affect several documents or drawings.



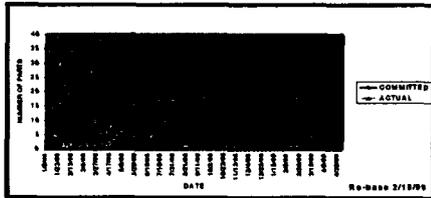
X-33 Change Activity

X-33 Vehicle Master Equipment List (MEL) was established, as reported last year. The Master Equipment List clearly identifies vehicle components or sub-systems to be delivered by team member to the X-33 manufacturing facility, the Integrated Test Facility, or other team members' facilities.

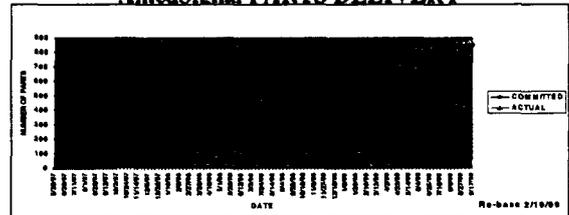


Refinement in the reporting of the promised delivery dates and the actual delivery dates was accomplished by creating a graphical representation of the MEL. The MEL charts are updated weekly and reported during the Friday morning engineering status meeting and the weekly program review meetings.

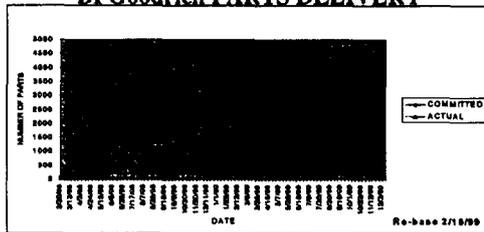
AEROJET PARTS DELIVERY



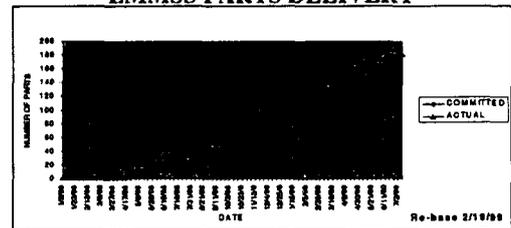
AlliedSignal PARTS DELIVERY



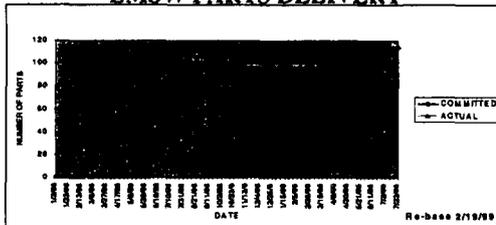
BFGoodrich PARTS DELIVERY



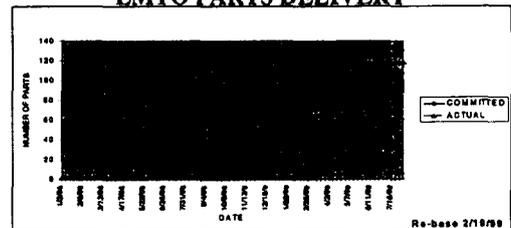
LMSS PARTS DELIVERY



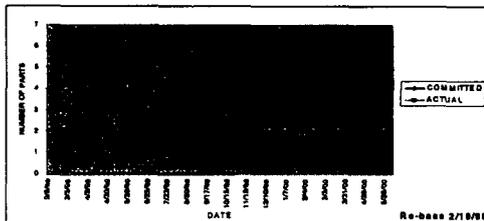
LMSW PARTS DELIVERY



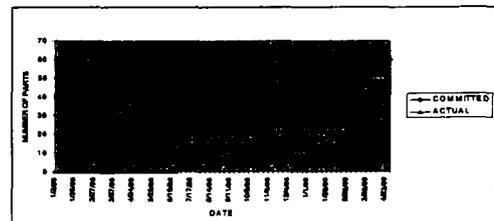
LMTO PARTS DELIVERY



RNAP (DOCKET/DVNE) PARTS DELIVERY



LMCN (SANDERS) PARTS DELIVERY



Master Equipment List Status Charts



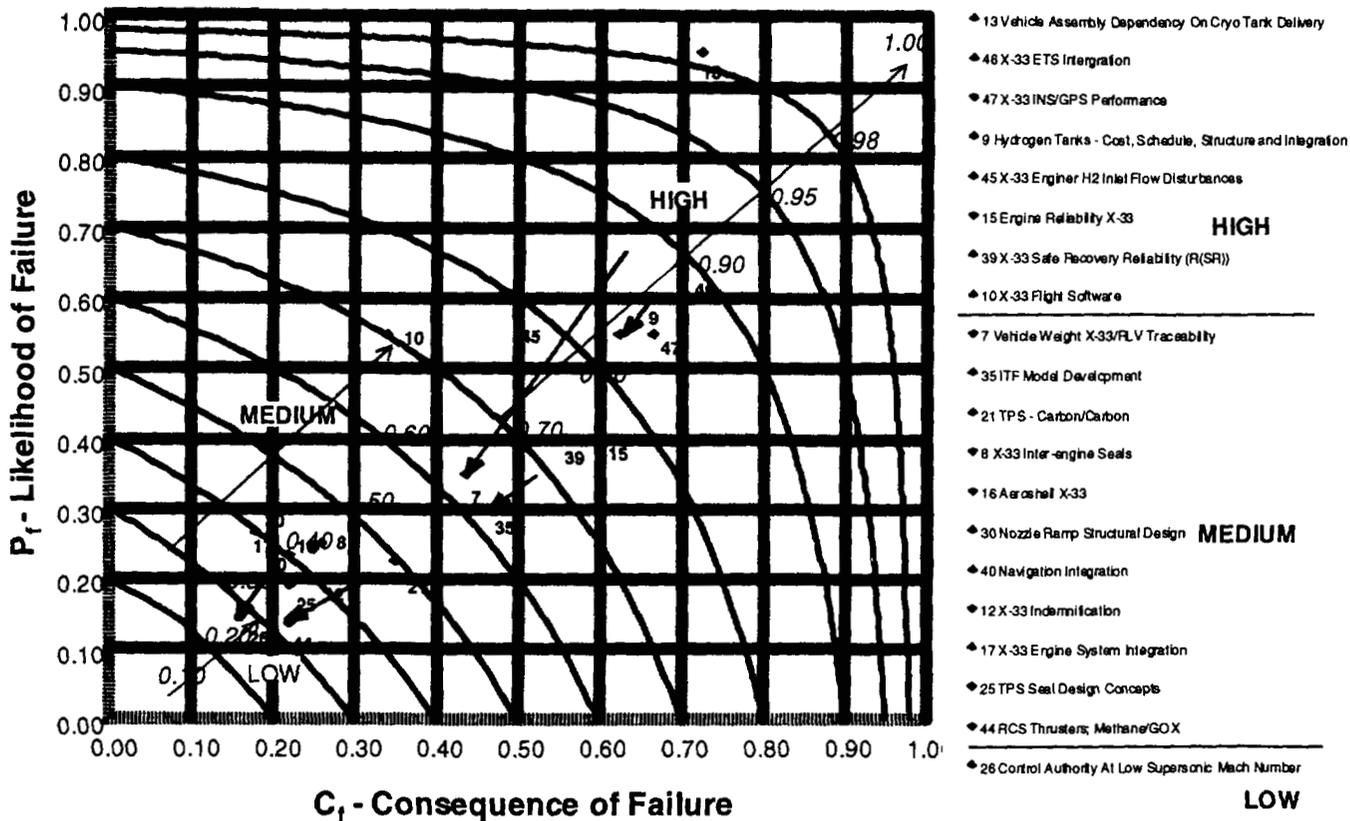


Risk Management

Risk Management continues to play an important part in identifying and reducing potential impacts to the program. A standard approach used by government and industry was implemented early in the X-33 Program and established at the beginning of the RLV Program. Refinements in the method of presenting risk data to management has allowed conveyance of mitigation plans, monitoring those plans, and establishing the accomplishments or setbacks against the mitigation plans. The Program Risk Board, chaired by the Program Manager, reviews and approves all risk actions. System Engineering's Risk Manager provides monthly updates and coordinates the quarterly Risk Management Board meeting. The January X-33 risk iso-chart is shown on the next page to illustrate the graphical summary of the risk items and any movement since the last risk meeting. Dark (green) arrows show the movement of a risk item based on meeting its mitigation plan objective during this time period. Red arrows are used to show increases in risk since the last meeting.

This data was generated by Lockheed Martin Skunk Works, Allied Signal Aerospace, Rockwell International, American Rockwell, B.F. Goodrich Aerospace, Rohr, Inc. and Sverdrup Corporation under NASA Cooperative Agreement NCC3-115, dated 2 July 1996





The latest X-33 Risk Management Board was held on January 26, 1999 and the RLV Risk Management Board was held September 30, 1998. Realignment of X-33 and RLV programs has necessitated rescheduling of the next RLV Risk Management Board meeting to the second quarter of 1999. The next X-33 Risk Management Board meeting will continue as scheduled in late March 1999.





In addition to the management of risks and their mitigation plans, 106 X-33 Technical Performance Measures (TPM's) are being tracked. TPM's cover primary technical performance areas for the vehicle, ground systems, and operations requirements. Examples include "rudder resolution", "touch labor crew", and "rapid turn around time." TPM's are graded as "okay" if their value meets or is better than the threshold requirement. Otherwise the TPM is graded as "Red." Aggressive management of the TPM's has resulted in 95 TPM's as okay (11 Red) in January 1999 and 100 TPM's okay (6 Red) in February 1999. Action plans were instituted in to bring all remaining TPM's to okay status at the completion of qualification testing in September 1999.

RLV Systems Engineering over the past year has focused on defining and managing requirements for the RLV system. Several key accomplishments are described below.

Formal and informal (Table-top) requirement reviews were held with representatives from all team members, NASA, and invited experts from around the country. A list of these reviews is shown below.

System Requirements Review -- Completed March 3, 1998
*VentureStar*TM Market and Business Requirements Defined in the
*VentureStar*TM System Requirements Document

Table Top Review of *VentureStar*TM System Requirements Document --
 Completed June 11, 1998
 Completion of action items generated at SRR and updated with
 additional Marketing and Business data

Table Top Review of Flight Segment Requirements Document --
 Completed June 17 & 18, 1998

Table Top Review of Ground Segment Requirements Document --
 Completed June 22 & 23, 1998

Draft of Requirements Management Procedure (DOORS) -- For Review
 July 8, 1998

This data was generated by Lockheed Martin, Boeing, Northrop Grumman, Rockwell International, and the Space Research and Technology Division of Boeing North America, American Rockwell, B.F. Goodrich Aerospace, and Sverdrup Corporation under NASA Cooperative Agreement # NCC1-57000, dated 2/11/96.





Review of *VentureStar*TM System Architecture Diagram and Specification Tree -- Completed July 13, 1998, Updating with higher fidelity for System Design Review in 1999

System Architecture Review/Optimized Design Review -- Completed July 29 & 30, 1998

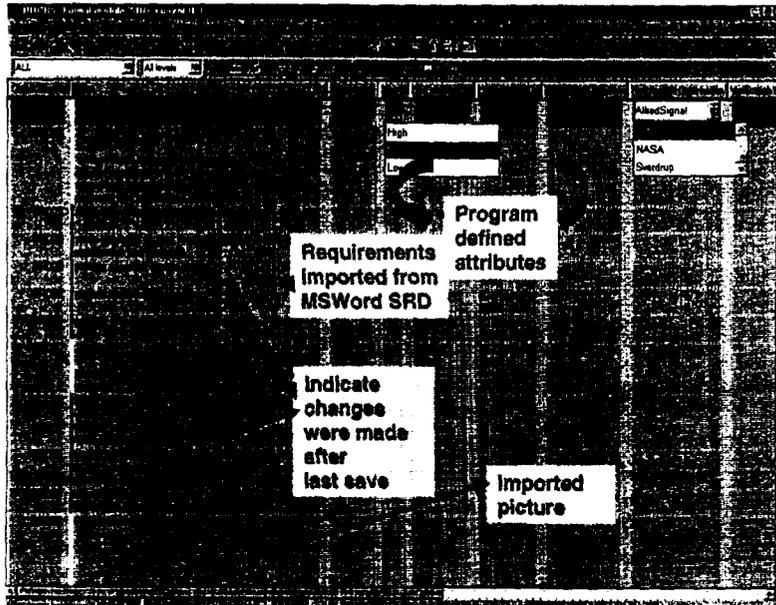
In addition to the reviews, System Engineering continued to support Marketing, Business Development, and the Program Office by participating and coordinating selected studies and analyzes. Included in this category was interface meetings with the International Space Station's Visiting Vehicle group, multiple commercial satellite customers, and a study on the potential impacts of Johnson Space Center's document JSC 28354 "Human Rating Requirements." A Tiger Team was initiated to study the potential impacts to the *VentureStar*TM Program of JSC 28354 "Human Rating Requirements" with support from LaRC and SAIC (Contracted through NASA). The study was completed in September 1998 and the results reviewed with NASA (Sam Armstrong) on October 7, 1998. The study found agreement with the guiding principles contained within the JSC 28354 Human Rating Requirements document and found no major impacts to the objectives of Commercial *VentureStar*TM Missions. Risks were found in the document concerning the nebulous nature of some stated requirements, the proving or demonstrating the quantitative Human Safety Requirements, and in providing the document to the FAA as a guide for regulations of humans in commercial space endeavors. After conferring with document authors at JSC, the authors stated they had communicated to the FAA the fact that the requirements were goals to strive for, not ready for incorporation into regulations. The greatest impact of these requirements would fall onto the design of an ISS Crew Module. A Phase A study was being conducted at LaRC for design concepts of an ISS Crew Module. The LaRC group, as part of our study team, had already been working to incorporate the JSC human rating requirements as part of their Phase A study and were in agreement with most of the goals for human safety. The areas which impacted the ISS Crew Module the most were requirements for the crew escape system to be

This data was generated by Lockheed Martin, Skunk Works, Allied Signal Aerospace, Rocketdyne, Ad Division of Boeing, American Rockwell, B. F. Goodrich Aerospace, and Sverdrup Corporation under NASA Cooperative Agreement NCC1-105, dated 2 July 1996

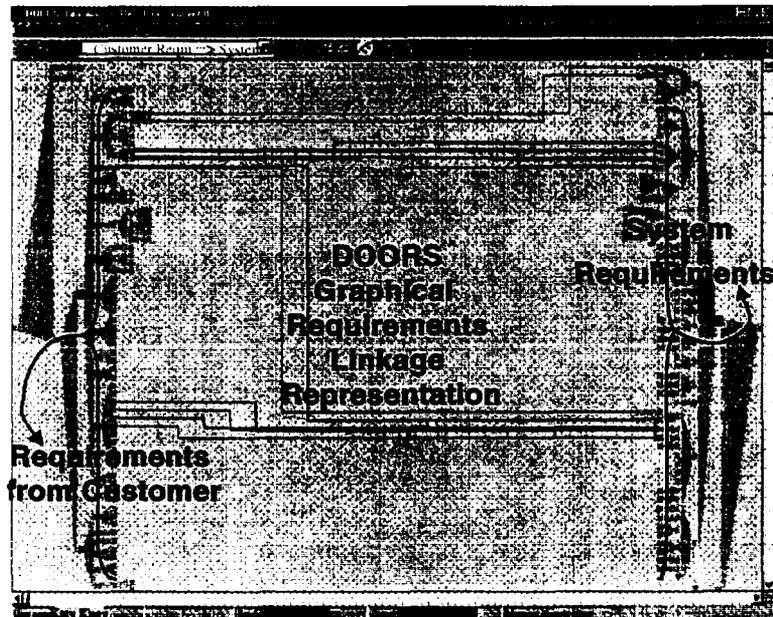


capable of saving the crew 99% of the time during all phases of operation from on the pad to vehicle recovery on the ground and in the definitions and capabilities implied with "human-in-the-loop" operation in conjunction with an autonomous operating vehicle.

Requirement management on the X-33 is accomplished using Microsoft Excel and Access database programs. With RLV, a new tool, named Dynamic Object Oriented Requirements System (DOORS), was selected. DOORS has an additional component called DOORS Net, which allows access to the requirements database through the Internet. DOORS allows the import of word processed documents, linkage to sub-system requirements, traceability matrices, graphical links, change histories, and change management. For RLV, DOORS is one of the requirements management tools chosen to effectively provide requirements baseline management and may include schedule, cost, and performance tracking to the system requirements. Examples of selected DOORS features and graphical capabilities are shown below.



DOORS Screen Format



DOORS Screen Format

System Engineering's requirements development and analyses led to the development of Upper Stage requirements suited to the RLV system. To further gain data on existing and proposed Upper Stage systems, a Request For Information (RFI) will be released for both domestic and international suppliers in 1999. Data from the RFI will provide the RLV Program with potential qualified Upper Stage suppliers.

In summary, 1998 has been an exciting year for X-33 and RLV System Engineering with the X-33 requirements beginning verification and the development of a robust set of RLV requirements.



Manufacturing

X-33 ASSEMBLY AND INTEGRATION

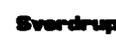
The X-33 has made very significant progress in all aspects of the manufacturing process. The tooling program is 95% complete, fabrication is nearing completion, and assembly is nearing the 50% complete point.

Tooling has delivered the majority of the assembly tools both internally and also to our partner B.F. Goodrich for carbon/carbon component assembly. This year the tools for all the flight controls have come on-line in production. We have also delivered the upper-inner tool to B.F. Goodrich's Riverside facility which is used for the drilling and trimming of the upper TPS panels. We have brought the associated upper outer TPS tool on-line at the Skunk Works assembly facility to build the mating sub-structure for the upper TPS panels. The remaining tooling tasks include delivery of the final portion of the canted fin leading edge, the fillet fairing, the nose cone, and the off-line TPS tool. The majority of these tools will be delivered by March of next year.

Fabrication and procurement effort is nearly complete at the Skunk Works. Over 6000 line items have been closed both the fabrication and procurement sides. Less than 310 and 150 line items remain in fabrication and procurement, respectively. All the key large machined titanium and composite components that tend to pace assembly and initiate fixture loading have been delivered.

LH² tank has had some setbacks but also has made very good progress. As of year's end all fabrication for the hydrogen tanks is now complete with the exception of two replacement lobe skins. Assembly of both tanks is progressing well. Tank 2 has completed all of its autoclave cure cycles (8) and is now in the process of getting three key finishing operations. These operations include thrust buster installation, insulation installation on the domes and sealing activities. Tank 1 experienced a set back with the failure of lobe skin 1 during one of the cures. We have since recovered from this failure which included the removal of both lobes 1 & 4 from this tank. The removal process is complete, and replacement lobes have been manufactured

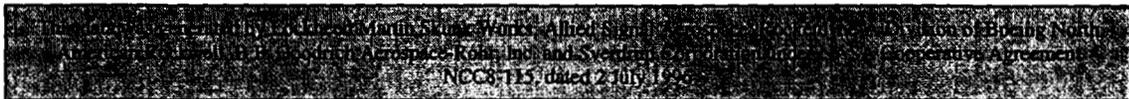
This data was generated by Lockheed Martin Skunk Works, AlliedSignal Aerospace, Rocketdyne A Division of Boeing, Northrop Grumman, American Rockwell, B.F. Goodrich Aerospace, Hughes Aircraft Company, and NASA Cooperative Agreement NCC1-103462 in 1999.





at Alliant's facility in Utah. We expect to have both of the tanks back to the Skunk Works by the middle of 1999.

Vehicle assembly is progressing well with all the flight controls now in assembly. These include the vertical stabilizers, rudders, canted fins, body flaps. The thrust structure is structurally complete. TPS sub-structure is complete in the area of the LOX tank and progressing well in the hydrogen tank areas. The nose landing gear structural box is now complete and installed. We also completed all of the truss tubes. We have also made significant progress on the installation of subsystems. Portions of all the systems are currently in work. These include nose and main gear hydraulic systems, active thermal control system, avionics bay inerting system, hazardous gas detection systems, reaction control system, air data system, purge and vent system, 1553 bus, fiber optic bus, 28 & 270 volt power, RS422, and instrumentation harnesses. Significant progress has also been made in instrumentation sensor installation.





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 day 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.

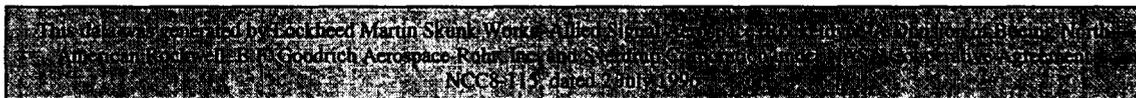
Ground Operations Flow Progress

While the basic Operations Flow remains intact, refinements in the 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. Recent site functionality checks have provided an opportunity to assess certain aspects of the turn around processing flow.

- The vehicle weight simulator has been mated and demated to the Rotating Launch Mount (RLM) twice. Each time the efficiency of the mate/demate operation improves. The last mate took approximately 3 hours, significantly less than last year's prediction of 7 hours.
- The translating shelter is fully operational. It has been moved many times in support of RLM checks taking 10 minutes to move from position to position. The Megadoors™ at the ends of the translating shelter have also been exercised on a daily basis.

Overland Transport

The overland transporter contractor competition resulted in selection of Contractor's Cargo Company to provide vehicle transportation services from the factory in Palmdale to the launch site at Haystack Butte and from the landing site at Michael AAF to the launch site. CCC was turned on in late February with transporter delivery in January 2000. Route risk mitigation





continues by negotiating to cross three military reservations in lieu of using public roadways.

Site Activation Progress

Activation of capabilities to support the X-33 flight test program continues to meet schedule requirements at the launch and landing sites. Other Site Activation accomplishments are provided by Sverdrup (launch site facilities) and LMTO (ground support equipment and transportation)

- The Flight Operations Center (launch site) was formally dedicated in a ribbon-cutting ceremony on March 5. Construction is complete with only a handful of contractor personnel remaining to resolve "punchlist" discrepancies found during equipment checkout.
- The Operations Control Center infrastructure has been fully rehabilitated and OCC equipment integration has begun. The heat, vent and air conditioning system has been repaired. 1965 vintage equipment racks have been removed and the electrical power system has been upgraded to support X-33 LMCMS equipment. An alarm system and security door locks have been installed. The computer network and consoles/furniture has also been installed. Installation of the Operational Intercom System is 75% complete and Operational Television is 80% complete. Five of nine console computers have been installed and are being used to check out the Ground Interface Modules, computers that issue low level commands to launch site equipment. The other four console computers are being used to develop software at the Integrated Test Facility at Dryden Flight Research Center.
- The Portable Operations Control vehicle, a corporate-owned Boudner motorhome, has passed roadworthiness inspections. Modification included removal of old telemetry equipment and addition of uninterruptable power supplies, equipment racks and wiring to support portable LMCMS equipment. Portable LMCMS will be installed after vehicle systems checkouts are completed at the Palmdale assembly building in January 2000.
- The Mobile Operations Control Center, a corporate-owned 20 foot trailer, has also passed roadworthiness inspection. Modification included



extensive rewiring to support Mobile LMCMS equipment. A fiber-optic patch rack, desks, cabinets, a Global Positioning System antenna and LMCMS equipment racks have been installed. The MOCC will be operational April 1 and will support Range Phase 4 integration testing in April and May '99.

- The Logistics warehouse and site staging facility are fully operational. The warehouse heating and air conditioning was repaired and shelves were installed. Door locks and a security alarm system was also added to the warehouse. Double-wide logistics vans, the launch site logistics staging facility, were placed on site, cleaned out and shelves installed.
- A Transition Team, composed of operations, maintenance and logistics engineers, participated in Sverdrup's "punchlist" and systems check activities in preparation for site handover. Duties of the transition team include learning peculiarities of site equipment operation, spares, and preventive maintenance schedule and to witness subcontractor buyoff demonstrations.
- Purchase Orders have been established to allow delivery of the various propellants and commodities needed to operate the launch site. To support systems checks, deliveries have been made of the following fluids:
 - Liquid nitrogen
 - Gaseous nitrogen
 - Gaseous helium
 - Liquid methane
 - Liquid propane
 - Diesel
- Operations personnel were trained for environmental compliance/sensitivity, hazardous materials handling and safety issues. Upon completion of training, badges were issued. At the end of this reporting period, the on-site operations personnel breakdown is:

• Site Management	1
• Maintenance Control	3
• Technicians	3
• Logistics	1
• Engineering Support	10 (part time)

This data was generated by Lockheed Martin, Allied Signal Aerospace, Rockwell International, Boeing, and American Rockwell, B.F. Goodrich, Sverdrup Corporation under the Sverdrup Cooperative Agreement, dated 2 July 1996.



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

The RMS&A IPT has made steady progress since the last activity report toward ensuring the X-33 system includes requisite operability characteristics. Simultaneously, RLV activity increased. The RMS&A Team is led by LMSW. Due to the X-33 program's transition from design/development to production, RMS&A manpower has been downsized throughout the team. A core RMS&A team is still positioned in Palmdale, and is leading activities undertaken throughout the country. Allied, Rocketdyne, BF Goodrich, Aerojet, Sanders, and LMTO maintained X-33 RMS&A staffing. NASA also continues to participate, having RMS&A team members at MSFC and JSC. Following are activities performed or led by LMSW:

Reliability

- X-33 Safe Recovery Reliability (R_{SR}) Modeling/Allocation/Prediction: Several prediction updates were performed, reflecting design change data, development test data, etc. The predictions were used as inputs to design/configuration and operations trades and 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): The fault trees are our prime analytical tool for compilation of Safe Recovery Reliability at the subsystem level. While few model changes were made relative to vehicle subsystems, our list of trees involving the ground system climbed to 23 over this past year, with most of them nearing completion. We have five additional trees involving the ground system to build during the upcoming months. (Even though our hardware designs are basically complete, we continue our search for potential hazards, as they can often be mitigated by operations practices or minor design changes.) The ground facilities were analyzed in two ways: Contribution to losing or significantly damaging the vehicle

This data was generated by Lockheed Martin Space Research Company, Lockheed Martin Aerospace, Rocketdyne-A Division of Boeing North America, American Rockwell, B.F. Goodrich Aerospace, and Sanders Corporation under NASA Cooperative Agreement #NNA96-001-000.



available on all LMSW workstations. *Relex* FMECA organizes data to minimize redundant data across the team, and provides linkage of functions at all required design levels. RLV FMECAs will be documented by applicable team members, linking hardware functions and mitigation in support of: (1) top level Fault Tree Analysis and vehicle-level Safety Hazard Analysis; (2) Licensing / Certification; (3) test requirements and fault isolation; and (4) Reliability Centered Maintenance (RCM).

Maintainability

- X-33 Turnaround Timeline Analysis/Optimization: Progress on the discrete event timeline continued. The timeline model for evaluating the two day turn and the consecutive seven day turns continued to evolve, and was used as input data for our simulation modeling. (See *Special Analyses* section.)
- X-33 Maintenance Planning: Completed development of prototype tool that performs Reliability Centered Maintenance (RCM) analysis. The tool follows the guidelines of MSG-3 (Maintenance Steering Group -3), a commercial aviation standard. Instead of the traditional manual analytic process requiring extensive labor hours, our prototype tool yields recommended inspection intervals automatically. The inputs include factors impacting the probability of a failure occurring and the consequences of that failure. The output is a "risk" value that is tabulated in a fashion similar to the Program Risk factors.
- RLV Maintainability Allocations: Major changes were made to the allocations. The baseline was derived from the X-33 allocations and predictions: We scaled them to match the size and complexity of the baseline RLV. The update considers the service-to-flight operating hour ratio for the RLV, and how many technicians can effectively work on the vehicle. It has been a key program objective (as related to life cycle cost) to limit the touch labor team to 50 heads: We are currently estimating that 47 technicians will be required. Turnaround time (seven days) and availability (72%) were evaluated to define the available maintenance window. At this early stage of development, all of the major program objectives for turnaround, availability and crew size are being met.

This material generated by Lockheed Martin Skunk Works, AlliedSignal, Boeing, BFGoodrich, BDEIND, Sverdrup, and NASA. A Division of Boeing North American, Rockwell International, BFGoodrich Aerospace, Rohr Inc., and Sverdrup Corporation are participating in the NASA Cooperative Agreement NCC7-115 under which this work was performed.

- RLV Maintainability/Operability: We are leading a series of meetings aimed at addressing various design/RMS&A/operations issues. The issues are documented / carried until resolution. Results have been very positive. We also participated actively in the Mission Module and Payload Processing working groups, participated in the Tug-Vs.-Transporter trade, and worked with Design in addressing other Maintainability/Operations issues.
- RLV Reliability Centered Maintenance (RCM) Program: We identified issues that must be addressed in our RLV RCM program. The RLV program must generate a Maintenance Plan (MSG-3) that satisfies regulatory requirements. (Those requirements are currently being developed by FAA-AST and the industry.) A phase-equalized or continuous maintenance program will be essential to RLV scheduled operations, due to small fleet size.

Testability / Integrated Diagnostics

- RLV Maintenance Monitoring: We began defining the requirements for maintenance monitoring sensors for the Main Engines, Structures, and Thermal Protection System. These sensors will be used exclusively for enhancing the fault detection and fault isolation characteristics of the system for the performance of maintenance. The objective is to reduce operations cost by reducing time-consuming inspections or costly component change-outs. Care is being taken to arrive at a balanced number of sensors/sensing methods, as sensors also require their own support resources. Additionally, we assisted in the drafting of the RLV System Management / Maintenance Management approach/strategy document.

Supportability

- X-33 Logistics Tasking: As is efficient/customary when a program begins transitioning into an operational phase, in mid-'98 our Logistics functions were transitioned from the RMS&A organization into a Ground Operations organization. Their tasking is reporting therein.



- RLV Computerized Maintenance Management System (CMMS) Software Candidate: We identified a candidate CMMS system for RLV: *Maintenance Supervisor 2000* is a low-cost commercial CMMS that would be ideal for RLV Logistics management. *MS2000* tools manage work orders, schedule maintenance tasks, track assets, and control inventory. It will integrate with Relex R&M and FMECA Software, with the evolving RCM software, with current X-33 operations task management software, and will support bar coding.

Special Analysis

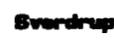
- Support to X-33 Expected Casualty Rate Study: We continued to support E(C) updates by structuring our reliability data to match changes to the trajectory data. The current program E(C) update includes unpowered flight, and joins flight dynamics assessments with failure mode quantification.
- X-33 Operations Simulation Modeling: Our progress continued developing *Extend* simulation models. The simulation is assisting in making operations decisions relative to turnaround optimization (*2 Day* and consecutive *7 Day*). Logistics delay times for TPS and Main Engine can potentially prevent achievement of turnaround goals. We are working with Rocketdyne and BF Goodrich to address workable issues. —
- RLV Operations Simulation Modeling: We completed a top-level *Extend* model of the integrated flight / ground system, examining *VentureStar*TM fleet operations over expected life cycle. The model is being used to support various operations and RM&S trades. Throughput analysis and payload manifest plan analyses were used to update the simulation model. The model indicates the optimum number of non-hazardous processing bays is four. The optimum number of hazardous processing bays is two. The optimum number of mission modules is four. The model is structured on a two-vehicle fleet, two maintenance facility/launch pad complexes, and 40 flights per year.
- RLV Life Cycle Cost Modeling: The *Extend* simulation software also supports Activity Based Costing (ABC) and workforce requirements. A test of the effectiveness was performed: It can be very useful in developing LCC estimates.

This data was generated by Lockheed Martin, Allied Signal Aerospace, Rocketdyne, and American Rocketdyne, American Rocketdyne, and Sverdrup Corporation. Data generated on 2 July 1996.



- RLV Phase III Bottoms-Up Cost Estimates: We provided inputs for Finance covering all RMS&A disciplines.

This data was generated by the Allied Signal Aerospace Corporation, a subsidiary of Lockheed Martin Corporation, and Sverdrup Corporation under NASA contract number NAG-1-015, dated 2 July 1996.





X-33 FLIGHT ASSURANCE

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, published last 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.

Two documents have been published to delineate the activities directly related to flying the vehicle. They are the Flight Test Plan (Rev A) and the Launch Area Management Plan (Draft). These two plans are the top-level documents that govern our operations procedures. Finally, IPT C and IPT D have been combined under a single manager resulting in seamless coordination as we prepare for first flight.

Four significant events have been accomplished which add operational flexibility to the X-33. First, FTS mode and hardware qualification requirements were determined. Second, the investigation of alternate landing sites have resulted in the identification of two potential sites. Both sites satisfy the

This data was generated by Lockheed Martin, AlliedSignal Aerospace, Boeing, American Rockwell, BFGoodrich Aerospace, Sverdrup Corporation and NASA. Date: 2 July 1996





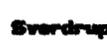
requirements. Final selection will be made after the final trajectory is determined. Third, we issued an RFP to design, construct and operate an overland transporter. This transporter will be used in lieu of the Shuttle Carrier Aircraft to return the X-33 from the landing site to the launch site. Finally, we traveled back to the FAA HQ to brief the Office of Air Traffic Control. As a result of this briefing, we requested and were granted permission to operate the X-33 over controlled airspace.

The Flight Assurance Office has also begun activities in support of the RLV program. We have initiated coordination with the FAA and with the Johnson Space Center. Each of these government offices have the potential to greatly influence the design and operating characteristics of the RLV. Ideas and issues were communicated to the FAA when we hosted a visit from the FAA Assistant Administrator for the Office of Commercial Space. Communications with the Astronaut Office at JSC has led to a fuller understanding of the crew requirements and their expectations.

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

LMSW Flight Test

Flight Test is responsible for ensuring that the flight test program is executed in a safe manner and that the X-33 program's objective, data to support RLV design and planning, is successfully collected. In order to perform this function, Flight Test accepts the flight vehicle at rollout, completes checkout of the vehicle and the vehicle/ground systems interface, prepares the mission plans, reviews the flight software, and executes the test flights. After each flight, Flight Test reviews the data for approval of the next flight and maintains the flight data database for other investigators.



The Flight Test team is divided into four branches; Ground Operations, Flight Test Engineering, RMS&A, and Range Operations. Ground Operations operates and maintains the launch site and prepares the vehicle for flight. Flight Test Engineering prepares the mission plans, manages data collection and archiving, performs quicklook data analysis, maintains and calibrates the flight test instrumentation, and executes the test flights. RMS&A provides reliability analyses for hazard remediation and to support flight approval through the FRR. Range Operations is responsible for X-33 program interface to all government range assets from Edwards AFB, NASA Dryden, and UTTR; it is an all-government branch. Systems Operators, a branch within Ground Operations, provides the engineering expertise for ground and vehicle systems. During ground operations, they operate the ground systems and provide engineering direction for maintenance and modifications. During flight operations, they operate the total system (ground and vehicle) during the countdown, safe the ground systems after liftoff, and monitor the vehicle in flight.

Flight Test Flow

Prior to rollout, Flight Test participates in vehicle SCOs with Manufacturing and the software V&V process with Engineering. Flight test planning also occurs during this period, including establishing the Flight Rules, publishing initial mission plans, defining the data measurands and the telemetry maps, and sequencing the post-rollout checkout activities.

Following rollout, Flight Test executes the checkout plan to prepare the vehicle for first flight, similar to any aircraft program. Simultaneously, Flight Test begins a training program for the OCC operators, runs the range, launch site, and landing site through dress rehearsals, and intensifies the IV&V scrutiny of the flight software. During this period, Flight Test provides the major support for the FRR process that is managed by Flight Assurance.

This data was generated by Lockheed Martin, Boeing, BFGoodrich, AlliedSignal, Sverdrup, Rockwell, and NASA. Lockheed Martin is a Lockheed Martin Company. Boeing is a Boeing Company. BFGoodrich is a BFGoodrich Company. AlliedSignal is an AlliedSignal Company. Sverdrup is a Sverdrup Company. Rockwell is a Rockwell Company. NASA is a NASA Cooperative Agreement.

Mission Execution

Flight test missions are conducted by Flight Test. Flights are scheduled based on Engineering requests, range priorities and readiness, weather, and vehicle status. Once Flight Test schedules a flight, Ground Operations begins a final prep of the vehicle, the launch and landing sites, and checks the range interface. One day prior to the flight, the Mission Conductor briefs the team and provides flight cards, specific flight rules, and checklists. The flight team then goes on 12 hours of crew rest and returns approximately six hours prior to liftoff to start the preflight process.

If all conditions are still go, the Test Director will turn the vehicle over to the Integrated Systems Manager for the preflight phase. The Mission Conductor continues to monitor the flight rules while the ISM prepares the vehicle in accordance with the Launch Commit Criteria. During the preflight phase, the Test Director, Range Safety, or any member of the OCC team can abort the mission. The flight team is split between Ridley Mission Control Center at Edwards AFB and the X-33 Operations Control Center at Haystack Butte. Range Safety, FAA representative, and Range Control Officer are in Ridley and the remainder of the team is at the OCC. There is provision for the AFFTC Commander to sit with the Ridley part of the team.

After liftoff, the Test Director has sole interface with the vehicle and is responsible for uplink commands, if necessary. The MOCC team can take over all required actions if the OCC loses communication with the vehicle. The ISM safes the launch site during the first few minutes of the flight, then turns his attention to assisting the landing site ISM prepare for safing the vehicle after landing. The Test Director relinquishes control of the vehicle to the landing site ISM after wheel stop and the vehicle initiating its autonomous safing actions, or at such time as mutually agreed between the Test Director and the landing site ISM.



The landing site ISM is responsible for fully safing the vehicle and returning the vehicle to the launch site, where the flight cycle begins again.

Progress Report:

Flight Test Instrumentation has fully defined the installation requirements for 1254 of the 1280 sensors. Of the remaining 26, 11 need only small adjustments in their location, 10 are awaiting base region tile information, 3 need final vehicle design drawings, and 2 locations need an additional sensor. No flight critical issues remain to be solved. In addition, 80 parameters have been wired and planned for within the software, to support catalytic heating measurements on the second flight.

Flight Test Engineering has completed the Weather Plan, the Flight Test Plan (including initial mission plans), an initial draft of the Flight Rules, a first draft of the Master Checkout Schedule, 15 of the 22 planned Test Information Sheets, and a flight schedule for July through September, 2000. However, the internal Flight Test "work to" schedule supports a first flight as early as 1 June 2000. All flight test displays for the OCC have been designed, and all except the annunciator panel have been demonstrated.

Data Processing has successfully demonstrated the flight test LMCMS system architecture, delivered a full up database manager, coded 9 out of 10 of the flight test displays, and provided a telemetry stream simulation for stress loading the LMCMS. Many of the report generators and other database tools have been demonstrated and have been found to be very user friendly.

Systems Operators have delivered the Rev B of their LMCMS requirements and have begun signing off the acceptance of their systems at the launch site. The second draft of the Launch Commit Criteria is available, ground system procedures are being delivered per the pre-rollout schedule, and the team is tailoring their software



loop timing to be compatible with the CDP (LMCMS central data processor) CPU performance. The ground launch sequencer requirements, the most critical single piece of ground software, have been delivered and run through an autocode utility to demonstrate rapid recoding capability which is essential for maintaining the launch schedule. The next significant task will be to define the ground simulation models that will allow the ITF to perform total system checkouts rather than just avionics checkout.

System Safety

The OSHA required Hazardous Materials Analysis is complete. The Ground Safety Plan (604D0130) has been released. The Operating and Support Hazard Analysis is in work. We continue a monthly program management review of Category I hazards.

Environmental Management

The Environmental Assessment draft is complete. The first environmental compliance training for the operations team is complete. The Storm Water, Spill Prevention, Environmental Management Plans and Permits are complete.

Range

Special Test Equipment (STE) is being installed at Michael Army Air Field Range site. The Range Safety Officer, Range Control Officer and the Federal Aviation Administration control consoles are relocated to the Ridley Mission Control Center at Edwards Air Force Base. The Range Integration and Test Plan is complete.

Range Safety

The Preliminary Flight Plan Approval is in work. The Risk Study to support the Preliminary Flight Plan Approval is in work.

This data was generated by Lockheed Martin, American Rockwell, B.F. Goodrich, Boeing North America, and Sverdrup Corporation under the terms of the Space Shuttle Program Cooperative Agreement.

Lockheed Martin Technical Operations

Support to the X-33/RLV Program by LMTO during the reporting period occurred in five major areas; launch support systems, ground support equipment, X-33 Design Engineering support, Flight Test operations development and RLV development.

Launch Support Systems.

LMTO is responsible for the development, delivery, and integration of critical products needed to support ground test and launch operations of the X-33 vehicle and Flight Operations Center. These include: T Minus zero umbilical systems, holddown/release system, vehicle positioning system, Independent Safing System, Ground Launch Sequencer, Subsystems Launch Commit Criteria, Subsystems ground software requirements and console displays.

- **T minus zero umbilical systems.** Final design/analysis was completed, hardware procured and/or manufactured. The ground umbilicals through which most ground to vehicle services and prelaunch command/data pass, have been developed using state of the art mechanism design to allow rapid alignment and vehicle mate operations with minimum ground crew support. Vehicle liftoff and plate separation occur automatically via direct mechanical linkage avoiding the operations intensive designs of other current launch umbilical systems that require ordnance and drop weights. Final assembly of the Hydrogen side Umbilical is complete and ready to begin integrated qualification testing at the Kennedy Space Center's Launch Equipment Test Facility (LETF). Initial mechanical assembly drop tests have been successfully completed. Final assembly of the Oxygen side Umbilical is near complete and will immediately follow the Hydrogen side Umbilical after it's testing is complete at the LETF. The vehicle half umbilical plate assemblies are complete and will be tested with the ground half systems as part of the integrated qualification testing. The vehicle umbilical doors and associated mechanisms which automatically actuate to cover the umbilical subsystems interfaces to protect from heating during ascent and reentry are in final production with all hardware procured and most delivered.





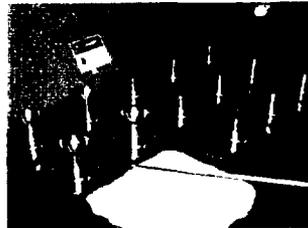
Ground LO2 Side Umbilical Tunnel

Flight Umbilical Plate

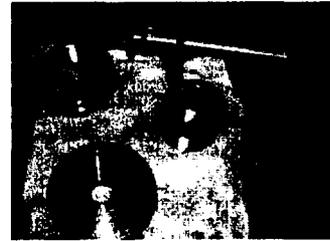
- **Holddown/T minus zero release system.** The launch and Ground Vibration Test holddown posts manufacturing and qualification testing were completed and then delivered to the X-33 Flight Operations Center in October, 1998. Both sets of holddown posts were precision aligned, installed and tested with the Rotating Launch Mount. All flight holddown mechanical attach hardware (titanium bolts, tension washers and frangible nuts) have been procured with expected delivery in April, 1999. The vehicle hardware components of this system; titanium bearing cup assemblies and bolt catcher assemblies, have been manufactured and are ready for vehicle installation.



Flight Holddown Posts Mounted to Rotation Launch Mount



X-33 Titanium Bearing Cups



Holddown Bolt and Hardware

The Laser Ordnance Firing System final design and manufacture has been completed. X-33 is the first space launch system application of this technology which represents significant operability improvements over current launch vehicle ordnance systems. All fiber optic transmission lines as well as data/command and power interfaces have been installed and tested. The Laser Pyro Initiator Control and Firing Module units are to be installed at the X-33 Flight Operations Center in early April.

An end to end systems test is planned this summer at the launch site where the laser firing system will execute a T minus Zero Release Command and fire a set of initiators installed in a set of flight holddown release hardware mounted in a test fixture attached to a flight holddown post.

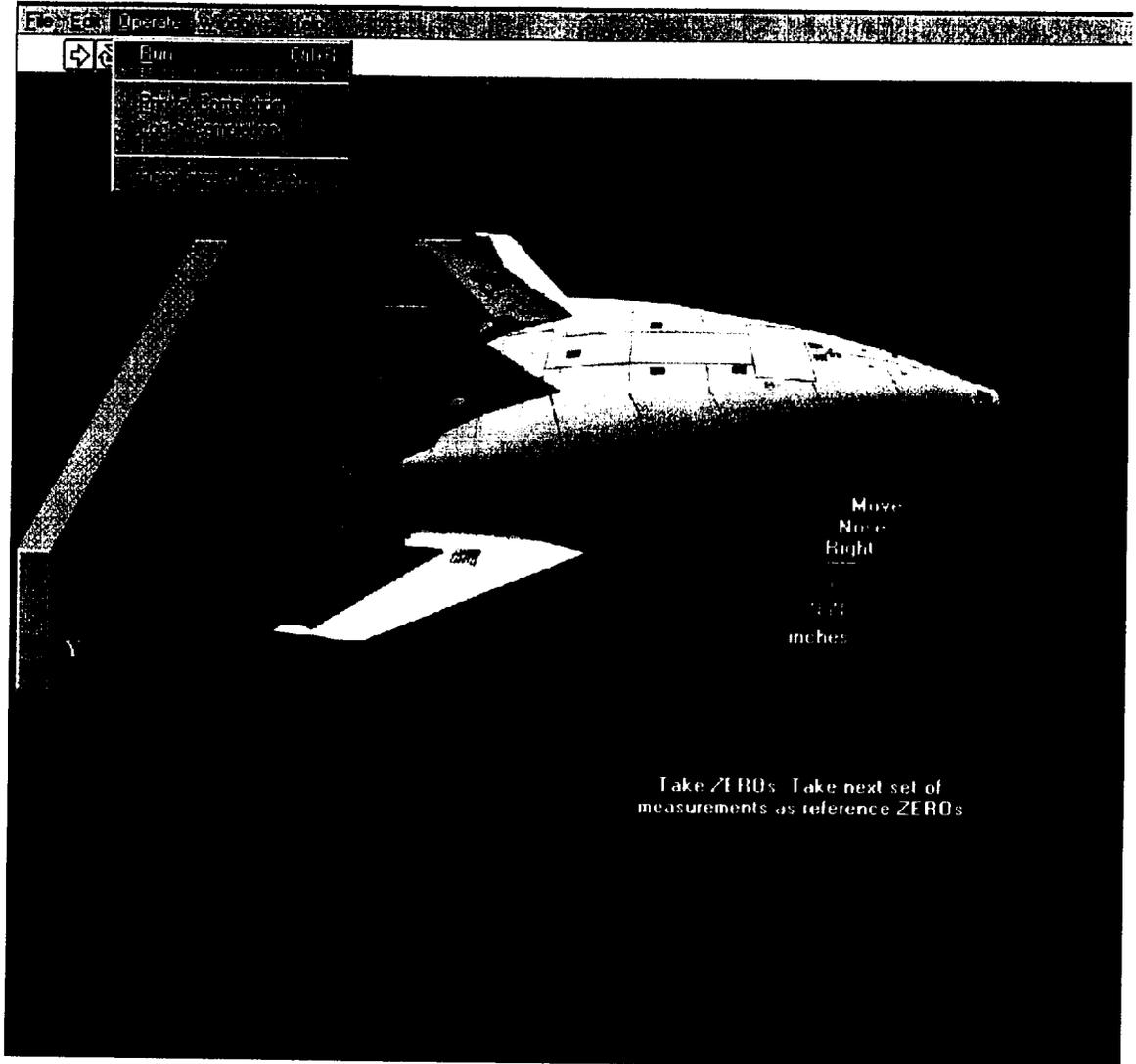
- **Vehicle Positioning System.** All hardware and software making up the Vehicle Positioning System was completed and delivered to the X-33 Flight Operations Center as originally scheduled. This system is an advanced concept design utilizing pneumatic jacks and actuators mounted on air bearings to position the X-33 vehicle for mate to the launcher HDP's while a built in laser alignment system provided detailed positioning





instructions via a PC Notebook. The entire system is controlled from a single small pneumatic control panel, which in future designs would be coupled to the PC making the entire operation of vehicle position and launcher mate an automated function. The system was utilized and performed flawlessly in performing the X-33 Mass and C.G. Simulator mate/demate operations to the rotating launch mount in December, 1998 and January, 1999. This system demonstrated considerable operability improvements over existing space launch mate operations and validate possible totally automated runway to launch pad processing for future operational systems.





Vehicle Positioning System PC Display





Forward Jack on Air Bearings



Laser Alignment With
Target on Holddown Bolt

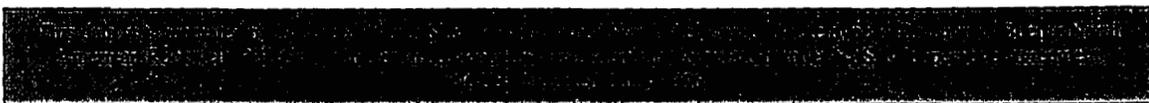
- **Independent Safing System.** The Independent Safing System (ISS) is a part of the X-33 Flight Operations Center Launch Mission Control and Monitoring System (LMCMS) and performs the tasks of a completely separate command/monitor system for performing ground/vehicle systems management and safing (if required) should any portion or all of the primary LMCMS fail during ground test or launch operations. Final hardware and systems software development was completed using state of the art COTS employing advanced health monitoring and a deterministic real time operations system. All hardware and system software has been assembled and tested within Building 704. Subsystems applications displays and software are in final development. The entire turnkey system will be installed at the X-33 Flight Operations Center this coming summer.





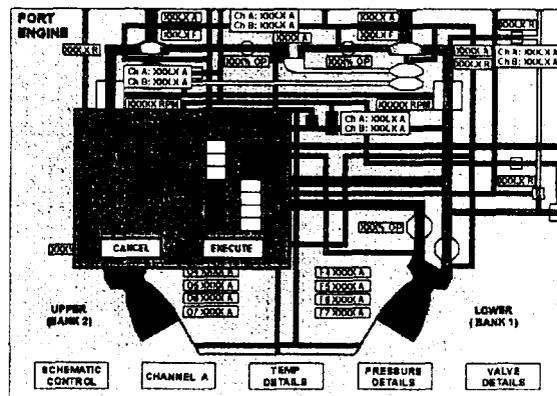
Independent Safing System in Lab Test Chassis

- **Ground Launch Sequencer/Systems Launch Commit Criteria.** The Ground Launch Sequencer (GLS) is the automated launch procedure that orchestrates and executes all X-33 vehicle and ground subsystems activities from the start of cryogenic propellant transfer (four hours prior to launch) through successful launch or recycle. The GLS concept under development for X-33 is a major step toward complete automation of launch operations for follow on operational space launch systems. The GLS system performs all vehicle/ground subsystems health monitoring and Launch Commit Criteria (LCC) verifications during its period of performance as well as provide for automated launch pad abort/safing and flight team critical advisory information. The GLS communicates with the X-33 Flight Launch Sequencer when active. The GLS detailed architecture, displays and sequencing and subsystems requirements have been developed. An automated code generation tool has been developed to allow the GLS application software code be created very quickly direct



from written software requirements documentation. This will allow for very responsive development and flight to flight updates to the software with minimum personnel, which is also key to performing the rapid vehicle between flight turn-around. Much progress has been made this year in the development and collection of subsystems Launch Commit Criteria as vehicle subsystems design and qualification tests have been completed. An LCC Document has been developed in draft form and will be updated as the subsystems operations knowledge base matures.

- **Ground Software Requirements and Displays.** LMTO responsible control and monitor displays for the X-33 vehicle and ground subsystems (all subsystems less Oxygen and Hydrogen main propulsion fueling subsystems) were completed over the past year. Ground and flight console display architectures were finalized to include efficient test management together with health monitoring techniques required to enable decision and management criteria for a minimal launch/flight test team. All integrated systems and subsystems ground application software requirements have been documented as vehicle subsystems design and operations information/requirements mature. It is through the implementation of the software created from these requirements that automated maintenance, servicing and checkout occurs.



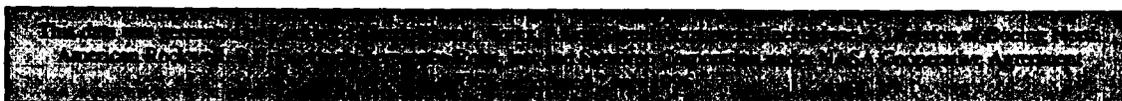
Sample X-33 Engine Console Displays



Ground Support Equipment.

LMTO is responsible for the development and delivery of certain equipment needed to support ground test, launch and landing operations of the X-33 vehicle and X-33 Flight Operations Center. Additionally, LMTO has the responsibility to coordinate, track and integrate into the operations planning all other suppliers of GSE including Government Furnished Equipment. In total, over 250 end item components were identified as needed to support the X-33 Flight Test Program. Over this past year all items were committed to either design/build or in the case of GFE items, documented commitments were obtained from the responsible organizations (MAAF, MAFB, EAFB, KSC).

- **GSE Design/Build.** LMTO is responsible for the design, development and delivery of the following GSE: Ground Purge interface connections, ATCS Ground Cooling Cart, Battery Pallet Lifting/Handling Device, Avionics Bay Inerting service equipment, X-33 Mass and CG Simulator, Propellant Tanks Purge QD sets. The X-33 Mass and CG Simulator was designed built and delivered to the X-33 Flight Operations Center where it was used in the highly successful X-33 Mechanical Ground Systems End to End Tests. All other equipment has been designed and is in procurement with delivery expected before summer end. The only significant major hardware not yet delivered is the ATCS Ground Cooling Cart that is in final assembly at LMTO in Cape Canaveral.





X-33 Mass and CG Simulator shown mounted to the Rotation Launch Mount

Flight Test Operations.

LMTO is responsible for providing key support, products and services as part of the X-33 Flight Test Operations Team for support to developing and implementing the X-33 Flight Test Project. Much progress has been made with many accomplishments toward the readiness to begin integrated test operations.

- A number of operations critical documents and policies were finalized and implemented to support the X-33 Flight Operations Center ground systems site activation and turnover activities from the facilities developer, Sverdrup Corp. The Quality Assurance Plan, Operations Safety Plan, X-33 Launch Site Activation Plan and X-33 Master Operation Plan documents are in final release form. All of these procedures have been developed to incorporate an aircraft like streamlined operations philosophy with a bias toward space launch vehicle requirements.



- An LMTO subcontractor Nelson Engineering, Inc. provided support to obtaining necessary environmental permitting for the launch site and supported the environmental issues associated with the X-33 Overland Transportation planning. Additionally, Nelson Engineering and LMTO Safety Engineering performed the necessary launch site transition training to all team personnel for rebadging to the operations phase.
- LMTO Safety Engineering developed and coordinated X-33 Program Emergency Management Plan briefings to all concerned Government Agencies.
- Our subsystems test engineers developed test procedures and supported the X-33 Flight Operations Center facility site subsystems activation working in concert with Sverdrup and their subcontractors. Parallel to this activity, they also were supporting the vehicle design engineers in developing the vehicle subsystems System Checkout Operations (SCO) procedures to be implemented later this year.
- The initial X-33 Flight Operations activities were conducted and was highly successful. End to end ground mechanical systems tests were completed in January, 1999 where the X-33 Mass and C.G. Simulator was mated using the Vehicle Position System to the flight holddown posts with non-flight holddown bolts, tension washers and nuts, rotated between horizontal and vertical multiple times and then demated. The entire mate operations was accomplished with a team of six personnel in less than four hours during the initial (never tried before) operations. The Ground Vibration Test holddown posts were installed to the RLM and then the tests were repeated.

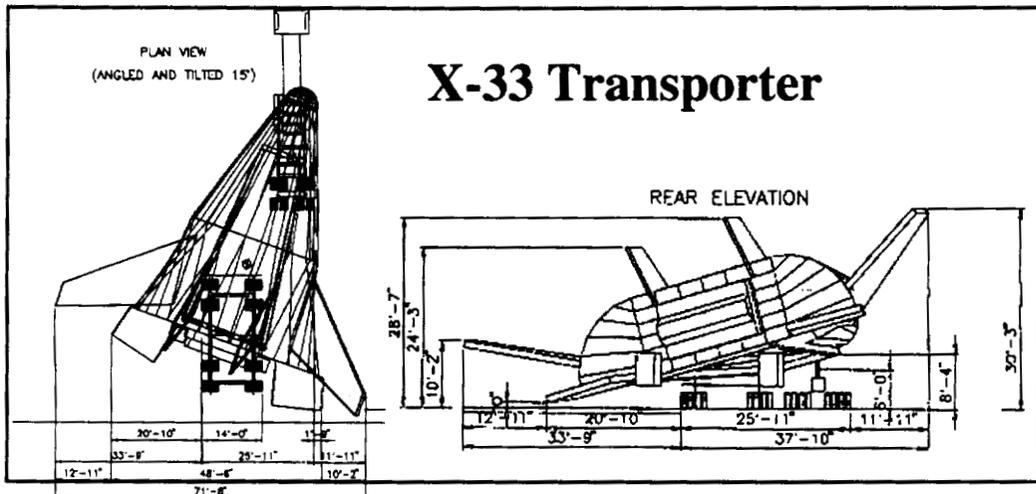




X-33 End To End Ground Mechanical System Test

- **X-33 Overland Transportation.** The X-33 Overland Transportation development effort has progressed from an idea stage to implementation over this past year. Transportation routes have been analyzed and generally defined, requirements for the transporter platform has been defined and a contract to Contractor's Cargo Company was announced by LMSW to perform the actual transportation effort including construction of the transporter. Coordination is continuing with government organizations to further improve the routes to avoid remaining obstacles and population centers in the current plans.





X-33 Overland Transporter Representative Requirements

- **Landing Site Operations Planning.** Landing operations planning has gotten much better defined through regular operations coordination meetings. The X-33 Landing Operations and Recovery Plan has been drafted. All GSE, personnel positioning and operations detailed sequencing have been defined for Michael Army Airfield post landing operations.



RLV Operations Development Support

LMTO played an integral part in the operations development of the RLV VentureStar™ in 1998.

LMTO lead the following: Mission Module Design working group, Payload Processing and Mission Module Integration, Vehicle maintenance and processing, Mission Operations and VentureStar™ ground data and control system architecture.

LMTO also supported systems engineering in development of the Flight Segment Specification, System Requirements Document, Ground Segment Specification and System Architecture Drawing. LMTO supported the bottoms-up cost analysis for the five major areas listed above and also the following: RLV T-minus zero umbilical system, holddown and release system, and midbody umbilical systems. The RLV operations team also supported Marketing on the satellite customer visits, developing customer needs and requirements. Technical support to marketing was also provided in developing an animated VentureStar™ video of vehicle and payload operations. LMTO led and supported several technical sessions at the July 1998 AIAA RLV Operations Conference. In addition, LMTO is supporting VentureStar™ Marketing at other conferences, trade shows, and program events.

- **Vehicle Processing Operations Development:** Developed the functional flow for maintaining and processing the Reusable Launch Vehicle (RLV) from landing wheels-stop to launch. Determined that processing the vehicle will occur without inerting the propellant tanks and drafted a risk mitigation plan. Completed a trade study to determine whether the RLV would be processed in a fixed hanger or a translating shelter over the launch mount Supported integrating vehicle design development with vehicle operations development. Twenty-five issues to date have been identified in the vehicle operations / design development interface meetings (eight issues have been closed). A trade study was initiated to determine the most cost effective and versatile method for transporting the RLV from the runway to the launch mount. Data



collection for the transport trade study and a decision analyses is near completion. Determined vehicle processing operations cost through the first year of flight for the bottoms up cost effort.

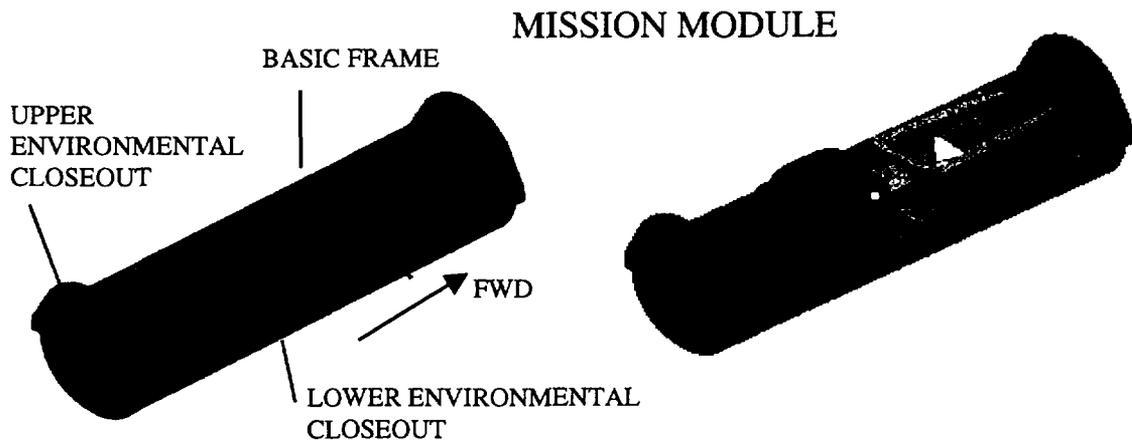
- **Payload Processing and Integration:** Functional flows for both processing and integration of commercial payloads into the VentureStar™ mission module have been developed. Conceptual design of ground support equipment required to support payload and mission module processing has been started. Two major trade studies have been completed by LMTO lead teams; the "VentureStar™ payload processing and integration orientation (horizontal versus vertical) Trade" and the "Mission module to VentureStar™ vehicle Umbilical Trade". Supported the RLV payload processing thruput analysis utilizing Extend modeling tool, which also determined mission module fleet size.
- **Mission Operations:** Developed initial functional flow of RLV mission operations tasks, including mission planning, control team training, and operations. Drafted communications and tracking architecture. Performed trade of space communications alternatives (support from Dennis Jenkins and LMWDL), resulting in a TDRSS baseline. Drafted command and control authority baseline. Organized ISS/RLV technical interchange meeting, February 1999. Created initial mission sequences. Participated in site selection effort. Provided updates to FAA Flight Safety Guidelines. Provided inputs to crew control requirements.
- **Ground Data & Control System:** The Ground Data and Control System (GDCS) provides the ground based computing resources to complete the RLV mission. System, Ground, Flight requirements were analyzed and requirements that drive the GDCS design were identified. Preliminary analysis indicates five major support services are required. The integration of these services into a single system, along with a robust vehicle and ground system design, enables dramatic processing efficiencies. The requirements, under development, do not force a single design solution and define needs from a customer/user perspective. The GDCS components are:



1. *VentureStar*[™] Control System - provides real-time display and control of the vehicle, associated ground equipment, mission modules and payloads for all mission phases and provides a control link to external customers.
 2. Data Analysis and System Health - stores vehicle / ground / payload data, provides near-real-time / archived data access and supports analysis and maintenance action monitoring functions
 3. Mission Planning - supports requirements definition, mission buildup, flight planning, unique mission software and vehicle mission contingencies
 4. Maintenance and Operations Support Service - provides ground planning, scheduling, logistics, component histories, configuration management and operational procedure controls required for ground and mission operations
 5. Process Control Network - provides office and business services including word processing, spreadsheet, requirement tracking, web access tools, data storage and external connectivity, etc.
-
- **Mission Module Development.** Weight limits for missions were developed and accommodations requirements were defined. Upper stage requirements and acquisition plans were developed with an RFI (request for information) being sent to potential manufacturers. Mission Module structural layouts were evaluated to verify weight allocations and the module to vehicle mounting/retention concept was completed. The module environmental closeout design was completed and included vehicle to payload bay door seals and interfaces. All of the payload services and accommodations were identified and a number of innovative concepts were developed to reduce weight and turnaround time.



Trades for payload retention, deployment, power, command, and communications were established. Mission Module to vehicle umbilical concepts were developed and the trade was completed. A preliminary ICD was developed to aid NASA team design of specialized International Space Station equipment.





LOCKHEED MARTIN SPACE OPERATIONS

TAEM and A/L Guidance and Flight Control Design

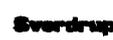
LSOC/Houston's prime responsibility is the design and integration of the Terminal Area Energy Management (TAEM) and Approach/Land (A/L) guidance and flight control for the X-33. We have continued to support the vehicle development process in the reporting period. Major design deliverable items included:

- Delivered Revision H inputs to the Detailed Design Description (DDD) document in July of 1998. This delivery included design changes to the interface/handover from the entry to the TAEM flight phase.
- Delivered Revision I inputs to the DDD in August of 1998. Changes include items to resolve several Problem Report/Change Requests as a result of the IV&V review team efforts.
- Delivered Revision J inputs to the DDD in December of 1998. Minor design updates included an additional filter to improve stability margins and a logic change for the speedbrake limit. Several cosmetic PR/CR changes resulting from the IV&V review of Rev I were also included.
- Delivered FORTRAN implementation of the guidance and flight control requirements to the Skunk Works and to NASA/Dryden on 6/5/98, 9/21/98, and 3/14/99.

Along with the periodic changes to the content of the DDD, I-load updates accompanied each revision. These reflected the development and maturing design for the following:

- Entry/TAEM handover design integration.
- Trajectory development to alternate intact landing sites
- Trajectory development to the Intentional Controlled Flight Into Terrain (ICFIT) sites. Along with the I-loads, we also furnished data to support configuration of real-time displays and establishment of flight rules for abort decisions to ICFIT.

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- Tune-up of guidance and flight control to reflect the changes in vehicle weight, aerodynamic data, and trajectory requirements.

In addition, we have assisted in integration of requirements for the Navigation Processing function, have 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

We have provided analysis support to a number of vehicle design changes and subsystem performance items. These include:

- Effects of loss of differential GPS on the heading alignment maneuver prior to landing.
- Load indicator margins for the aerosurfaces and landing systems in dispersed conditions.
- Effects of the aero database update on 4/21/98.
- Impacts of aerosurface actuator bias/position accuracy in the transonic region of flight.
- Splitting the inboard and outboard elevons to provide increased drag in rollout.
- Evaluation of updated ground effects data on landing performance

TAEM and A/L Dispersion Analysis

As the vehicle configuration has matured, we have performed numerous studies to evaluate vehicle performance and robustness with respect to system and environmental dispersions. The following items summarize activities in this area:

- Effects of updated aerodynamic uncertainties
- Effects of updated aerosurface hinge moment uncertainties
- Assessment of the TAEM guidance capability to accommodate trajectory dispersions at Entry/TAEM transition



- Effects of winds aloft on trajectory downmode to straight-in
- Effects of winds aloft on the ICFIT trajectories

Modeling and Simulations

The SES 6-DOF simulation has been updated to reflect changes and maturity in vehicle and environmental models as information has become available. The simulation has been installed at the Skunk Works, the ITF at NASA/Dryden, and at Allied Signal to provide the development and verification community with simulation capability. The major releases are summarized below:

- Released SES V1.6 on 6/5/97. Major updates included upgraded actuator models, capability to split elevons in rollout, modified nosewheel steering logic, and upgraded differential braking logic.
- Released SES V1.7 on 9/21/98. Updates included incorporation of the navigation processing function (emulation of flight software), changes to the Entry/TAEM transition logic, and simulation of flight software transport delay and module sequencing.
- Released SES V1.8 on 3/12/98. Major updates included an upgrade to the aerosurface actuator model, variable mass properties, the July 98 aero data base, GRAM wind and atmosphere capability, and an emulation of Guidance and Control corresponding to the final version of the requirements document (DDD).

We were tasked to develop a model for wind and atmospheres to be used in verification facilities and have delivered the product to NASA/Dryden in February 1999 for incorporation into the ITF. It provides table lookup capability along a reference trajectory using data selected from the GRAM 98 data base. This model will accept data files as needed to support the formal verification and validation process.

Coordination and development of landing system models has been an ongoing effort. We have taken the lead in defining model requirements and acquiring the data needed to support development of flight software requirements for this area.





Frequency Domain Analysis

As the system design has matured, we have updated the stability analysis tools to reflect the vehicle and subsystem configuration. We have automated the capability to extract the airframe transfer functions along the trajectory for use in stability evaluation. This tool, Flexible Airframe Analysis (FAR), is run as an attachment to the time domain simulation (SES) and provides capability to rapidly obtain a linearized vehicle state at the desired operating point. Stability margins are evaluated using the Matrix-X tool. Frequency domain design evaluations have included:

- Tune-up of rigid body stability margins for the Rev J version of the G&C configuration. This included identification of an additional filter required for adequate margins in the yaw channel and gain profile adjustments to satisfy margin requirements specified in the X-33 Vehicle spec.
- An evaluation of flex body stability margins. This is an ongoing effort as the aerosurface actuator model matures.
- Evaluation of the stability margin sensitivity to design wind environments and mass property dispersions.

Verification and Validation Activities

We have devoted significant resources towards development and integration of tools and processes to support the integrated GN&C verification for the X-33. In addition to the simulation and modeling items listed above, the following have been accomplished:

- We assisted in the installation and checkout of the TAEM and A/L guidance and control modules into the ITF simulation at NASA/Dryden. This is in support of a batch simulation capability planned for that facility.
- We delivered check cases and wrappers to Allied Signal/Teterboro in support of flight software development.
- We have installed the TAEM and A/L guidance and control models in the Maveric Simulation at NASA/MSFC in support of an end-to-end simulation capability. Some checkout and integration remains to be done.





This simulation will be needed for end-to-end monte carlo analysis of system and environmental dispersions in preparation for flight certification.

- We have developed a draft of the X-33 Integrated GN&C Verification Plan. This document specifies the test and analysis activities required to complete final system level verification.

Ancillary Support

Routine support to the X-33 GN&C development activity included:

- Participation in weekly Flight Sciences telecons
- Response to community requests for special trajectory and performance data
- Review and redlines to the associated requirements and interface control documents
- A status of the GN&C system design and analysis results was provided at the X-33 Analysis Review in December, 1998





Lockheed Martin Aeronautics - Denver

RLV/X33 research accomplished by Lockheed Martin Aeronautics during the reporting period has been substantially reduced from the effort performed in previous reporting periods. The reduction in Aeronautics effort was a result of the program restructure in February 1998. The remaining effort occurred principally in two areas of the cooperative agreement Work Breakdown; Aeronautics provided engineering support to the Skunk Works primarily in X33 Development and Systems Engineering.

Systems Engineering

Aeronautics has provided systems engineering for both X33 and RLV development, with the level of support appropriate to their respective phases 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. The major continuing effort is risk management with Aeronautics maintaining the databases, facilitating the risk board meetings, and generating the reports for X33 and RLV risk identification, assessment, and mitigation.

X33 Development

Aeronautics support to X33 development has had two principal parts: the bonding of X33 structural truss-tubes to endfittings and the development of integrated health monitoring (IHM) ground software.

Aeronautics completed development testing, fabrication and delivery of all X33 2" & 4" diameter bonded truss tube flight hardware. The development testing efforts consisted of multiple end fitting bond tests and tube Euler buckling tests conducted at operating temperature extremes. The development testing results were reported in document X33-TR-98-001, Composite Truss Tube Development Testing Final Report, 7 August 1999.



Truss tube flight hardware fabrication activities consisted of receiving and prepping LMSW-provided filament-wound composite tube detail parts, adhesive bonding machined titanium end fittings at each tube end, conducting 100% ultrasonic inspection of the bonded joints, and installing LMSW-provided rod ends into the end fittings. After fabrication, each tube assembly was subject to acceptance testing that consisted of thermal cycling, axial proof loading to design limit load, and ultrasonic inspection of each bonded joint. After acceptance testing, each tube assembly was prepared for delivery by seating the rod ends, then cleaned, tagged and bagged. A total of 90 flight truss tube assemblies (20-2" dia., 70-4" dia.) were delivered to the program. In addition, Astronautics completed fabrication and delivery of flight spare parts consisting of machined end fittings and adhesive bonding detail parts.

The IHM activities included work on software modules, documentation, and test procedures. During 1998 the following documents were prepared and delivered: Functional test procedures for LMCMS Application of Integrated health Monitoring (CSCI); 604K6840 Rev NC; and a Software Development Plan Revision. The development of the IHM Application continued with the following modules completed and tested: IHM Database; IHM Display; Master Dispatcher; and Execution Engine. Following the tests modifications were made before final tests to be conducted in 1999.

Power Pack Test Data was received in the last quarter of 1998 from Rocketdyne. The tests were conducted at Stennis Space Center. These data were used to start the development of the Model Preparation and Model Evaluation modules. The interface with the PDS was tested and modifications suggested for improving the usability and performance. The IHM team also supported the LMCMS group developing the Master Measurement Database and helped develop a better schema.





Sanders - A Lockheed Martin Company

Sanders is responsible for the development of the Vehicle Health Management Subsystem and the Core Launch and Mission Control Management System.

The VHM Subsystem is comprised of 2 VHM Computers, 50 Remote Health Nodes, and 60 segments of Fiber Optic interconnect cabling. The VHM Subsystem is responsible for acquiring and recording data from over 1200 flight test sensors and data on avionics flight critical buses. A subset of the acquired data is downlinked to the ground system.

The Launch and Mission Control Management 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.

Vehicle Health Management Subsystem Progress

- Delivered 6 out of 50 Flightworthy Remote Health Nodes.
- Successfully completed Remote Health Node Qualification Testing.
- Delivered Remote Health Node Simulation to the ITF.
- Successfully completed Fiber Optic Bus Qualification Testing.
- Delivered Flightworthy Fiber Optic Bus Cables.
- Completed VHM Subsystem System Checkout Procedures
- Delivered and integrated Flightworthy VHM Computer Hardware and Build 5.0 Software to the ITF.
- Completed final development and test of VHM Computer Software.
- Successfully completed three interface integration tests with the JPL Avionics Flight Experiment at the ITF.

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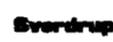




- Successfully completed Electromagnetic Compatibility Testing on the VHM Computers.

GSS Progress

- Completed delivery of LMCMS Build 5, during July 1998. The MOCC LMCMS Hardware was installed at LMSW and configured as a system development lab for Test/Ops Applications Software. The Build 5 software was installed and integrated at LMSW and the ITF.
- Completed CSCI testing of LMCMS Core System Software, approximately 72,000 SLOC, at Sanders.
- Completed procurement, assembly and ATP of LMCMS Core System Hardware.
- Completed delivery of LMCMS Build 6, during December, 1998. The POCC LMCMS Hardware was installed at the ITF and configured to support X-33 system integration. The Build 6 software was installed and integrated at LMSW and the ITF.
- Completed delivery the OCC LMCMS Core System Hardware, during January 1999.
- Completed Phase 1 of the OCC LMCMS Site Installation during February 1999:
 - LMCMS Ground Interface Modules installed and wired at Launch Site
 - LMCMS Ground Interface Network Communications Equipment Installed at Launch Site
 - LMCMS Time Distribution Equipment installed at OCC.
 - LMCMS Computer System Equipment Installed at OCC.
 - LMCMS Network Communications Equipment installed at OCC and ROC.
 - Network Communications established between OCC and ROC.
 - Network Communications established between OCC and Launch Site.
 - Remote Control of Ground Interface Modules from OCC.





Lockheed Martin Michoud Space Systems

X-33 2219 LIQUID OXYGEN (LOX) TANK 1998

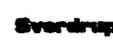
The X-33 LOX flight tank was delivered to LMSW in February 10th, 1998 via air transport using an Airbus A300-600ST Beluga. The tank was unloaded and positioned next to the Vehicle Assembly Jig (VAJ) for final installation of interface fittings and RCI closeouts. The tank was installed into the VAJ where TPS support structure, landing gear box, and other interface equipment were located and installed on the tank. At the completion of 1998 all of the LOX tank hardware including MPS pressurization and PU lines were completed.

The X-33 LOX Structural Test Article (STA) fabrication was completed in 1998 and instrumented and delivered by barge to MSFC on February 19th, 1999. The baseline test site at Building 4699 was planned for testing the LOX tank as well as the two LH2 tanks. Due to schedule conflicts an alternate test location was selected for the LOX tank STA test at Building 4619 and is scheduled for test on March 25th, 1999. In 1998, the test program was rebaselined to a minimum set of test requirements at the new test site. Fabrication of test tooling for the ballast and landing gear simulators was completed as well as the intertank strut simulators.

The design, fabrication, manufacturing, and proof test of the flight LOX tank was completed in an impressive 19 months to meet the vehicle schedule requirements and the STA tank was built in a more cost effective fashion and delivered a year later. The following is a summary of the challenges and significant lessons learned that facilitated the tank program:

Key Challenges:

- 1.0 Multi-lobe Design Tolerances. The configuration of the tank required considerable evaluation of the tolerance build up during design and fabrication. Weld shrinkage in the tank skins combined with mechanical frame installation presented a unique challenge during final trim and closeout welding.





- 2.0 Low Cost Soft Tooling. Since only two tanks were fabricated, low cost tooling was necessary to minimize the program cost. Weld land thickness was purposely increased to accommodate weld peaking and miss-match anomalies. Hawthorn clamps were used to position the tank skins for tack welding and low cost portable weld machines were used to weld the tank panels.
- 3.0 Complex Tank Interfaces. The number and type of interfaces to the tank were evolving during the build process. Considerable frame rework was necessary to meet the late design changes. In process optical position verification permitted last minute shimming to bring the hardware back to specification to meet the ICD tolerances.
- 4.0 Design Release Before Final Loads. The basic tank engineering was designed and in fabrication well before the final tank flight loads were completed. Adequate design margins were incorporated into the design to accommodate potential loads changes.

Lessons Learned:

- 1.0 Establish Concurrent Integrated Product Team. The tank program was managed with a dedicated team supported by selected "equivalent" skills as required. Communication and integration of engineering, procurement, manufacturing and test was fundamental in meeting near term milestones.
- 2.0 3D Solid Models with Limited Dimension Drawings. A combination of computer models and "on floor" drawings were successful in capturing the engineering design for procurement fabrication and for installation on the tank. Models were sent direct via the Internet to machining vendors for fabrication and the drawings captured the critical dimensions and tolerance requirements. A simplified drawing redline system was established to manage and control changes.
- 3.0 Control Point Engineering Product Structure. The engineering product structure was organized around the tooling and build stations. This forced concurrency during the drawing signoff with engineering, manufacturing and tooling.





- 4.0 Make Provisions for Anticipated Requirements Changes. The design process incorporated considerable engineering changes. Advanced planning drove out selected scarring requirements particularly in the frame design and slosh baffle interfaces to continue tank fabrication while significant engineering changes occurred.
- 5.0 Utilize Existing Processes. One of the contributors to the tank schedule was eliminating the need to invent new fabrication processes. Welding, clean, proof test and RCI installation steps utilized existing ET processes and facilities on this program.

The completion of the X-33 LOX tank has demonstrated the design, integration and manufacturing issues required to proceed with an RLV LOX tank in the future. Although the X-33 tank is aluminum, composite materials development is in work to prepare the program for a composite RLV LOX tank. The design and integration issues addressed in the X-33 tank are similar to those for the RLV tanks with the exception of the material.

This data was prepared by Lockheed Martin Aerospace Research Corporation under NASA contract number NAG-1-010, dated 7 July 1990.



X-33/RLV Composite Technology

Quarter Scale Composite Multi-Lobe Propellant Tank

A reusable Launch Vehicle (RLV) quarter scale (10 foot tank length) multi-lobe Liquid Hydrogen (LH₂) propellant tank was designed and partially fabricated during the Phase I RLV/SSTO program. During phase II activities in previous years, the remaining tank fabrication tasks were completed, insulated and instrumented. Thirty cryogenic pressure cycles were completed at the NASA Stennis Space Center to demonstrate several key technologies in addition to the tank's performance.

During the past year cycle life testing was continued for an additional 48 cryogenic pressurization cycles (total of 78 cryogenic pressurization cycles) at NASA's Lewis Research Center's Plum Brook Testing Site. The composite hydrogen tank structurally has performed consistently in all of the testing. The technology advances from this phase of the testing were primarily in the areas of material performance, various leakage repair methods, bonded and bolted joint performance, instrumentation, and RCI. The key data derived from this mission life cycle test program was related to the performance of each of the systems as a function of cycle life. Several leakage repair techniques showed limited cycle life while 3 types of repairs developed by LMMSS under IRAD showed no change for the cycle life capability demonstrated to date.

Composite Material System Liquid Oxygen Compatibility Demonstration

The liquid oxygen (LOX) compatibility material testing database on the down-selected LM baseline was expanded to include limited manufacturing anomalies, mechanical property testing, flammability testing, cryogenic cycling effects, and permeation data. The first steps toward scale up from the coupon level efforts were completed with the fabrication of a sub-scale tank (3 foot by 5 foot) which was fiberplaced at NASA's Marshall Space Flight Center. This sub-scale tank was used as a manufacturing pathfinder, working with the LM LOX compatible material system, and resulted in



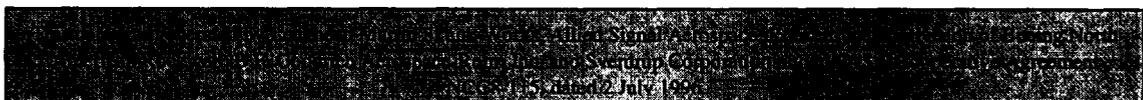
numerous lessons learned to support the fabrication of the large scale LOX demo tank for RLV. Two 18-inch LOX bottles were fabricated and are currently being prepared for LOX compatibility testing at NASA MSFC.

X-33 Flight Composite Propellant Tank Coverplates

Five composite coverplates were fabricated: one for qualification testing and four for the flight tanks. All the covers have successfully passed cryogenic acceptance testing at NASA MSFC. The acceptance testing included dimensional checks, ultrasonic inspections, three cryogenic pressure cycles per cover, and a post proof ultrasonic inspection. The qualification test article is currently in progress with 16 cycles successfully performed to date. The composite coverplates are the result of some unique development work performed under the LMMSS IRAD to handle the thermal expansion/contraction issues between composites and metals. This unique technology breakthrough culminated in a patent pending for LM.

X-33 Composite Propellant Tank Repair Technology

A propellant containment solution for the X-33 woven Y cruciform, the primary joining hardware of the composite LH2 tanks, was developed under LMMSS IRAD. The woven Y cruciform hardware's ability to contain propellant was evaluated and tested in order to tailor the repair method for the hardware unique features. The final repair method was demonstrated on the LMSW Double-D sub-scale LH2 tank and tested at NASA MSFC with LN2 and LH2 for a total of 5 cryogenic pressurization cycles. This repair method is currently being applied to the X-33 flight LH2 tanks in Sunnyvale, California.



REUSABLE CRYOGENIC INSULATION (RCI) AND VEHICLE HEALTH MONITORING (VHM)

The Reusable Cryogenic Insulation (RCI) and Vehicle Health Monitoring (VHM) development and qualification efforts were completed during 1998. In addition flight vehicle applications of both were completed on the LO2 tank and some MPS components. The RCI efforts concentrated on completion of qualification activities for the Airex R82.60, SS-1171, and CryoCoat materials and the application of the SS-1171 material to the LO2 tank and various MPS lines and valves. The VHM efforts were concentrated on completing the development of the flight fiber optic sensor development and application technique development and application of the Distributed Temperature Sensor and FTI to the LO2 tank.

RCI PROGRESS

RCI Material Qualification

The Qualification of the Airex R82.60 and SS-1171 insulation for use on X-33 was completed in 1998. This testing included basic material properties, cryoflex with and without heating effects, thermal mechanical testing and thermal conductivity. The Airex foam was qualified mainly for acreage composite applications and the SS-1171 was qualified for all metal (LO2 and MPS) acreage applications and as a closeout material on composites. The CryoCoat UL-79 material was removed from the qualification process after the SS-1171 proved to be a better closeout material for composites. Further formulation studies must be done with the CryoCoat to make it a viable RCI material.

RCI Hardware Application

The SS-1171 material was applied to the X-33 LO2 tank and various MPS components during the year. This application was completed successfully within all engineering requirements both onsite at MAF and offsite at LMSW in Palmdale for closeout applications. MPS components completed during the year were four 4" valves and one LO2 feedline section. In addition the



thermoforming of Airex panels for application to the LH2 tank domes was initiated during the year to support LH2 tank manufacture.

TASK AGREEMENT SUMMARY

LaRC-08 Thermal Mechanical Testing

Successfully tested four additional panels with the Airex R82.60 and the SS-1171 insulation materials on Aluminum and Composite substrates to support the material qualification effort. Each test consisted of 50 cycles – 25 pre-launch/abort cycles and 25 pre-launch/launch cycles. Test configurations consisted of SS-1171 on Aluminum with VHM and ESD coating and for repeatability and Airex on composite for repeatability and with various closeout insulations.

SSC-01 10 Ft. Composite tank RCI support

SS-1171 was applied to a 7” by 72” area of the composite tank using three different surface preparation techniques. This area and the Airex and CryoCoat materials previously applied were subjected to 48 additional cryocycles at LeRC thereby successfully demonstrating the continued cycle capability of the Airex and the capability of the SS-1171 material to be used in closeout applications on composite tankage.

VHM PROGRESS

Distributed Temperature Sensor (DTS)

The Distributed Temperature Sensor (DTS) system is a measurement system the measures temperature using optical fibers and laser light. The development of this system has been completed with the selection of the fiber, qualification of the process used to apply it on the foam surface, selection of the connector harness, and completion of the laser VME card for the avionics bay.



The system was successfully installed on the foam surface of the LO2 tank, which includes 280 feet of optical fiber and the harness. The VME cards will be installed in the avionics bay later during X-33 assembly and a fiber system will be installed on a dome of one LH2 tank in Palmdale.

Distributed Strain Sensor (DSS)

The Distributed Strain Sensor (DSS) is a measurement system that measures strain using optical fibers laser light with Bragg Gratings etched on them. The operation of this sensor has been verified and qualified over the -423°F to $+350^{\circ}\text{F}$ X-33 environment through lab testing and scaled tank testing such as the 10 sq. ft. Composite tank. The sensor and the bonding process were successfully qualified and the eight fibers to be applied to one LH2 tank in Palmdale have already been manufactured by LaRC. The laser VME card has been completed along with the connector harnesses.

Distributed Hydrogen Sensor (DHS)

The Distributed Hydrogen Sensor (DHS) system is a measurement system that measures the presence of hydrogen using optical fibers and laser light. The system utilizes the DSS fibers and VME cards but incorporates a bonded on Palladium tube at the Bragg locations to provide for hydrogen sensing. The flight fibers for the LH2 tank application have been manufactured by LaRC and the University of Maryland and proven out operationally. In addition the bonding technique was developed and verified so that the hydrogen sensing could be isolated from the strain sensing component of the fiber.

Acoustic Emission Sensors

Acoustic Emission (AE) testing is a nondestructive inspection technique that monitors the sounds generated by defects such as cracking or delaminating in composite structures. Implementation of this technology on X-33 consists of a post flight test to determine any change in one joint of one composite LH2 tank. The progress here includes completion of qualification testing (cryogenic cycling, thermal cycling, and vibration), selection of the sensors



and preamps, qualification of the application technique for the sensors, preamps, and harnesses, and testing and analyses to support waveform analysis during the X-33 flight program.



MAIN PROPULSION SYSTEMS (MPS)

LO2 Feed Fill and Drain System

The first hardware related to the 8" feedlines was delivered from Arrowhead Products. These lines contained an external gimbal flex joint. Also 50% of the fill and drain line was delivered. EMA valves for the inboard and outboard configurations completed ATP and were delivered to Michoud. 8" TIVs were at ATP when a problem was encountered with the electronic controller unit provided by Allied Signal. The test was postponed and is planned for early 1999.

LH2 Feed Fill and Drain System

The fill and drain valves were both acceptance tested, insulated, and delivered to Palmdale. Two (2) flight feedlines were fabricated and delivered to Michoud. One was instrumented and insulated and provided to Boeing for power pack testing at SSC. A Valve simulator was also provided as part of the power pack test hardware support. The second line and valve will be provided as needed to support the dual engine testing planned for late 1999.

GO2 Press Vent and Relief System

The 2" and 4" GO2 pressurization lines that attach to the LO2 tank were assembled onto the vehicle. The first 4" EMA vent valve was delivered and assembled on to the vehicle. The LO2 PU system was also assembled on to the vehicle. This included the small tubing and the pressure transducers.

On the thrust structure about 75% of the small tubing related to the GO2 and GH2 pressurization system was delivered and installed. This contained two types of small solenoid valves that had passed qualification at both -320



degree F and -440 degree F. The latter valve is the first flight qualified valve to operate at this temperature.

The five flight cryogenic helium bottles successfully passed ATP and were delivered to Palmdale along with the associated tubing and brackets that fit within the LH2 tanks.

GH2 Press Vent and Relief System

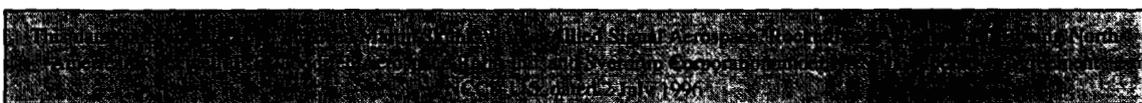
Pressurization lines for the whole system have been delivered. Small tubing was 90% complete and was delivered and assembled to the vehicle thrust structure. The 4" EMA vent valve was also delivered to Palmdale.

Integrated Helium System

The basic system design was completed. However the system underwent a change to incorporate the need for a hydrogen vent duct purge. The structural members of the system were designed, fabricated, and delivered to Palmdale.

Electrical

All the pressure and temperature sensors completed qualification testing. Also all flight transducers were delivered. The liquid level electronic box and ECO sensor box completed qualification. All level sensors and ECO sensors were also delivered.





STRUCTURAL TESTING

Task Agreements

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

In 1998, the LMMSS Structural Test Team managed a total of thirty-one (31) Task Agreements, of which eleven (11) were active. These TAs covered activities at Marshall Space Flight Center (MSFC), Langley Research Center (LaRC), and Lewis Research Center (LeRC). Accomplishments under the TAs to date include testing performed to certify X-33 or evaluate RLV technologies:

- Completed LH2 densification testing using 10' LH2 Tank and accumulated additional cryogenic pressure cycles on structure; a total of seventy-five (75) cycles have been completed with no outstanding issues.
- Completed additional certification testing of X-33 Helium Tankage on EP-16; completed the cryogenic proof testing required to certify the six production tanks for flight usage.
- Completed verification testing of RCI test panels for X-33 usage (LaRC-08).
- Completed LH2 Feedline water flow testing at MSFC (ED31-19) to verify feedline design.



- Completion of verification testing of the Composite LH2 Tank Cover Plates (EP-28) and acceptance testing of two of the four cover plates.





X-33 SYSTEM INTEGRATION AND ANALYSIS

LMMSS Systems Engineering and Analysis for the X-33 has completed approximately 85% of the baseline certification by analysis tasks for LMMSS hardware systems. These include the LO2 Tank, Main Propellant System (MPS), Reusable Cryogenic Insulation (RCI) and Vehicle Health Monitoring Systems. Each system includes mechanical and functional analysis activities as well as systems integration tasks.

The LO2 structural analysis effort has been completed through basic design and proof test with only the Structural Test Article test and final stress report to be completed in 1999. All functional analysis of the LO2 Tank (volume, weights, environments, etc.) is complete.

The MPS structural analysis is 80% complete with only final analysis of the Propellant Utilization and Integrated Helium Supply and Delivery Systems remaining in 1999. Evaluation of qualification results from Main Propellant System (MPS) is ongoing for the remaining lines and valves to be tested in 1999. Functional analysis and modeling of the MPS performance is baselined with recent trajectory changes and related dispersion analyses being supported on an as required basis. Baseline logic (algorithms) has been delivered and the MPS Control System ICD approved. Support to the Integrated Test Facility software validation effort, Systems Test support tasks and final flight predictions remain.

All RCI / VHM analysis and testing is complete with only support as-required being provided to resolve vehicle assembly driven nonconformances.

All ICDs were completed. Effort remaining includes reconciliation of interferences occurring during vehicle assembly and final compilation of analysis verification data books.





CRYOGENIC SYSTEMS OPERATIONS

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.

In the area of assembly, test and launch operations requirements documentation, we completed and delivered 6 of 6 volumes of the Test, Operations and Maintenance Requirements, Specifications and Criteria (TOMRSC) documentation. These LMMSS volumes detail the launch site activation and flight test operations required to be performed to support the LO2, LH2, GHe, RCI, GN2, HazGas and RCI. The LO2, LH2 and IHSDS data is the core data included in the MPS Subsystem Control ICD which also has been updated and re-released. We also completed and delivered 2 of 3 volumes of the Test and Checkout (T&CO) Requirements documentation. These LMMSS volumes define the required activities associated with vehicle post installation checkout and post-assembly vehicle system checkout (SCO). The third volume, addressing ground vibration testing (GVT), has been initiated and substantial progress has been made.

We managed the LO2 Tank post delivery operations through installation of the tank into the X-33 assembly fixture. We implemented the technical detail defined in the T&CO documentation by supporting the post installation checks of several MPS components in the X-33 assembly. In preparation for MPS system checkout in building 704 after vehicle assembly is complete, we delivered two SCO procedures which implement the T&CO documentation and provide for functional verification of the MPS LO2, MPS LH2 and IHSDS systems onboard the X-33 vehicle.

We provided key launch site checkout and turnover support including detailed technical requirements, planning and implementation for the checkout of the fluid and pneumatic systems. We defined and verified the fluid and pneumatic system criteria invoked by LMSW on Sverdrup for launch site construction turnover. We provided the necessary detailed procedural checkout and verification sequences and steps (a total of 10





separate procedures) for Sverdrup and their subcontractors to perform and participated in their implementation to ensure launch site fluid and pneumatic system compliance.

We have defined and delivered requirements for LMCMS application software to support ground and flight system operations for LO2, LH2, GN2, GHe, HazGas, Leak and Fire Detection and Deluge Water. We continue to support the software development effort and initiated and implemented weekly software and hardware integration meetings to support this effort.

We have defined and scheduled and initiated the development of approximately 25 procedures required to implement post-turnover ground system/LMCMS validation, operations and maintenance in preparation for vehicle roll-out to the launch site. Twelve (12) additional unique procedures are required to implement first flow X-33 operations including GVT, tanking tests and flight readiness firings. Five (5) additional unique procedures are required to implement flight test operations.

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.



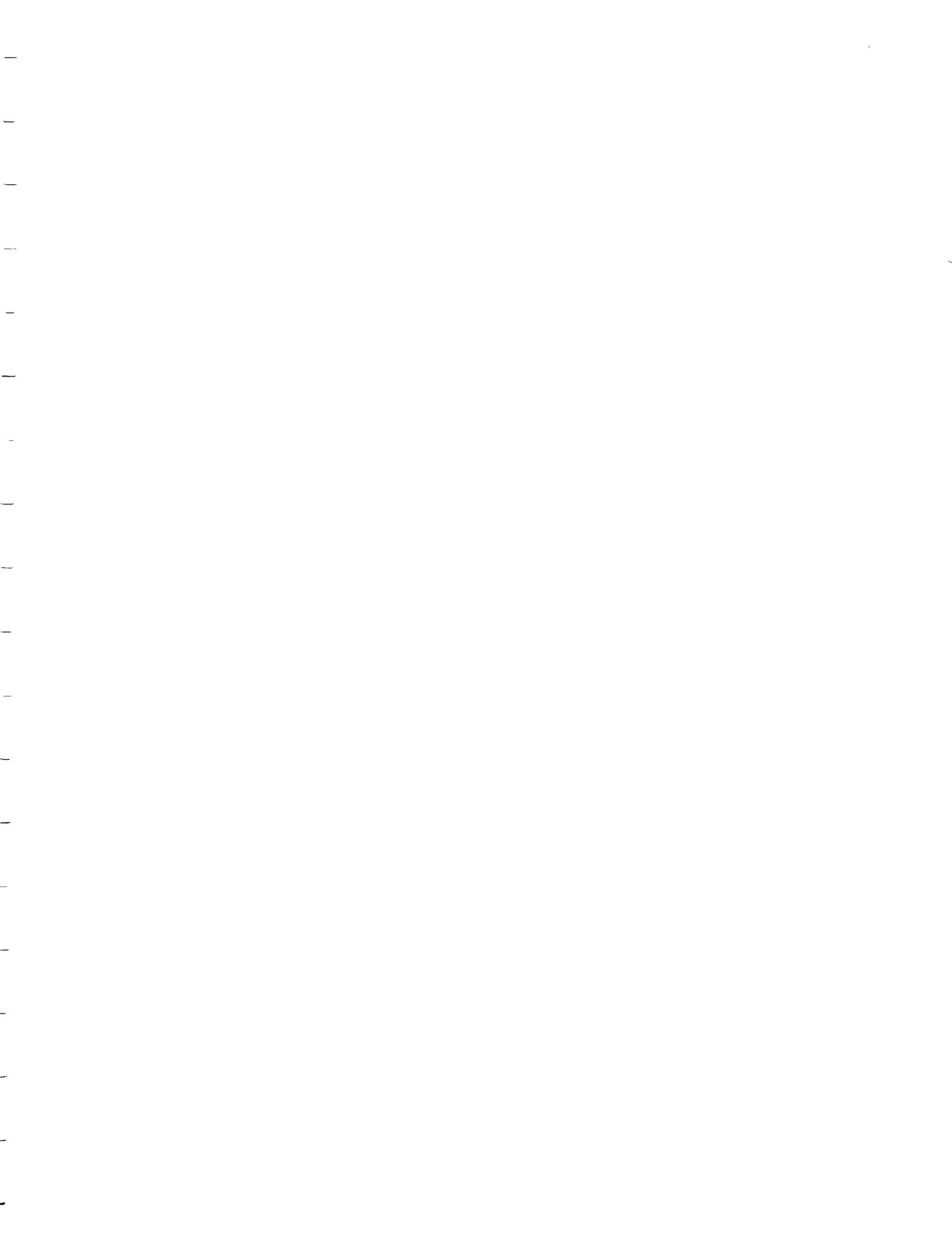
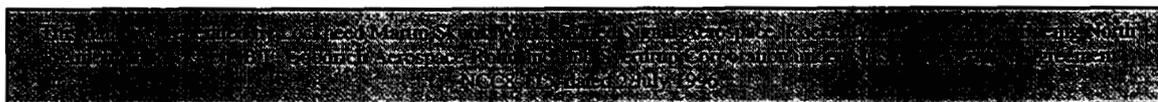


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Communication Systems

The Radio Frequency Subsystems (Radar Altimeter, Communications, and Range Safety) progressed nearly to plan during the reporting period of April 1998 through March 1999. The three subsystem test sets completed design, fabrication, and calibration, and the associated subsystem-level Acceptance Test Procedures (ATP) were released. AlliedSignal received 80% of flight hardware from subcontractors enabling subsystem ATP to be successfully performed for Radar Altimeter Subsystem Shipset #2 as well as Communications Subsystem Shipsets #1 and #2. In October 1998, Communications Subsystem Shipset #1 was delivered to LMSW. In March 1999, Radar Altimeter Shipset #2 (spares) was delivered to LMSW, to join Shipset #1 already delivered in January 1998. The remaining 20% of subcontracted flight hardware is scheduled to be delivered by the third quarter of 1999, allowing delivery of the Range Safety Subsystem Shipset #1 and delivery of the remaining spare hardware (Communications Subsystem Shipset #2 and Range Safety Subsystem Shipset #2) in that quarter. The Air Force Flight Test Center (AFFTC) and Utah Test and Training Range (UTTR) Range Safety Offices approved the Qualification Test Program for the RF Subsystems in December 1998. Testing commenced in February 1999, and is scheduled to complete in the third quarter of 1999.

Environmental Control Systems

Active Thermal Control System (ATCS)

Work continues on or ahead of schedule for all aspects of this system. Helium heat exchanger hardware deliveries for flight and spare units were completed ahead of schedule. The pump package assembly and motor/controller assemblies were delivered on schedule. All flight and spare ATCS hardware deliveries to LMSW are now complete. All qualification testing has been successfully completed. Qualification test reports were submitted for the integrated pump package assembly and the helium heat exchanger which completed the subsystem qualification program. Detailed system analysis was performed to show positive temperature margins for all



flight profiles. A higher fixed helium flow rate from the Integrated Helium Supply and Distribution System (IHSDS) was negotiated with LMMSS to increase performance, thus allowing removal of the helium shutoff valves from the vehicle. ATCS servicing and test equipment was built and delivered to support upcoming system test and checkout in Palmdale. Initial meetings were held to assure requirements compliance and identify additional actions necessary to have a complete ATCS verification and validation package.

Purge and Vent System

The four flight Purge Ducting packages completed delivery in November 1998.

Flight VME Circuit Card Assembly (CCA) completed development testing and the first two CCA's were delivered to AlliedSignal-Teterboro in July 1998 for integration into the Data Interface Units (DIU's). The vendor shipped ten more Flight CCA's to Teterboro from August through December 1998.

Door frames and door panels for the vent door assemblies were received from BF Goodrich in July 1998. The Qualification unit was assembled and testing began in October 1998. The unit successfully completed thermal cycling test. After completing the vibration test, the door resolver and the temperature sensor failed the post vibration performance test. Failure analysis was completed for both components. Design revisions have been made and risk reducing development tests are being performed to evaluate the revised design.

Hydrogen Detection System (HDS)

Qualification and System Integration testing of the Hydrogen sensor and Versatile Modular Eurocard (VME) controller card was completed. Fabrication and delivery of the HDS hardware was accomplished as planned. All 8 flight VME cards (4 flight and 4 spares) were fabricated, tested, and delivered to AlliedSignal-Teterboro. All 40 hydrogen sensors (20 flight and 20 spares) were fabricated tested and delivered; 22 to AlliedSignal-Torrance and 18 to LMSW.





Avionics Bay Inerting System (ABIS)

The ABIS flight and spare hardware was ordered, fabricated and delivered to LMSW Palmdale. The hardware consisted of a primary regulator, secondary regulator, shut off valve, tank assembly, and check valve.

Flush Air Data System (FADS)

The Flush Air Data System Remote Pressure Sensors (RPS) program has completed Safety of Flight Electro Magnetic Interference (EMI), Safety of Flight Environmental Testing and Software Qualification. All flight-worthy hardware has been delivered.

Landing Systems

Component hardware deliveries are 90% complete. Nose wheel well hardware has been delivered. Main wheel well hardware delivery completion is scheduled for March 1999. Brake Control Dynamometer testing was completed and the Brake Control Unit (BCU) boxes will be upgraded and retrofit during the 2ND quarter of 1999. Integration test setup continues. Checkout is scheduled for April 1999 and testing is scheduled to immediately follow and continue till the end of 1999. All scheduled tests will be completed in 1999. Requirements tracking, Verification and Validation (V&V) and Master Delivery List (MDL) matrix tracking processes continue.

Power Management and Generation Systems

Flight Control Actuation System (FCAS)

FCAS has all baseline drawings released. Flight and qualification hardware has been fabricated for assembling the baseline design Electro-Mechanical Actuator (EMA) and Pneumatic Load Assist Device (PLAD) system.



Development testing has lead to some redesign and rework of the baseline EMA to meet performance and vibration requirements.

Development testing has demonstrated EMA performance. A 12% load margin and a 10% rate margin have been shown on the primary channel. A 10% load and 8% rate margin have been shown on the secondary channel. An initial performance deficit was solved late in 1998 by increasing motor torque and designing a custom low-loss-multiple-row thrust bearing. Motor brake capacity was increased to balance the additional torque provided by the motor. Expedited development bearings have proven the performance of the design, and flight bearings are currently being received.

Development vibration testing has shown the F-20 heritage motor is unable to meet the X-33 environment. The motor built to demonstrate the design solution is complete with testing eminent.

A "worst case" flight duty cycle run on an EMA showed significant thermal margin for the electrical motor. The duty cycle run was on an in-board elevon Michaels 9-D-5 trajectory from launch to wheel stop. The motor temperature increased from 70 F to only 100 F, with the over temperature shut down limit of 400 F.

Final development testing is underway to show the FCAS meets all of its X-33 performance and environmental requirements. Flight hardware delivery and qualification testing are in line to meet the vehicle build and certification schedule.

Electric Power Control & Distribution System (EPCDS)

The High Voltage and Low Voltage Power Control Assembly (HV/LV PCA) designs were completed, and circuit card development testing commenced in June 1998 which successfully completed testing in September 1998. High-risk circuit cards successfully underwent corona testing at Marshall Space Flight Center. The first HV/LV PCA engineering units completed manufacture and went through intensive electrical checkout without any major problems or re-works. Analysis work on the HV/LV PCAs shows



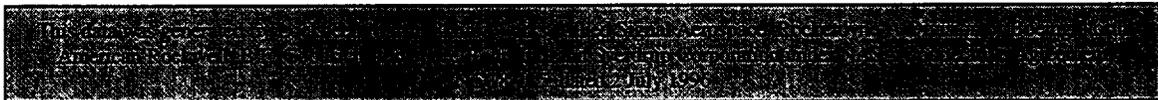
positive margins for weight, thermal and stress. Software Critical Design Review (CDR) for the PCA was held in June and the software emulator was completed and used to verify the integration of the operational software with hardware. Qualification Test Procedures were submitted to Palmdale in April 1998.

DC/DC Converter successfully completed Safety of Flight (SOF) testing and EMI/EMC testing. Flight and spare DC/DC Converter hardware were delivered to Palmdale in January 1999. Flight UPS Battery was delivered in February 1999.

Battery Power System (BPS)

The BPS underwent a Systems Preliminary Design Review (SPDR) in April 1998. In May 1998, additional requirements for the BCU were identified to handle regeneration energy from the FCAS actuators. The solution to maintain power quality was to incorporate a Dynamic Brake Resistor (DBR) into the existing BCU. The DBR senses the bus voltage and dynamically switches in a resistive load when the bus voltage exceeds a specific value. The first DBR breadboard was completed in October 1998. Circuit Card layout and development card testing was finished by December 1998. The first engineering BCU with DBR was completed in January 1999 and successfully underwent electrical functional testing. The second BCU engineering unit was completed end of February 1999 and will commence EMI testing in March 1999

The batteries passed qualification testing in December 1998. The flight batteries were delivered to Palmdale in February 1999. The Battery Diode Modules (BDM) went through vendor re-selection and screening. Flight BDMs will be delivered end of March 1999.



Vehicle Management System (VMS)

VMS Hardware

The first 3 Vehicle Mission Computers (VMC) were delivered to Lockheed. They were subsequently returned to AlliedSignal Aerospace - Teterboro to be retrofitted with the new Cross Channel Data Link (CCDL) CCA and are ready to ship. Prior to shipment, these units will be used for VMC Formal Qualification Test (FQT). The last 3 VMCs are in Environmental Stress Screening (ESS) testing and will be completed by 4/1/99. The VMC went through its complete qualification testing and is beginning re-qualification with the new CCDL (completion date – 3/31/99).

All Engine Controller Data Interface Units (ECDIU) have been built and delivered to Rocketdyne. The ECDIU has completed its environmental portion of qualification testing and will complete the EMI section by 3/31/99.

All Forward and Rear Data Interface Units (FDIU & RDIU) will be completed by 5/15/99. Three of the four RDIUs have completed testing and are ready for delivery to Lockheed; the fourth will be completed by 3/15/99. The RDIU will be qualified by similarity to the FDIU. Two of the FDIU are also completed, less the Nose Wheel Steering CCA. FDIU qualification will be completed by 4/30/99.

VMS Software Development Activities

The Vehicle Subsystem Manager (VSM) Build 3 software delivery was completed during the 2ND quarter 1998 to support full I/O manager capabilities. The software was completed in accordance with the 5/8/98 modified Interface Requirements Management (IRM) database. Integration of this software delivery was completed during the 2ND and 3RD quarter 1998 at NASA's Dryden Flight Research Center Integration Test Facility (ITF).

Flight Manager Build 4 software was completed and delivered to the ITF during 3RD quarter 1998 to support nominal vehicle ground and flight phases



up to and including Ascent. The software was completed according to 604D0034F+ (Guidance, Navigation, and Control Design Description Document) and IC604K0001D (Vehicle Build 4 IRM database). Integration of this software delivery is underway with other team member software deliveries through 1ST quarter 1999. This allows the ITF to test the integrated VMC with simulated vehicle and ground environments through the Ascent phase of flight.

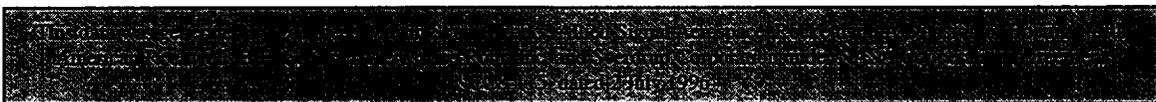
Flight Manager Build 5 software was completed and unit tested at AlliedSignal Inc., Teterboro, NJ during 1ST quarter 1999. This software includes vehicle ground and flight phases up to the Terminal Approach Energy Management interface. It also includes abort guidance and flight controls logic. The software was completed according to 604D0034I, approved Problem Reports, and the Navigation Processing section of 604D0034J, and IC604K0028B (Vehicle Build 5 IRM database).

Flight Manager Build 6 software requirements analysis was completed. This software supports all vehicle ground and flight phases, and all abort logic. It was completed according to 604D0034J, approved Problem Reports, and IC604K0029 (Vehicle Build 6 IRM database).

Engineering Test Station (ETS) software was completed and delivered during the 2ND quarter 1998, to support ECDIU software development by Boeing Rocketdyne Division.

Forward Data Interface Unit & Rear Data Interface Unit/ETS (F&RDIU/ETS) Build 5 software was completed and delivered in place at AlliedSignal Inc., Teterboro, NJ during 1ST quarter 1999. This software supports all communication interfaces with the VMC's and common sensor and interface functions. The software was completed according to 604D0126C (Vehicle Management System Requirements and Design Document), and IC604K0028.

Fault Tolerant Executive (FTE) Build 6.1 software was delivered in support of the Redundancy Management System (RMS) functionality during 4TH quarter 1998. This software supports modifications to the Cross Channel



Data Link Circuit Card, and allows for greater flexibility in triplex VMC operation. This software also includes enhanced error log capabilities allowing more detailed assessment of VMS errors. The software was completed according to 604D0126C (Vehicle Management System Requirements and Design Document), and IC604K0028.

System 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 CCDLs:**
 - The Triplex continues to operate in its original configuration.
- **Simplex VMC with no CCDL Present**
 - Two VMC chassis have been added to this stand. By re-arranging assets, they can be used as a second Triplex system. It will be used to support the VMC FQT.

In order to perform Simulation with the DIUs, AlliedSignal designed one ETS for each DIU. Each ETS contains a full set of complementary CCAs to interface to the DIU I/O signals.

- This year the Engine ETS testing was complete and the hardware was delivered to the ITF.
- The design of the forward and rear ETS hardware is completed and operational in the SIL.
- A Forward/Rear DIU software development environment has been created in the lab which contains the following:
 - Four DIU prototype chassis (2 forward and 2 rear).
 - Four ETS chassis (2 forward and 2 rear).
 - Simplex VMC
 - External DIU power supplies and load plates.





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





53-05

**ANNUAL PERFORMANCE REPORT
X-33 THERMAL PROTECTION SYSTEM**

For The Period
April 1, 1998 - March 31, 1999

By

**BFGOODRICH AEROSPACE
AEROSTRUCTURES GROUP**



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X-33/SSTO THERMAL PROTECTION SYSTEM

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. 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. Significant tangible progress has been made this past year as the program evolves rapidly into the manufacturing and assembly stage.

During the past year the vehicle has reached final configuration, and baseline trajectories have been established. The vehicle aerothermal environment database was updated to the vehicle configuration and the appropriate dispersion factors. All major design issues have been resolved. This has allowed BFG to move forward with final TPS definition components such as the Body Flap, Elevon, and Leeward Aeroshell split lines between AFRISI and FRISI, and the split lines in the windward metallic TPS. In achieving closure on key technical issues many trajectories have been assessed both with the use of preliminary indicators and with detail analyses as shown in the December 98 analysis review. Qualification for flight analysis is well underway.

Major and critical tests have been successfully concluded in the past year helping to validate the TPS systems both from a component level and from an integrated system level. The tests conducted at the High Temperature Tunnel (HTT) at NASA Langley concluded with multiple runs on the metallic and leeward thermal blankets including off-nominal design. The combined environments test, a significant integrated system level test, was also successfully concluded. Other tests, all focused at validating the thermal

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protection system, have been successful, and will be discussed in detail in the body of this report.

Maintainability aspects of the metallic TPS panel designs have been demonstrated as meeting all of the X-33 and RLV goals. Demonstrations were carried out with both flat and curved panel arrays, with actual installation on the vehicle using the installed flight hardware standoff brackets. Curved honeycomb demonstration panels were successfully fabricated enveloping and validating the capability to fabricate the complete range of panels.

BFGoodrich has made progress in manufacturing the TPS systems. All vehicle body standoffs have been delivered. The installation of the standoff brackets to the thermal protection substructure has been demonstrated, with panel installation, validating the tooling and installation philosophy. Insulation plugs for the body standoff brackets have also been delivered along with approximately 50% of the standoff brackets for the canted fin. Metallic honeycomb panels are in production. BFG has made significant progress towards developing acceptance criteria and production processes to increase production rate and yield. To date 48 flat panels have been delivered. BFGoodrich has receipt of the first Metallic isogrid panels from suppliers. The majority of the leeward aeroshell graphite honeycomb panels have been fabricated. Many have been fit checked on the FAJ and/or the vehicle. Refractory composite parts are in production at our supplier, C-Cat.



VEHICLE CONFIGURATION (DESIGN AND ANALYSIS)

Structural Advancements

TPS Structural/Dynamic Analysis

BFG has completed the sizing of thirty-five body TPS assemblies, fifteen canted fin assemblies and all of the nose gear Inconel 617 TPS panel assemblies for static and dynamic loading using linear FE models. The Inco 617 panel skins, core and standoffs have been sized for aerodynamic and basic thermal loads with preliminary compressive strength data. Durability analyses of the skin, core and standoffs to the liftoff, ascent and reentry acoustic and vibration loads with preliminary fatigue data.

Detailed *FE* strength analyses of the nominal Malmstrom 4 trajectory for a highly loaded flat, a 60 inch curved and a 30 inch curved Inco 617 panel assembly have been completed. The detailed models utilize preliminary stiffness, strength, plasticity and creep material models.

The seal analyses to date have been performed for the Malmstrom 4 trajectory. The Inco-617 flat panel primary seal has been analyzed for the Malmstrom 4 trajectory temperature and pressure time history. Transition seal has been analyzed at room temperature with enforced deflections and pressure. Flat panel and 60 inch radius curved Inco-617 panel primary and secondary seals have been analyzed under the maximum burst and crush pressure conditions. Isogrid flat and curved panels analyses are currently underway.

Flutter analysis and flight tests have been completed for the Flat Inco-617 panels with 0.006 inch thick seals. Flutter analysis has been completed for a flat Inco-617 Isogrid antenna panel.

Six MA-754 Isogrid TPS assemblies have been sized for static and dynamic loading using linear FE models. The MA-754 isogrid skins, ribs and standoffs have been sized for aerodynamic and basic thermal loads with preliminary

material strength and stiffness data. Durability analyses of the isogrid skin, ribs and standoffs to the liftoff, ascent and reentry acoustic and vibration loads with preliminary fatigue data. Detailed structural and thermal analysis iteration of the nominal Malmstrom 4 trajectory for a highly curved Isogrid panel assembly is in work.

Leeward Aeroshell TPS Structural Analysis

General sizing of the panels is complete for static and fatigue loading. Detailed Finite Element Models were created for each panel on the leeward aeroshell for final analysis. Detailed strength and durability substantiation analysis and documentation is underway.

Allowable manufacturing defects have been analytically determined for the leeward aeroshell graphite/epoxy bond panels. Results from this analysis are being incorporated into the manufacturing specification.

Flutter analysis for avionics and payload doors have been completed and our report delivered to LMSW.

Structural component tests have been completed. Materials static and fatigue strength tests have also been completed. Flight test instrumentation has now been defined.

AeroThermodynamics Advancements

Aerothermal Environments

Aeroheating and plume heating environments were obtained and used to assess the proposed Michael-9 series of flights. A constant factor of 1.4 was applied to the aeroheating rates for the proposed first flight trajectory, Michael 9a-8, in order to account for trajectory dispersions. Aeroheating environments for specific locations in the elevon cove, the elevon-to-elevon



gap region, the body flap cove, and the body flap hinge region closeouts will continue to be analyzed in coordination with LMSW.

Trajectory Constraints

The metallic panel thermal/structural stress and long-term creep indicators were updated and then incorporated into a FORTRAN subroutine and delivered to LMSW for assistance in trajectory design. These same algorithms were expanded for use with all panels on the X-33 vehicle. Given the aeroheating database, all panels can now be rapidly assessed for new trajectories. Using this method several panel designs were modified to support the flight of the Michael-series of trajectories.

Design

Leeward Aeroshell Basic Panel Design

ACHIEVEMENTS: 1998 saw the completion of the majority of the Leeward Aeroshell drawings and closure of the majority of design issues. Twelve of the 13 bond panel drawings were released and all 13 assembly drawings were off-boarded. Panel attachment schemes were finalized. Carrier plates, transition seals, and vertical fin seals have been detailed and drawings off-boarded. Final interface definition was agreed with team members; LMSW (leeward to base), Michoud (hydrogen and oxygen exhaust plates), and Allied Signal (ECS vent design and antenna installation, performance, and grounding). The leeward canted fin design was initiated and the leeward cove region design is nearing completion. Mapping of the FRSI/AFRSI/AFRSI 2500 blankets was completed. The relative motion of the substructure with respect to the leeward panels was defined and gap definitions were extracted. Hi Temp was chosen to design the field AFRSI blankets for the Leeward panels. The closeout blanket design was completed by BFG. Several weight trade-off studies were performed including a study on the use of supported versus unsupported adhesive to bond the precured skin to the core. The use of unsupported adhesive saved weight and was

evaluated as structurally sound. The removal of two ECS vents in the #7 panel also reduced weight.

QUALIFICATION: Transition seal design (between metallics and leeward) was fully defined and tested in combined environments. BFG completed HTT testing of the carrier plate concept, used to verify attachment concepts. Testing was also completed on the spring back of hi-temperature bulb seals based on seal compression and temperature.

INSTRUMENTATION: Ames completed the instrumentation island design and testing for installation into the AFRSI blankets. Final instrumentation locations and types were defined.

Leeward Aeroshell Penetrations

All penetrations have been designed and incorporated into the panel assemblies. This includes RCS thrusters, antennas and their brackets, access panels, ECS vent panels and doors, and exhaust vents.

Windward Aeroshell Metallic Panel Basic Design

There are two basic panel types, with two material variations on the windward body. The primary panel type is made of Inconel 617 with .006" inner and outer facesheets brazed to .0015" thick, 3/16" cell core with a total thickness at .50". Areas on the vehicle that are subjected to higher temperatures require .010" thick facesheets and .0035", 3/16" cell core. The other primary panel type is a .50" machined isogrid made of Inconel 617, or MA 754 where exposed to higher temperatures. The isogrid panels are used primarily at locations of high curvature where producibility or high stresses dictate their use. Isogrid panels are also used when a penetration, such as an RCS thruster or antenna is located. The use of isogrid panels is minimized, as they are relatively heavier than honeycomb brazed panels.

All brazed or isogrid panels are attached to standoff brackets with PM1000 fasteners that have an integral cap/socket that fills the cavity of the insert in



the panel, and provides a smooth loft surface for the vehicle. Typical panels have four inserts and fasteners at the corners.

The panel-to-panel seals consist of a primary shingle seal, which is an extension of the outer skin, and a secondary seal system. The secondary seal system has a 'J' hook and a leaf seal that contacts the 'J' seal. The secondary seal system has been designed to provide "fly home" capability if the primary seal fails.

Refractory Composite Basic Design

Engineering has been redesigned for the nose cap, skirt, and chin panel assemblies to accommodate a change in material suppliers. 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 and the carbon/carbon details have all been released. Increased fin rotational deflections 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 has been released for the one-piece carbon/carbon component.

Elevon Seal System

The elevon seal system minimizes the flow of high-energy air from windward to leeward and the reverse direction. It also minimizes spanwise flow, preventing overheating of critical structure between the canted fin and the elevons, such as the hinges, actuators, canted fin aft spar, and elevon forward spar.



The elevon seal system consists of three primary type seals that are connected to form a continuous seal from one end of the elevon to the other. The three seal types are: the field bullnose seal, the hinge seal, and the closeout seal. The bullnose seal is an externally sprung loaded silica seal with titanium seal retainers and support fittings. The hinge seal is an externally sprung loaded wiper seal and fixed hinge seal with titanium seal retainers and pressure shelf. The closeout seal is a Nextel bulb seal over-wrapped with wire mesh to provide durability.

All seals are in fabrication.

System Optimization / Trade Studies

Nickel vs. Iron ODS Material Usage Trade Studies

Trade studies have been performed in order to down select the high temp alloys and forms that will be used on the X-33 Metallic TPS. Nickel-based Oxide Dispersion Strengthened (ODS) material was selected over Iron-based ODS material due to 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 due to constraints in the vehicle build schedule, problems obtaining the required minimum gauges and joining development work required for the honeycomb sandwich panel configuration.

TEST AND VALIDATION

Overall Testing Program

Significant milestones of the X-33 TPS test program were achieved during the last year of activity. Some of these tests include the F-15 flight test of various TPS materials, the aerothermal test of a 7-panel array of metallic



TPS in the NASA-LaRC 8ft. High Temperature Tunnel, the Combined Environments test of 9 panels conducted at NASA-MSFC, and arc jet tests of different TPS components. Other testing activities, such as material properties tests, are on going and nearing completion. The significant accomplishments of the last year are summarized in the following sections.

Thermo-Vibro-Acoustic (TVA) Test

Inconel 617 honeycomb 1125 type TPS panels were tested at the Wright Patterson Air Force Base (WPAFB) heated progressive wave tube for 4 life times (60 flights) to the Malmstrom V4 trajectory. Both heating and acoustics loads were applied simultaneously to the panel. The purposes of the tests were to determine if 1) if combined heating and acoustic cycle would damage a panel, and 2) if manufacturing induced voids in the face sheet-to-honeycomb braze would propagate under flight loads.

The test plan is given in document X33T0052 and X33T0026. The test report is provided in document X33T0058. The thermal loading matched the outer skin temperature of panel 8-9 on the windward surface, a highly loaded panel, at 35 points along the flight trajectory. Maximum temperatures reached 1600 F at the center of the panel. The ascent ramp in temperature, which produces the greatest temperature differences in the panel, was accurately reproduced. Acoustic drivers that generated a coherent sound wave across the panel surface provided sound excitation. The flight acoustic spectra were accurately represented between 20 and 600 Hz, a range that contains the fundamental mode and other responsive modes of the panel. The maximum sound pressure levels represented the zone 14 lift off case. For the ascent and reentry portion of the flight the zone 6 acoustic levels were used since they are higher than the zone 14 for these phases of the flight.

The single panel was mounted in the fixture on the stand off support brackets, which were attached to the fixture representation of the substructure. The panels were equipped with primary overhanging seal but they were not fitted with secondary seals. The panels did have fully

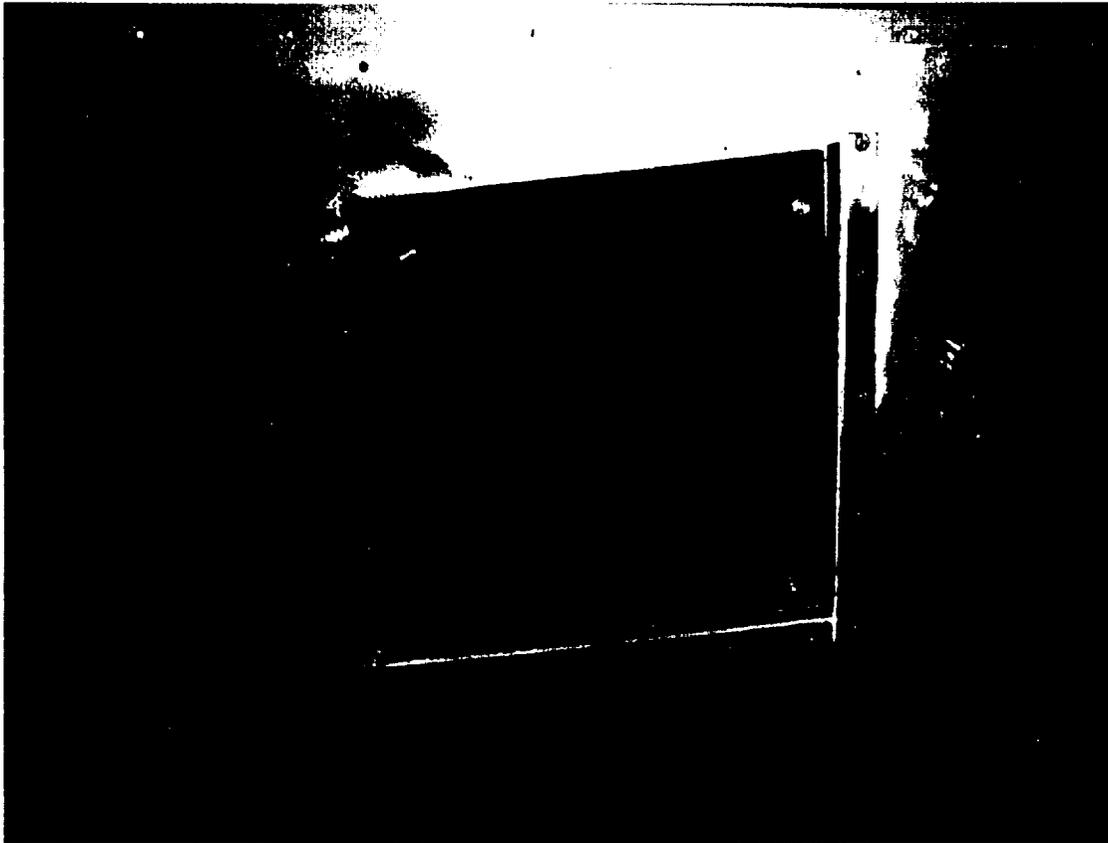


representative insulation pans, inserts, closures and fasteners. The panels had initial manufacturing-induced voids in the braze between the honeycomb core and the panel skins. Instrumentation included thermocouples for both panel tests. Strain gages and accelerometers were used for the first panel tests.

The panels were inspected after completion of 60 flight cycles. The panels, inserts, closures, primary seals, and insulation withstood 4 life times cycling without failure and panels were capable of sustaining design loads and fulfilling their function at the end of the test. Some deformation was found in the panel seals, closures, and skins at the end of the tests. Wrinkling of the panel outer skin occurred opposite a large existing braze void but no cracking was evident. One of the panel initial braze voids propagated 3 or four honeycomb cells – 0.5 to 0.75 inch – after 4 life times. This small propagation was not felt to compromise the load bearing capability of the panel. There was no propagation of any of the other braze voids.

An additional PWT test was performed at BFG Chula Vista to evaluate the feasibility of repairing damaged insulation pans on metallic TPS panels. An 1125 flat TPS panel with insulation pan damage patch repairs in two locations was tested under zone 14 liftoff acoustic loads. One of the patch welds failed. Inspection showed that the patches did not have correct spot spacing and there was insufficient weld penetration. A second test was made with non-rigidized patches that allowed for better contact at welds and a double row of welds was used. This repair withstood the zone 14 lift off acoustic loads and further testing with the addition of 6 dB. The test validated insulation pan damage repair.





Photograph of panel mounted in the WPAFB progressive wave tube
Acoustic waves propagate from right to left

Refractory Composites Testing

Carbon-Carbon Basic Mechanical & Thermal Property Testing

A series of tests are currently underway to measure the physical, mechanical and thermal properties of the C-CAT Carbon-Carbon, ACC-4 material system. Testing is being performed to fully characterize or verify pre-existing data for the C-CAT material. Mechanical property testing is being performed at both B.F. Goodrich/Aerospace and NASA/LaRC. This includes basic



material properties, damage tolerance and repair techniques. Thermal property testing is currently underway at Southern Research Institute (SoRI). Pre-exposure of specimens is being performed at B.F. Goodrich/Aerospace and Composite Testing Analysis (CTA).

All mechanical property testing of the Carbon-Carbon materials is being performed at room temperature. Included in the overall material characterization is a series of environmental/temperature pre-exposure testing that simulates the range of anticipated service conditions. Thermal property testing involves specimens subjected to either arc jet or elevated temperature environments to determine the material's thermal characteristics.

Damage tolerance and repair testing require a series of environmental tests performed on a number of Compression-After-Impact (CAI) specimens made from the C-CAT material system. The specimens are being impacted at two energy levels that produce either threshold damage to the laminate substrate, or substrate damage (i.e., delamination and fiber breakage). These specimens will then be arc-jet tested up to a maximum anticipated in-service exposure temperature under cyclic reentry conditions

Material Characterization Arc Jet Tests at NASA Ames & JSC

Arc-Jet and Side-Arm-Reactor Testing was completed at the NASA/AMES facility on the C-CAT Carbon-Carbon ACC-4 material system. Arc-Jet samples were exposed to high-energy hypersonic air using the flat-faced cylinder configuration. Material stability was evaluated using mass loss, X-ray fluorescence analysis and room temperature spectral hemispheric reflectance data. In addition, atom recombination coefficients were determined using both the side-arm-reactor and arc-jet data.

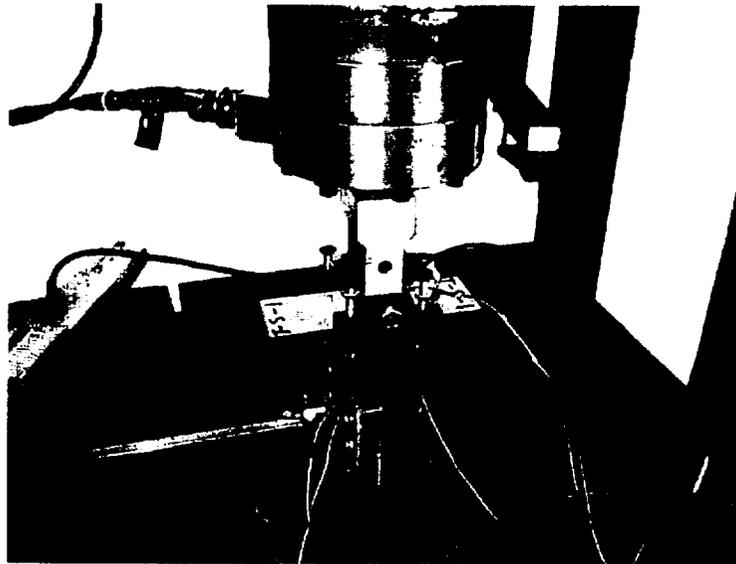
Carbon-Carbon Sub-Element Testing

A series of sub-element mechanical tests are currently evaluating the strength and durability of various key design elements in the refractory composite TPS structures and associated seals. These tests serve to



substantiate the TPS (material & seal) designs and confirm analytical predictions. Testing focuses on design features for which analytical methods are the least proven.

A number of generic flange and "T-Section" static and fatigue Interlaminar Tension pull tests are in-work with testing to be completed by May of 1999. A typical "T-Section" test setup is shown below.



C-C "T-Section" Pull-Off Test

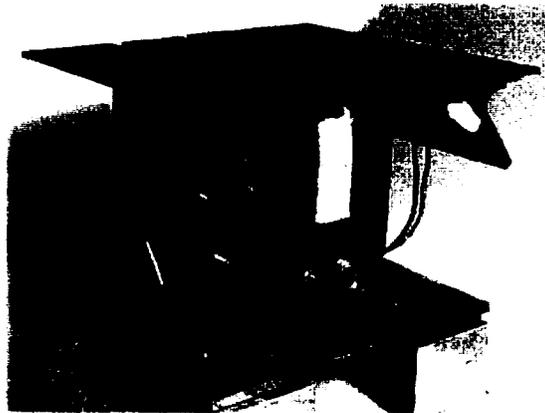
Carbon-Carbon Joint/Seal Verification Test

A series of environmental exposure (e.g. radiant heat and arc jet) tests will be performed at NASA/JSC on the various proposed joint/seal designs. Segments of various joint/seals designs will be used to represent critical design features for thermal analysis of seals and joints. The first article was completed and ready for shipment to NASA/JSC in early March of 1999.

The article consists of three different C-C segments. Adjoining legs either have a nose cap attachment (clevis) or leading edge fillet attachment designs



(bolted hole with shorter distance from OML). The photo below shows the completed Carbon-Carbon sub-element article. The exposed surfaces incorporate the overlap joint seal features of the nose cap and leading edge.



All C-C Joint/Seal Test Article

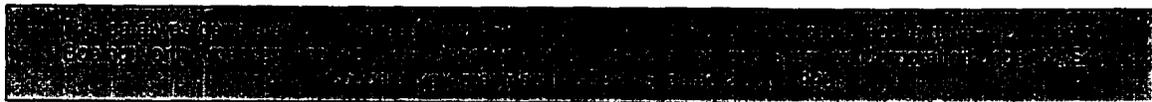
Radiant heat tests will be used to anchor thermal models. Arc jet testing will primarily measure gap heating effects and determine seal performance.

Leeward Aeroshell Testing

Leeward Aeroshell Hot Gas Seal Tests

Four Leeward seal configurations were tested at MSFC. The latest test sequence verified final configuration of the seals to be qualified for X-33 flight. The seal were tested at 10 degree angle of attack (AOA) with bulb preloads that ranged from .020 to .50 inch. The seal to flow orientation included 0 and 90 degrees. The seals withstood the flow environment and the test objectives were met.

Thermo-Vibro-Acoustic (TVA) Test



PWT tests were conducted at BFG on FRSI, AFRSI and AFRSI 2500. These single panel models were pre exposed to arc jet and F-15 flight test environments. The PWT testing included exposure to sound pressure levels that represent ascent, oscillating shock, and re-entry conditions of the X-33 trajectory. All 3 models were tested to four lifetimes.

Leeward Aeroshell Bulb Seal Arc Jet Testing at NASA JSC

Leeward Aeroshell bulb seals were arc jet tested at NASA JSC. The bulb seal was surrounded by two pieces of AFRSI, and was successfully tested to a surface temperature of 750F.

FRSI Blanket Arc Jet Testing at NASA JSC

FRSI blankets were arc jet tested at NASA JSC. The FRSI was tested on aluminum substrates to surface temperatures up to 850F. The purpose of this test was to justify the use-temperature of FRSI to a higher temperature than 750F, which is the use-temperature for Space Shuttle. As a result of these tests, the use-temperature of FRSI was extended to 800F for X-33.

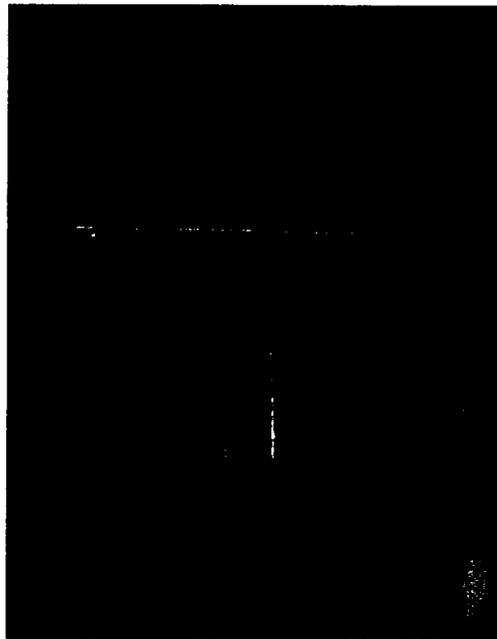
FRSI Blanket Radiant Heat Testing at NASA JSC

FRSI was tested at JSC in the radiant heat facility. The objective of these tests was to increase the FRSI reuse-temperature to 800 deg F. The blankets were bonded to sandwich panel substrates that represent minimum thermal capacity for the leeward composite structure. The test objectives were met and FRSI was tested to OML temperatures greater than 800 degrees Fahrenheit without insulation or coating failure. Heat input that represents the Malmstrom 4 vehicle heat load was used. As a result of these tests, the use-temperature of FRSI was extended to 800F for X-33.

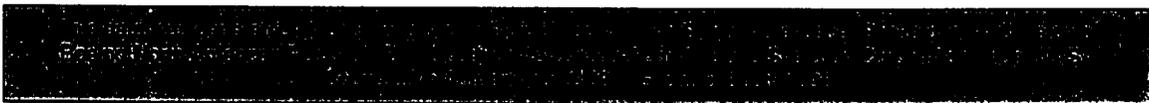
Aerothermal Test in the NASA-LaRC High Temperature Tunnel (HTT)



Leeward Aeroshell AFRSI TPS with bulb seals was successfully tested in the Langley 8-foot HTT. Two test models were evaluated. One model incorporated 2 AFRSI blankets with a butt joint transverse to flow. The second model included 3 AFRSI blankets and 2 sets of mating bulb seals. The bulb seals ran parallel and transverse to tunnel flow. Fourteen of the planned fifteen test runs were completed. The test sequence included radiant preheat prior to insertion of the model into the flow environment. Test conditions included 0, 3, and 6 degree AOA, with radiant preheat temperatures to 1500 F. The test results verified AFRSI blankets and bulb seals to be durable and capable of withstanding the Malstrom 4 trajectory heating.



HTT Test of AFRSI Blankets with Bulb Seals



Windward Aeroshell Testing

Material Property Tests for Metallic

A series of tests are underway to develop the mechanical material properties for MA754 plate, MA754 textured rod, Inconel 617 brazed sandwich and skin properties, Inconel 617 hardened foil, and the properties of an Inconel 617 foil to foil welded joint. BFGoodrich, NASA-LaRC, and several commercial laboratories are performing different elements of the test program.

The material property testing follows established test standards using specimens excised from production material. These tests will determine material properties as defined in LMSW Report 604D0011, "Structural Design Criteria and Design Loads" (ref. 1) and LMSW Report 604D0017, "X-33 SSTO Equipment Thermal, Acoustic, Vibration, Shock and Associated Environmental Design and Test Criteria."

Test results will be used to establish the metallic TPS structural design material properties database, following standard test and data reduction methods. These results will be used for substantiating analyses, for qualification of the X-33 and for developing acceptance criteria of parts and material for component production. Allowable defects testing has also been completed by BF Goodrich to aid in developing acceptance criteria for the manufacture of brazed Inconel 617 panels.

Material Characterization Arc Jet Tests at NASA Ames

Materials characterization arc jet tests were carried out at NASA Ames, from January 98 to present. Data includes emissivity, mass loss, surface recession survivability, and catalysis (recombination rate). This was done at NASA Ames for several metals with a variety of coatings on them.



Arc Jet Testing

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

A metallic Inconel honeycomb 4 panel array was arc jet tested at NASA JSC. This model had been tested in Phase 1, March 1997, and since then was rebuilt and re-tested in August, 1998. The current test series was performed to qualitatively assess seal leakage. Fixturing was built by JSC to allow the measurement of mass and energy 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. The model was tested in several arc jet conditions. After testing the model with all seals intact, a portion of the shingle seal was removed.

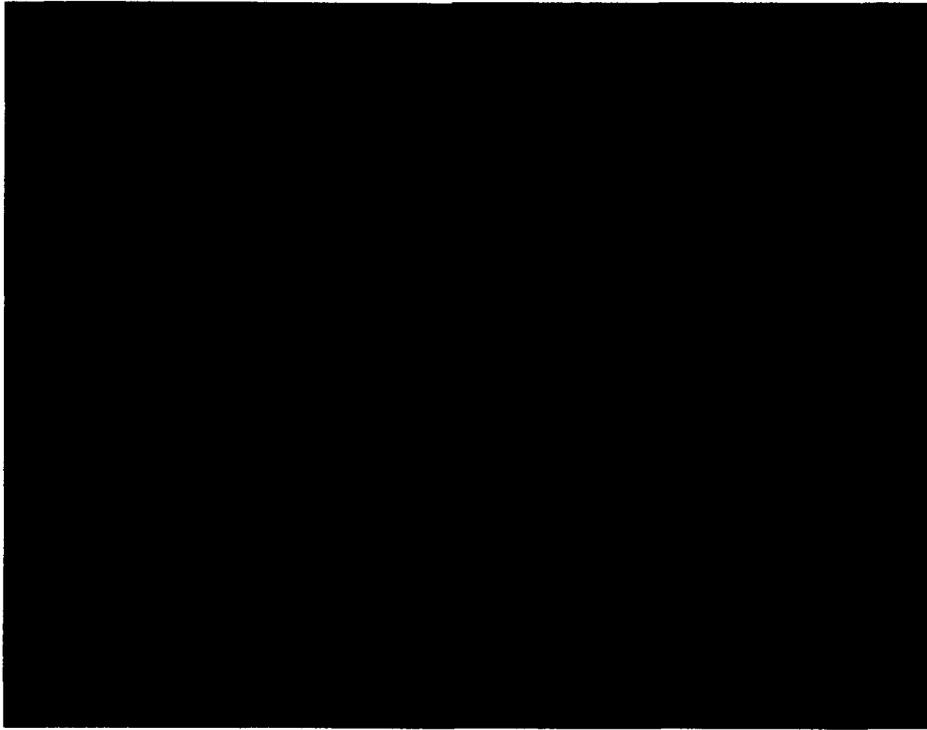
Arc Jet Testing of a Flat Inconel Metallic Honeycomb TPS Panel

Testing of a metallic honeycomb TPS panel in the Arc-Jet was performed at ARC to validate thermal models and qualitatively assess panel performance and seal leakage.

Arc Jet Testing of a Flat Inconel Isogrid Panel with an Antenna

A flat Inconel isogrid panel with an antenna mounted at the center was tested in the ARC arc jet. The hot face of the antenna is made of quartz. The antenna was being operated during the test. The photo below shows a thermal image of this panel during the warm-up phase of the arc jet testing. The antenna is in the center of the image. Due to the high thermal mass of the quartz face of the antenna, the temperature is lower than the surrounding isogrid panel. In this image the ribs of the isogrid structure are visible since the ribs have a different "thermal mass" than the thinner metal across the face of the isogrid cell. The ribs take longer to heat up than the cell face. The performance of both the antenna and the Isogrid panel was as expected.





Thermographic Image of Antenna Isogrid Panel Heating
During an Arc Jet Test

Arc Jet testing of a Flat MA754 Isogrid Panel with an RCS Jet Nozzle

A flat MA754 isogrid panel with an RCS (reaction control system) Jet nozzle mounted at the center was tested in the NASA-ARC arc jet. The performance of both the nozzle and the Isogrid panel was as expected. The photo below shows a thermal image of this panel during the cool-down phase of the arc jet testing. The RCS nozzle is in the center of the image. In this image the rib structure of the isogrid structure is visible since the ribs have a different "thermal mass" than the thinner metal across the face of the isogrid cell. The ribs remain warm longer than the face of the isogrid cells.





Thermographic Image of an RCS Nozzle Isogrid Panel Cooling
After an Arc Jet Test

Arc Jet testing of a Curved Inconel Metallic Honeycomb TPS Panel

Testing of a curved metallic honeycomb TPS panel in the Arc-Jet was performed at ARC to validate thermal models and qualitatively assess panel performance and seal leakage.



Radiant Heat Testing

Full Panel Bowing Tests

Radiant heat tests to evaluate thermally induced bowing of both honeycomb and Isogrid full-sized diamond shaped Inconel TPS panels were performed at NASA-JSC in the Radiant Heat Test Facility (RHTF). The purpose of the test was to verify analytical predictions. In this test, the surface of a honeycomb panel was heated rapidly, generating a thermal gradient through the TPS panel and causing it to bow. An instrumentation technique using LVDT's (linear variable differential transformers) was employed to measure panel displacement. Preliminary results indicate that the bowing is 10% less than predicted.

F-15 Flight Test

During the early ascent phase of the X-33 and the latter portion of the descent phase, the vehicle TPS is exposed to significant aerodynamic pressure and shear loads including impinging shock at transonic speeds. This test was designed to evaluate the durability of the blanket TPS and metallic panel over-lapping seals to X-33 aerodynamic loads. In addition, the tests were used to show that the TPS system is in compliance with the following requirements: 604D0008 paragraphs 3.1.3.4, 3.2.5.2 and flutter criteria per NASA SP-8057 paragraph 4.4.1.3.

In May and June of 1998 a series of six test flights was flown at Dryden Flight Research Center using NASA's F-15B flying test bed. The test articles were mounted on a NASA supplied Flying test fixture which in turn was mounded to the under side of the F-15B. Different configurations of Metallic panels, FRSI, AFRSI, AFRSI 2500 and DurAFRSI blankets were flown and validated for flutter and transonic shock environments.

The six flights were successfully completed and met all of the requirements established in the F-15B Flight Test Plan.



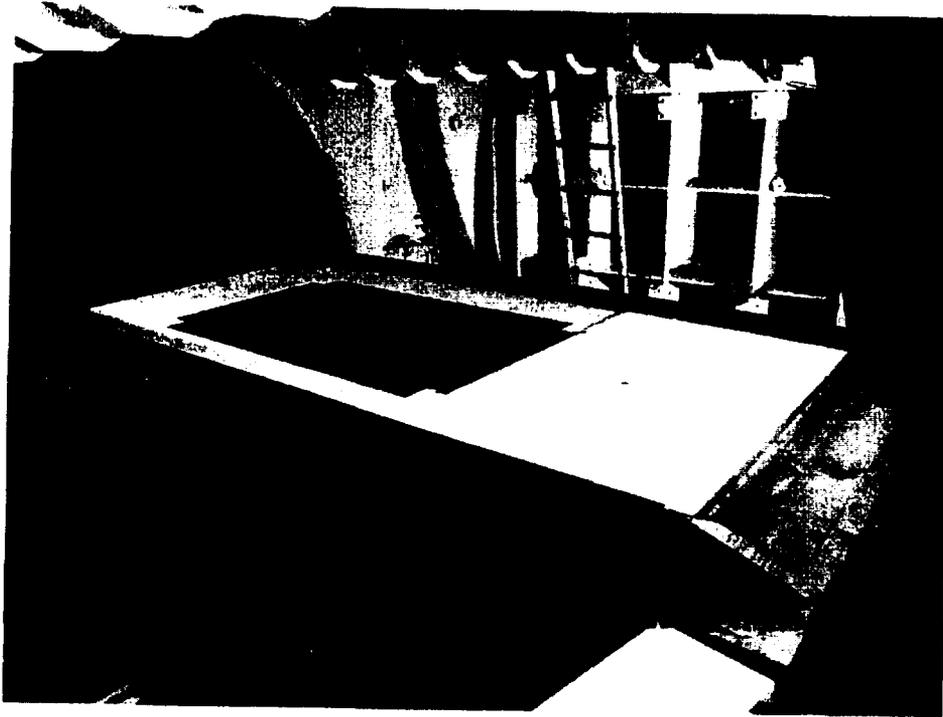


F-15 Flight Test of X-33 TPS Materials

Aerothermal Test in the NASA-LaRC High Temperature Tunnel

Aerothermal testing was successfully conducted in the NASA-LaRC 8' High Temperature Tunnel on a representative test model of the windward surface thermal protection system (TPS) of the LMSW X-33. The 32" x 54" model consisted of seven Inconel 617 TPS panels. The panels were mounted to standoff brackets and substructure clips identical to that used on the flight vehicle. The purpose of the test was to 1) obtain thermal and structural data for correlation of analytical models, 2) evaluate the durability of the panel-to-panel interfaces while exposed to multiple cycles of high temperature, hypersonic flow, and 3) obtain thermal and structural data for hardware off-design cases.



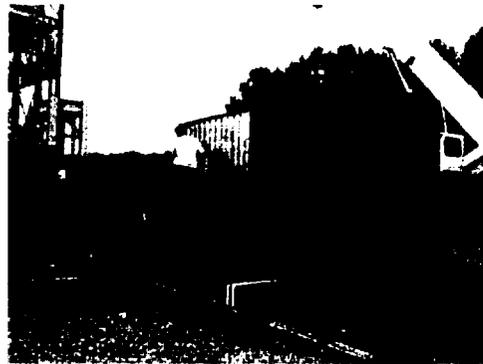
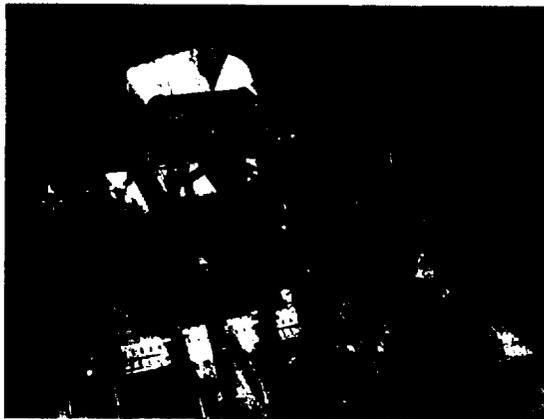


HTT Test of X-33 Windward TPS

The test program was completed in July 1998 with a total of sixteen aerothermal runs conducted on two test articles. The test data obtained were used to correlate radiation heat transfer models of the Inconel honeycomb panels. Seal leakage data obtained during the tests validated the windward TPS surface seal design for X-33 flight requirements. Seal durability was demonstrated for both the as-designed seal and intentionally damaged seals. Off-design cases, including simulated steps, failed attachment fasteners, and damaged seals were tested without failing the TPS panels or attaching hardware. Tests in which the combined temperature and pressure environments of the X-33 flight trajectory were exceeded, were also successfully conducted

Combined Environments Test

A test article representative of the X-33 windward TPS was successfully tested at the NASA-MSFC Combined Environments facility. The model consisted of an array of nine metallic TPS panels that were mounted on a representative section the vehicle substructure and LOX tank. The model was assembled into a large steel plenum box and subsequently installed in the NASA-MSFC Combined Environments facility for test. The model was exposed to simultaneous temperature, acoustic (Zone 6 and 14) and simulated aero-pressure loads that were representative of X-33 flight environments.





Combined Environments Test Article and Installation

Sixty (60) equivalent X-33 mission cycles were completed in October of 1998. Post-test inspection of the model revealed no significant damage or failure of the test hardware. The test has been completed. The test report and analysis for Phase A (metallic to metallic panel) is being written and will be released by the end of March 1999.

Seal Testing

Seal testing has been continuing at BF Goodrich and at NASA-MSFC. Leakage tests under subsonic and supersonic conditions have been conducted for various seal configurations at the NASA-MSFC Hot Gas facility. The leakage rates obtained are less than the required .015lbm/ft flow rate required for the maintaining the BF Goodrich conducted acoustic and flutter tests for the primary shingle seal and secondary seal configurations. Leakage tests were also performed for secondary seal designs. Spring rate, permeability, and wear/abrasion tests are underway at BFGoodrich for Nextel rope seals that will be used in the refractory composite components.

Additional tests are planned for the body flap main and outer seals, the elevon seals, and the intersection region of the windward TPS panels.



Producibility Trials and Demonstrations

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. MA 956 (PM 2000) was dropped from consideration due to material embrittlement by the selected braze alloy. 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.



MANUFACTURING

Manufacturing Processes

Inconel 617 Metallic Panel Brazing Process Definition

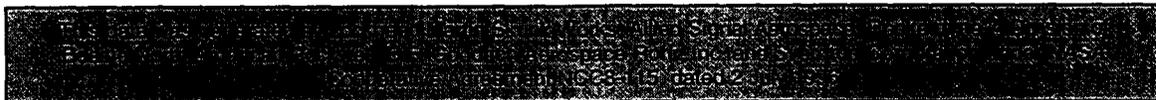
Several brazing alloy foils were evaluated with Inco 617 face sheets and core to replace the salt-and-pepper shaker method used in Phase One of the program. A robust braze cycle was developed. As a result of weight reduction efforts, tests showed that the braze foil could be as thin as 1.0 mil. and still form an adequate bond when measured using Flatwise Tension (FWT) tests. Low Cycle Fatigue (LCF) tests revealed that insufficient braze liquid was present during the braze cycle to form an adequate braze fillet. The braze thickness was increased to meet LCF requirements. No mechanical properties were adversely affected by the braze foil thickness increase.

Although the basic braze cycle has been set, slight adjustments in braze cycle components and tooling setup have been incorporated to maximize the first-pass yield of the process. In general, three different sorts of panel loads are recognized; flat panels, curved panels, and heavy facesheet / heavy core panels. Each has slightly differing tooling and braze parameters 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. Additional analysis of production runs has identified several variables in the braze cycle itself, such as heat-up rate and forced-air cooling, that both shorten the panel bond cycle and increase the braze uniformity in the as-brazed panel.

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.

Isogrid Panel Fabrication

Isogrid Fabrication Process

The fabrication process starts from engineering release where engineering data is converted into tooling and flat pattern data. Next the plate stock is trimmed to the data plus excess and then its trimmed is verified. The detail part is preformed to an approximate radii close to the engineering detail surface. Next the preformed plate is mounted in tooling on a mill and rough machined. After rough machine the plate is stressed relieved and remounted on the mill for final machining. Final machining is very critical it establishes the outer surfaces the ribbed frame and trims the excess from the periphery. Following final machine a hand finish operation removes the cutter marks, de-burrs the edges, polishes and cleans up the machined surfaces. The final operation is the quality verification where the physical part is verified to the engineering configuration.

Isogrid Final Assembly

The final assembly requires the attachment of several different details; shingle seals, secondary seals and the insulation pan. The shingle seals are water jet cut to profile and seam welded to the isogrid. The secondary seals are waterjet cut to profile, formed and then welded to the isogrid. The isogrid insert holes are then broached and outer surface is dust-blasted for paint preparation. The isogrid panel is then paint; cure and paint bond is verified. After that the insulation pan is formed, the insulation packed put into the pan and then its welded to the back side of the isogrid.



Refractory Composites

Fabrication of the leading edge, fillet, and fin tip components is in progress. All densification tools have been received and manufacturing of all components has begun. Ten leading edge components have completed densification. All sections of the canted fin assembly tool have been delivered and set up at the vendor with the exception of the left-hand fillet assembly tool (scheduled for the first week of April 1999). Tooling for the nose cap assembly is in work and production of the nose cap is in progress.

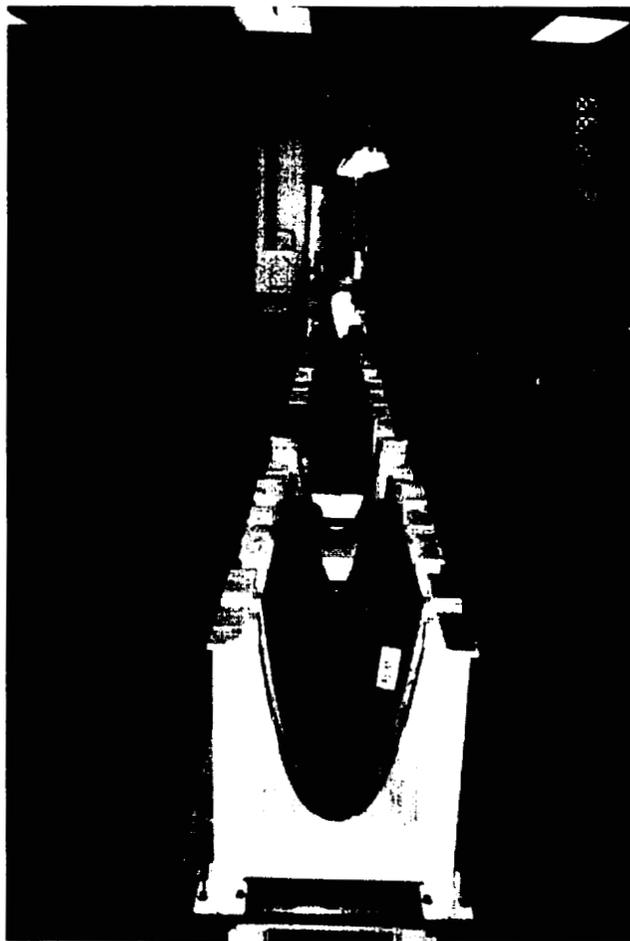


Photo of C-C Leading Edge Components in Assembly Tools



Leeward Aeroshell Tooling and Manufacturing

Composite Lay-up Tools - The last of 17 Leeward Aeroshell composite lay-up and cure tools were completed in November of 1998. These tools are constructed of graphite epoxy face sheet with a rigid welded steel backup structure. Thermal growth mismatch (CTE) between the backup structure and face sheet are controlled through the use of machined steel pads which allow X, Y, and Z travel of the backup structure during autoclave cure of the panels. The face sheet is integrally stiffened with composite stringers. The largest of the tools is approximately 18 ft. X 15 ft.



Photo of Leeward Aeroshell Composite Tool

Machined Foam Patterns - In order to facilitate manufacture of the composite tools a foam "pattern" was used to control surface definition, trim features, and miscellaneous cutouts. Each composite tool required a dedicated foam pattern. The patterns consisted of several layers of 12 inch



thick 12 lb. density foam, which were adhesively bonded together in monolithic fashion and then machined to vehicle contour. Large gantry mills were used to machine the surface of each tool, followed by "hand finishing" and sealing. CATIA loft databases were translated to IGES format to provide cutter path definition of each pattern surface. The largest of foam patterns weighs approximately 22 tons. Each pattern is supported by a welded steel platform that is used to facilitate handling and shipment of patterns.



Photo of Leeward Aeroshell Foam Pattern

Composite Panels – As of February 1999 15 of 17 composite Leeward Aeroshell panels are complete through the manufacturing process. These panels are constructed of graphite epoxy prepreg, epoxy adhesive and aluminum honeycomb. The Leeward Aeroshell is approximately 2000 sq. ft. of composite panel acreage. Integral threaded inserts are manufactured into each panel to facilitate lifting and handling. Composite Carrier Plates are used to attach composite panels to vehicle bulkheads. The composite panels are covered with FRSI and AFRSI thermal blankets to insulate the outer surface of each composite panel to below 250 degrees F during flight. Flexible



seals are mounted to edges of all panels to maintain sealing of adjacent hardware.

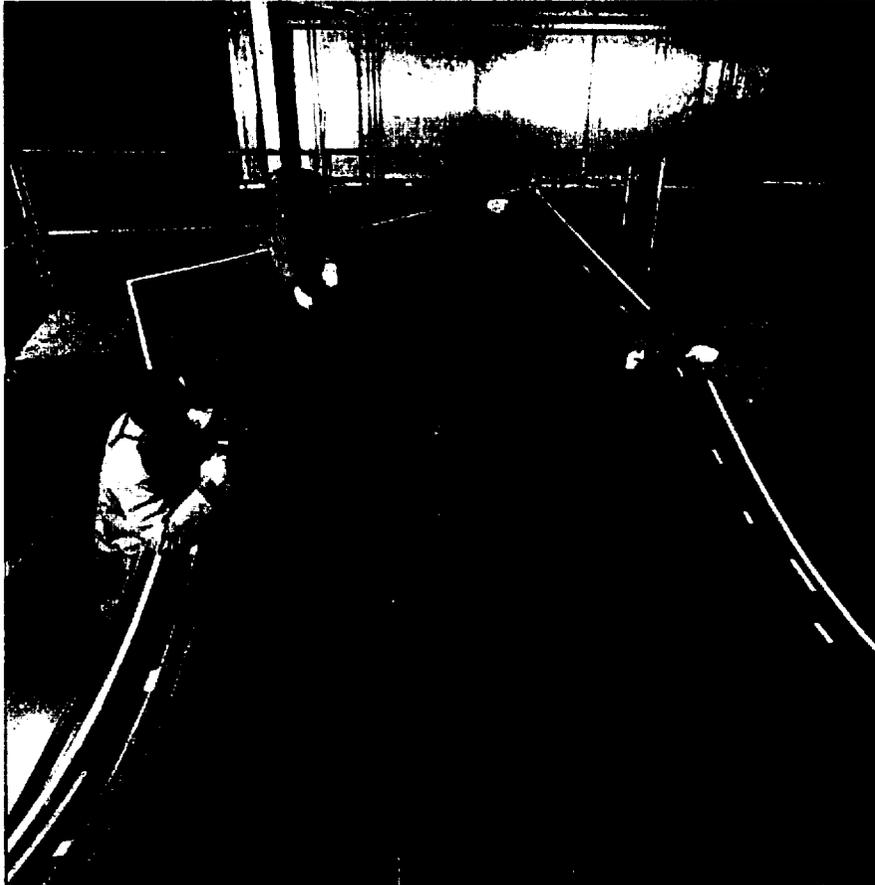


Photo of Leeward Aeroshell Composite Panel

Leeward Aeroshell Tooling Validation - Validation of each tool is accomplished through in-process inspection during the tool manufacturing process. Dimensional inspection is accomplished after foam pattern machining and after completion of post cure of each composite tool. Each tool

and pattern are mapped-out into 12 inch grids and dimensionally verified using Laser Tracking inspection equipment. This data is compared to the CATIA loft database and an inspection report is prepared for each tool. As a part of tool qualification each composite tool is run through an autoclave thermal profile to ensure uniform heat-up can be maintained during composite panel cure. As a part of this process vacuum and pressure integrity is tested to ensure no loss of vacuum is encountered during the process cycle. Upon completion of dimensional inspection, thermal profile, and pressure/leak test the tool is certified for use.





RELIABILITY AND MAINTAINABILITY

Reliability

Line Replaceable Unit (LRU) Reliability Prediction

The LRU Reliability Prediction is a point estimate analysis based upon the design details for the TPS that are available at that point in time. The Reliability Prediction considers the anticipated X-33 operational environment (including ground transportation and handling) and is 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.

Critical Items List (CIL)

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

Preliminary Hazard Analysis (PHA)

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

Subsystem Hazard Analysis (SSHA)

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





identified hazards is documented on a 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

Risk analysis to identify risks associated with the TPS that may impact the system reliability has been completed.

Maintainability

Scheduled Maintenance Tasks

BFG has provided, through team milestone L-25, the recommended scheduled maintenance tasks for the TPS. These maintenance tasks consist of required inspections and refurbishment tasks for each line replaceable unit (LRU) for the TPS. BFG has completed the input of reliability data into the LMSW Reliability Centered Maintenance (RCM) program. This is the probability of failure and the consequence of failure for each LRU. The RCM program produces a list of maintenance tasks to mitigate (through maintenance) the most significant predicted failures to the X-33 vehicle. Since the TPS is the external surface of the vehicle the RCM program identified a critical list of TPS inspections to mitigate foreign object damage. These critical inspection tasks are loaded in the LMSW Processing and Maintenance Activity system. Each TPS inspection will be utilized to document and track the condition of the TPS to isolate the root cause of damage to the TPS throughout the flight test program.





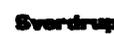
Demonstrations / Validations

The metallic windward TPS was designed to provide access to critical subsystems in the vehicle. Thirteen flat 933-1125 panels were installed, on standoff brackets, on the vehicle at LMSW. Each metallic windward panel overlaps the panel directly behind. A 933-1125 panel, surrounded by other panels was removed to demonstrate the speed of removal. A 933-1125 panel was removed and replaced in 19 minutes. A curved mockup of the vehicle was built to demonstrate the removal of a curved 933-1126 panel. A 933-1126 panel was removed and replaced in 17 minutes. Those demonstrations validated the TPS design for rapid access on the windward flat surface and the curved chine of the X-33. Some large graphite/epoxy leeward panels were also installed on the vehicle at LMSW. As the #1 left and #1 right hand panels were installed on the upper structure the technique for installation was validated. The keys to unencumbered installation were to ensure the lifting fixture was rigged to hold the panel in the orientation required to position the panel on the frame, and to install fasteners at the fixed locations first. The forward and aft nose landing gear door structures were positioned in the nose landing gear box. The doors were opened and closed to verify the range of motion and door/seal position. This validated the installation procedure for the forward and aft nose landing gear doors.

Mechanical Structures

Landing Gear Doors

The forward and aft nose landing gear door structures are assembled. The preliminary installation of the forward and aft nose landing gear doors is complete. The doors require the assembly of the TPS and the flight test instrumentation before they can be rigged for flight. The main landing gear door assembly tools are complete. The bond panels for the left hand and right hand doors are complete. The main landing gear doors require structural assembly, TPS assembly and flight test instrumentation before installation on the vehicle at LMSW.



Elevons

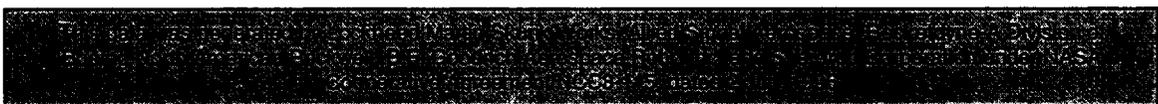
There are four elevons that are movable control surfaces for the vehicle. The assembly of all four elevons is in progress. The right hand inboard elevon and the right hand outboard elevon require flight test instrumentation. The elevons are titanium box structures that will have ceramic tiles bonded on the external surface for thermal protection.

Canted Fin Structures

The titanium inner fixed fairing structures were delivered in a kit to LMSW and will be assembled on the canted fin structure in the assembly tool. The inner fixed fairing will have ceramic tile bonded to the external surface. The standoff brackets for the windward metallic TPS panels on the canted fin have been delivered to support the build sequence of the canted fin. The canted fin assembly tool controls critical positioning of the standoff brackets. The standoff brackets had to be available at LMSW while the canted fin structure was still in the assembly tool. Fabrication has started on the metallic fillet panels. These panels close out the intersection between the canted fin structure and the fuselage structure.

Control Surface Seals

There are seal systems between the fixed and moveable control surfaces. The elevons are installed on the aft end of the canted fins. The body flaps are installed on the aft end of the fuselage. Both types of moveable control surfaces have sealing systems. Fabrication of the seal details is in progress. The seal details are assembled on the vehicle at LMSW. The seal systems must be installed using the assembly tools at LMSW.





QUALITY ASSURANCE

Quality Assurance Plan

A Quality Assurance Plan based on ISO 9001 has been implemented to ensure that 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 has been implemented to 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-conformance's 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.

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

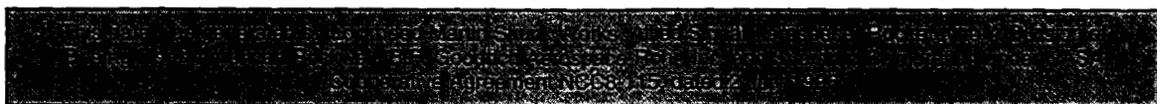


inspection systems, inspection documentation, metrology, calibration, special process controls, material storage handling and purchase material controls.

Nondestructive Testing Methods

Evaluation studies were completed and Pulsed Infrared Thermography (PIRT) was selected as the primary nondestructive testing method for post braze metallic TPS. A Thermography Nondestructive Testing (TNDT) technique has also been developed for the vehicles Leeward Aeroshell. These assemblies are comprised of large graphite/epoxy aluminum honeycomb sandwich panels.

Ultrasonic pulse echo and through transmission inspection techniques are the secondary or back up methods for both metallic and graphite/epoxy assemblies. One Level III and two Level I personnel at our facility have been certified in thermography to perform these inspections.





X-33/RLV PROGRAM

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**AEROSPIKE ENGINES
ANNUAL REPORT
(RD99-251)**

April 1, 1998 – March 31, 1999



Rocketdyne Division



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FORWARD

This document is an Annual Performance Report and is submitted in accordance with Clause 17(1) of Cooperative Agreement No. NCC8-115. It describes the aerospike engines progress made during the past year in support of the X-33/RLV Program.



ACRONYMS AND ABBREVIATIONS

ATP	Authority to Proceed
CDR	Critical Design Review
CT	Computer Tomography
CTTD	Composite Turbine Technology Demonstrator
CWI	Combustion Wave Ignition
CWIS	Combustion Wave Ignition System
DFR	Design For Reliability
DOF	Degree of Freedom
ECDIU	Engine Controller Data Interface Unit
EMA	Electro-Mechanical Actuator
EMAEC	Electro-Mechanical Actuator Electrical Controller
EPL	Emergency Power Level
FSRD	Flight System Requirements Document
FTP	Fuel Turbopump
GG	Gas Generator
GGV	Gas Generator Valve
GLOW	Gross Lift-Off Weight
GSE	Ground Support Equipment
GSRD	Ground System Requirements Document
HIP	Hot Isostatic Pressure

HPFTP	High Pressure Fuel Turbopump
HSL	Hardware Simulation Laboratory
IPD	Integrated Powerhead Demonstrator
IR&D	Independent Research and Development
LaRC	Langley Research Center
LeRC	Lewis Research Center
LOX	Liquid Oxygen
LMSW	Lockheed Martin Skunk Works
LSTB	Linear System Test Bed
MSFC	Marshall Space Flight Center
NASP	National Aerospace Plane
NDE	Non-Destructive Evaluation
OMS	Orbital Maneuvering System
PRA	Pressure Regulation Assembly
PPFIV	Powerpack Fuel Isolation Valve
PPO	Powerpack Out
PRA	Pressure Regulation Assembly
PRD	Preliminary Requirements Document
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RSC	Rockwell Science Center



SCO	System Checkout
SiC	Silicon Carbide
SRD	System Requirements Document
SSC	Stennis Space Center
SSTO	Single Stage To Orbit
STE	Special Test Equipment
VMC	Vehicle Mission Controller
VMCI	Vehicle Mission Controller Simulator Interface





1.0 OVERVIEW

Substantial progress was made during the past year in support of the X-33/RLV program. X-33 activity was directed towards completing the remaining design work and building hardware to support test activities. RLV work focused on the nozzle ramp and powerpack technology tasks and on supporting vehicle configuration studies.

On X-33, the design activity was completed to the detail level and the remainder of the drawings were released. Component fabrication and engine assembly activity was initiated, and the first two powerpacks and the GSE and STE needed to support powerpack testing were completed. Components fabrication is on track to support the first engine assembly schedule. Testing activity included powerpack testing and component development tests consisting of thrust cell single cell testing, CWI system spider testing, and EMA valve flow and vibration testing.

Work performed for RLV was divided between engine system and technology development tasks. Engine system activity focused on developing the engine system configuration and supporting vehicle configuration studies. Also, engine requirements were developed, and engine performance analyses were conducted. In addition, processes were developed for implementing reliability, mass properties, and cost controls during design. Technology development efforts were divided between powerpack and nozzle ramp technology tasks. Powerpack technology activities were directed towards the development of a prototype powerpack and a ceramic turbine technology demonstrator (CTTD) test article which will allow testing of ceramic turbines and a close-coupled gas generator design. Nozzle technology efforts were

Page 6



focused on the selection of a composite nozzle supplier and on the fabrication and test of composite nozzle coupons.

2.0 XRS-2200 ACCOMPLISHMENTS

2.1 ENGINE SYSTEMS DEVELOPMENT

Significant XRS-2200 engine systems development progress was made. Activity included engine control system design and assembly, engine control software development, and initiation of powerpack testing.

2.1.1 Control System Design and Assembly

In control system design and assembly, a majority of the components have been received from the suppliers, some testing has been conducted, and progress has been made on harness fabrication. Components received include all of the ECDIU's and EMAEC's and a majority of the flight instrumentation. For the ECDIU's, a recycle to the supplier will be required for replacement of improperly manufactured heat sink board interfaces. Also, the GG EMAEC's encountered significant difficulties during powerpack testing which will result in most units being returned to the supplier for rework. All of the harnesses for the four engines were completed through initial production in support of a program payment milestone, and final lengths were developed using Pro-E modeling. Rework of the harnesses to the final lengths was initiated.



2.1.2 Control System Software Development

Control software development included release of OI-1 software to support powerpack testing. The OI-1 release was revised several times to implement additional capabilities as the testing program grew more complex. All released software was verified at the hardware simulation laboratory (HSL) at NASA MSFC. In support of test stand operations, versions of the VMC simulator and VMCI software were also released. The engine control laws were developed and delivered to the software team as well as to LMSW. The control laws now provide control for all modes of engine operation. Updates are expected over the next year as powerpack and engine test data becomes available.

2.1.3 Powerpack Testing

Powerpack testing was initiated at the A-1 test stand at NASA SSC on Powerpack #1. Six tests were run through December 1998 demonstrating ignition; open loop transition to the 80% power level; transition to closed loop control; operation at the 57%, 80%, and 100% power levels; 15% and 30% power level ramp rates; and a maximum demonstrated duration of 109 seconds. One redline cutoff for LOX pump primary cavity seal pressure was revealed to be the result of a facility drain line-sizing problem. This was corrected. Figure 1 shows a hot-fire test on the A-1 test stand.

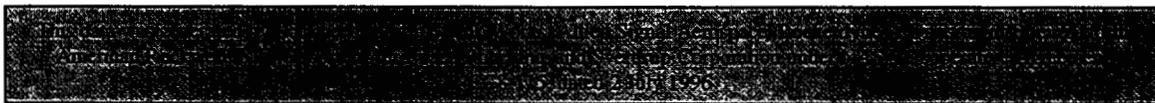




Figure 1. Powerpack #1 Hot-Fire Test On A-1 Test Stand

2.2 POWERPACK AND VALVES

2.2.1 Gas Generator and Heat Exchanger

Fabrication and assembly of the gas generator and heat exchanger program deliverables was completed. This included four gas generator units of which two units were delivered for powerpack assembly in 1998. All of the heat exchanger units were completed. Figure 2 shows an instrumented gas generator used for powerpack testing, and figure 3 shows the completed heat exchangers which were delivered to support powerpack assembly.



Figure 2. Gas Generator Instrumented for Powerpack Testing

2.2.2 Fuel and Oxidizer Turbopumps

Two each of the planned four fuel and oxidizer turbopump assemblies were completed and delivered in support of powerpack assemblies during 1998. The third and fourth fuel and oxidizer turbopumps are being completed. Figure 4 shows a completed fuel turbopump assembly.



Figure 3. Completed Heat Exchanger Assembly

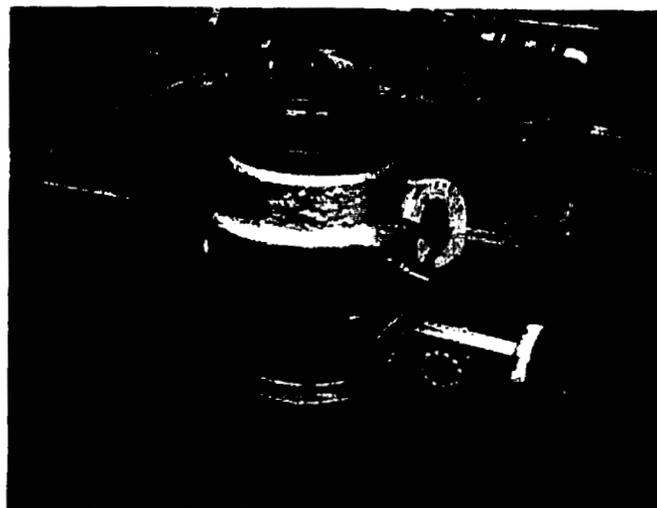


Figure 4. Fuel Turbopump Assembly

This data was generated by Lockheed Martin Skunk Works, Allied Signal Aerospace, Rocketdyne-A Division of Boeing North American Rockwell, B.F. Goodrich Aerospace-Rohr, Inc., and Sverdrup Corporation under NASA Cooperative Agreement NCC8-115, dated 2 July 1996.

2.2.3 Valves

Significant progress was made on the XRS-2200 valves during 1998 including completion of small valve details to fully support all powerpack assembly units and partial completion of gas generator valve (GGV) development testing. Also, an assessment of the effect of powerpack fuel isolation valve (PPFIV) leakage to the operating powerpack during powerpack out (PPO) was conducted.

Valve activities in support of powerpack assemblies included completion of details for the bleed valves, relief valves, 3-way solenoid valves, and spin start relief valve. Combustion Wave Ignition (CWI) valve critical design reviews were completed and all action items closed. CWI valve fabrication and assemblies are in work.

GGV flow and torque and life cycle testing were successfully performed at NASA MSFC, and vibration testing was initiated. Figures 5 and 6 show fuel and oxidizer GGV's installed in the valve test stand for life cycle and vibration testing, respectively. Also, fabrication of hardware details for the thrust vector control valves (TVCV) was completed. Figure 7 shows completed TVCV hardware.



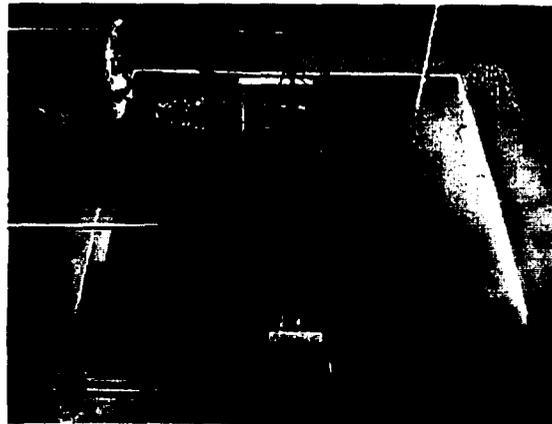


Figure 5. Fuel GGV Assembly During Life Cycle Testing

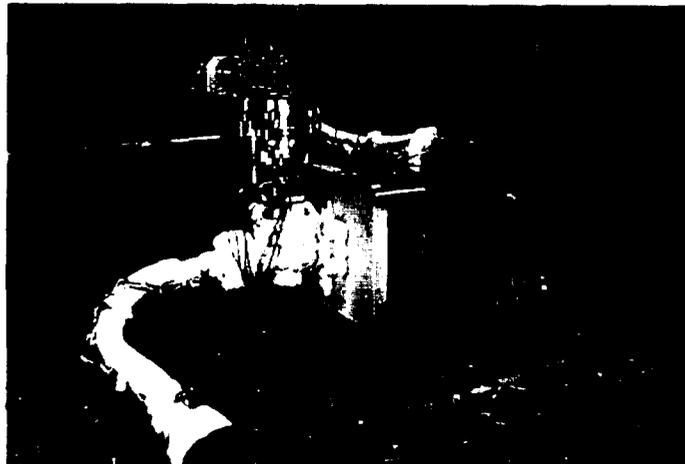


Figure 6. Oxidizer GGV Assembly During Cryogenic Vibration Testing

This data was generated by Lockheed Martin Skunk Works, Allied Signal Aerospace, Rocketdyne-A Division of Boeing North American Rockwell, B.F. Goodrich Aerospace-Rohr, Inc. and Sverdrup Corporation under NASA Cooperative Agreement NCC8-115, dated 2 July 1996

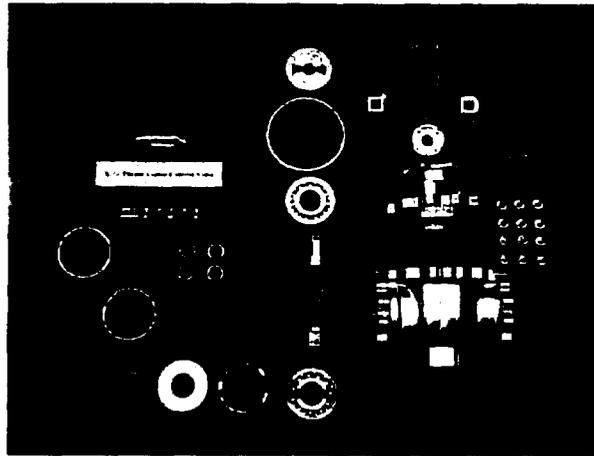


Figure 7. Thrust Vector Control Valve Hardware

An assessment of the effect of PPFIV leakage to the operating powerpack during PPO operation was conducted which involved a combined turbomachinery and valve analysis effort. During PPO operation, fuel vapor is introduced into the flow inlet of the operational fuel pump due to leakage past the PPFIV of the inoperable powerpack into the vehicle fuel tank and across the fuel tank crossover duct. Analysis concluded that the fuel vapor will not adversely affect the operating fuel pump. Also, the PPFIV's will be assembled to minimize the reverse flow leakage across the valve. This solution was tested at cryogenic conditions to ensure no adverse design effects. A planned PPO test during dual engine testing will verify the analysis.

2.3 THRUST CELLS ARRAY

2.3.1 Combustion Wave Ignition System

Testing was completed at NASA LeRC on the combustion wave ignition system (CWIS) spider test rig. The CWIS spider test rig shown in Figure 8 simulates a full engine ignition system consisting of 20 igniters, feed and combustion wave tubing, small engine valves, and spark ignition equipment. A total of 92 hot fire tests was conducted to map and verify combustion wave propagation and pilot ignition for the engine tank head pre-pressurization start conditions.

The tests demonstrated engine-type valves and resulted in the development of valve timing, prime rates, purges, and the overall ignition sequence. Margin was demonstrated above and below the full range of planned tank start pressures. The test program also resolved the significance of propellant feed geometry on ignitability as well as the impact of pre-start purge timing on ignition. A close-up of several igniters firing in their simulated combustion chambers is shown in Figure 9.



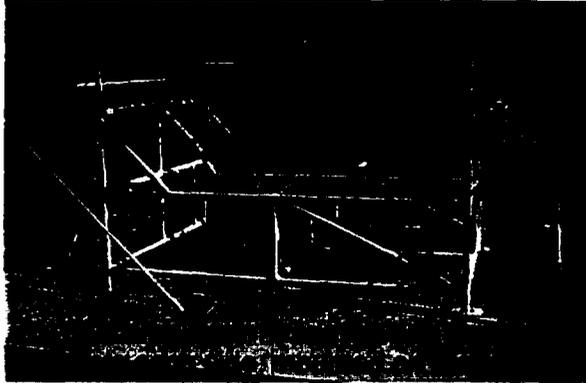


Figure 8. CWIS Spider Test Rig

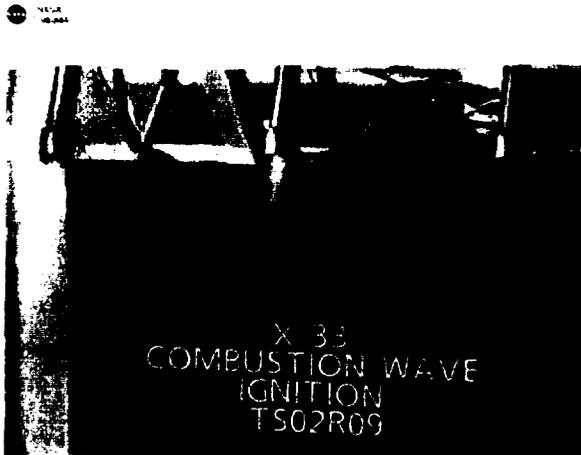


Figure 9. CWIS Spider Test Rig Igniters

This data was generated by Lockheed Martin Skunk Works, Allied Signal Aerospace, Rocketdyne-A Division of Boeing North American Rockwell, B.F. Goodrich Aerospace-Rohr, Inc. and Sverdrup Corporation under NASA Cooperative Agreement NCC8-115, dated 2 July 1996

2.3.2 Thrust Chamber Assembly

2.3.2.1 Single Cell Testing. The first flight configuration thruster was delivered to NASA MSFC for hot fire verification testing and installed on Test Stand 116 as shown in Figure 10. Consisting of a regeneratively cooled chamber, main injector, and CWI igniter, a total of 13 mainstage firings and 986 seconds of operation were accumulated on the thruster. Operability, cooling, pressure drops, and compatibility of the components were demonstrated. The testing bounded the engine operating map from 56 to 119% engine power level and 3.9 to 6.4 engine mixture ratio. Highlights of the testing included:

- two 100% power level firings for 150 seconds each
- one 72% power level firing for 250 seconds (test stand duration capability)
- one 115% power level firing at engine mixture ratio of 6.2 for 90 seconds.



Figure 10. Single Cell Thruster Installed On MSFC Test Stand 116

The 115% power level firing resulted in throat overheating; however, the test conditions for this test are worse than those expected during an actual mission. As a result of the overheating, two final tests were added to demonstrate thruster durability for flight with and without polishing maintenance. The two final tests consisted of 40 second and 100 second firings at adverse altitude conditions. Capability for flight was confirmed.

Testing is now concluded, and the hardware will be returned from NASA MSFC for evaluation.

2.3.2.2 Hardware Fabrication

Thrust cell array hardware fabrication proceeded to support engine assembly. Injector production is proceeding as planned, and fabrication issues for the combustion chambers and ladders were resolved.

Thirty injectors have been completed. This supports the first development engine (engine assembly 1) and half of the first flight engine (engine assembly 2). Thirty additional injectors were assembled and are nearing completion of final machining and installation of the inlet elbow. These will fulfill both flight engine assemblies (2 and 3) and are expected to be complete in March 1999.

Ten combustion chambers have been completed. A total of 14 more are through HIP braze assembly and are in the final stages of machining, proof testing, and calibration. Latent issues with braze restriction found in units 11 and 12 during calibration have caused many of the completed chambers to be subjected to reinspection via computer tomography and high-energy digital x-ray. It is believed that this issue is limited to chambers that were special furnace brazed a second time to repair aft bond leaks. Fabrication of the thrusters is proceeding to support the engine assembly schedule.

An issue that was discovered during engine 1 ladder fabrication was resolved. A gross unbond of the copper face sheet due to poor brazing was found which jeopardized the completion of the ladder. After a lengthy investigation, the cause of the poor brazing was traced to tool distortion at furnace temperature. As a result, the tooling was strengthened, and a good bond



joint was realized on the next unit. The ladders are now making rapid progress.

2.4 NOZZLE

2.4.1 Nozzle Ramps

Significant progress was made on the thrust ramp production hardware. The engine 1 thrust ramps successfully completed both brazing cycles and all final machining steps. Ramp 1A, shown in Figure 11, is being prepared for final assembly, which will include the attachment of the inlet and discharge lines. The thrust ramps for the first flight engine (engine 2) are also progressing and have been successfully processed through the first braze cycle.

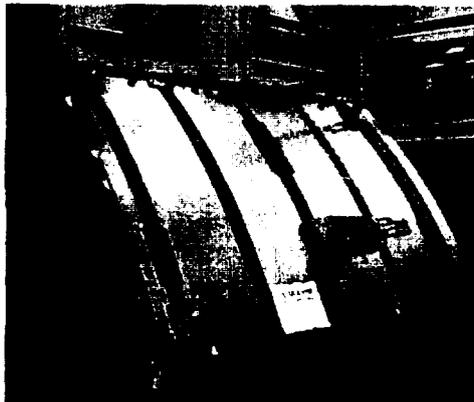


Figure 11. Nozzle Ramp 1A

2.4.2 End Closeout Assembly

The first engine end closeout assembly, shown in Figure 12, has progressed to final bonding and installation of the thermal protection tiles. The first two assemblies completed are planned to support the ground test program; two flight-weight panels being fabricated will support the flight program.



Figure 12. First Engine End Closeout Assembly

2.4.3 Base Closeout Assembly

Significant progress has been made on the first base closeout assembly. The internal structure of the first unit, shown in Figure 13, has been welded and is being prepared for the external skin. Fabrication of all of the detail components for the remaining base closeout assemblies is nearing completion.

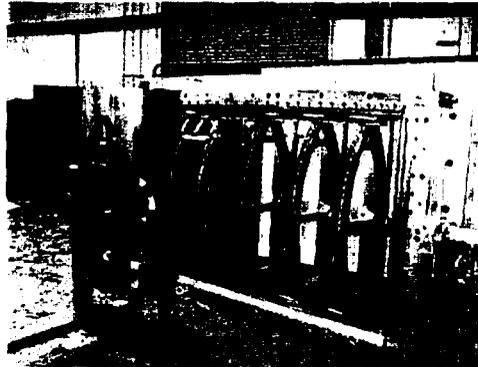


Figure 13. First Base Closeout Assembly

2.5 ENGINE DESIGN AND ASSEMBLY TEAM

2.5.1 Engine System Assembly and Hardware Fabrication

Significant engine design and assembly progress was made during the past year. This includes the near completion of the detailed design and assembly planning activities as well as the assembly of the first two powerpacks.

In support of engine 1 assembly needs, detailed part designs are nearly complete and all major engine assembly drawings are either complete or are in work and will be released to support the assembly schedule. In addition, streamlined assembly planning will be in place, and the engine solid model will be used on the assembly floor as an aid.

The first two powerpack assemblies were completed in 1998. Delivery of the powerpack frames, ducting assemblies, and system hardware supported powerpack assemblies 1 and 2. Figure 14 shows the first welded tubular

titanium powerpack frame, and figure 15 shows the first completed powerpack assembly. The second and third powerpack frames were also received. Weekly hardware meetings were instituted to support powerpack assembly and will continue for the first engine build assembly which was initiated at the end of 1998.

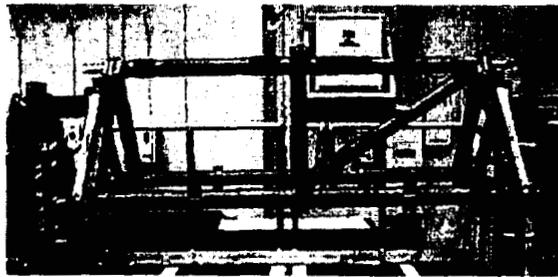


Figure 14. Powerpack Frame #1

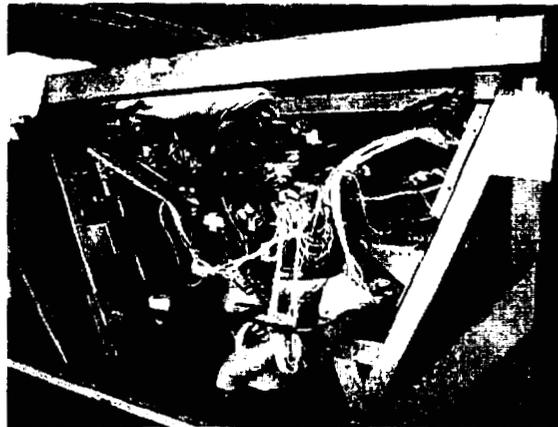


Figure 15. Powerpack Assembly #1

2.5.2 GSE/STE Hardware Fabrication

Ground support equipment (GSE) and special test equipment (STE) activities were focused on completing the GSE/STE designs and fabricating the fixtures needed to support powerpack testing and handling. Three powerpack test fixtures and GSE handling structures were delivered to support powerpack testing. Figure 16 shows a powerpack test fixture. Design of the engine handler and dual engine test equipment is in process to support single and dual engine test. Also, in the area of operations, support was provided to LMSW to develop the system checkout (SCO) procedure, and delivery of the master interface tooling to LMSW was coordinated.

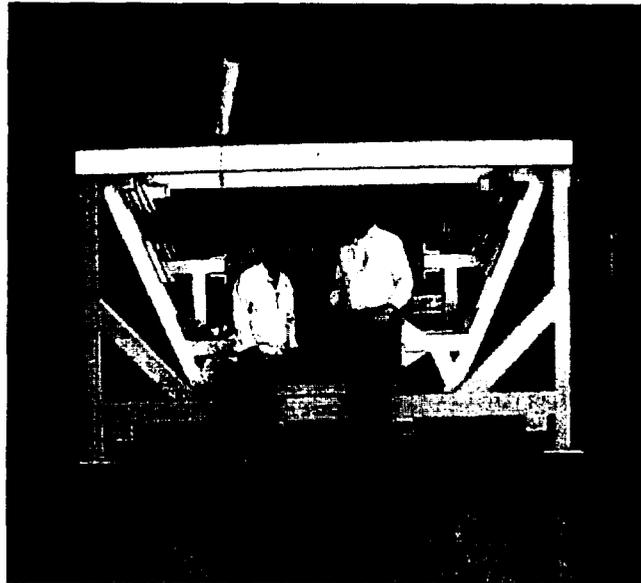


Figure 16. Powerpack Test Fixture

2.6 SYSTEMS ENGINEERING AND INTEGRATION

The 1998 systems engineering and integration (SE&I) activity was directed towards supporting a number of on-going program efforts. These included

coordination of internal and external engine integration issues, configuration management including drawing release and change request management, risk management, requirements verification planning, and maintenance of requirements and interface control documents. Specific SE&I accomplishments during 1998 included the release of 612 engine system design drawings and 474 ground support equipment drawings, on-going risk coordination with LMSW and maintenance of an engineering risks watch list, creation of a verification database, and update and release of the Prime Item Development Specification (PIDS) and engine hardware and software Interface Control Documents (ICD's). In addition, a structural requirements document was updated and released.

2.7 AEROJET X-33 RCS SYSTEM

The RCS completed several major milestones including the delivery and installation of the five propellant tanks, fabrication and testing of the two flight pressure regulation assemblies, completion of system verification testing, and acceptance testing of all eight flight thrusters.

2.7.1 Propellant Tanks

Delivery of the five high-pressure gaseous propellant tanks was completed. The two oxygen tanks were delivered in April 1998, and the three methane tanks were delivered in July 1998. Concurrently, a methane tank successfully completed qualification testing consisting of 200 pressure cycles followed by a burst test. The burst pressure was approximately 8900 psia indicating significant margin against the 7500 psia design burst. Figure 17 shows a methane tank installed on the vehicle.



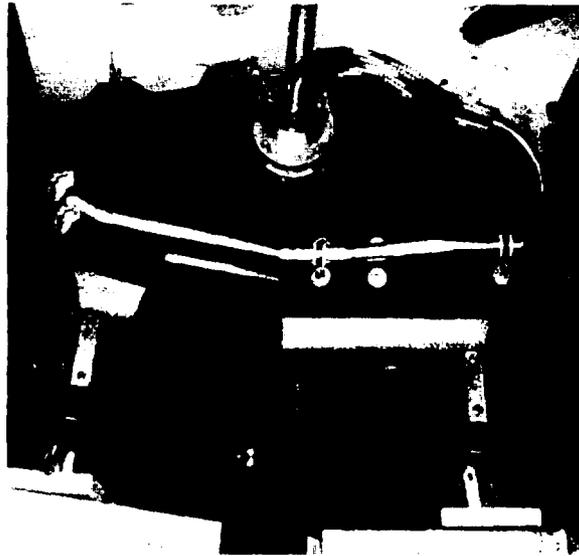


Figure 17. RCS Propellant Tank Installed On X-33 Vehicle

2.7.2 Pressure Regulation Assemblies

The oxygen and methane pressure regulation assemblies (PRA's) are shown in Figures 18 and 19. Each PRA contains two regulators, a primary and a secondary unit, plus isolation valves and sensors. As a part of the system verification testing conducted, the two assemblies were tested at both nominal and extreme simulated mission duty cycles. These two units were refurbished and then delivered to the vehicle in February 1999.

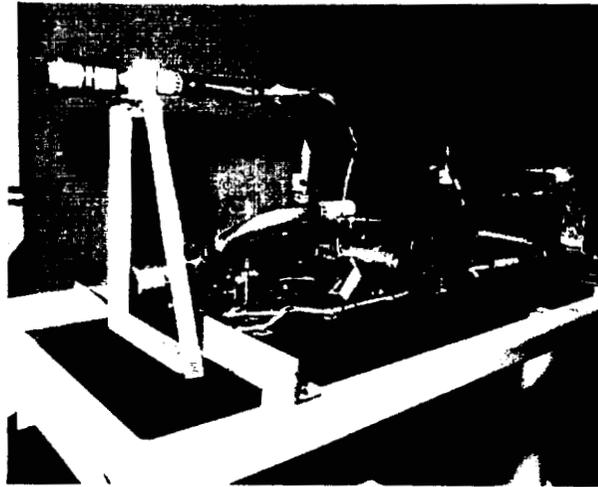


Figure 18. Oxygen PRA

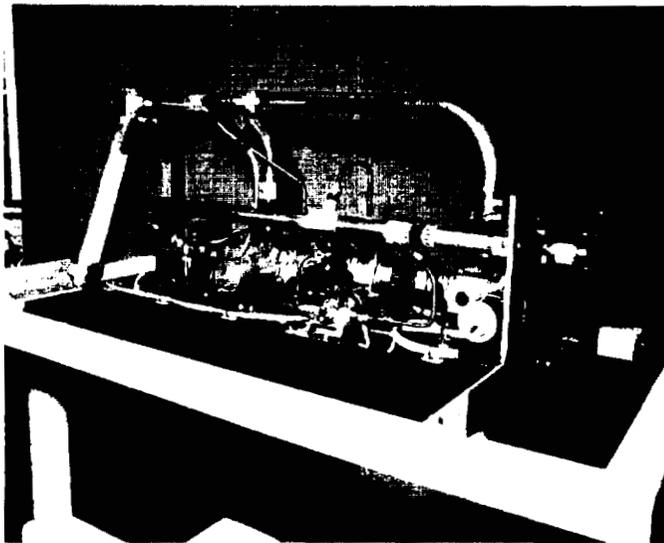


Figure 19. Methane PRA

This data was generated by Lockheed Martin Skunk Works, Allied Signal Aerospace, Rocketdyne-A Division of Boeing North American Rockwell, B.F. Goodrich Aerospace-Rohr, Inc. and Sverdrup Corporation under NASA Cooperative Agreement NCC8-115, dated 2 July 1996

2.7.3 System Verification Testing

System verification testing was successfully completed in December 1998. The test set up consisted of a full set of five propellant tanks (two vehicle spares and three system test units), two flight PRA's, two sets of simulated vehicle thruster supply lines, three thrusters (qualification and development units, not deliverables), and two thruster valve and venturi sets capable of simulating two additional thrusters. Figure 20 shows the tanks and Figure 21 shows the three thrusters in a test pod. This test set-up allowed verification of system level requirements including total impulse, five thruster on capability, and switch over from the primary to the secondary regulator. During testing, the RCS completed a simulated Michael 7C6 mission duty cycle. Data analysis from the test indicates that the RCS provides the required total impulse of 112,210 Lbf-sec with 7.4% propellant margin.

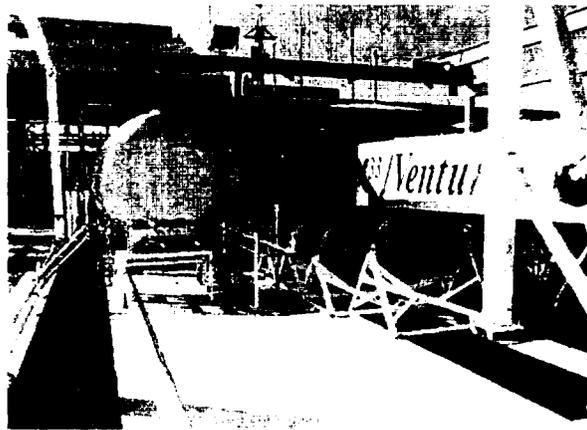


Figure 20. System Test Propellant Tanks

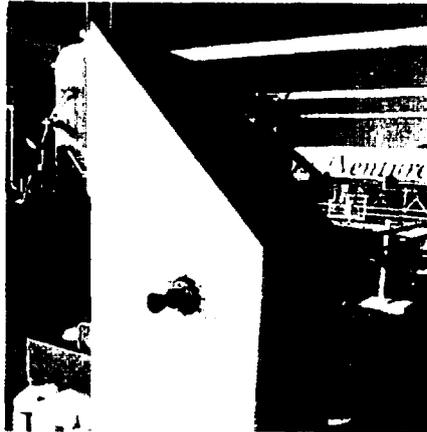


Figure 21. System Test Thruster Array

2.7.4 Thrusters

Flight thruster acceptance testing was conducted for all eight thrusters. Prior to thruster acceptance testing, several other activities were conducted including fabrication and qualification testing of sequencer, exciter, and thruster module subassemblies. In addition, verification of the flight software was completed, and a thruster qualification unit was assembled and completed qualification testing. The eight flight units were assembled and acceptance tested.

As a result of several Haynes 188 nozzle failures which occurred during thruster pre-qualification testing dating back to 1997, it was decided to change the nozzle material from Haynes 188 to silicide-coated Columbium to provide a more robust and longer lived product which meets the cycle life and reliability requirements for the vehicle. Columbium possesses an approximately 600 °F higher temperature capability than Haynes 188.

Initial testing of a Columbia nozzle pathfinder shown in Figure 22 successfully completed over thirty extreme mission duty cycles. This success was repeated with a second nozzle that also completed thirty mission duty cycles. A third nozzle was used to support flight thruster acceptance testing and accumulated hot fire duration and cycles comparable to the first two units. The successful flight qualification of the RCS thruster nozzle concluded an ongoing collaboration between Aerojet, NASA, and industry partners to evaluate and solve the Haynes nozzle problem.

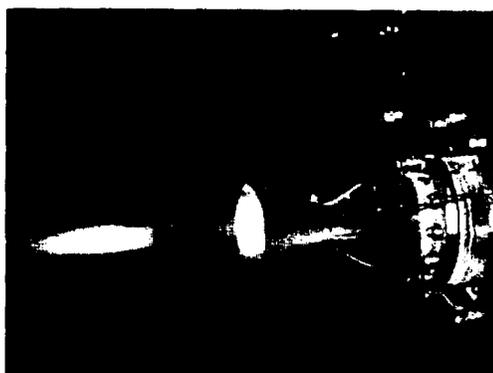


Figure 22. Columbia Nozzle Pre-Qualification Testing

The Columbia nozzles are expected to complete fabrication in February 1999. The eight flight thrusters are currently in stores at Aerojet awaiting final definition of vehicle location. When that occurs, the flight nozzles will be attached and the thrusters will be shipped. Figure 23 shows a flight thruster mounted on a holding fixture without a nozzle. Two flight spare thruster units will be assembled and are scheduled to be acceptance tested in April 1999.



Figure 23. Flight Thruster Awaiting Nozzle

This data was generated by Lockheed Martin Skunk Works, Allied Signal Aerospace, Rocketdyne-A Division of Boeing North American Rockwell, B.F. Goodrich Aerospace-Rohr, Inc. and Sverdrup Corporation under NASA Cooperative Agreement NCC8-115, dated 2 July 1996

3.0 RS-2200 ACCOMPLISHMENTS

During the past year, integrated product teams were established to support the engine system development and technology tasks. In engine system development, significant progress was made toward developing a viable engine configuration. In addition, requirements were developed, and engine performance analyses were conducted. Also, processes were developed for implementing reliability, mass properties, and cost controls during design. Powerpack technology accomplishments included development of a gas generator design, CTTD test article, and a prototype powerpack. Nozzle ramp efforts resulted in the selection of two composite ramp suppliers and three candidate ceramic architectures.

3.1 ENGINE SYSTEM

3.1.1 Engine System Design

3.1.1.1 Engine Design

Several engine design models were created during the past year in support of LMSW vehicle configuration studies. In addition, significant progress was made in evolving engine design concepts and approaches.

3.1.1.2 Linear System Test Bed Performance Study

A study was conducted to compare the RLV engine performance analysis method with the method used for the LSTB program in the 1970's. The study compared and defined the differences in the prediction methods used for both engines.

The study concluded that the methods used in the 1970's to determine the effect of base pressurization in vacuum result in significantly higher predicted engine performance when compared to currently used analysis methods. An evaluation of the current prediction methodology was conducted and was found to be correct based on a review of cold flow tests conducted in Phase 1. Using current methods, the predicted LSTB vacuum specific impulse decreased by 7 to 10 seconds. Results from X-33 flight tests will provide additional anchoring data for performance predictions.

3.1.1.3 Engine System Structural Analysis

The first version of an engine system finite element model was completed in November 1998. The model has 70,000 degrees of freedom. A solids submodel with 110,000 degrees of freedom was used to obtain equivalent orthotropic properties for the composite ramp used in the main model.

3.1.2 Systems Engineering and Integration

RLV SE&I activity was focused on supporting the development of the engine system through a wide variety of activities which included requirements development, risk engineering, performance analysis, mass properties, design to cost, and design for reliability. Also, a study was conducted to identify orbital maneuvering system (OMS) configuration candidates.

3.1.2.1 Requirements

A draft of the RLV Main Engine PIDS was completed during the latter half of 1998. This draft contains preliminary values for many parameters that are yet to be defined; however, the specification addresses all engine requirements and will help guide the RLV engine design. A requirements traceability matrix was also created to trace engine requirements back to



their sources.

3.1.2.2 VentureStar Definition Support

Rocketdyne provided support and inputs to various LMSW VentureStar definition activities. These included an input to the System Application/Optimized Design Review held in July 1998 as well as numerous reviews of system requirements documents including the SRD, FSRD, and GSRD. In addition, input was provided to support risk management activities. A total of seventeen propulsion related risks were identified by Rocketdyne and submitted to LMSW.

3.1.2.3 Engine Performance.

3.1.2.3.1 3-DOF Decks

Several engine steady state 3-DOF performance decks were developed and submitted to LMSW to support vehicle definition and trajectory studies. The first was submitted in July 1998 as Payment Milestone RY-06 for the "threshold" vehicle 033. A subsequent deck was submitted for the narrow engine vehicle 034. In addition, engine performance deltas were provided to support studies of other configurations based on a simplified engine performance prediction methodology. The 3-DOF deck performance code predicts axial and normal forces and pitching moments as a function of power level, engine mixture ratio, % TVC, altitude, mode of engine operation (normal versus PPO), engine inlet conditions, tank repressurization, and vehicle cooling requirements.

3.1.2.3.2 6-DOF Deck

An engine mainstage 6-DOF performance deck was developed and submitted



to LMSW to support definition of engine control requirements. This deck was submitted in October 1998 as RLV Payment Milestone RY-08. The 6-DOF deck models all thrust and thrust vector forces as a function of altitude and mixture ratio during mainstage operation including mainstage transients. It incorporates all engine operating groundrules and constraints and dedicates specific engines for yaw and pitch/roll control.

3.1.2.3.3 Prototype Powerpack Balance

An engine power balance was developed in support of the prototype powerpack technology development effort and was submitted as RLV Payment Milestone RY-05. Sized for a 3.0M lbm GLOW vehicle with seven engines, the power balance provided a 5% development margin compared to the anticipated flight vehicle engine design at the time. The power balance incorporated material properties limits and constraints on flow, pressure, speed, etc. as defined by the powerpack analysis group.

3.1.2.4 Phase 3 Bottoms Up Cost Estimate

A Phase 3 engine cost estimate was developed and submitted to LMSW in October 1998. The estimate provided comprises a baseline point of departure for future engine and vehicle design to cost activities and includes non-recurring costs (from Phase 3 ATP through certification of the engine design); recurring production costs for the main engines, OMS engines, and RCS (including spares for two vehicles); and operations and support costs for the first year of flight operations. The cost estimate package included program and engine description sections and an extensive cost section consisting of task descriptions, cost summaries, and cost estimate assumptions for each WBS element. Also included were a critical path schedule, top level bill of material, Pro-E pictures, component characteristics data, and weight summary.



3.1.2.5 Design For Reliability

The design for reliability (DFR) process is a new process at Rocketdyne which was instituted on the RS-2200 engine design to provide a means of improving the inherent reliability of the engine as an integral part of the component design process. Definition of the process has principally been a collaborative effort between the reliability, quality, and structural analysis functions; however, significant contributions were also provided by the reliability groups at Rocketdyne, LMSW, and NASA MSFC. Numerous working group meetings were held to resolve reliability questions of mutual interest and to refine, define, and review the DFR process.

3.1.2.6 Mass Properties

Mass properties support was utilized in the development of mass properties estimates for each of the engine configurations which were evaluated including those which were the bases of the engine decks. Estimates were also developed in response to vehicle configuration study inquiries from LMSW. Lastly, a review of XRS-2200 weight growth was completed to identify components that have been most susceptible to weight growth.

3.1.2.7 OMS Definition

A study was conducted to evaluate engine configuration candidates for the RLV OMS. Two candidates were considered: use either the main engine (one or more RS-2200's with restart capability) or use separate dedicated small engines. As a result of the study, the need for better definition of the OMS requirements was identified. This will be especially important as the trajectory definition matures.



The evaluation concluded that both options have merit. Use of the main engines may offer some weight savings; however, this option involves higher risk at this time. For separate engines, two propellant options were considered: LOX/hydrogen (same as used by the main engines) and LOX/ethanol (same as used by the RCS). The LOX/hydrogen option was preferred due to the weight penalty associated with the lower performing LOX/ethanol option.

As a result of the evaluation, the use of separate OMS engines was baselined by LMSW; however, it was concluded that the main engines still provide a viable alternate for performing the OMS function which may offer some weight savings. Issues also remain for use of separate engines including the lack of a good mounting location on the vehicle and the possible need for extreme gimbal angles in the event of loss of one engine.

3.2 TECHNOLOGY

3.2.1 Powerpack

3.2.1.1 Ceramic Technology

A risk mitigation program was initiated to reduce the risks associated with implementing ceramic turbine components in the RLV flight engine program. This effort covered a wide range of tasks ranging from fabrication development activities to lab- scale sub-element testing.

3.2.1.1.1 Blisk Development

Ceramic blisk concepts from three suppliers were evaluated.



3.2.1.2 Prototype Powerpack

Design of a prototype powerpack was initiated. This included design of a gas generator and fuel and LOX turbopumps.

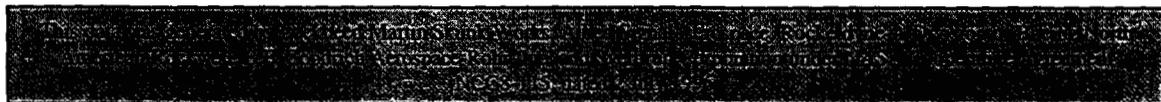
3.2.1.2.1 Gas Generator

Design activities for an RLV gas generator were initiated last year and progressed to a Critical Design Review (CDR) held in March 1999. Initial design activities focused on conceptual design trade studies to develop the best GG design concept for the RLV flight engine. Subsequent activities focused on ground based development hardware designs for the gas generator, CTTD turbine inlet housing, and prototype powerpack turbine inlet housing. Fabrication activities for the hardware were initiated, primary vendors were selected, and raw stock materials orders were placed. Test planning activities also progressed and included several trips to SSC, release of the PRD for gas generator testing, and facility configuration and test plan development.

3.2.1.2.2 Fuel Turbopump

Fuel turbopump (FTP) design activities were initiated to support a prototype powerpack design. Initial FTP design effort consisted of trade studies to evaluate generic design concepts. Based on the study results, trends were identified which guided later design efforts.

In May 1998, a program decision was made to adopt a high pressure hydrogen turbopump design which had been developed for the Integrated Powerhead Demonstrator (IPD) program. This decision was made based on schedule concerns with the new FTP design pump section components, specifically, the crossover castings and the main housing casting. By



applying a 1.50 scale factor, the IPD turbopump could be scaled up to nearly meet the engine balance design point. Using the existing scaled up casting drawings, the pump crossovers, main housings, and impeller forgings could be ordered much earlier than for a new centerline design.

In November 1998, a proposal was made to use existing hardware for the FTP pump and gas generator sections. A plan was devised to scale down the turbine section to match the SSME HPFTP requirements, mate this turbine to the pump section, and use the CTTD gas generator (which is about 20% oversized for this application). As part of the plan, it was shown that this effort still showed traceability to the flight powerpack.

3.2.1.2.3 LOX Turbopump

The design of the RLV prototype LOX turbopump made excellent progress during 1998. Rough sizing and component and assembly layout occupied the first half of the year. A conceptual design review was held in August 1998 to review the preliminary layout and design philosophy.

During the second half of the year, preliminary design of the pumping elements, housings, and turbine was begun and detailed solid models were made of all of the major components. Pump flow paths and blade shapes were completed, and detailed structural analysis was begun on the bladed hardware in the boost pump.

3.2.2 Nozzle Ramp Technology

3.2.2.1 Composite Nozzle Supplier Evaluation and Selection

Two rounds of technical evaluation meetings were held with potential composite nozzle suppliers. The first round of meetings was held in



December 1997 at NASA MSFC, and the second round was held in January 1998 at Rocketdyne. The suppliers presented different material combinations and design approaches for the RLV nozzle. In all, presentations were received from 21 suppliers. Bid packages were prepared and sent to the ten suppliers with the most promising concepts and materials. Proposals were then received in March 1998 from all but three of the suppliers.

A formal review of the proposals was jointly conducted with NASA team members at Rocketdyne in March 1998. The team recommended five suppliers for continued development based on technical merit. Following a financial review of the suppliers and their costs, purchase orders were placed and technical kick-off meetings were conducted with each of the supplier teams. The teams, with technical support from NASA and Rocketdyne, then evolved their concepts and developed designs for various test coupons and panels. Following this effort, CDR's were conducted at Rocketdyne with each supplier team. The final CDR was completed in October 1998.

After completing an independent review of the various concepts, the Rocketdyne/NASA team elected to proceed with development of the design concepts from two of the five suppliers. Purchase orders were then placed to continue design development and initiate fabrication of test coupons.

3.2.2.2 NASP Technology Panel Coupons

In addition to the composite nozzle activity described above, an effort was made to develop cooled composite technology by using an advanced version of the NASP technology panel.



3.2.2.3 Open Warp Channel Architecture Technology Coupons

An additional effort was conducted at the Rockwell Science Center to fabricate hot-fire test coupons that utilize an open warp channel architecture approach. This approach produces a fiber architecture that is optimized to contain the high-pressure hydrogen coolant in the RLV ramp design. Initial work on this concept was funded by RSC IR&D and by a separate IHPRPT contract.





ANNUAL PERFORMANCE REPORT

For The Period

April 1, 1998 - March 31, 1999

By

SVERDRUP TECHNOLOGY, INC.

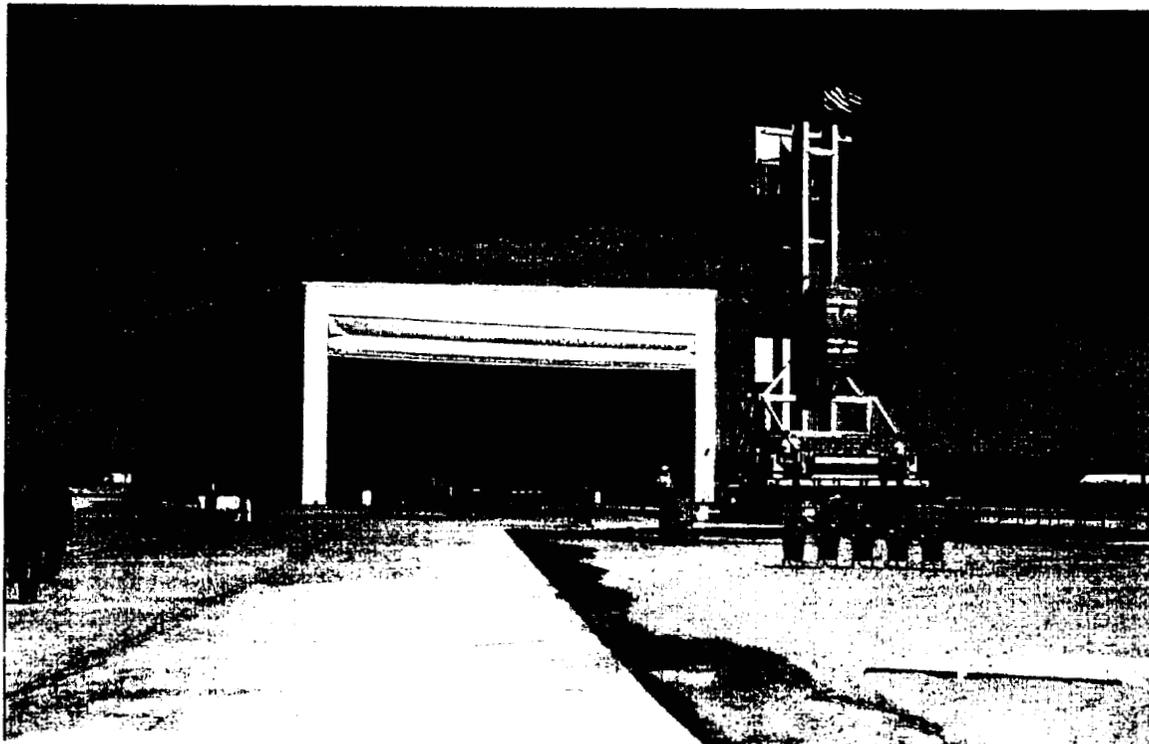
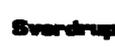




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X-33 LAUNCH AND LANDING FACILITIES

RESPONSIBILITIES

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

PROGRESS

The past year has seen the completion of the construction of the X-33 Flight Operations Center. Construction was completed in December of 1998, with systems checkout and testing continuing into early 1999. Integration of the site with LMCMS partner-supplied systems began in

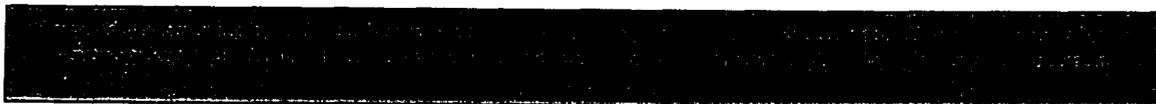
December and will continue through rollout of the X-33 vehicle.



Dedication of the Flight Operations Center and turnover to Lockheed Martin Skunkworks occurred on March 5, 1999 during a ceremony held at the site.

Figure 1 - X-33 Flight Operations Center

The construction of the X-33 Launch Complex has been performed within the Edwards AFB and Air Force Research Laboratory (AFRL) systems 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.

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 were disappointing, however, the small business awards met 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 was kept within the budget.

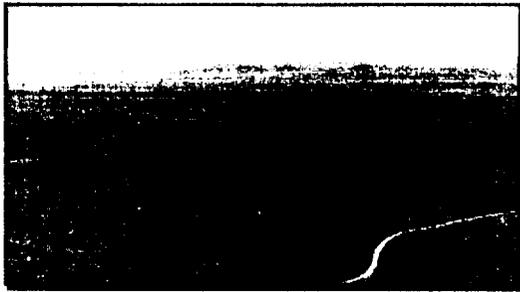
Development of the landing sites is progressing with many of the modifications necessary underway. GSE commitments are in place.

The personnel training program developed by Sverdrup for persons entering the launch site construction areas, was modified by Lockheed for use in training and access control to the Center during flight operations to maximize safety and minimize intrusion upon the environment. This training program included operational and Air Force Research Laboratory safety, environmental training with emphasis on protection of the Desert Tortoise, and EAFB and AFRL security training.

The effectiveness of the Sverdrup construction safety program is evidenced by the completion of the construction of this project (approximately 100,000



man-hours) with NO lost time accidents. 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. Actual construction started on the site the following week.



**Site Conditions circa
November 1997**



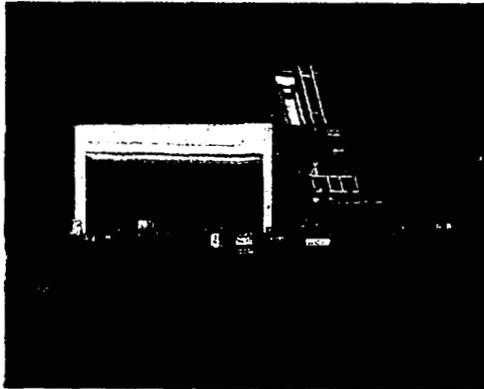
**Site Conditions circa
December 1998**

Close cooperation between Sverdrup, the construction workers, and the environmental biologist permitted construction 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.

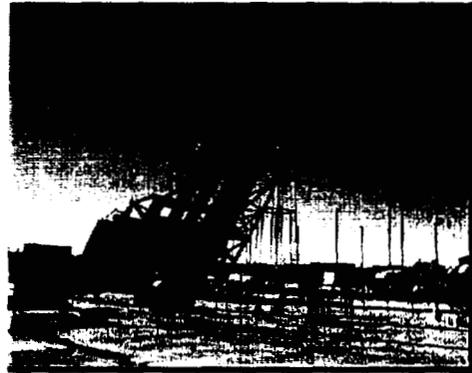


STATUS

Launch Pad & Launch Mount

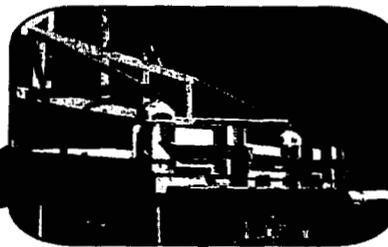


The launch pad is complete. The photos shows the launch pad with the Translating Shelter located in the Engine Removal Position. The strongback and RLM is in the process of being rotated to vertical



with the X-33 Mass and CG Simulator installed. This simulator is used to simulate the mass and CG of the vehicle to permit testing of the RLM/SB system.

The photo below illustrates the position of the X-33 vehicle when erected in the vertical launch position. The RLM in this photo is configured for the ground vibration test (GVT) Mass & CG Simulator.



The configuration for GVT requires that the flight configured hold-down

posts be replaced with a fixture that allows the test article to "float" on the RLM. The phot below shows the air bags that will be inflated to provide this isolation.

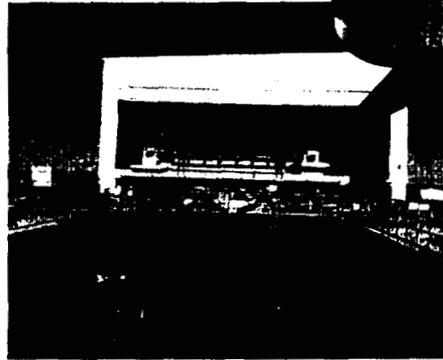


The strongback is elevated by a pair of hydraulic cylinders which will rotate the vehicle from horizontal to vertical in 15 minutes.

The RLM in this photo is configured with the flight hold-down posts

and rotated to the vertical position. The Translating in the background is positioned engine installation position.

The flame pit in the foreground contains the sound suppression spray system. This system has undergone initial testing.



launch Shelter in the

water

Hydrogen burn-off pyro canisters are located on the flight hold-down posts. These pyros will be ignited shortly prior to engine ignition to burn off any residual hydrogen before engine starting.



Fluids and Gases

All fluids and gas systems are complete and undergoing integration testing. Performance testing of the liquid hydrogen and liquid oxygen systems has been postponed to minimize the amount of time that hazardous materials are located on the site. This testing is scheduled for midyear.

Many valves and instruments control the fluids and gas systems. To minimize the amount of interconnecting piping and to reduce cost at the same time providing more efficient operations, most of these items are grouped together on several panels located around the site. A typical panel is pictured at right.



The operating controls are placed on one side of the panel with the component located on the opposite side. A small portion of a panel is shown at right.

Several hundred valves are located on 10 such panels.



The liquid nitrogen system shown at left provides liquid nitrogen to a vaporizer to generate gaseous nitrogen for purging the X-33 aeroshell when propellants are on-board. Sufficient capacity is contained in the horizontal storage vessel to sustain flow for normal flight operations plus residual to support a 4-hour launch hold. The system has the capability to increase



flow rates of nitrogen to counteract increased hydrogen leakage into the aeroshell.

Adjacent to the liquid nitrogen tank (tank in the background) is a helium unloading and pressurization system that unloads helium from tube trailers at 2,900 psi and charges two on-site storage vessels to 6,500 and 5,500 psi.



Liquid hydrogen is stored in 5 vacuum-jacketed vessels manifolded into a common system, and located in an area on the opposite side of the site from the oxygen storage.

Included in the hydrogen storage area is a facility for generating gaseous methane from liquid methane (shown at right).



Liquid oxygen is stored in a single horizontal tank on the opposite side of the site from the hydrogen storage area to minimize the possibility of an oxygen fed hydrogen fire/explosion in the event of a tank leakage or spill. In addition the oxygen tank is located at a lower elevation

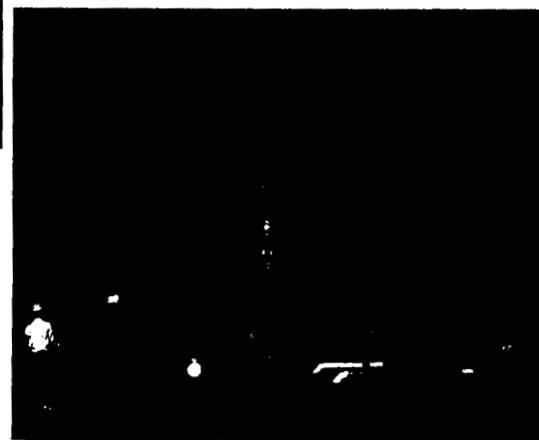
to prevent an oxygen spill from flowing along the ground to the hydrogen area.



Included in the oxygen storage area is a system to generate gaseous oxygen for use as the oxidizer in the vehicle RCS system (methane is the fuel).

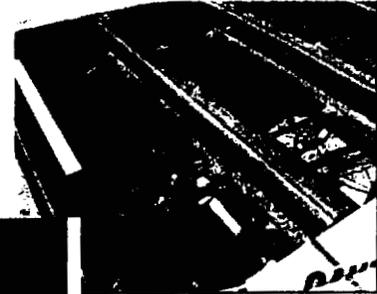


During checkout procedures, all cryogenic systems were "cold-shocked" with liquid nitrogen in order to check the systems at cryogenic temperatures.





Fluids, gases and electric power and data are passed to the vehicle via underground/under pad trenches in order to provide



an unobstructed launch pad. These systems terminate at a ground plate at the end of the trenches. Flexible hoses and cables connect the ground plate terminations to the umbilical FT-0 plates.



A sound suppression system (SSW) in the flame trench reduces the effects of the engine exhaust noise on the vehicle. Water is supplied from a 250,000 gallon elevated water storage



tank located on the site.





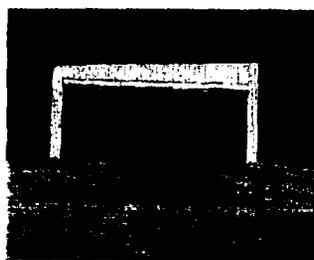
Just prior to engine ignition, large valves in the SSW water supply line are opened. Approximately 80,000 gallons of water are discharged through the spray nozzles located in the flame trench. The remaining 170,000 gallons of water in the tank are reserved for fire

protection systems.

The Translating Shelter protects the X-33 during horizontal processing. This structure is mounted on rails and is self propelled via motorized trucks. Telescoping doors on each end provide access for the vehicle. The launch pad has three positions to accommodate the shelter; a service position at the launch point to cover the vehicle when mated to the launch mount; a launch position at the far end of the site out of harms way from launch blast and noise; and an intermediate position allowing access to the aft section of the X-33 for engine removal and installation.



Engine Installation Position



Launch Position



Service Position

Electrical/Communications

Electrical power and communication systems are complete and tested with integration testing ongoing.



Power for the site is provided by California Edison via EAFB power grid. The X-33 site includes an incoming electrical substation with a diesel powered emergency generator sized to handle all critical electrical loads.

Two electric rooms on the site accommodate dc power supply and distribution for

operating the X-33 as well ground systems, battery and UPS backup in the event of loss of incoming power, fire alarms, paging (OIS), and all data communications including video from 11 cameras strategically placed around the site.



The photo at left shows a bank of 28 vdc and 270 vdc power supplies. The photo below is a typical interconnect panel where the cabling from field devices are joined with cabling from the Ground Interface Modules (GIMs).



Sverdrup's responsibility did not include installing the equipment in the control room (OCC), however,



Sverdrup support other partners with this activity. Sverdrup subcontractors installed electrical distribution systems, emergency generator and backup UPS system.

Signals from the 11 site cameras are fed via fiber optic cables to this video control center (OTV) where operators can select and manipulate various cameras.

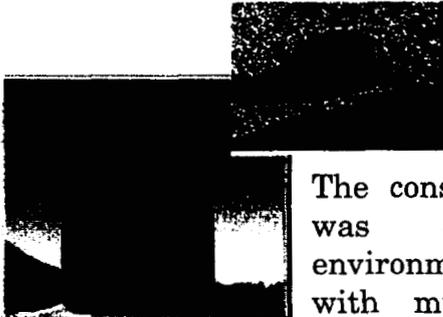


Operations of the X-33 vehicle and launch site systems are controlled from these LMCMS terminals furnished by another X-33 partner.

The heart of the control system is the LMCMS, which is located in racks in the Operations Control Center (OCC). Cost savings were realized by reusing racks systems previously installed for another program rather than procuring new ones.



Environmental



The construction of the facility was completed in an environmentally friendly manner with much attention to the protection of the Desert Tortoise (an endangered species) populations. Prior to construction, a sweep was made to ensure that no tortoises were in harm's way. A certified biologist observed all earth moving operations and performed weekly inspection of the site, offering advice on procedures to enhance the safety of the endangered species. 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.



All air emissions testing required have been completed and all equipment is in compliance with the environmental requirements.





Conclusion

The X-33 launch site is complete and ready for final integration testing and flight operations.

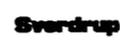
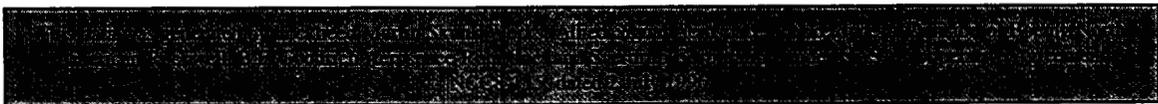
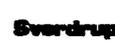




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AMES RESEARCH CENTER**X-33 ENGINEERING SUPPORT****AEROTHERMODYNAMICS AND VERIFICATION**

- A significant accomplishment was the release of the high fidelity, CFD-based aerothermal environments databases for the Rev F loft.
- Forty three-dimensional real-gas solutions were computed with numerous improvements over the previous databases. These data were used as anchor points for the engineering code, HAVOC, which was then used to generate aerothermal design databases for the design and all candidate flight trajectories. Special attention was given to the environments of the canted fin and vertical tails, which in the current configuration are substantially different from the previous Rev C loft.
- Figure 1 shows a comparison of the computed radiative equilibrium surface temperatures for the Rev C and Rev F Lofts at the peak laminar heating point on the TPS design trajectory.

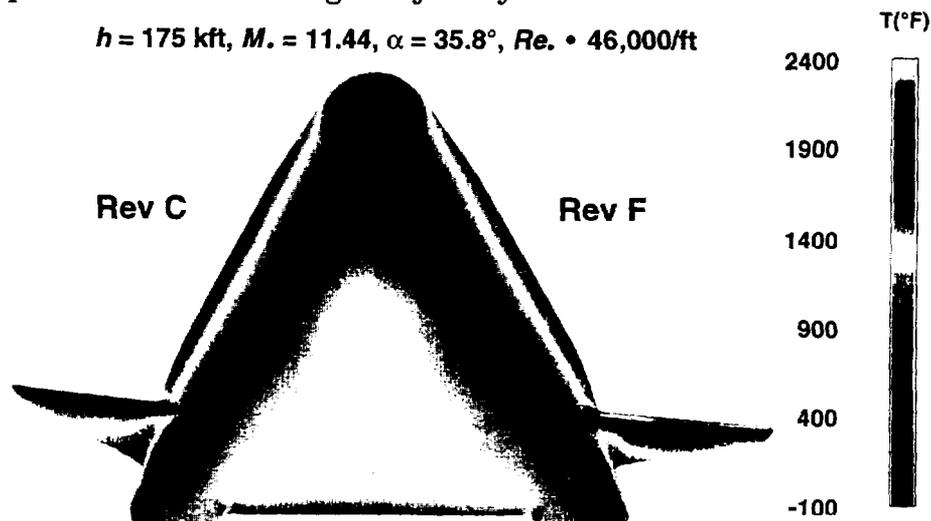


Figure 1

- A detailed study of the impact of trajectories with negative angles of attack on the Rev F loft aerothermal environments was carried out to determine the possible detrimental interaction between the larger vertical tail and the bow shock wave. An angle of attack of -5° for three Design Space points (M=6, 9, 12) was considered in the computations. The computed solutions revealed no shock wave impingement problem on the vertical tail.
- One X-33 flight test objective is to measure “real-gas” effects. A unique analysis capability was developed to help tailor trajectories that will result in significant and measurable catalytic heating to satisfy the objective. The catalytic heating was determined using all relevant CFD simulations from which a “catalytic corridor” was constructed. The catalytic corridor was provided in the form of equations and tables. Figure 2 displays the predicted level of catalytic heating at thermal control body point 1 (on the windward centerline at the Carbon-Carbon/Metallic TPS splitline) for two trajectories: the design (Malmstrom-4) trajectory and a flight (Malmstrom-6E) trajectory.

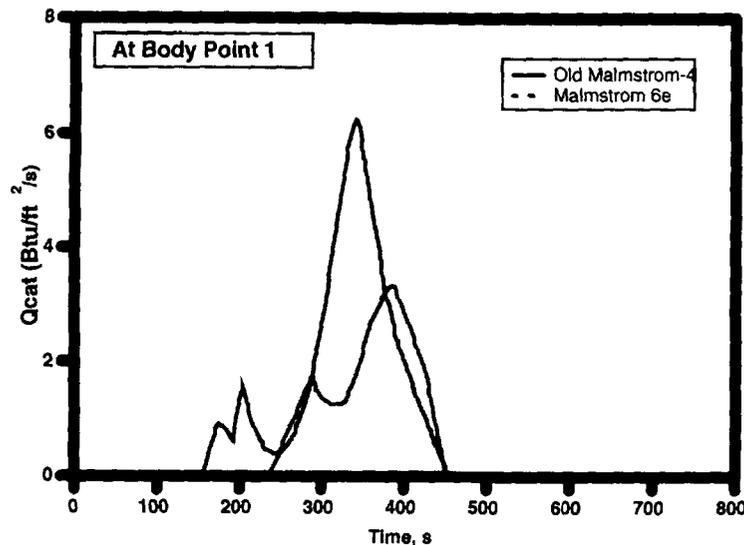


Figure 2

- A detailed high-fidelity analysis was undertaken to quantify the catalytic jump. The TPS consists of materials with differing catalytic properties and evaluation of the catalytic jump was significant for the TPS design to accurately account for the heat-flux and heat-load augmentation.
- Unlike all previous hypersonic flight vehicle programs, the acreage TPS was designed solely from CFD-based aerothermal environments. The credibility of the CFD methodology was established very early in the X-33 program by comparing the CFD predictions with flight and other ground based measurements for hypersonic vehicles such as the Space Shuttle Orbiter, X-38, and X-34. To further establish the accuracy of the design predictions, a validation study was undertaken with available NASA Langley M=6, ideal-gas, hypersonic experimental data.
- Good to excellent agreement was found between computed results and experimental data for laminar test conditions as indicated in Figure 3. A major conclusion of this study was the determination that the aerothermal design database was conservative.

X-33 Rev-F CFD/Phosphor Comparison, Test 6763, Run 56
 $M_\infty=6.0$, $\alpha=20.0^\circ$, $\phi=10^\circ$, $Re_\infty=2.16 \times 10^8/\text{ft.}$

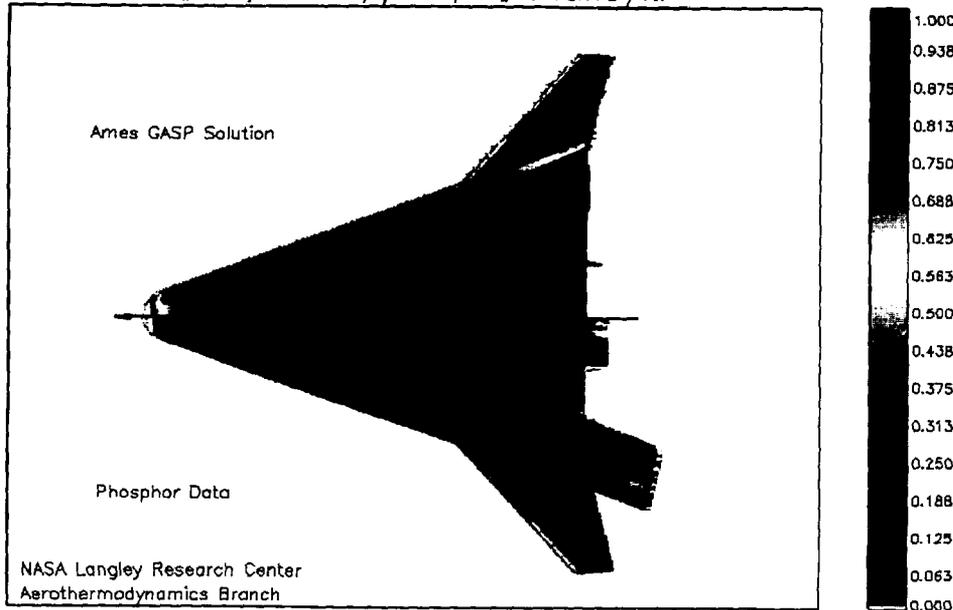


Figure 3

- During the actual flight, small yaw is possible. To assess the TPS design and to develop a preflight prediction methodology, the Rev-F database was augmented with high fidelity CFD solutions with yaw. The focus of this effort was provide high-fidelity anchor points for the HAVOC engineering approach and help establish sensitivity of the aerothermal environment to yaw (in addition to Mach number, dynamic pressure, and angle of attack).
- Figure 4 illustrates the contours of the temperature difference (between $\phi=2.5^\circ$ and $\phi=0^\circ$) for the peak laminar heating point on the design trajectory. The computations are also useful in assessing the impact of yaw on the TPS splitlines, especially on the leeward aeroshell.



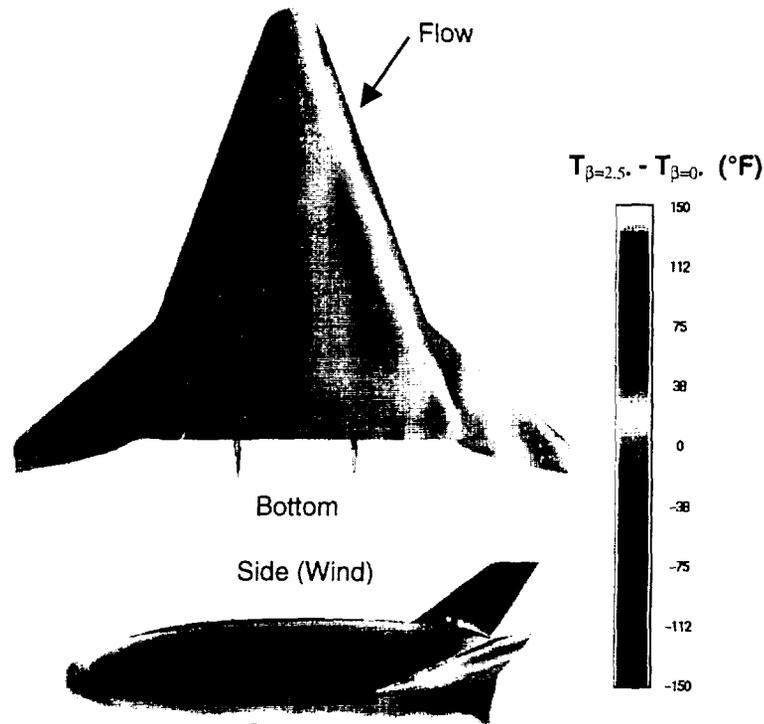


Figure 4

- An assessment of the design margin for the first flight is a necessary and significant step towards flight readiness. To meet this challenge, an uncertainty analysis coupled to the expected flight environment was developed.
- The quantitative uncertainty estimates were derived from all available and relevant data and were based on comparison of the predicted CFD results with NASA Langley M=6 tunnel data for the scaled X-33 configuration, CFD simulations and comparisons with M=10 data for the X-38, comparison of the CFD simulations with M=6 and M=10 data for the X-34 (laminar and turbulent), and the flight data comparison with the Space Shuttle Orbiter.
- The results, in terms of available margin in the environment, are summarized in Figure 5. Lower, nominal and upper bounds, in terms of



percentage, at each thermal control body point on the windward surface are shown. The current analysis showed the Michael 9A-8 flight environment to be conservative compared to the design environment. This approach and the resulting estimates were first of a kind, and can be applied easily to other trajectories as well.

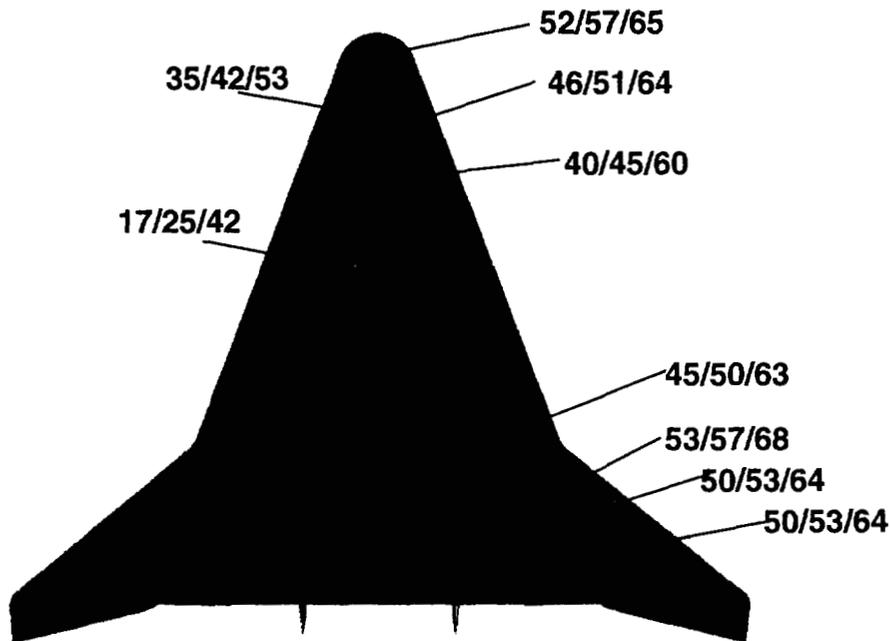


Figure 5

- Quickly developed and implemented enhancements to the HAVOC Engineering Code to respond to changing requirements, especially flight trajectories. HAVOC results widely used by the entire X-33 Engineering Analysis Team.
- Provided HAVOC generated aerothermal databases for all released flight test trajectories using GASP CFD solutions as benchmarks. Figure 6 exemplifies the type of information in the HAVOC data base for peak heating predicted for a power pack out (PPO) abort scenario for a Michael Air Field mission.



Michaels_9A-8 PPO Abort Trajectory: HAVOC Interpolated Temperatures

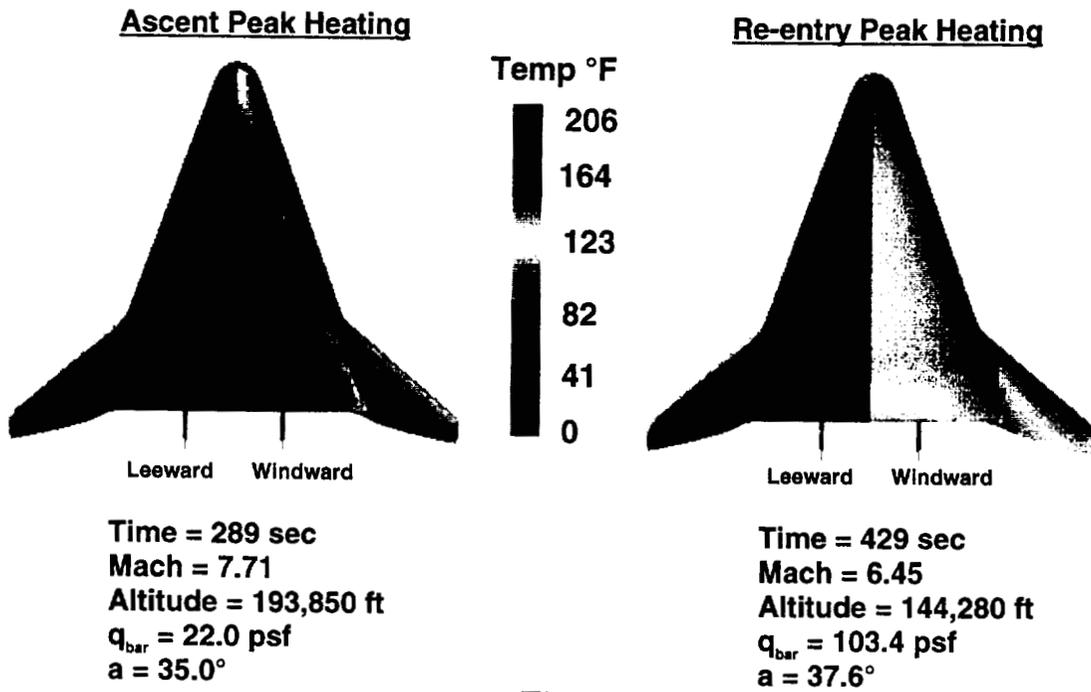


Figure 6

- Supported and participated in the X-33 Analysis Review on December 7-10, 1998.



TPS ANALYSIS AND VERIFICATION

- Compared the pre-test detailed FEM analysis with calibration data from the nine-panel array tested in the MSFC Combined Environments Test Facility in September 1998. Typical results at the center of the middle panel are presented in Figure 7. BFGoodrich is selecting system-level qualification cases for further comparisons.

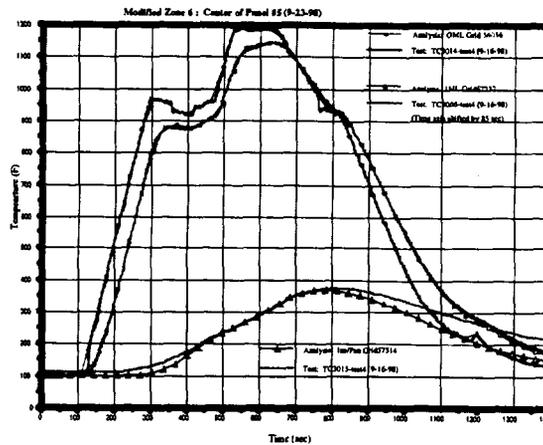


Figure 7

- The X33 Thermal Design Database continued to provide material properties for the entire X-33 design team. The database is updated as needed with the addition of new materials and modifications to existing materials. Figure 8 below presents total access to the database web site at Ames. The X-33 team has accessed the database over 7000 times.



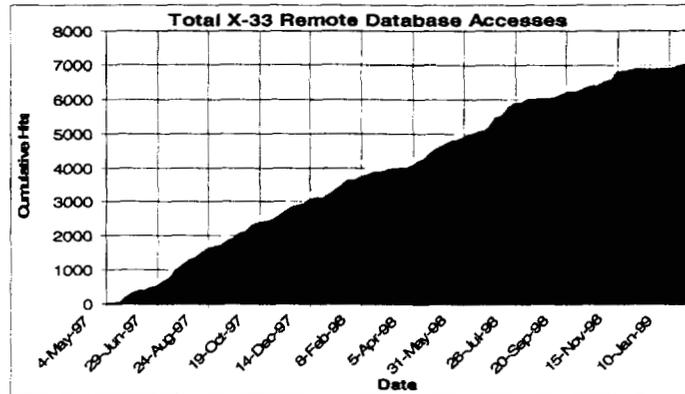


Figure 8

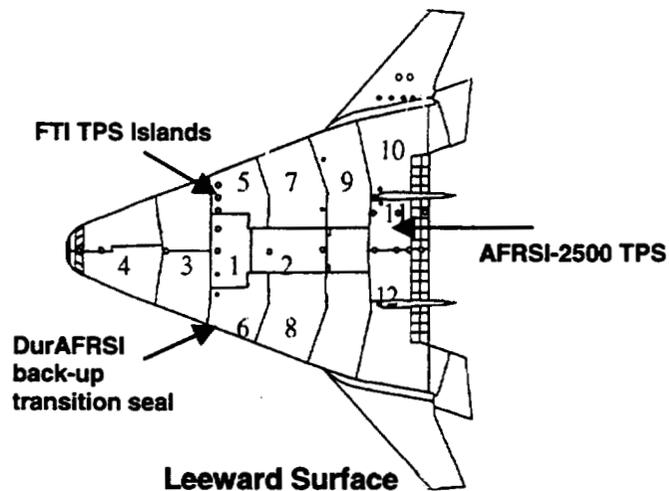
TPS Design and Qualification Testing for Leeward Aeroshell

- Supported BF Goodrich by completing design, fabrication, and TPS qualification testing for AFRSI-2500 blankets, flight test instrumentation (FTI) islands, and NASA Ames developed DurAFRSI metallic-blanket transition seals, for application on the vehicle leeward aeroshell.
- Developed a qualification test plan within schedule, cost, and facility availability constraints by subdividing aerothermal, aerodynamic, and vibroacoustic environments to enable testing using NASA Ames arcjet, NASA Dryden F-15B, and BF Goodrich Progressive Wave Tube (PWT) facilities, respectively.
- Designed and fabricated test articles of AFRSI-2500 blankets, FTI islands, and DurAFRSI transition seals.
- Exposed test articles to each environment sequentially to obtain the accumulative effect of the three induced flight environments. See Figure 9 for TPS locations on the vehicle and qualification process with typical test article performance.
- Successfully demonstrated that AFRSI-2500 blankets, FTI islands, and DurAFRSI seals are suitable for use on the X-33 leeward aeroshell.



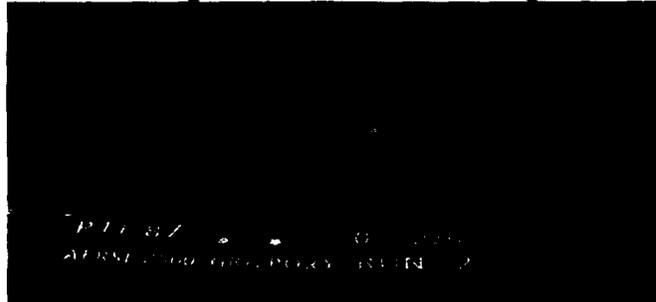
DurAFRSI seals are currently baselined as a backup transition seal for X-33.

- Delivered FTI islands hardware (44 units) to BF Goodrich in December 1998.
- Documented qualification results in final reports, which are in final review.



Sequential Leeward TPS Qualification Testing

Begin with Arc Jet Testing



AFRSI2500 three-panel array installed in the arc jet after 11 exposures.

Then, F-15B Flight Testing



FTF-11 configured with two flexible blanket panels with FTI islands in the forward test locations, with two streamwise DurAFRSI seal panels in the rear test locations.



Finally, PWT Testing



Streamwise DurAFRSI Seal forward facing edge following PWT testing showing excellent structural integrity.

Figure 9



TPS Surface Characterization

- Tested and characterized optical properties, aerothermal stability, catalytic efficiency, and morphology for an additional ten X-33 and potential RLV TPS/coatings.
- Documented the results in an AIAA paper, co-authored with BF Goodrich colleague and provided information to the electronic X-33 Thermal Design DataBase.

Surface Catalysis Flight Experiment (SCFE)

- Provided BF Goodrich with an Engineering Requirements Document for satisfying the flight test objective of measuring real-gas effects.
- Initiated development of low-catalytic efficiency coating for vehicle metallic TPS panel (1,1).
- Identified panel modification required for SCFE data acquisition.
- Defined arc jet test articles and environments for SCFE flight hardware characterization and verification test programs.

TPS Arc Jet Testing

- Completed a total of 182 arc jet runs in 42 weeks of testing in three different arc jet facilities. Testing included:
 - TPS material/coating characterization
 - Thermal preconditioning for other testing, e.g. fatigue
 - TPS component flight qualification

Figure 10 illustrates the hot plasma TPS test articles during exposure to reentry heating environment. Also illustrated are three metallic panels after testing in the 60 MW Interaction Heating Facility (IHF).



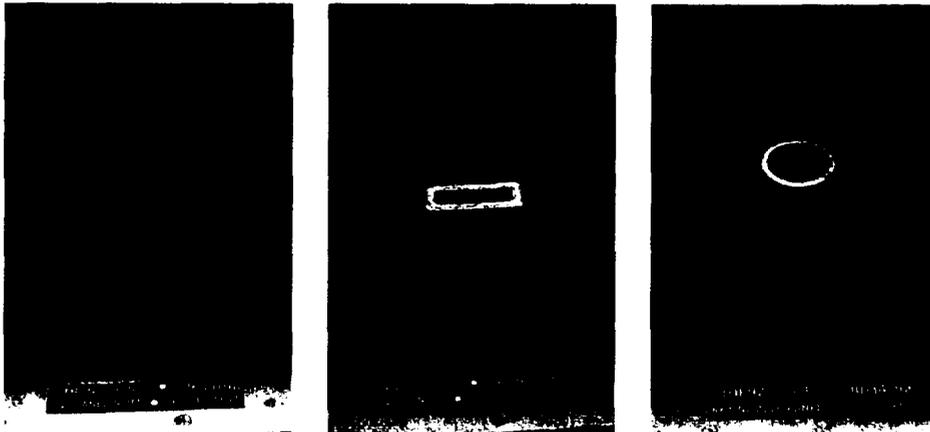


Figure 10

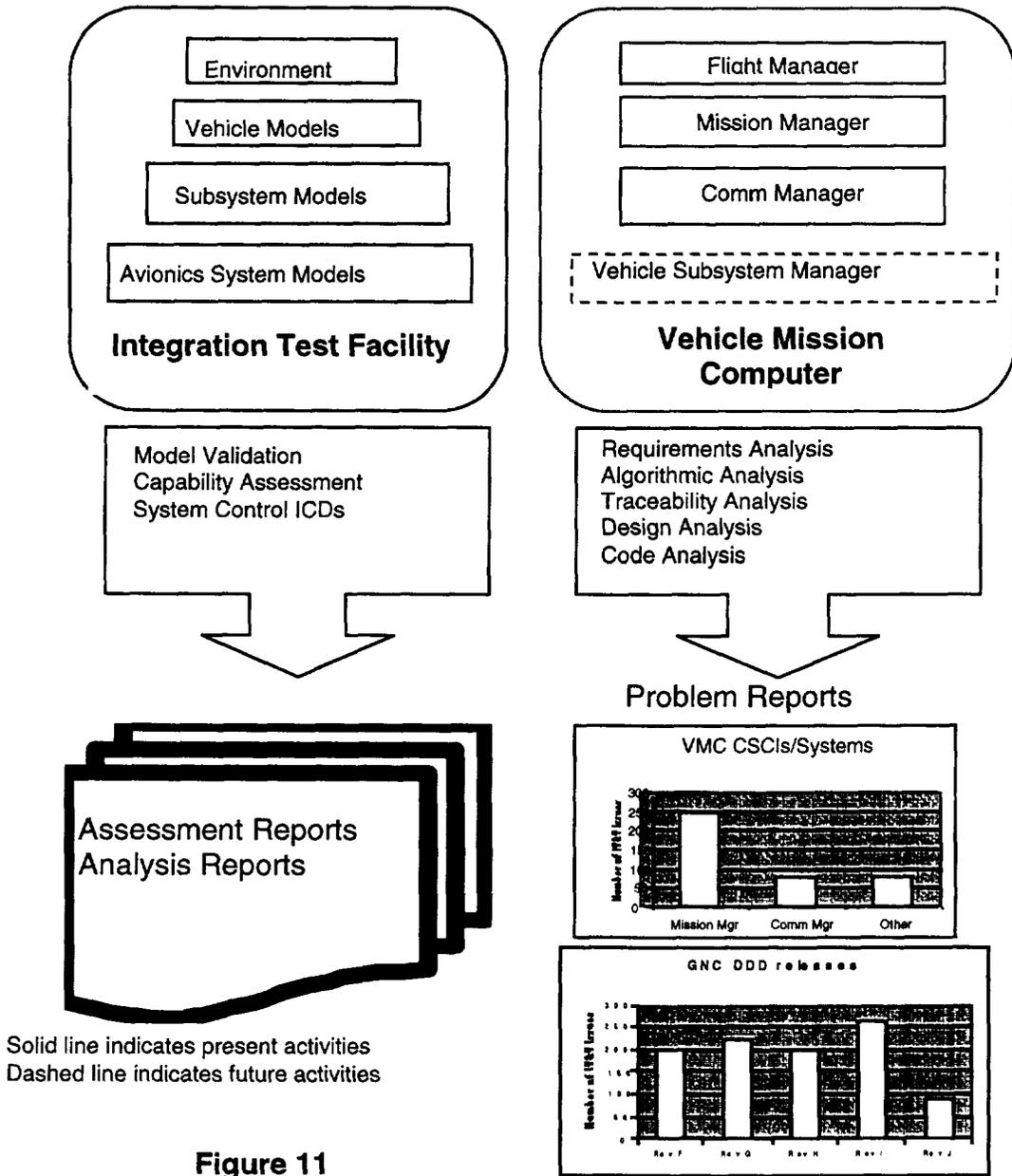
The performance data from these tests provided verification of the TPS design and satisfied qualification test requirements.

Flight Software Independent Verification and Validation (IV&V)

- Reviewed and analyzed all major software design documents
- Documented results in Assessment, Analysis, and Problem Reports and provided them to the Program



- An overview of the IV&V scope of activities is presented in Figure 11. The bar charts show the number of issues identified, most of which have been resolved.



RLV ENGINEERING SUPPORT

Aerothermodynamics and TPS Analysis

- Delivered a HAVOC aerothermal database for VentureStar several designs and trajectories. An example from the database is given in Figure 12.

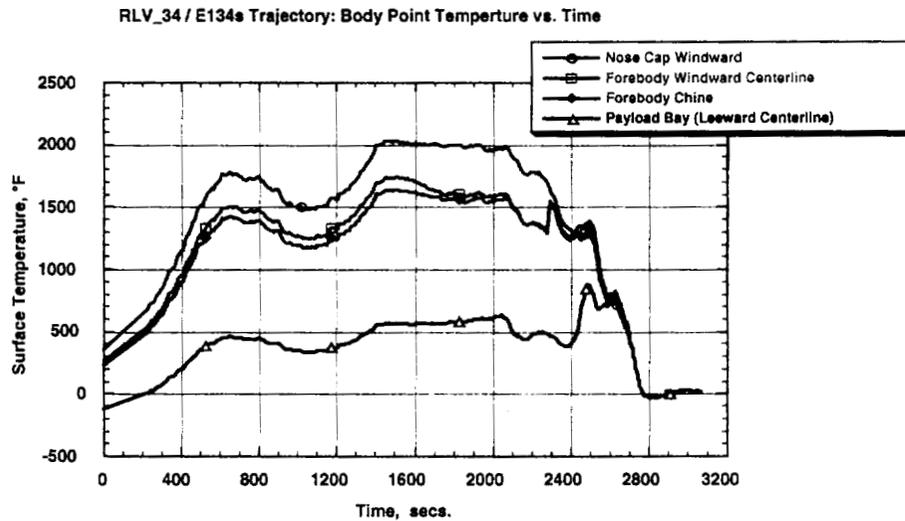


Figure 12

- Developed engineering methods to assess partially catalytic heating impact for several RLV configurations and trajectories. The plots in Figure 13 show the difference in temperature between fully catalytic, partial catalytic, and low catalytic recombination coefficients for two body points.



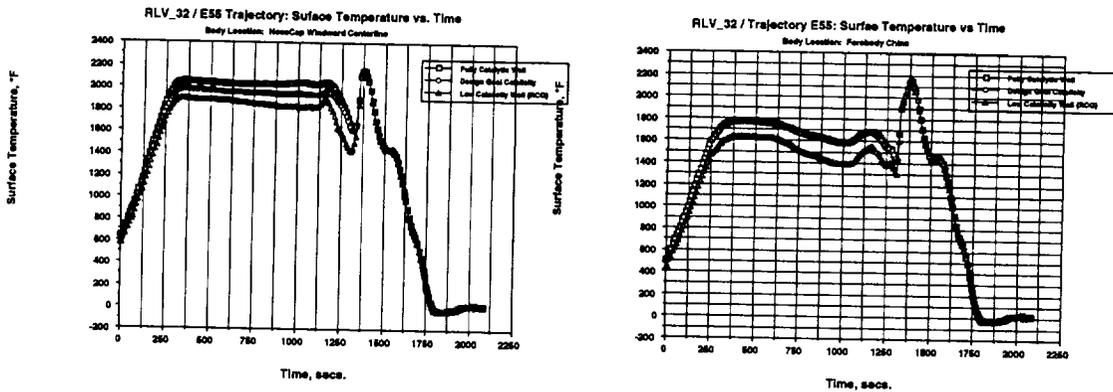


Figure 13





DRYDEN FLIGHT RESEARCH CENTER

X-33 Thermal Protection System Durability Studies (Task DFRC-25)

Summary:

A thermal protection system (TPS) is required to insulate the X-33 from the harsh environments of high-speed flight. A flight experiment was recently completed which subjected candidate X-33 TPS materials to anticipated aerodynamic loads of the X-33 ascent and re-entry flight profiles using the NASA Dryden F-15B Flight Test Fixture (FTF). Results of the F-15B flight tests have been included as part of the overall flight qualification of the X-33 TPS by BF Goodrich Aerospace.

Objective:

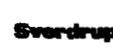
The objective of this flight experiment was to evaluate the durability of several X-33 metallic and blanket TPS configurations exposed to aerodynamic pressure and shear loads, including impinging shocks at transonic speeds, expected during X-33 flight. The TPS articles examined included:

- Metallic TPS panels supplied by BF Goodrich.
- Thermally cycled and non-thermally cycled Flexible Reusable Surface Insulation (FRSI), Advanced FRSI (AFRSI), and AFRSI 2500 test panels supplied by NASA Ames Research Center.
- Several transition seal designs, supplied by both NASA Ames and BF Goodrich, for testing between metallic and blanket TPS panels.

In addition, a NASA Ames method of integrating thermocouple and pressure instrumentation into the X-33 blanket TPS was examined on several of the FRSI and AFRSI test articles.

Experiment Overview:

The two forward left-side panels on the FTF were replaced by a large carrier plate to simplify the installation of the various TPS test articles and to allow



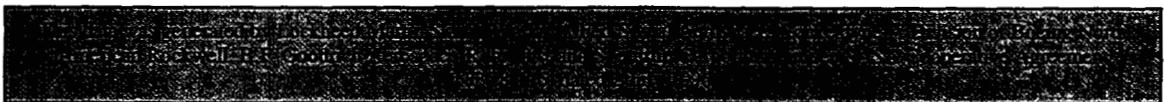
for quick configuration changes between research flights. The forward quadrants of the carrier plate were generally used to examine the effect of shock impingement loads, previously identified at this location under transonic conditions. The aft quadrants of the carrier plate were used to examine the effect of shear loads on the TPS.

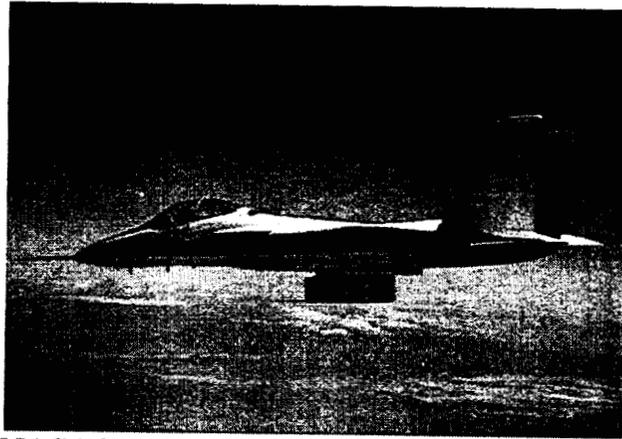
Six different TPS configurations were flight tested, with each flight consisting of the following general test points:

- Shear stress exposure: low altitude and subsonic Mach flight conditions.
- Shock impingement exposure: level acceleration / deceleration cycles at transonic Mach conditions.
- Transonic flow exposure: constant transonic Mach "dive" which yielded increasing dynamic pressure loads.

Results:

Six flight tests were conducted to a maximum Mach Number of 1.4 and dynamic pressures as high as 790 lbs/sq.ft. Surface pressures were obtained to document flow conditions and test article loads. In addition, in-flight video and detailed pre- and post-flight photos were used to document the condition of all test articles. This highly successful flight test program was completed in May 1998 as part of the overall flight qualification of the X-33 TPS.





NASA Dryden F-15B with the FTF located on the lower centerline.



Close-up view of the FTF showing one of the X-33 TPS configurations.



X-33 Flight Control Support to Flight Test (TASK DFRC-05)

Summary

The X-33 Vehicle will include the automatic control system reconfiguration capability in the event of an actuator failure. The reconfigurable system will increase the possibility of landing the "crippled" X-33 at a landing site with a jammed or floating actuator. Nonlinear simulation results show a definite improvement with reconfiguration as compared to the nominal control system with the same failure. Also included in Task 06 is the independent analysis of the control system, evaluate the FADS alpha and beta control strategies.

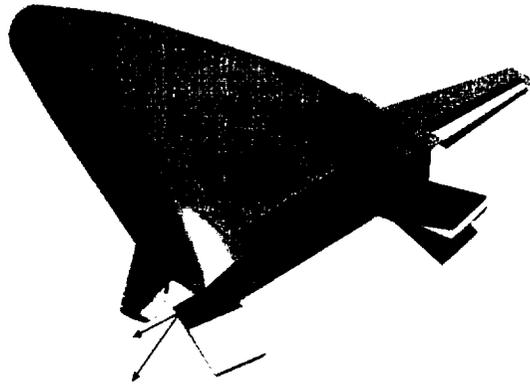
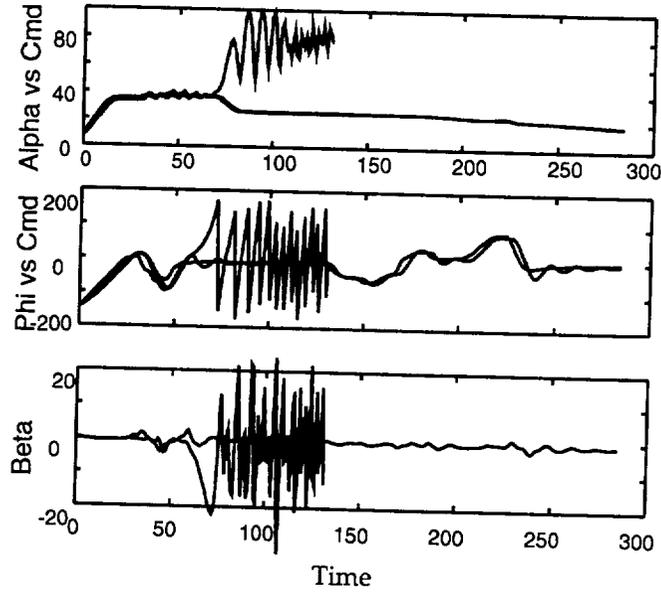
Objective: Increase the likelihood of landing the X-33 with a failed actuator or delay flight termination to a less severe location. Other objectives include maintaining stability, rejecting gust and perform maneuvers while having acceptable stability margins.

Approach: The constrained control allocation approach was taken for the reconfigurable design. The X-33 has 8 control surfaces and in the event of one failed surface the other 7 healthy surfaces are used to control the vehicle. The off-line sequential quadratic programming method was used because rate saturation and rate limiting can be accounted for in the design. The ability to incorporate the nonlinear surface rate limiting and position limiting was very important in the success of the controller

Results:

The following time history shows the nominal control system and the reconfigurable controller with a right outboard elevon jammed at 25 degrees (failed at 10 seconds into the entry phase of flight). As can be seen the reconfigurable controller is stable with the failure and flies a "nominal trajectory". As of February 1999 the ascent and entry flight phase of the X-33 has been designed with a reconfigurable control system. The TAEM flight phase is under design at this time.





X-33 Aerodynamic Characterization, PID, Aero Model Updates (Task DFRC-02)

The Dryden aerodynamic task supported several efforts relating to the design of the X-33 maneuver input system and simulation testing of the complete X-33 flight system.

The Programmed Test Input (PTI) software system, which performs small amplitude maneuvers during the X-33 flights for aerodynamic and thermal analysis, was finalized over the past year. PTI software and test cases to validate the software were delivered to Allied Signal and the ITF. Flight rules which govern the safe operation of the PTI maneuvers were developed and delivered to the LMSW flight test group.

The previously released aerodynamic uncertainty model received a major revision this year. The original Dryden model was developed from historical lifting-body and Space Shuttle Orbiter data. The latest update uses a statistical evaluation of the large X-33 wind tunnel database to better refine the uncertainty model. This update accounts for the actual variations that were measured between different models and tunnels. Ground effects uncertainties were also included for the first time.

A Matlab-based analysis tool was developed to quickly analyze the large amount of Monte-Carlo simulation data that will be obtained during the X-33 software validation process. The tool identifies the simulation runs where limits or margins were exceeded and helps to reveal which uncertainties caused the problem. The tool can also catalog the available margins on the temperatures, loads, winds, etc.



Extended Test Range Design and Operations (Task DFRC-09)

The last year has resulted in many accomplishments , leading up to final integration and test of the extended test range. A major task realignment was completed in the previous reporting period and lead to the purchasing of all remaining equipment in the last year. Test of subsystems is nearly complete as we plan for the upcoming integration and test phases. The Integration and Test Facility range simulation has been tested. Flight trajectory data is used to create simulated radar data and real-time attenuation of all RF signal paths.

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 as an integrated team. Wallops Flight Facility has provided the 9 meter components with installation at Dugway Proving Grounds scheduled for April. Dugway Proving Grounds has prepared the range landing site with a graded area, power and the required cement pads for range installation. NASA Goddard has ordered the communication links installed from Edwards to Dugway.





Nine meter telemetry and uplink dish being constructed at
Dugway Proving Grounds

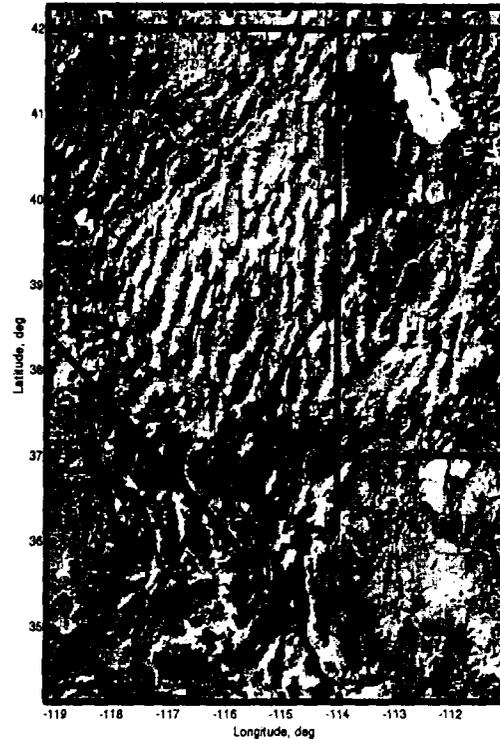


X-33 ITF Software Integration (Task DFRC-06)

The X-33 Integration Facilities located at Dryden continued to support the X-33 program. Additional office space became available in April 1998 to support an increased number of LMSW employees on site.

A single major software build with two updates were integrated, verified correct and released to Allied Signal and LMSW VMC developers. Build number 4 was delivered in July 1998 and builds 4.1 and 4.2 were delivered in January 1999 and February 1999 respectively.

Integration of the triplex VMC system for Ascent flight was achieved in September 1998. A single set of FADS hardware has been integrated into the hardware-in-the-loop (HIL) simulation. Litton INS/GPS unit integration and testing were performed at the MAST facility located at MSFC using the X-33 ITF simulation. Hardware Forward, Rear and Engine Data Interface Units (DIU) and Engineering Test Stations (ETS) were delivered to the lab and integration with the HIL simulation has begun. The real-time recording system has become operational.



EDWARDS AIR FORCE BASE

The Air Force Flight Test Center (AFFTC) continued to provide support to insure the timely completion of construction of the X-33 launch site and related ground support systems. The AFFTC Access to Space Office provided the interface to Edwards AFB facilities and services including support from Civil Engineering, the Communications Squadron, and Environmental Management. Installation of a fiber optic cable from the AFRL central switch to the X-33 launch site and Operations Control Center (OCC) was completed, providing a high data-rate fiber optic connection to the existing Edwards AFB fiber ring which includes NASA-Dryden and the subsequent communication with the X-33 extended range assets. Other projects initiated and nearing completion include upgrading of the phone service from copper cable to fiber optic cable, repair and replacement of chillers and air handlers and upgrades to electrical wiring in the OCC and warehouse, and refurbishment of the escape tunnel at the OCC. Backshop support included beginning breakdown and refurbishment of two C-5A work-stands for use at the launch site. A draft of a Launch Area Management Plan was completed and provided to the LMSW Flight Assurance IPT for further guidance/action.

The AFFTC Environmental Management Office continued to provide environmental support enabling the construction of the launch complex to continue on schedule. These contributions included conducting the required training of personnel who may come in contact with the local endangered species (desert tortoise).

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 90 pairs of balloons released 3 hours apart. This was a continuation of a study begun last year and was completed on 25 Sep 1998.

AFFTC engineering successfully advocated the need for a Best Estimate of Trajectory analysis to support the post-flight analysis of the flight data. Development of the computer program required to compute predicted trim



aerodynamics data from the LMSW provided aerodynamic data tables were initiated. This program will be required for post-flight data comparisons. The software description of the Automated Programmed Test Input data maneuvers was reviewed and finalized in the avionics Design Description Document. Assistance was provided in the development of many of the test planning documents (flight test profiles, weather plan, master measurement list, flight test objectives, flight rules, etc). Propulsion modeling techniques developed by the AFFTC last year that allow improved interpolation/extrapolation of limited engine performance data to create an expanded propulsion model were included in the Boeing Rocketdyne Division Rev 6.0 X-33 engine model release. Techniques for determining vehicle effective specific impulse based on flight data were developed which will be used to develop software for determining installed engine thrust and specific impulse from X-33 flight data. Engineering personnel participated in design review, test planning and work status meetings.

The X-33 Range Safety Requirements Document was published and coordinated through the AFFTC Commander and NASA Dryden Director. The draft Range Safety Operations Requirements document was published and is out for review. The initial Missile Flight Control Officer training was completed at Vandenberg AFB in October 1998 for Range Safety Officers from AFFTC, NASA Dryden and Hill AFB. The range safety console was moved from the OCC to the Ridley Mission Control Center (RMCC) and the critical design review for this console was completed. The critical design review for the Flight Termination System airborne RF subsystem was completed. The impact predictor (Test Evaluation Command and Control System) software was completed and is undergoing certification testing. Most of the purchases of range safety system hardware have been completed.

The AFFTC participants in the Extended Test Range Alliance continued to define the range support for the X-33. These tasks included determining pre and post-mission timelines, location of equipment and personnel at both the launch and landing sites, development of the communications flow, defining interfaces between OCC, RMCC, etc., and developing the scheduling plan for resources and outside agency support. Additional accomplishments included preparation of a program briefing to the FAA Headquarters, and determined



airspace/air traffic interfaces. Participated in reviews of the Range Safety subsystem design and operation, including changing the location of the Range Safety consoles from the OCC to RMCC. Obtained range components such as the radios for the use by the launch site operations personnel. Prepared/reviewed support request documentation for other supporting ranges, began documentation for range operations, assisted in development of flight rules, weather plan, etc., and participated in reviews and meetings regarding range support.

A timely and comprehensive response was provided to the request to rebaseline the AFFTC support for the program extension through Dec 2000. A plan was developed to reduce costs in FY99 to enable the AFFTC support to continue.

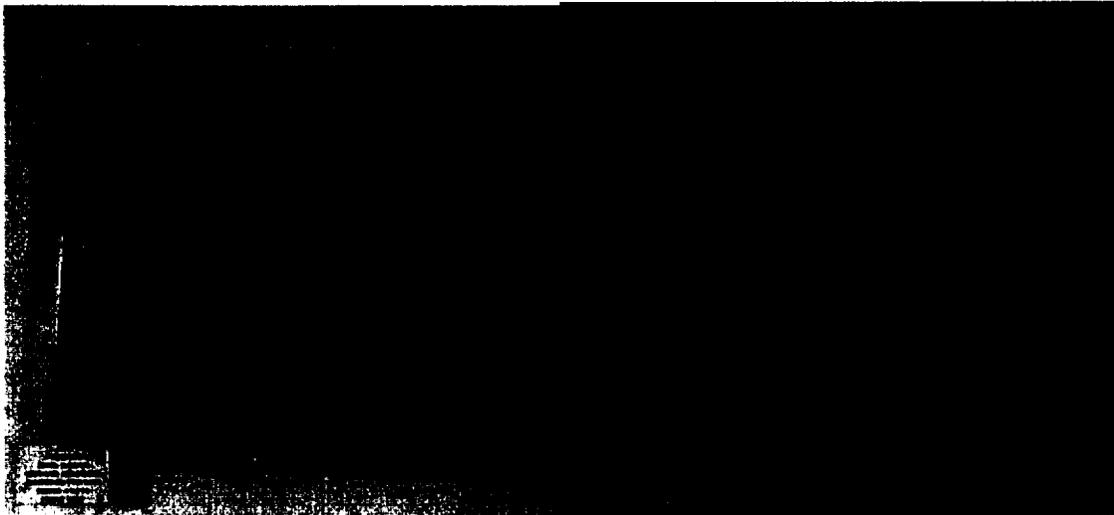


Johnson Space Center

Aerothermal Evaluation of Low Temperature Elastomeric Bulb Seals

Arc jet testing of elastomeric bulb seals incorporated in BF Goodrich Aerospace's (BFGA) design for thermal protection on the leeward side of the X-33 was performed at the ARMSEF. The objectives of this test program were to verify the thermal performance of the bulb seal design and to determine if any noticeable degradation in the elasticity of the seal occurred.

A series of five test runs were performed on an Advanced Flexible Reusable Surface Insulation (AFRSI) blanket model that incorporated an elastomeric bulb seal. The test program began with three runs at the 720°F conditions with the seal being visually and mechanically inspected after each run. Since no degradation was evident, two additional runs were performed to take the temperature at the bulb seal to 750°F. Again, there were no discernible negative effects on the seal. Thermal instrumentation located at the bondline suggested that the seal's thermal performance was comparable to the surrounding AFRSI for the short run duration utilized for this test program.



Pre-test

Post-test

High Temperature Aerothermal Testing of Felt Reusable Surface Insulation

BFGA's design for thermal protection on the leeward side of the X-33 includes the use of Felt Reusable Surface Insulation (FRSI). While FRSI has been in use for several years on the Space Shuttle Orbiter fleet, the FRSI proposed for use on the X-33 varies somewhat from the Orbiter specifications which impose certain requirements for material, coating, thickness density, etc. BFGA contracted the JSC ARMSEF to perform a series of tests to determine the maximum single use temperature and to investigate if the reusable temperature limit of 750°F specified for Orbiter FRSI could be increased for the X-33 material.

The objectives were met by subjecting the test article to environments ranging from 750°F to 940°F. Exposure at the 940°F test condition produced significant discoloration and flaking of the DC 92-007 coating. It became brittle to the touch; however, it proved suitable thermal performance for single use.



Pre-test

Post-test



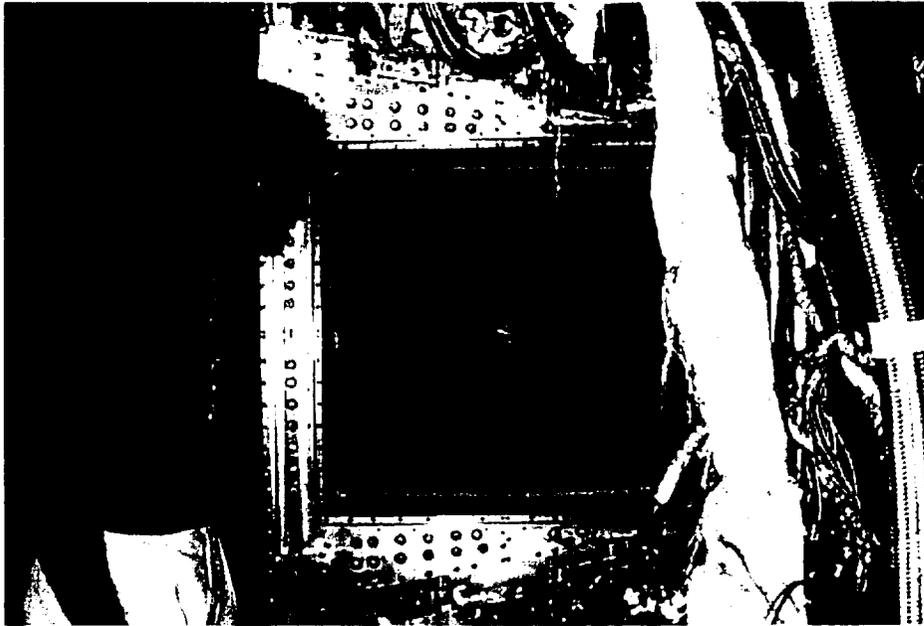
X-33 Four-Panel Flyable Damage

Arc jet testing of the metallic four-panel array manufactured by BFGA continued with the Flyable Damage test program. This test program was designed to evaluate the ingress of heated gasses through the panel at various stages of simulated seal damage. Data from this program will be used to develop a correlation for predicting the heating effects of seal leakage.

An old metallic four-panel array test article originally provided by BFGA (Rohr) was utilized for this test program. The test article was installed in the 24 inch by 24 inch test section of JSC's unique channel nozzle test configuration. A water-cooled heat exchanger was mounted on the back of the test article. Thermocouples were installed throughout the test article and heat exchanger to measure the response of the supporting hardware.

A series of test runs were made in accordance with the test matrix. After evaluating the data, BFGA representatives assessed that the test objectives might be better met with longer duration runs. Two long duration runs of 3400 and 2400 seconds were made. It was determined that for a more accurate assessment of the flow through characteristics, the test article needed to be instrumented with heat rate sensors. Testing on this old four-panel array was discontinued at this juncture.





Pre-test with the Arrow Head removed



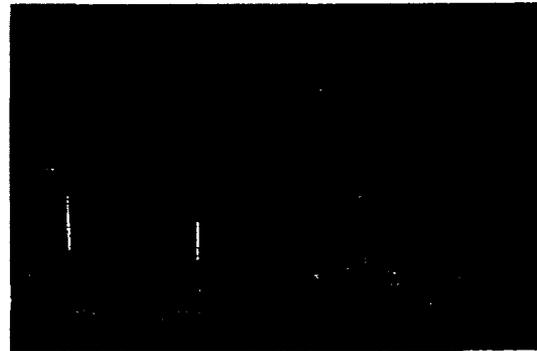
Thermally Induced Bowing of Metallic TPS Panels for X-33

A performance evaluation of Thermal Protection System (TPS) Inconel honeycomb and iso-grid panels was performed at the RHTF. The purpose of the test was to assess and quantify the deformations experienced by these panels when they are subjected to various thermal environments. This was accomplished by incorporating either 10 or 11 linear variable displacement transducers (LVDT) in each of the two test articles provided. These LVDTs measured the out-of-plane linear displacement of the flat panels during and after the heating cycle.

The honeycomb test article was exposed to thermal environments that produced surface temperatures up to 1700°F and thermal gradient as high as 390°F. This thermal environment produced measured deflections as high as 0.315 inches. The panel was also exposed to a thermal profile representing a complete ascent reentry mission. This thermal environment produced displacements as high as 0.276 inches.



Pre-test photo of the honeycomb panel



Post-test photo of the honeycomb panel



The iso-grid test article was exposed to thermal environments similar to those described for the honeycomb panel. The surface temperature of this panel reached temperatures as high as 1608°F and thermal gradient as high as 331°F.

This thermal environment produced displacements in excess of 0.40 inches. The mission profile produced displacements as high as 0.340 inches.



Pre-test photo of the iso-grid panel



Post-test photo of the iso-grid panel

Radiant Heat Testing of Felt Reusable Surface Insulation (FRSI) for the Leeward Aeroshell of X-33

Radiant heat testing of Felt Reusable Surface Insulation (FRSI) for X-33 was conducted in the RHTF. The objectives of this test were:

1. to evaluate the thermal performance of FRSI at temperatures in excess of 750°F in a radiant heat environment,
2. to determine the maximum use temperature of FRSI for X-33, and
3. to qualify FRSI for X-33 flight at the highest use temperature through a simulated lifetime exposure.

The first and second objectives were accomplished by exposing one test specimen to increasingly higher temperature environments until coating failure was noted. This series of tests indicated that the maximum reusable surface temperature of the FRSI was 850°F. After this temperature was determined, a second test article was used to accumulate a total of 7500+ seconds of test time above 850°F. That amount of time roughly approximates the mission life of the leeward aeroshell TPS.



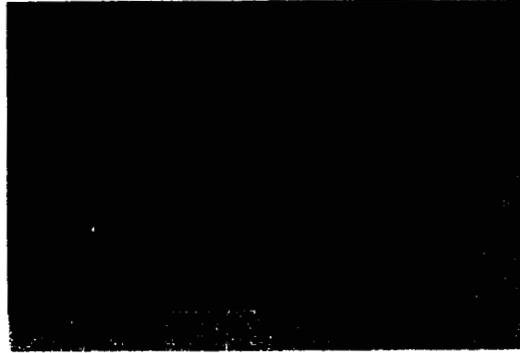
Pre-test



Post-test



X³³



Close-up Post-test



Kennedy Space Center

Task Agreements

KSC-01 STS to RLV Transition

1. Contributed to studies analyzing the possible crew accommodation and space station logistics re-supply missions.
2. Performed initial analyses for possible VentureStar™ siting, examining issues such as logistics, propellants, environmental, weather, down range tracking, supporting payload processing options, and general impacts with respect to existing facilities and infrastructure

KSC-02 Holddown Post Testing

1. The holddown post testing consisted of pre-load tension tests, bolt catcher tests, and holddown post proof load tests. The pre-load tension tests completed in September, 1998. Two tension washer assemblies were used to define a torque procedure to reach a target bolt tension load of 126,000 pounds. The procedure was executed five times on tension washer assembly SN-004 and SN-005, with tension versus set screw torque recorded for each test. A misalignment test of 1 degree angle and 1-1/2 degree angle was successfully performed on tension washer assembly SN-004 and SN-005.
2. The bolt catcher test met all specified testing requirements. Two high-end tests were run successfully at 138,000 pounds, while a third test resulted in the test bolt breaking. The bolt catcher was not installed when the separation occurred. Two low-end tests were done at 113,000 pounds and 80,000 pounds. For each test performed, the thickness of the energy absorber was measured and recorded before and after testing, the number of clip tube prong sets passed through was recorded, and the descriptions of the events were recorded and photographs were taken. All requirements were met.

3. The holddown post proof load test was successfully completed during October, 1998. Four ground vibration test (GVT) holddown posts and four ground support equipment (GSE) holddown posts were proof loaded in two configurations each. Requirements were changed to add strain gages to one GVT post and one GSE post. Valuable data was obtained and furnished to the Lockheed stress engineers to correlate the holddown post stress during proof loading to the finite element model data.
- 4.

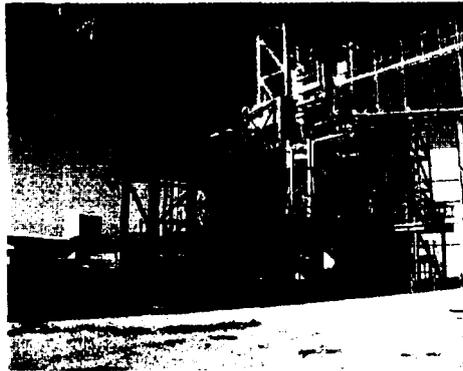


Holddown Post

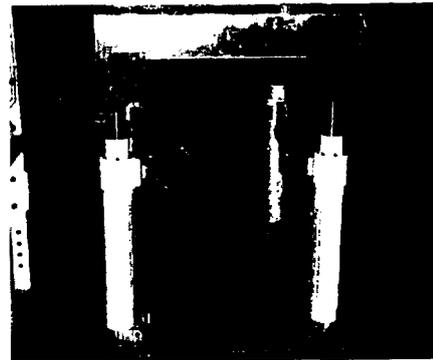


KSC-03 Umbilical Plate Testing

1. Designed and fabricated the horizontal and vertical test stands.
2. Integrated the vertical test stand into the Launch Equipment Test Facility (LETF) liftoff simulator.



Vertical Test Stand



Struts

3. Developed test plans to validate both LH₂ and LO₂ umbilical systems for umbilical mating, tracking excursions, and release / retract operations. Additionally, testing at cryogenic temperatures is planned to validate leak-proof joints, alignment, blast doors and flight doors operations.
4. Developed launch equipment test facility verification test requirements document (604T6401).
5. Developed LETF T-0 umbilical system facility cryogenic and mechanical system checkout procedures (KSC-MM-4634)
6. Wrote retract latch valve qualification test procedure and performed tests(KSC-MM-4724)
7. Performed centering strut and collet functional test.



KSC-04 Programmatic Support

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

KSC-05 Support to IHM Development

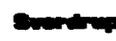
1. All work was stopped on this Task Agreement at the direction of the X-33 Program Office.

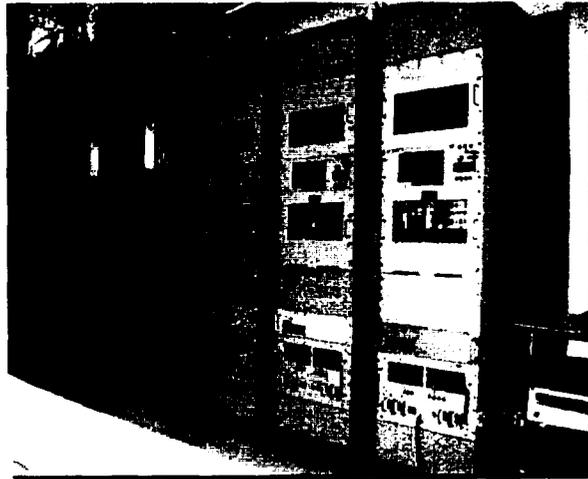
KSC-06 Phase II EA/EIS Support

1. Continued to provide support to MSFC on supplemental Environmental Assessments to address periodic 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. Designed, fabricated, and shipped the GIM racks to the launch site, providing hardware, software, and digital engineering support to the X-33 launch mission commands and monitoring system (LMCMS). Original interface design provided robust capability for the GIM to reestablish command phase-lock after receiving a bad command. Subsequent changes directed by Lockheed Sanders allow for the possibility of loss of command phase-lock on every subsequent command after receipt of a bad command, a higher risk approach.





Ground Interface Modules

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. Provided complete design package for the following umbilical subsystems:

<p>T-0 UMBILICAL GROUND SYSTEM CONTROL SCHEMATIC GN₂ CONTROL PANEL ASSEMBLY RECEPTACLE ASSEMBLY, COLLET LOCK RECEPTACLE HOUSING, COLLET LOCK RECEPTACLE PIN, COLLET LOCK RECEPTACLE SLEEVE, COLLET LOCK RECEPTACLE SHEAR PIN, COLLET LOCK RECEPTACLE SHIM, COLLET LOCK RECEPTACLE, SHEAR PIN</p>	<p>RECEPTACLE, ALIGNMENT PIN COLLET LOCK ASSEMBLY ALIGNMENT PIN ASSEMBLY SHEAR PIN LEVEL STRUT ASSEMBLY RETRACT LATCH ASSEMBLIES COLLET LANYARD ASSEMBLY CENTERING STRUT ASSEMBLIES ACCUMULATOR ADAPTER FITTING BLAST DOOR MECHANISM ASSEMBLY</p>
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KSC-09 Weight and Center of Gravity Simulator

1. Performed analyses and furnished drawings.

***Vehicle Positioning System*****KSC-10 Fault Tree Analysis**

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

KSC-11 Hazardous Gas Detection Equipment

1. Supported analyses of linear aerospike engine (LASRE) at both White Sands, NM and DFRC, CA.
2. Prepared the hazardous gas detection equipment and coordinated requirements for equipment to be shipped to launch site. Equipment capability is as follows:

Hydrogen	500 ppm	100%
Helium	500 ppm	100%
Nitrogen	500 ppm	100%
Oxygen	100 ppm	25%
Argon	100 ppm	1%
Methane		1-20%

KSC-12 Pyro Initiated Controllers (PIC)

1. Assessed requirements for 32 NASA standard initiators (NSI's) and 32 radially outward firing initiators (ROFI's) in support of X-33 H₂ burn testing during FRF and launch.
2. Began preliminary arrangements for shipping 2 PIC control panel assemblies (CPA's) to launch site, including other software, assembly / installation drawings, operations and maintenance directives (OMD's) and acceptance test procedures (ATP).

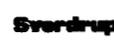


Langley Research Center

Systems Analysis

Task 5 - RLV System Concept Evolution and Trades

- Developed first 5 lobe LH2 tank configuration with payload bay "pooch" on lee surface. Concept utilized in future LMSW baseline configuration, resulting in significant overall vehicle weight reduction.
- Assessed many alternate "out-of-the-box" lifting body, aerospike engine concepts including 5 lobe LH2 tank; LOX aft; high fineness ratio; dorsal fin; conical tanks with axisymmetric aerospike engines; highly integrated aerospike engine with conformal tanks; mid-mounted aerospike with single ramp nozzle; etc.
- Developed entry trajectories for several RLV configurations, including 0023, high fineness, 0033, to minimize heating while meeting cross range requirements.
- Developed a reference peak heat rate vs. hypersonic W/CLS curve to enable rapid prediction of sensitivity of aerothermal environment to vehicle weight, size and lift coefficient.
- Developed curves of peak heat rate vs. cross range.
- Assessed controllability of RLV 0023 and follow-on configurations.
- Completed transonic aerodynamic CFD analyses, Euler and viscous, of configurations 0023 with and without the payload "pooch."
- Completed wing sizing for 0023 and 0033.
- Suggested full-Mach range trim requirement be included in 5 weekly tracked LMSW Goals/Objectives.
- Developed engine databases including thrust vectoring predictions for each aerospike engine design.
- Completed optimized trimmed and untrimmed ascent trajectories.
- Determined optimum vehicle propellant weight ratio to minimize vehicle dry weight.



- Developed capability to perform bottoms-up structural sizing weight estimates. Completed bottoms-up structural sizing on 0023 configuration components. Results agreed with LMSW and Michoud results. Applied method to follow-on baseline and “out-of-the-box” configurations.
- Completed sizing on RLV 0033 to close vehicle with 25K payload and no margin, and 25K payload with minimum 15% margin.

Task 7 - X-33 Reliability, Maintainability & Logistics

- Provided information on low-speed and high-speed tile impact damage for reparability issues.

Aerothermodynamics**Task 2 - Thermodynamics**

- Completed hypersonic testing of “pillowed” thermal protection panels to determine potential effects of TPS panel thermal expansion on boundary layer transition.
- Completed hypersonic testing to investigate boundary-layer transition tripping along “attachment lines.”
- Validated previously developed criteria for prediction of X-33 boundary layer transition characteristics.

Task 4 - Wind Tunnel Testing

- Completed aerodynamic loads/hinge moment testing in the following facilities:

16-Foot Transonic Tunnel	Transonic
Unitary Plan wind Tunnel	Supersonic
- Completed reaction control system/aerodynamic interactions testing in the following facilities:





Unitary Plan Wind Tunnel
31-Inch Mach 10 Tunnel

Supersonic
Mach 10

Vehicle Health Management / Non-Destructive Evaluation

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

- Fiber-optic strain and hydrogen sensors delivered to Lockheed-Martin Michoud for installation on LH2 flight tanks.
- Acoustic emission (AE) sensors/preamplifiers delivered to Lockheed-Martin Michoud where they were successfully flight qualified and await installation on LH2 flight tanks.

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 tested at Lockheed Sanders with flight Distributed Strain Sensor system.

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

- Fiber-optic Bragg grating sensors produced for testing of ground-test panel
- AE ground test interface hardware fabricated and successfully tested.



Structures and Materials

Task 8 - Thermal-Mechanical Testing of Cryogenic Insulation

- Completed testing of second set Al-Li 2195 panels with Spray-on Foam Insulation (SOFI) from -320•F to 350•F. The SOFI was machined on one half (6" x 12") of the test panels, while the other half had the "rind" from the spray on process.
- Completed testing of Gr-Ep panels with Airex™ LMMSS, cryocoat, and SOFI insulations from -423•F to 350•F. Cryocoat plugs cracked during thermal/mechanical cycling.
- A new 16-loop control system for the thermal-mechanical test rig was developed, installed, tested, and used in tests. This new control system will be used for the 100-cycle tests of RLV panels to be performed in Task 21.

Task 9 - Cryogenic Pressure Box Test of LH2 Tank Section

- The "check-out" panel was assembled and installed in the Cryogenic Pressures Box Facility. Air pressurization testing has begun.
- The LMMSS composite sandwich panel (fabricated by Alliant TechSystems and instrumented by LMMSS) has been assembled with test facility interface hardware and is ready for integration and test in the Cryogenic Pressure Box Facility.

Task 15 - Metallic TPS Thermal and Structural Analysis and Design

- Performed seal flutter calculations which predicted flutter observed in 8-Foot High Temperature Tunnel tests of X-33 TPS.
- Incorporated panel flutter capability into MARC finite element code.
- Developed analytical technique to analyze panel flutter at arbitrary flow angle.
- Developing method to analyze nonlinear boundary conditions for panel seal flutter.



Task 16 - TPS Materials Thermal Characterization Tests

- 4-point bend tests at elevated temperature were conducted to determine face-sheet ultimate strength.

Task 18 - High Temperature/Speed Tests of X-33 TPS System

- Completed aerothermal tests in 8-Foot High Temperature Tunnel of metallic TPS array representative of acreage TPS on X-33 windward surface.
- Completed aerothermal tests in 8-Foot High Temperature Tunnel of two joint concepts for blanket TPS on the leeward surface of the X-33.

Task 20 - Development of Cooled Nozzle for Linear Aerospike Engine

- Studies were conducted on the impact of SiC densification on bare and coated refractory metal tubes, including burst tests, SEM, and microhardness. These studies provided guidance on the best coatings to use for the nozzle coolant tubes.
- LaRC was assigned by Boeing Rocketdyne to provide technical and design guidance to one of six competing ramp study teams, and also supplied the nozzle ramp concept that was developed by the team. The team "shepherded" by LaRC had a successful critical design review and was ultimately one of two teams selected for the next phase.
- Test plans, including a modern design of experiments test approach (MDOE), were developed for testing an actively cooled specimen in the Vortek (a high powered industrial radiant heater) at AFRL. Manifolds for the specimen were designed, and instrumentation was installed at LaRC (requiring development of a new, high temperature installation procedure for thermocouples). Testing of the specimen was conducted in early March and MDOE data will be evaluated.



Task 21 - Thermal-Mechanical Testing of Cryogenic Insulation - RLV

- Larger (1-foot x 4-foot) test chambers being designed to allow for more features to be incorporated on test panels, such as stringers and Thermal Protection System (TPS) substructure attachments.

Task 26 - Cryogenic Insulation Development (RLV)

- NASA developed polyimide foams (TEEK) have passed 50 cycles of thermal mechanical testing at -423°F and 400°F without damage. They have also passed the NASA flammability testing (NHB 8060.1), and have demonstrated excellent compressive strength and thermal conductivity at ambient, cryogenic, and elevated temperatures.
- A follow-on TEEK foam has been developed (TEEK.2) which has 2 to 4 times the compressive strength of the original polyimide foam, while maintaining all of the original foams excellent characteristics.
- Process demonstrations have shown that TEEK foams can be foamed in place into honeycomb core. These demonstrations have been performed for honeycomb cell sizes from 1/8 inch and up, and z-direction height of 1/4 inch and larger.

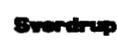
Task 29 - Improved Metallic TPS (RLV)

- Identified several alternative metallic TPS concepts.
- Tested several fibrous and multi-layer insulations for use in metallic TPS, under steady-state conditions as a function of temperature and pressure.
- Compared measured insulation performance with values used for X-33 TPS design.
- Developed and validated analytical method to predict fibrous insulation performance.
- Developed several sol-gel coatings for Inconel 617, and tested these up to 200 hours in HYMETS at 2000°F .





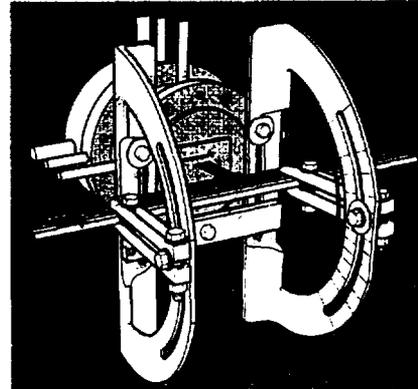
- Static oxidation testing performed on several coatings for MA 754 and MA 956, up to 2000•F.
- Both sol-gel and Pyromark coatings are being evaluated for PM 1000.



**Glenn Research Center
(Formerly Lewis)****Task No. LeRC-3: Composite Aerospike Nozzle**

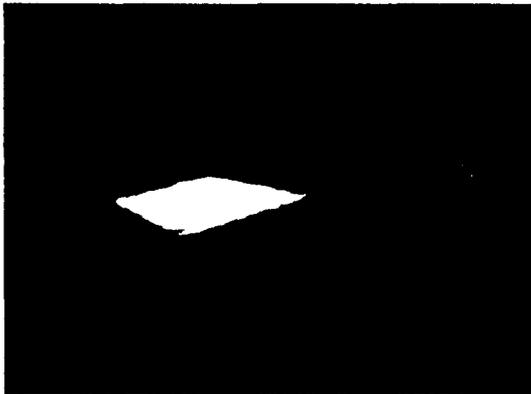
Primary goal of the GRC Composite Aerospike Nozzle task is to:

- Provide technical guidance to Rocketdyne/MSFC/GRC/LaRC team and selected vendors on composite development.
- Conduct hot-fire testing of sub-elements in single thrust cell test stand (Cell 22)
- Conduct thermodynamic and kinetic degradation modeling of ceramics in combustion environments, via analysis and experimental verification.
- Conduct microstructural analysis of as-fabricated and tested coupons and sub-element test articles.
- Conduct mechanical and thermal property life prediction testing of coupons.



GRC and composite aerospike nozzle government/industry team accomplishments to date are:

- Completed selection and downselection of nozzle concepts.
- Evaluated vendor proposals and vendors.
- Conducted non-destructive evaluation of composite panels.
- Conducted thermodynamic and kinetic degradation modeling of ceramics in combustion environments, via analysis.
- Prepared Cell 22 for hot fire testing on composite nozzle concepts.



Task No. LeRC-4: Aerospike Engine Health Management

The Aerospike Engine Post -Test Diagnostic System (PTDS) (Release 1.0) was delivered to Rocketdyne. This delivery and user training culminated a year of detailed design, implementation and testing at GRC.

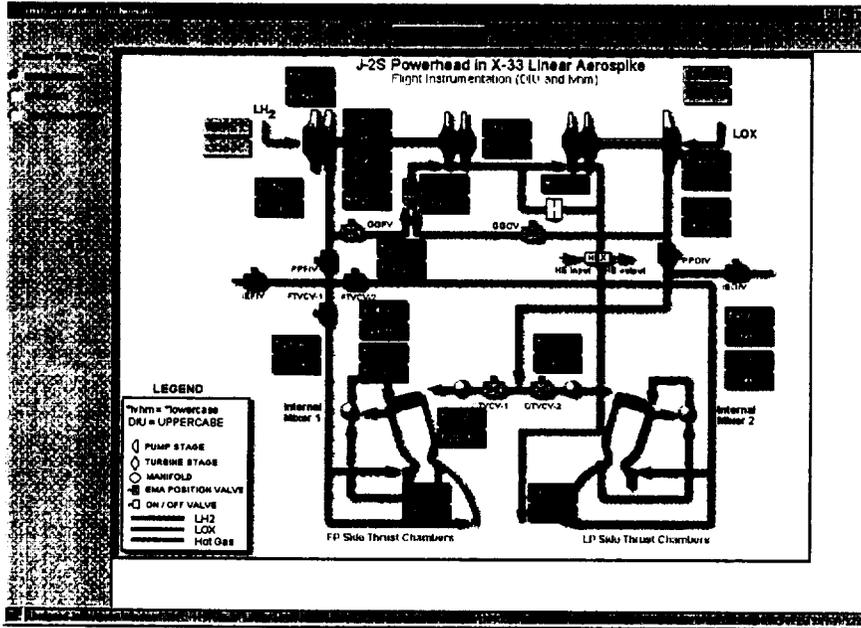
The PTDS was designed to reduce the time associated with routine data review and to increase the accuracy, completeness and repeatability of rocket engine data analysis. The PTDS has a modular design to facilitate extensions as new knowledge becomes available. Primary objective of the first release was to provide analysts with easy access to data, and to capture top-level knowledge about the system. Subsequent releases will incorporate deep knowledge and perform detailed tracking of component behavior. Although the first priority of PTDS was the analysis of flight data, the delivered PTDS has been analyzing powerpack assembly test data since September of 1998.

Included in the first release of PTDS were both the Analysis and Viewing functions:

1. The Analysis function determines events, processes FIDs, performs margin analysis, detects hard sensor failures and identifies potential soft sensor failures. It runs open and closed loop versions of a dynamic simulation of the aerospike engine and compares actual and model-predicted values, and performs detailed calculations to predict parameters associated with the turbomachinery and gas generator.
2. The Viewing function permits viewing of Analysis results (both measured and calculated) associated with the current and previous tests. The Viewing function is Web-based and permits an analyst to access analysis information and/or data via reports, schematics or a plotting capability. The plotting capability was delivered with canned plot packages that had been specified by engine component analysts and with a user interface to permit specification of new plot packages or to view data and PTDS calculations interactively.

The next release of PTDS will include knowledge necessary to accommodate engine testing, additional reports, enhanced plotting capabilities and

statistical tracking functions.



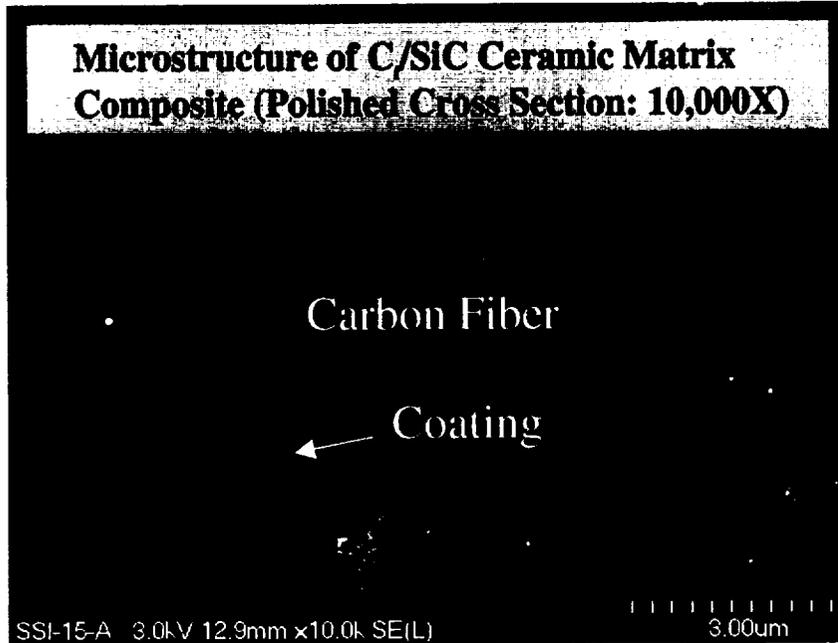
This figure contains one of the Web-based Viewing screens a user would use to obtain information from the PTDS and plot Aerospike engine data.



Task No. LeRC-5: X-33 CMC Sub-element Risk Mitigation

Throughout 1998, NASA GRC provided support to the RLV Ceramic Turbine Team's material and sub-element development efforts at three Boeing Rocketdyne contractors. A revised Task Agreement was completed in September 1998. The Team had selected GRC to perform testing of Torque Sub-elements, Blade Sub-elements, and coupon specimens. Researchers from the Structures and Acoustics Division provided plans for performing these tests at GRC. The test objectives are to gain an understanding of torque transfer (from blisk to shaft) capabilities, blade fatigue resistance, material environmental durability, etc.

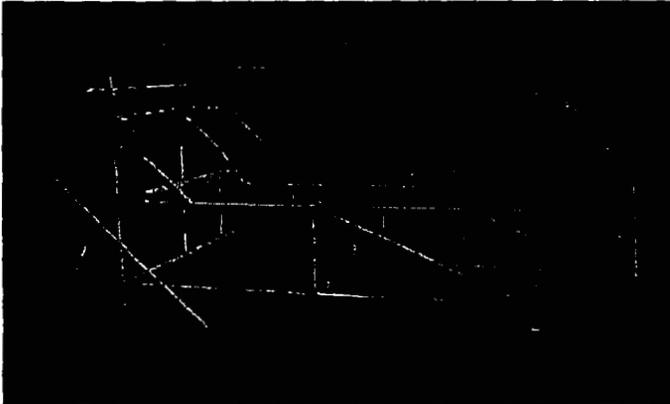
GRC was also selected for the lead role in analyzing microstructural features of Carbon fiber-reinforced Silicon Carbide matrix (C/SiC) composites. Materials Division personnel completed characterization of carbon fibers and Polymer Impregnation Pyrolysis (PIP) C/SiC composite materials for blisk development efforts. Their emphasis was placed on determining Processing/Microstructure/Properties relationships. That is, they examined fracture surfaces of tested specimens and polished cross sections of as-received (untested) composite materials, and attempted to 1) determine the effect of processing conditions on the resultant microstructure, and 2) understand how the microstructure influences the material properties such as tensile strength and elastic modulus. High quality preparation of polished specimens and excellence in electron microscopy (both high-resolution imaging and material chemical analysis) made it possible to routinely analyze specimens at magnifications up to 50,000X.



Task No. LeRC-10: Multi-Element Combustion Wave Ignition Tests

NASA GRC, in co-operation with Rocketdyne, Boeing Company, successfully completed Combustion-Wave Ignition System testing of rocket engines. This ignition system greatly simplifies ignition in rocket engines with a large number of combustors. The goal of the tests was to verify the soundness of the combustion-wave ignition system design and to define the system operational characteristics. The testing activity and results will help ensure the eventual successful flight of X-33 and the next generation of reusable launch vehicles.

A total of 103 hot fire ignitions were conducted to map out the X-33 start conditions under which ignition would be feasible. The test program



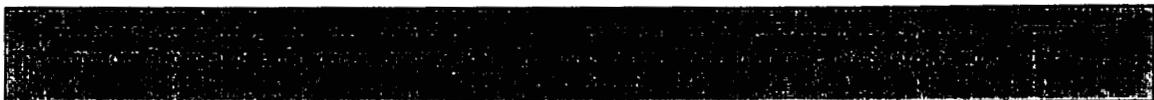
identified the timing in the ignition system for the propellant valves and exciters, and outlined the tank pressure envelop for a successful ignition. In addition, it verified the soundness of the design of the whole propellant flow system, consisting of elements such as lines,

valves, and orifices in terms of their sizing and their pressure and temperature capability. The tests characterized check valve performance, cooling of pilot tips, the J2 spark exciters, and the LOX geisering phenomenon in the system.





The test program has successfully proved that the ignition system design is indeed sound. It identified the optimal hardware configuration, propellant conditions, and operational characteristics for a successful launch pad engine operation of X-33.





Marshall Space Flight Center

X-33 Safety and Mission Assurance:

The MSFC Safety and Mission Assurance (S&MA) Office has taken a more active role in assessing the X-33 Program safety as a result of a recent amendment to the Space Act to indemnify x-programs. In response to this new role, an X-33 S&MA Office consisting of an S&MA lead from MSFC and support contractors has been set up. The MSFC S&MA Office has also released an X-33 S&MA Plan which was co-signed by the NASA X-33 Program Manager and the Lockheed Martin Skunk Works (LMSW) Program Manager. The purpose of this plan is to ensure that risk assessment and management, quality surveillance, reliability, and maintainability analysis and system safety activities are implemented in the X-33 Program per the CA plans and requirements.

The MSFC S&MA Office continues its effort to support the reliability analysis milestones and reviews for the propulsion system development. Efforts also continue in support of failure modes and effects analysis on both the linear aerospike engine and the main propulsion system (MPS). Significant efforts have also gone into assisting LMSW with the development of fault tree analysis on the ground support system, flight termination system, and the MPS.

X-33 Natural Terrestrial Environment:

Weekly archiving, distribution, and analysis of rawinsonde wind profile pairs for Edwards Air Force Base (EAFB) continued. Seasonal low-pass filtered versions of these data bases were derived and updated for application in studies to establish the amount of wind loads relief that could be achieved by biasing vehicle guidance with respect to a wind profile measured a few hours prior to launch. Consultations were provided on X-33 applications of the Global Reference Atmosphere Model for determination of aerodynamic heating effects, vehicle control system dynamics, and terminal area energy management (TAEM) operations. Studies were completed that establish the



probability of X-33 launch availability given launch restraints for surface wind speed, precipitation, cloud cover, visibility, and thunderstorm occurrence.

Flight Control Actuator Electromagnetic Interference (EMI) Testing:

MSFC performed the Safety of Flight EMI testing of an X-33 Flight Control Actuator in support of Allied Signal. MSFC procured, developed, and installed ground support hardware to operate the X-33 FCAS in a flight-like manner and wrote EMI test software to facilitate the FCAS EMI test requirements. Testing required under the task agreement consisted of MIL-STD-461D Radiated Emissions - Electric Field (RE102), Conducted Emissions - Power Leads (CE102), Radiated Susceptibility - Electric Field - Modified (RS103), Conducted Susceptibility - Power Leads (CS101) and Conducted Susceptibility - Structure Current - Modified (CS109). The testing was conducted in MSFC's Control Mechanisms Development Laboratory using a portable EMI screen room. The actuator was tested in a loaded configuration by installing the actuator in a spring-mass simulator (located in the screen room); designed by MSFC, and commanding the actuator to a position that represented the required load during testing. This test series was conducted and supported by a team consisting of members from the Propulsion Laboratory, Systems and Integration Laboratory, Astrionics Laboratory, the X-33 Project Office and the customer. The task required extensive participation/coordination between all involved. Testing was conducted during the month of August 1998, with test setup beginning in late July. The hardware was returned upon completion of test and an EMI test report delivered to Allied Signal and LMSW in October, 1998.

X-33 Antenna Testing:

Antenna verification tests were performed on four S/L-band and four C-band antennas by measuring the radiation distribution pattern in the principal planes. Spherical coverage antenna patterns were also measured on one S/L-band antenna and one C-band antenna. The test articles were flight units and consisted of the following model numbers: S/L-band Herley-Vega Model 815S-4 (S/N's: 001, 002, 003, and 004) and C-band Herley-Vega model 820C





(S/N's: 2711, 2712, 2515, and 2716). The principal-plane cut antenna patterns were measured in the MSFC anechoic chamber and the spherical coverage antenna patterns were measured on the 400-foot antenna range. These tests were performed to verify the operational parameters of the flight units. The S/L-band antenna measurements were performed at the following two frequencies: 2205 MHz and 1804.5 MHz. The C-band antenna measurements were performed at the following two frequencies: 5585 MHz and 5660 MHz. Antenna patterns were digitally collected, saved, and supplied to Allied Signal.

RF Communications System Testing:

MSFC facilitated integrated subsystem testing of 2 flight sets of command and telemetry system flight hardware. Subsystem performance exceeded specification requirements and no hardware incompatibilities were discovered. Each flight set consists of 2 L-Band receivers, 2 S-band transmitters, 2 bit synchronizers, and 1 RF combiner unit.

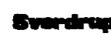
MSFC loaned a microdyne telemetry receiver to the program for use in the communications test set.

Selection And Test Of Electrical Switchgear:

The Electrical Division performed corona testing on several pieces of X-33 engineering unit hardware from the EPS, FCAS, and Active Thermal Control Systems. The testing was performed in order to verify that the Corona Design Guidelines Document had been adhered to and that there existed no mechanical design problems that would facilitate the initiation of corona and partial discharges at mission operational voltages and pressures. This testing was performed as part of the X-33 Task Agreement EB-01 and will conclude with a corona test of the High voltage power control assembly in Ottawa, Ontario in the spring of 1999.

INU/GPS Hardware in the Loop Simulation:

The X-33 GPS/INS system, a Litton LN100G, was delivered to MAST on June 2, 1998, to undergo a series of functional tests. Approximately 25 tests were



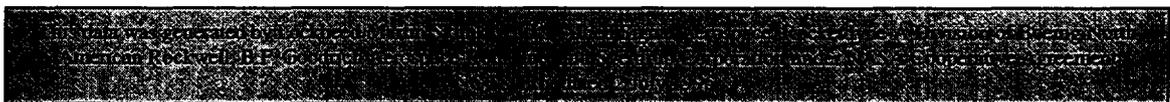
designed to test the unit in both an open-loop and closed-loop manner and were scheduled to last approximately 3 months. Software was developed in-house to perform the open-loop testing while the Dryden ITF simulation is being used for the closed-loop tests.

Upon delivery of the unit to MAST it was integrated into the lab and testing was immediately started. The unit was delivered with a known error in performing Differential GPS (DGPS) processing. DGPS is required to obtain the accuracy needed for landing. Subsequent testing in MAST revealed several other major software problems in the LN100G. These problems include errors in the ICD, errors in commanding both the INS and GPS, poor satellite tracking by the GPS, errors in the INS aiding the GPS, etc. Numerous telecons with LMSW, Allied Signal, Litton, and Rockwell Collins (GPS receiver manufacture) have been held to determine corrective action and/or work around for the errors found. As a result of the errors found and the amount of time required by Litton to make corrections, this task agreement was renegotiated with LMSW and extended through the first quarter of CY 1999.

To date, Litton has identified or delivered corrections to most of the major problems found and testing in MAST has verified the delivered corrections. There is currently some 15 remaining action items out of 40, resulting from the testing, that have not been closed. A fix for proper DGPS processing has not yet been found. However, recent tests at Litton seem to indicate that the Collins GPS software is at fault. A fix to DGPS and the remaining know software problems are expected within the next two to four weeks. Once new software is delivered the tests will be "formally" run, analyzed, and a final report will be written.

X-33 H2 Sensing/Detection System:

The Astrionics Laboratory of MSFC has supported Allied-Signal in supplying a system of solid-state wide range state-of-the-art H2 transducers for the X-33 craft. These units are being supplied by a teaming of Expert Microsystems, Inc., of Orangevale, Ca, and Makel Engineering of Chico, Ca. The units are remotely located and accessed from VME boards located within



the data system. The system was assembled and flight qualification tested during this reporting period. Thorough testing and calibration was done realizing that, once installed, it would be extremely difficult to reaccess the units. System fit and verification units were delivered to ASA and the flight units were delivered to Palmdale. They are currently awaiting integration.

Propulsion System Testing:

X-33 main engine thrust chamber testing was conducted at MSFC this past year. The Test Readiness Review was completed the week of August 3 and blowdown tests started August 7, 1998. All planned testing was completed in the first week of September 1998 (a total of 12 tests). During the last run at 115% some erosion to the nozzle was noted. Rocketdyne's review of the test data determined that additional testing was feasible. Three additional tests were conducted in December 1998. A total time of approximately 1150 secs was put on the X-33 thrust chamber. The thrust chamber remains in the test stand and Rocketdyne is looking for additional funding to run more tests on this chamber.

Flow testing for the gas generator fuel valve was completed in August 1998. The test objectives were met and Rocketdyne has evaluated the test data. Post test leak checks of the valve revealed an internal leakage over the specification value. Life cycle testing on the GGFV and GGOV was completed in September 1998. After GGFV revealed excessive internal leakage, the GGFV was removed and returned to Rocketdyne for evaluation. In the mean time, the GGOV was successfully cycled 1000 times at cryogenic LN2 temperatures. Facility preparations, test article strain gage application, LN2, GHE, and GN2 plumbing for the vibration testing were completed. In January 1999, the cryogenic vibration test of the GGOV was well underway. The x-axis and z-axis testing has been completed. Some minor anomalies with the controller/software occurred during the testing and are currently being addressed by Rocketdyne.



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

In August 1998, Allied Signal submitted a modified scope of work for this task (EP02) asking for consultation on the system level EMI test to be performed in Toronto. This will include review of procedures and setup. If there is a discrepancy between the EMI data obtained in EP02 and that which MSFC produced in EP03, it is requested that MSFC be involved with the evaluation and resolution. Other tasks include the shipment of the MSFC X-33 inertia simulators to Toronto in November 1998.

LH2 Composite Double Cylinder w/Woven Joints Test:

After initial cryo testing MSFC's Test Stand 500, which demonstrated significant leakage, the tank had the previous sealant stripped, media blasted, and resealed with pelseal sealant by LMSW. The tank reinstalled for further testing in September 1998. Again significant leakage occurred and upon further investigation of the inside sealant of the inner tank, the pelseal sealant appeared to have cracked where tank repairs were made; thus, incriminating the sealant and sealing process. The tank was shipped to LMMSS on September 29 for further sealant selection and application. After application of a different sealant, "polyseal," and initial testing with liquid nitrogen, the tank was returned to MSFC in November for final verification testing with liquid hydrogen. The tank was pressure loaded with LN2 40 psig and leak checks performed. The tank was then loaded LH2 to cryo temperatures with LH2. During each LH2 test, the tank was pressure loaded to 40 psig for five cycles at 2 minutes per load cycle. Since only a few small "repairable" leaks occurred LMSW declared the test a success and an acceptable sealant demonstrated for application to the flight tanks. After the test the tank was removed from the test stand and returned to LMSW.

Propulsion System Design Reliability and Operability Modeling:

X-33 design reliability and operability support activities concluded with the X-33 CDR. Since then, weekly logistics telecons and reviews have been supported.



Propulsion Health Management System Development:

Since integration of Integrated Health Management (IHM) in Stennis Space Center (SSC) Test Stand A1 and A1 Test Control Center in September 1998, MSFC file management of IHM has been the IHM activity. IHM code development planning and work is continuing for representing the Real Time Vibration Monitoring System (RTVMS). The RTVMS procurement phase for key hardware is in process and FY99 funds are available. Planning for local communication testing between IHM and RTVMS is under way and will be resolved at SSC when RTVMS is integrated. Offline high speed observer activities and enhancements are continuing at MSFC.

X-33 Composite Turbine Project Support:

The coordination of efforts for the turbomachinery tasks is continuing. However, Rocketdyne or LMSW has still not signed the modifications to these tasks signed by MSFC. Therefore, the work performed under these tasks is somewhat limited until the new agreements are signed. The majority of the coordination effort is being spent on the supersonic turbine testing effort. The test article modifications are being designed by EP Lab personnel and coordinated with ED Lab personnel specializing in Computation fluid dynamics (CFD) analysis and fluid flow testing. Rocketdyne is still discussing an additional EP task to utilize the MSFC "blade burner" rig for testing the ceramic blade options being developed. The task request has been placed on hold until the budget restructuring for the program has been completed.

Reusable Launch Vehicle (RLV) Main Engine Composite Nozzle Concept Design:

In July and August 1998, Boeing/Rocketdyne processed purchase orders with five industry partnership leads for the construction of small test panel/coupons of their cooled composite concept. MSFC is shepherding the Atlantic Research concept. In September and October 1998, the task representatives (including MSFC) finalized test matrixes and coordinated test planning for the small test coupons and panels. The five industry



partnerships finalized the designs for these test articles and conducted Critical Design Reviews (CDR's). After reviewing the CDR materials, the task representatives completed their evaluation of the concepts and selected the industry partnerships for the next phase, fabrication and testing. As of January 1999, Boeing/Rocketdyne was finalizing contracts for the next phase for these winning partnerships. At that time, Ames Research Center (ARC) was the only partnership with a finalized contract and they have started coupon production. MSFC has also been busy re-scoping all composite nozzle task including EH-04, EP-14 and EP-05 based on a further understanding of the work involved for the project.

RLV RCS IPT Participation:

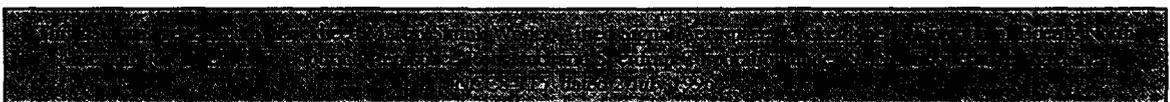
In August 1998, parametric studies were conducted evaluating the effect that varying the attitude autopilot proportional gains for roll, pitch, and yaw has on propellant usage in different versions of the RLV six-degree of freedom (6DOF) docking model. In addition, two changes to the model assumptions were made during this reporting period, requiring many previous runs to be repeated. The first change involved the use of bimodal thrusters, 800 and 150 lb thrust, to be used for the RCS. The second change involved increasing the feedback rate to obtain a faster system response. In September 1998 an autopilot gain optimization study to identify the solution set of attitude autopilot proportional gains for roll, pitch, and yaw (KR, KP, & KF) to minimize propellant usage was completed and the results delivered to the customer. This was conducted using four different versions of the RLV 6DOF docking model. The initial results indicate that varying KF over a range of KP values does not significantly improve propellant usage performance. However, varying KR over a range of KP values shows a zone where propellant usage is minimized to approximately 120 kg for a rendezvous maneuver initiating at a range of 300 meters. This is a significant improvement over simulations using the initial version of the 6DOF model (rlvnocam.all), where propellant usage averaged 250 kg for a similar rendezvous maneuver. In November through January 1998 the gain optimization study was continued using the 6DOF model to evaluate different thrust levels of attitude control and translational RCS thrusters. The objective of this study was to evaluate performance of the RLV RCS



using bimodal thrusters with low thrust levels set at 40 lbf. A range of different RCS configurations and autopilot gains were evaluated to identify the optimal configuration that minimized propellant usage. This study was conducted using the latest version of the 6DOF model with the set of gains [KP(4), KR(6), and KF(4)] identified in the gain optimization study and varied the proximity autopilot gains [KP(5), KR(5), and KF(5)] to derive a solution set to optimized propellant consumption.

Ascent, Entry, Abort Trajectories, and Guidance:

Numerous X-33 abort trajectories were generated in support of the detailed analysis of X-33 flight. MSFC-developed guidance algorithms were refined, tested in simulation, and documented in detail. Modules including these algorithms were delivered along with test cases. Thousands of trajectories were simulated, varying vehicle, engine, and environmental parameters, to test the success of the guidance in flying the X-33. The performance monitor, an MSFC-designed algorithm to simulate the rest of an X-33 flight as it is occurring and to reshape the trajectory or retarget to a different landing site as necessary, was also refined, documented, and delivered. The X-33 Propellant Utilization System Model was integrated into simulation at MSFC, and numerous improvements were suggested to the builders of this software. In conjunction with MSFC flight controls personnel, the MAVERIC high-fidelity X-33 simulation was kept up-to-date, with the latest vehicle and subsystem models and guidance and control algorithms. Multiple versions of this software were delivered to LMSW and used extensively by multiple X-33 team members. GN&C integration was supported through continual personnel co-location in Palmdale, through December 1998. Significant assistance was given in helping to compile the draft GN&C Verification & Validation document. Work progressed on tasks to perform X-33 post-flight trajectory reconstruction and to improve the mission planning process turnaround time for X-33. VentureStar trajectories were generated to examine and attempt to reduce entry heating. A 3 degrees-of-freedom simulation was developed and used to understand VentureStar flight performance reserve and entry heating dispersions (by running numerous trajectory simulations with multiple vehicle, engine, and environmental parameters varying).



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 August 1998, November 1998 and January 1999 that kept the DDD current with the flight control design process. Flight software test cases were provided with the incremental DDD updates to support system and unit level testing of the flight software design. Analysis was performed and documented to support an Analysis review in December 1998. The MAVERIC six-degree-of-freedom simulation was kept up-to-date with incremental model updates as the vehicle design matured and test data became available for analysis. MAVERIC was released to, and was heavily used, by LMSW, Allied Signal and the Integrated Test Facility with each incremental DDD update. The MAVERIC simulation was used extensively to analyze system level dispersions for the multiple missions developed over the year. Work was done to analyze VentureStar stability and control. We analyzed VentureStar approaches to the International Space Station through simulation and determined the RCS sizing, location, and propellant requirements.

Structural Loads & Dynamics:

Vehicle loads for load cycle 5 were performed and have been provided to LMSW. The loads included the flight events of liftoff, ascent, reentry, and landing events. The analyses for the ascent and reentry loads used external pressures supplied by MSFC and Langley Research Center (LaRC) 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 load data is part of the input into the X-33 Structural Design Criteria and Design Loads Document (604D0011). MSFC successfully constructed and provided a table of comparisons between specific structures in the X-33 vehicle for the cycle 4a and cycle 5-load results. A landing transient analysis was initiated and preliminary results have been provided to LMSW.



Individual finite element models (FEM) of the launch platform, vehicle aeroshell, and aero surfaces were provided for integration into both a loads model and a ground vibration test model. MSFC performed the integration of the two X-33 models. This was accomplished with the other partner's FEM and MSFC FEM being integrated into two total X-33 systems FEM. Using the integrated loads FEM, the dynamic characteristic analyses were performed of the critical flight configurations. This data was supplied to the MSFC's Control Division where control stability and POGO analyses could then be performed. This dynamic analyses were done at numerous tank fill levels and included hydroelastic FEM being incorporated into the system FEM LOX tank. The hydroelastic models were supplied by LMSW at Michoud. Using the integrated ground vibration test FEM a set of primary dynamic modes were determined for three LOX tank fill levels (empty, partially filled, and full). MSFC provided ground vibration tests (GVT) pretest analyses on two of the fill levels, empty and partially filled. Pretest analyses of the "IRONBIRD" on top of an isolation system was also provided. Results from both the "IRONBIRD" and vehicle pretest analyses included locations of accelerometers and predicted analytical parameters (i.e., model assurance criteria, orthogonality and cross-orthogonality). The pretest analyses results were provided and coordinated with the X33 partner's and LMSW.

Vibration criteria for the LOX tank, LH2 tanks, avionics panel and landing gear were provided to LMSW. Additionally, pyrotechnic shock criteria for components mounted near the holddown posts were also provided.

X-33 Dynamic Testing:

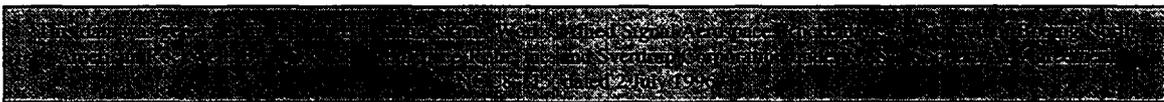
Planning has continued for the series of GVT that will be conducted by the MSFC Dynamics Test Branch at the X-33 launch site at EAFB in California. The tests had been planned for spring and summer of 1999, but have now been postponed. The first two planned tests are of the rotating launch mount with a vehicle mass simulator and the GVT suspension system with the same mass simulator. Test planning assumes these tests will now be conducted late in 1999. The vehicle tests, which include full-fuel, partial-fuel, and empty configurations, will now most likely occur in the spring of 2000.



Additionally, a test of the Thermal Protection System (TPS) in two local areas is planned. Pretest analysis was used to define target modes for the tests. High modal density and very closely spaced modes are predicted. Pretest analysis has also been used to define a baseline set of instrumentation for the vehicle tests. Coordination with LMSW manufacturing personnel is on going to determine when the instrumentation will be installed, how the cables will be routed, and how the instrumentation will be removed. Work on the location and support of the shakers also continues, as do numerous safety and logistical issues. Draft procedures have also been generated. Weekly telecons also continue. The only task agreement for the GVT that has been approved is the original task agreement, ED71-01. This original task agreement only included one test configuration as opposed to the six now planned and also shows that the work on the task should have been completed by January 1, 1999. MSFC/ED73 continues to work under the assumption that the task will soon be revised to reflect the current schedule, funding, and test requirements.

A series of vibration tests was conducted at MSFC to verify the integrity of the installation procedure for the flight instrumentation on the LOX tank. A sample of the LOX insulation adhered to an aluminum panel was provided to MSFC. A triaxial accelerometer was mounted on the panel using the installation method proposed by LMSW. The sample was subjected to random excitation in each axis at the levels expected during flight. Testing showed that the procedure was acceptable to install flight instrumentation on the LOX tank.

The X-33 combined environments test on a nine panel array of inconel 617 metallic panels mounted to a representative section of the X-33 vehicle was completed in October 1998. The test article was subjected to simultaneous delta pressure, thermal, and acoustic profiles for two vehicle locations. Thirty flight cycles were simulated for each location. Integrity of the metallic TPS panels was validated for the combined environments.



Induced Environments:

Refinements and updates of the X-33 ascent plume induced thermal environments continued during the past year. Cycle 3.2 ascent plume induced environments for the Michael-8a-1 ascent trajectory were generated and transmitted to LMSW. All previous plume induced environment cycles were generated using the Malmstrom 4 trajectory. The Cycle 3.2 Michael-8a-1 total ascent plume heat load was 9% higher than the previous Cycle 3.1 Malmstrom 4-plume heat load. The increase was driven by the lower loft nature of the Michael trajectory, which enhanced the radiative heating contribution to total plume heat load. Additional CFD base flowfield analysis was performed for a single low altitude Michael-8a-1 trajectory point to aid in the Malmstrom 4 to Michael extrapolation process. These environments were followed by the release of ascent plume heating environments for the Michael-9a-8 nominal and power pack out ascent trajectories at a limited number of body points. Trajectory indicator plume environment body points were defined for the Michael-9a-8 trajectory release which could be used by the base thermal analysis community to assess plume heating for various flight trajectories under consideration. The Michael-9a-8 total plume heat load was 11% higher than Michael-8a-1 trajectory and 21% higher than the Malmstrom 4 trajectory total plume heat load. The Michael-9a-8 power pack out total plume load was 14% higher than the nominal Michael-9a-8 trajectory case. An extensive effort was also made to investigate the sensitivity of plume induced flow separation (PIFS) to angle of attack at various altitudes. A comparison of PIFS environments and extent of forward separation was made for the Michael-9a-8 and Malmstrom 4 trajectories. A CFD investigation of X-33 plume induced flow separation was also initiated.

Efforts to refine the convective and radiative base thermal environment generation methodology also continued during the year. Three internal memos were published providing comprehensive documentation of all previous CFD base flowfield analysis. The reports provide specific CFD generated convective and radiative thermal environments for various X-33 thermal design body points and stream line flow visualization plots of the base flowfield. This data will be used to calibrate and adjust the engineering level methodology currently in use. Moreover, it significantly enhanced our



understanding of the behavior of the X-33 base flowfield during powered ascent.

Fabrication of a 2.25 % hot fire short duration subscale model of the aft portion of the X-33 was completed and subsequently tested at the University of Alabama in Huntsville. This test represented the first successful hot fire of an actual subscale model of the X-33 vehicle and linear aerospike engine. The sea level data from these tests compared very favorably with similar sea level generated CFD data. The model was transferred to the MSFC Nozzle Test Facility to conduct a series of altitude simulation tests.

B.F. Goodrich requested additional test time in the MSFC Hot Gas Facility for qualification of the AFRSI blanket material used on the X-33 canted fin. This material test is in addition to the final seal (corner configuration, metallic baseline shingle seal, and body flap seal) tests. This test is scheduled for early May 1999, and will deplete the existing funding and manpower resources for the X-33 hot gas seals tests at MSFC.

During the past year, MSFC performed additional aeroshell compartment ascent and reentry venting analyses to support Allied Signal design reviews. These additional cases corresponded to the Michael 9A-5 and 9D-3 trajectories with various combinations of vent door failures. Also, efforts are continuing to incorporate the latest Wind Tunnel pressure data into the venting analysis along with distributed leakage areas for the canted fins.

In support of loads cycle 5, two additional supersonic flow CFD cases were computed during this reporting period. Both cases were run with an inviscid scheme on a grid generated in the previous reporting period. The pressure and pressure coefficient data from these two runs were reviewed and transmitted to LMSW.

Fluctuating pressure measurements were acquired during the 3% model Wind Tunnel tests at LaRC's 16ft propulsion tunnel in June 1998. MSFC installed the transducers and helped during the checkout and data acquisition. LaRC processed the raw data into 1/3 octave spectra. A database and Fortran Program were developed to manage the large amount



of data. The program scaled the data to full-scale frequencies and amplitudes. The maximum band levels for each measurement was plotted versus Mach number, angle-of-attack, and sideslip angle. Although the trends and certain conditions look reasonable, most of the data seems to be masked by facility noise. LMSW is currently reviewing the data.

ED32 is currently working with SSC and LMSW to acquire acoustic and overpressure environments from the XRS-2000 hot fire tests planned for this summer. MSFC and SSC are working together to purchase the required equipment and put together a test plan. The current plan calls for twenty microphone measurements and six overpressure measurements. Some of this instrumentation and methodology will be used for the X-33 FRF's and flight instrumentation.

Cycle 1.0 and Cycle 1.5 plume induced base thermal environments were generated for the September 1998 RLV-0033 configuration. Major differences between the RLV and X-33 base-heating problem were identified. These differences include addition of fences on the RLV engine, higher engine operating chamber pressure, larger expansion ratio, extension of seven engine segments across the base eliminating inner base cavity, larger vertical tail which extends further aft enhancing radiation viewfactor of engine plumes, aft facing payload bay "hump", and canted wings which extends further aft with inboard edge facing the plumes.

In addition, CFD analysis was initiated to support the RLV plume induced environments task. A new parallel version of the FDNS flow solver will be employed to perform the analysis. The analysis requires generation of a complex three dimensional structured grid. A preliminary computational grid was generated using the Gridgen code with a geometry CAD file provided by LMSW. The grid has 13 zones with approximately 2.3 million grid points. The grid is currently being reviewed and initialization files for the flow solver are being created.

A CFD grid was generated for RLV configuration 34 in order to generate surface pressure loads. Using this grid, 23 inviscid CFD runs were made to determine surface pressures on the windward surfaces of the vehicle. Runs



were made at 0 degrees sideslip angle and -2 and 6 degrees angle of attack for freestream Mach numbers of 0.8, 0.85, 0.9, 0.95, 1.1, and 1.2. Runs with zero degree angle of attack and sideslip were made at Mach numbers from 1.5 to 5 in increments of 0.5 Mach number. Three final runs were made for Mach 1.2 with varying combinations of angle of attack and sideslip. Results were checked against one-dimensional predictions. Pressure and pressure coefficient data were transmitted to LMSW.

CFD analyses were conducted in order to improve the wide flow range performance of the X-33 turbopumps. Early on, the stationary components (i.e., the stator and diffuser) were identified as the largest risk components to wide flow range performance. CFD analyses were conducted to identify potential design improvements to the stator and diffuser components. A total of 50 CFD cases were completed (5 stator geometries and 5 diffuser geometries at 5 different flow-rates for each). These 50 cases required a significant amount of both manpower and computational resources. Inherent in any CFD analysis, are trial-and-error processes (e.g., grid mapping, time step, etc.) which are mentioned here to lend emphasis to the effort put forth. In addition, MSFC has worked in cooperation with Rocketdyne to determine viable component designs and to direct both the analysis and test programs. Following a Preliminary design review in December 1998, the decision was made to focus on the diffuser component. Therefore, the on going analyses are focused on improving diffuser performance. All analyses will be completed by the end of April 1999, following which the CFD-guided design will be manufactured and tested.

Thermal Assessment and Thermal Control:

Thermal analysis support continued in the internal compartment environments development area. The internal environments were published for the new Malmstrom 4 trajectories and the 8 and 9 series of the Michael trajectories. During the process of determining these updated internal environments, the vehicle model was changed to reflect the "as built" configuration. Detailed thermal analyses were accomplished on several different vehicle components in support of both LMSW and BFG requests. These included such components as the S clips used for TPS panel support,



TPS transition seals in the LOX and LH2 tank areas, the RCS thruster port, the vehicle battery cover, the reduced insulation in the LH2 tank areas, and the effects of TPS seal leakage and radiation on the compartment internal temperatures. The results of these analyses were documented and coordinated with LMSW and BFG. In addition, small separate thermal models were used to address various other issues in support of the program. Results from these analyses and models using the Michael 9a-8, 9a-8 dispersed, and 9d-5 trajectory environments were presented at the X-33 Analyses Review at Palmdale in December 1998. This also included updating the earlier X-33 thermal analyses of models such as various TPS support structures, intertank, LH2 thrust structure, and the body flap.

Thermal analysis support was also provided for the development of an X-33 pressure scanner model to assist in the determination of thermal testing environments for the instrument. A TPS corner model originally developed by ARC was brought in-house for modifications to support BFG IHGF TPS panel testing.

Support included analyses of the Active Thermal Control System and documentation of the results. The system was analyzed based on the current design and options such as using air-cooled coldplates were also evaluated.

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

Ground test facility preparations for both tests are nearing completion with LO2 testing slated to begin within the next several weeks. The structural test portion of the LH2 facility preparations will be complete with the location of the data acquisition and the load control systems at the test stand. Several items of hardware have been fabricated and assembled and all other cryogenic piping, valving and miscellaneous facility preparations are nearing completion for both tests. The "ready to test" right hand LH2 tank is expected at MSFC in the mid to late April time frame to be installed in Test Stand 4699. Task agreements have been modified to accommodate changing requirements in both LH2 and LO2 tank tests. The scope of the LO2 testing



has decreased based on load analysis results. The number of active loads for the test has been substantially reduced and LO2 has been replaced with de-ionized water, which will fill only 50% of the tank capacity which has resulted in reduced support strut loading. Manufacturing delays with the LH2 tanks have moved originally scheduled tests of both tanks. Structural loads testing of the left-hand tank is being considered where originally only cryogenic loading was planned. Consequently, the design of an existing test position has been modified to accommodate both the left and right LH2 tanks, LH2 fill and vent lines, load lines, support structure, access platforms, and weather enclosure to support development, testing, and flight hardware configurations.

Transportation plans for delivery of the LH2 and LOX STA tanks to MSFC have been completed. The LH2 Transportation Plan was signed in July 1998. The Transportation Plan specifies the roles and responsibilities of the transportation activities for the LH2 tanks on the NASA Super Guppy. These activities include loading, transporting, and unloading. The most cost effective transportation arrangements were made for the LO2 tank utilizing the MSFC managed barge. The LO2 tank was transported to MSFC from MAF on the NASA barge, *PEARL RIVER*, in February 1999. MAF loaded the tank on the barge, and MSFC unloaded the tank once it arrived. Upon completion of testing at MSFC, the tank will return to MAF on the barge.

LH2 Tank Composite Coverplate Test:

MSFC built up Test Stand 300 for coverplate pressure testing and conducted port and fit checks with the test fixture. Approximately three months later, the coverplate qual test Article arrived for instrumentation installation and check out. Work around schedules was worked to accommodate the X-33 schedule. In January 1999, four flight coverplates were successfully tested at TS300 with no leaks out of specifications. The qualification coverplate will start testing on February 1, 1999.



LO2 Composites Component Fabrication:

After the initial fabrication and testing of the LO2 full-scale flight tank number one, we have repaired and reinspected the tank for future testing.

LOX Compatibility Program:

Planning and design for a number of tests in phase IV of the LOX Compatibility Test Program were pursued in this performance period. Notable test areas include the following:

- 1) Vibration Test of an 18" composite bottle that will be filled with LOX and subjected to a vibration to simulate launch environments. This test will be conducted in June 1999.
- 2) Design of an Internal Mechanical Impact Test for the 18" bottle. This test, conducted after the Vibration Test, will simulate an internal mechanical impact of a tank filled with LOX and pressurized to flight conditions.
- 3) Oxygen Cleaning and Composite Materials Test Program was initiated to give an initial "quick-look" at the cleanability of composites, the relative hazards of contaminants with oxygen compatibility and composites, and proposed methods of oxygen cleaning that can be scaled to large propellant tanks.
- 4) Initiation of Mechanical Properties Test of Composite Materials Immersed in LOX test series plan was initiated in December and called Structural Tests of GTDP Components. The test plan will test the mechanical performance of 3 configurations of composite materials in LOX. The configurations include a tensile specimen, lap shear test specimen, and bonded and bolted joint concept. The test sequence will develop capability to test materials for mechanical properties while immersed in LOX; a capability that does not presently exist.

NDE Applications In Support of X-33:

In the last year we have performed thermography and shearography tests on Phase I work and under a task agreement, TA-EH09, on metallic TPS, and on LO2 composites. We have performed and monitored Acoustic Emissions



from the Boeing North American tank dynamic testing and inspected the semi-conformal mini tank and made application/ inferences to X-33. We have mapped out leak initiation paths in the LMSW composite joint test articles and used ultrasonic resonance testing on lobe 4 of flight LH2 tank #1 in California to verify joint integrity. MSFC has inspected qualification and flight composite LH2 cover plates to verify the torquing process required to place machined inserts near the portholes.

Engineering Cost/Business Planning Support:

Business planning support included review of business-related milestones with Lockheed Martin Enterprise Development group members and education and advocacy efforts on LM-recommended RLV development incentives (co-development and government guaranteed loans). Major progress on incentive advocacy efforts was demonstrated with the introduction of the "Breaux Bill" in Congress. Although the legislation did not pass both sides of Congress last year, a revised bill this year has increased support from legislators and support groups. Economic analysis support included enhanced market, incentive and macro-economic modeling and presentation of results in both national and international fora.

Environmental Engineering and Management

A Class I and III Cultural Resource Inventory: Landing Site Operations, U.S. Army Dugway Proving Ground, Utah, was completed and issued January 4, 1999. The survey was issued in response to program requirement changes at the landing site.

A Record of Environmental Consideration for the X-33 Landing Site Range Communication Station at Dugway Proving Ground (DPG) was issued in January 1999. The record permitted construction of a relatively small range communication station at DPG, Utah, in support of X-33 vehicle landing operations.

The Annual Report to US Fish and Wildlife Service for 1998 was submitted in February 1999. The report is required according to the Biological Opinion



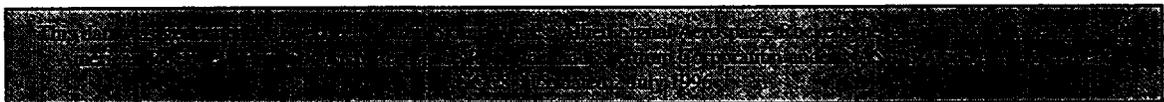
for the X-33 Advanced Technology Demonstrator Program and Support Activities at Edwards Air Force Base and provides information on habitat disturbance due to construction activities.

A Memorandum of Agreement on X-33 Advanced Technology Demonstrator Vehicle Program between Air Force Space Command (AFSPC) and NASA for use of Malmstrom Air Force Base is in final comment phase.

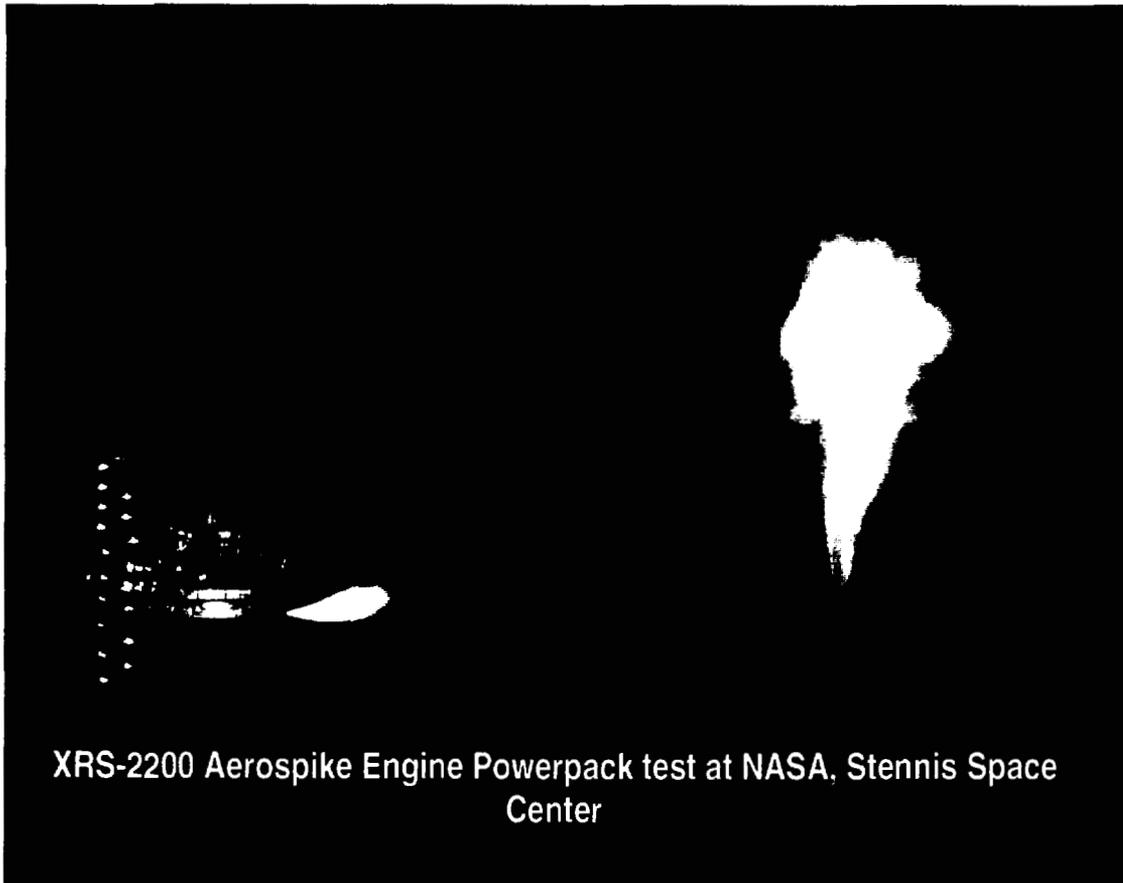
Indemnification was made available to the X-33 Program under PL 105-276. This was signed into law on October 21, 1998. It will be codified at 42 USC 2458 b. This is indemnification for experimental aerospace vehicles. It will require an agreement between the developer and NASA. Also, a safety review will be required the same as 308 of the Space Act.

X-33 Resident Office Support:

The Materials and Processing Lab at MSFC has been supporting the on going investigation of problems associated with the composite LH2 tanks that were discovered at Sunnyvale in December 1998. Most of the support has been in determining what caused sub-standard bonds between the core and facesheet material of the tank. Photomicroscopy, chemical analysis and polymer chemistry studies are some of the tests performed by MSFC to support this investigation. The Non-Metallics Materials Division has been working in cooperation with LMSW to determine the integrity of the tanks by using a "plug-pull" technique. Daily telecons and many on-site visits have resulted from this investigation.



Stennis Space Center



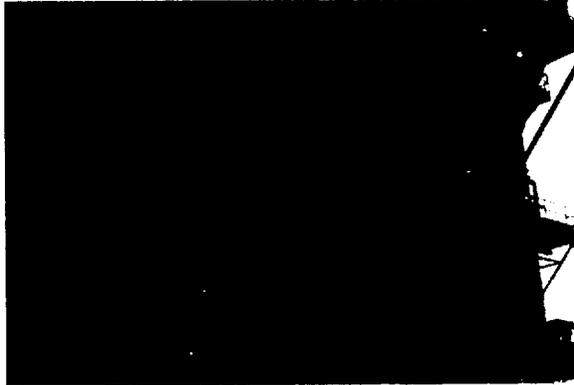
Activation of the A-1 test stand at NASA's Stennis Space Center, MS began in March 1998 to test the XRS-2200 Power Pack Assembly (PPA), single engine and dual engine configurations. Sixty-three (63) activation tests were conducted to check out and calibrate various facility systems prior to first powerpack test. Systems activated were Liquid Hydrogen and Liquid Oxygen PPA discharge, hot gas turbine discharge, cold helium and cold helium heat exchangers, helium spin start, hydrogen flare, 270/28 VDC power systems, low/high speed data, and control systems. Approximately 1,449,692 gallons

of LH₂ and LOx were consumed throughout activation. The first powerpack test was conducted on October 2, 1998. The test went full duration with no anomalies. Eight tests were conducted on PPA001 between 10/2/98 and 1/16/99 for a total of 639.6 seconds. Six tests were conducted on PPA002 between 2/3/99 and 3/2/99 for a total of 656.2 seconds. There were no facility anomalies during the tests. Approximately 849,642 gallons of LH₂ and LOx were consumed throughout these tests. During PPA002 testing, test team personnel were able to conduct tests every 3 days demonstrating the quick turnaround required to meet the aggressive engine test schedule to come.

Additionally, SSC test team personnel removed and replaced gas generator oxidizer (GGOV) and LH₂ fuel (GGFV) valves several times as well as GGFV & GGOV electromechanical actuator (EMA) Controllers. The Fuel Turbopump on PPA002 had to be removed and reinstalled due to contamination found during inspections. The team has responded to the aggressive nature of the test schedule in an outstanding manner.

Stennis Space Center personnel supported 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. Stennis provided to the Plumbrook Facility a gaseous Leak Detection System which included a Mass Spectrometer, a Programmable Logic Controller, Flow Control Valves, computers to control and monitor the process, along with several of the tubing and piping used at SSC when the Multi-Lobe tank was tested at SSC. SSC provided technical support to the NASA Plumbrook facility by providing all necessary documentation concerning the Leak Detection System. SSC provided two engineers to assist in assembling the system, preliminary testing support and training of Plumbrook personnel on the operation of the system. Engineering personnel visited the Plumbrook facility on two separate one-week periods to integrate and validate the Leak Detection System and assist in the first week of testing.





Powerpack being lifted into
A-1 Test Stand
Stennis Space Center, MS



Photo of Powerpack in A-1 Test Stand
Stennis Space Center, MS



Test Team personnel working on the Powerpack
at the A-1 Test Stand
Stennis Space Center, MS