annual report to the nasa administrator by the aerospace safety advisory panel

part II–space shuttle program

section 2–summary of information developed in the panel's fact–finding activities

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ANNUAL REPORT TO THE NASA ADMINISTRATOR

by the

AEROSPACE SAFETY ADVISORY PANEL

PART II - SPACE SHUTTLE PROGRAM

Section 2 - Summary of Information Developed in the Panel's Fact-Finding Activities

June 1975

PREFACE

Section I provides a summary of the Panel's observations and conclusions on the Space Shuttle Program.

Section II summarizes the information developed during the Panel's inspection activities since our last report on the Shuttle program. The criteria for inclusion of information in this volume is its relevance for a safe and successful mission. This section is organized in a manner that points up the management areas and the individual elements of the Shuttle system providing a summary of the basic management or design approach including the most obvious limits or hazards that are significant to crew safety. It also provides the status of the situation with particular attention to the current resolution of those hazards.

We hope the report will be of assistance to those in the Shuttle Program as a checklist to assure that the right questions continue to be asked at the right time. But the report is also written for a larger readership to assist them in understanding this complex program and its more salient details.

CONTENTS

1.0 INTRODUCTION

1.1 Purpose

This section, Section II, provides a summary of the information developed during our inspection activities and in a detailed review of documentation used in the Space Shuttle program. Its intent is to provide the reader with an idea of the data examined by the Panel and a description of the program at this time. Another purpose is to provide specific background information and supporting details to augment the data provided in "Section I - Panel's Observations and Conclusions." In addition this material will be utilized by the Panel in further reviews during the coming year as a baseline and reference manual.

1.2 Scope

The structure of this volume follows the basic organization of Section I. It extends the coverage of the Shuttle elements to include those specific subsystems considered critical to crew safety. This volume also discusses such technical management areas as systems integration test program planning. It also covers such specific crew safety areas as the Orbiter Thermal Protection System, safety and reliability efforts on so-called secondary structure, and lightning protection. Such a compilation of data is necessarily a compromise between detail and brevity and this accounts for the numerous figures and tables used in this volume.

2.0 SHUTTLE PROGRAM MANAGEMENT

2.1 Technical Management System

A management overview was provided in the Panel's annual report dated March 1974. The material provided at that time is still valid and need not be repeated here. Our emphasis has been on those aspects of technical management that support and control Shuttle requirements and design, hazard identification, resolution or acceptance of risks, and the safety implications of test planning. With this in mind the Panel focused on the following specific areas: (1) the review system to establish and assure implementation of design requirements and concepts, (2) management of the development of the Orbiter Thermal Protection System and Space Shuttle Main Engine Electronic Controller, (3) integration management applied to the element interfaces and the risk management itself, and (4) special management approaches developed to meet special program needs. To maintain the brevity of this report only the key data developed by the Panel are presented here.

2.1.1 Orbiter Thermal Protection System

Management of the Orbiter Thermal Protection System (TPS) within the total Shuttle system framework must account for the many technical and scientific disciplines and interfaces which affect the requirements, design, fabrication and verification of the operational hardware. The disciplines and interfaces, or elements, of TPS management include the following:

- o Disciplines
  - o Aerodynamics and Flight Mechanics
  - o Heat Transfer and Fluid Mechanics
  - o Structural Design
  - o Materials
  - o Structural Dynamics
  - o Testing and Environmental Simulation
- o Interfaces

o Structures	o Ground Support Equipment
o Mission Design	o Prime and Subcontractors
o Mechanical Systems	o NASA Element Organizations
o Thermal Control Systems	o Flight/Ground Test Offices
o Propulsion Systems	o Flight Operations

Thus development of the TPS requires a multi-faceted NASA/Contractor management and technical organization. The TPS, as a part of the Orbiter, falls under the direction of JSC in the manner shown in Figure 1, "JSC TPS Management Organization" and in Figure 2, "JSC TPS Management Organization Detail." Overall management is under the direction and control of the Orbiter Project Manager (Level III) through the Orbiter Engineering Office. Day-to-day technical management is through two divisions of the Engineering and Development Directorate - Engineering and Analysis Division and the Structure and Mechanics Division.

All of these operations are integrated and directed by the TPS Manager who is within the Structures and Mechanics Division of the Engineering and Development Directorate. The prime contractor for the TPS is the Rockwell International Corporation who also is the prime contractor for the Orbiter vehicle. Rockwell International has, in turn, subcontracted the development and production of the TPS tiles to the Lockheed Missiles and Space Company, Space Systems Division at Sunnyvale, California. NASA has, at the same time, arranged with their own Ames Research Center and Langley Research Center for technical support.

The NASA roles in TPS development are shown below:

- Johnson Space Center
  - Requirements definition
  - Management of the Prime Contractor
  - Integration of Technology
  - Testing and Assessment of the System
  - Overall Test Program Management
  - Test Facility Development
- Ames Research Center and Langley Research Center
  - Development of New Technology (including Material Characterization)
  - Development of Test Facility
  - Technical Review and Consultation
  - Testing and Evaluation

The Contractor roles have been described as follows:

- Rockwell International
  - Design of the TPS high and low temperature systems
  - Conduct of all thermostructural analyses on Orbiter
  - Perform TPS subsystem qualification testing
  - Provide detail drawings and other required documentation (procurement specification defining performance requirements, statement of work defining tasks, define quantity and schedule, and subcontractor change notices)
  - Administer Subcontractor and materials procurement
  - Conduct of periodic reviews to assure proper conduct of TPS program
  - Define and implement installation and maintenance operations, including refurbishment and replacement at launch site
- Lockheed Missiles and Space Co.
  - Develop and optimize coated tiles
  - Provide material property data on tiles and coating
  - Demonstrate compatibility between tiles and coating
  - Fabricate, acceptance test and deliver subsystem elements

The Preliminary Design Reviews conducted to date on Orbiters 101 and 102 and the Space Shuttle System have not fully covered the

Orbiter TPS. A detailed review is expected in mid-year 1975 to assess whether the TPS design and implementation meets Shuttle requirements.

2.1.2 Space Shuttle Main Engine Controller

The SSME Controller for each engine in conjunction with the flight control system monitors and controls the three Main Engines during the ascent portion of the Shuttle mission. The Controller also develops data on engine parameters that are used during the ground servicing cycle. The Controller depends on comparatively new technology and has a varied development history starting with the Viking program. As the result a management system has had to be developed commensurate with the technical disciplines, Shuttle interfaces, product quality assurance requirements and attendant management visibility needed to meet the demands placed upon this critical subsystem.

Marshall Space Flight Center (MSFC) is responsible for the design and development of the Space Shuttle Main Engine. The Rocketdyne Division of the Rockwell International Corporation is the prime contractor for the SSME and they in turn have a subcontract with Honeywell, Inc. for the design, fabrication, and validation of the SSME-Controller.

To summarize briefly, management and hardware development history of the Controller has not been a smooth road. Approach to the design itself was not conventional and therefore a large history/data base did not exist. As a matter of fact the packaging concept and use of plated-wire memory contributed a great deal to the initial management and technical problems. The challenge was to develop a management team and establish a management system to assure an effective approach to development and producibility and to control and resolve problems on a timely basis.

Through the diligent efforts of NASA, the Rocketdyne Division of Rockwell International and the Honeywell, Inc. organizations, the SSME-Controller program now appears to be "on the track" at this time, and the management and general controller activities are said to be "tracking close to plan, with encouraging results."

During this period of the Controller's evolution, the Panel centered on the following three questions:

(a) Have the management lessons learned on Viking been systematically reviewed and the appropriate ones incorporated in the management system for the Shuttle SSME Controller? This was based on the continuing emphasis by NASA's senior management, as well as the Panel, that lessons learned from prior programs be applied to on-going programs as appropriate.

(b) Will the plated-wire memory concept support the requirements and schedule of the SSME and Shuttle program? This was based on the knowledge that such technology represented a new and essentially high-risk technology.

(c) Based on the past history of computer development programs and the known schedule and cost problems that had arisen on this program, what are the fundamental challenges and ability of the NASA/Contractor team to resolve them in an orderly and timely fashion?

Specific comments on these areas examined by the Panel are provided below and support the previous statements concerning the SSME-Controller status at this time.

While the Panel found no single reporting format available which systematically stated the significant lessons and their disposition on the Shuttle program, the Honeywell Program Manager had his staff review the minutes and audits from the numerous Viking reviews and identify specific actions that could impact their operations on Shuttle. They then documented why those problems would not occur on their Shuttle project. To further enhance the management control of the program, the Program Manager defined a detailed work breakdown system and negotiated work/budget contracts with each major component supervisor. A problem control and resolution system was established which assigns action officers to each problem and monitors the solution as well as its timeliness. Additional technical and middle level supervision was added to the project. These people were drawn from the Martin Marietta Company and the Collins Radio Company.

Based on the Panel's experience with Apollo and Skylab, the configuration management system appears sufficiently disciplined for control of engineering and test drawings, specifications, fabrication procedures, and material processing. Production is essentially a manual buildup process at the bench. Tool control and special tools to support the manufacture and test of the components have been improved and developed where such support is needed. Standard process instructions and detailed fabrication layouts have been developed from Viking experience and with the help of MSFC to train and certify Shuttle personnel. An important lesson from Viking is the significance of anticipating production problems. Thus Honeywell established a detailed categorization of production errors so trends and corrective action can be identified early. All of these improvements have resulted in a higher degree of quality control and workmanship.

The plated-wire memory design, fabrication and validation process as described to the Panel indicates (1) there is adequate experience to date with the development of the plated-wire memory to warrant confidence at this time, (2) there does not appear to be a clear understanding of the fundamental physics associated with this type of component to assure that surprises would be anticipated and a timely course of resolution decided upon and implemented, and (3) if additional development surprises did occur, they probably could be solved by trial and error given sufficient time but that such surprises would probably impact the current tight schedule for the early pre-production controllers as well as costs.

The accomplishments of the SSME-Controller team during the past year have been significant but much has yet to be done. Close monitoring by NASA/Contractor team must be continued to assure on-time delivery of properly operating units to support the SSME engine test program and other major orbiter/system tests prior to the first orbital test flight.

Two significant problems remain at this time - Master Interconnect Board wire routing/shielding in the memory area in which noise is being coupled into the memory sense lines due to wire routing and inadequate shielding and intermittent parity errors. These problems are discussed in more detail in later sections of this report.

Technical management of the SSME-Controller <u>software</u> had some of the same problems as found in the Controller <u>hardware</u> program. Verification testing revealed numerous errors. As a result an assessment team, composed of non-Shuttle segments of the Honeywell organization, Rocketdyne, and NASA personnel was instituted. The following actions were taken as a result of the team's review:

(a) Software efforts were strengthened by adding technical personnel at Honeywell along with organizational changes at both Rocketdyne and Honeywell.

(b) Software was simplified and deliveries were phased to meet minimum Integrated System Test Bed (ISTB) test program needs.

(c) Technical management changes were made so that software is debugged prior to release for verification runs. Daily schedules and audits are used to assure knowledgeable management control. "Memory scrub groups" at Honeywell and Rocketdyne have been established to update and assure software compatibility. Such changes have enhanced the Honeywell planning efforts and contribute to a proper balance between those personnel developing the software itself and those doing the software verification.

2.1.2 Integration Management

One key to the proper allocation of resources to the total Space Shuttle program is the adequacy of the Space Shuttle element integration effort. This is an activity conducted by the JSC program office with the direct support of the Rockwell International Corporation, Space Division. All other NASA Centers and Prime Contractors involved in the Shuttle program contribute as appropriate. The ultimate responsibility for integrating the total Shuttle program is NASA's, but much of the crucial work to assure the success of this effort is accomplished by the System Contractor, Rockwell International. Consequently, the Panel asked (1) what are roles of each, (2) what tasks are being done by each and what work areas are not receiving sufficient emphasis, (3) are there congruent expectations among the many elements of the program regarding system integration, and (4) what is the degree of communication among those involved and management's sensitivity to the problems inherant in the continuing integration effort?

In its Annual Report for 1973 the Panel discussed this area and received a response as shown in Section 7.3 of this volume. This dealt with the results of Rockwell's effort to separate their integration task from the Orbiter task, and with the increase in tasks assigned to Rockwell International as the "System Contractor."

2.1.3.1 NASA

The Space Shuttle program organization centers its integration effort in the Systems Integration Office within the Space Shuttle Program Manager's office at JSC. This is the Level II operation and is also the "lead center" on the program. The responsibilities of this Systems Integration Office are:

(a) Review, control and manage the systems integration activities for the Shuttle program.

(b) Manage the design, development, test and engineering for the Shuttle carrier aircraft project.

The functions carried out by this office are shown in Table I. "Detailed Program Inter-relationships" are spelled out in the current issue of Volume II of the JSC 07700 Level II program definition and requirements documents.

The JSC Systems Integration Office has on-site representatives from Marshall Space Flight Center, Office of Aeronautics and Space Technology (NASA Headquarters), JSC's Engineering and Development Division, Shuttle Carrier Aircraft Project Office, and the Kennedy

Space Center. There are three major sub-groups in this office - Systems Engineering, Technical Integration, and Test and Ground Operations. These functions at JSC are staffed by approximately 100 Civil Service people (35 JSC program office, 15 co-located from KSC and MSFC, 50 Engineering and Development).

The necessary coordination in support of the specific tasks to achieve true Shuttle system integration uses many of the methods developed on Apollo and Skylab programs. Informal and formal channels are used freely, but controlled by the program and element project managers. The more formalized review system is a definite part of the integration effort as always and is discussed in a later section of this report.

Of particular significance are the more than 30 formalized panels and working groups working on a day-to-day basis. They encompass all programmatic areas and are composed of NASA, contractor, and USAF personnel. The Panels are established as a continuous entity to cover specific technical and technical management regimes. Working groups are established to meet a specific technical task that requires timely resolution and which is terminated once that problem is resolved. A list of the Panels and Working Groups is provided in Table II.

Areas of coordination/integration, that fall between the Panel type operation and the review system, are the System Integration Reviews (SIR's) and the Computer System Integration Reviews (CSIR's).

Their purpose is to review, control, and manage the systems integration activities. These activities include (1) integration contractor system tasks, (2) element contractor system tasks, and (3) NASA system tasks which are conducted at both Headquarters and Centers.

Approximately every three weeks this group meets, basically through tele-conference methods, to take up the many systems' problems given to them for their resolution. As stated at a recent Preliminary Design Review ... "Where more clout is needed to achieve resolution of baseline data it goes to the Systems Integration Review Panel (SIR)." Here is an example of the material handled by the SIR. A question was raised during the Shuttle Systems Preliminary Design Review (March 1975) concerning the lack of data to assure that the proper hardware and proper facilities are available to conduct development and verification of the ascent flight control system. Rockwell was directed to prepare a presentation to SIR with recommendations on meeting the required depth of documentation in the Master Verification Plan, Volume II - "Combined Elements Verification - Ascent Flight Control."

Another example of integrated technical management is shown in the KSC/MSFC "Memorandum of Understanding For Shuttle External Tank and Solid Rocket Booster Support Equipment." This document is included in Section 7.4 of this volume.

2.1.3.2 <u>System Contractor</u>

System Integration and Shuttle Orbiter efforts are both conducted under the same NASA contract number. However, separate cost, budget, schedules, and work authorizations are used. Both the Shuttle Orbiter and Shuttle System Integration Program Managers (they are Rockwell International Space Division Vice-Presidents) report to the Space Division President; thus both have equal stature and authority. The System Contractor's role, as described to the Panel, is quite broad. It is spread over four increments of time:

(a) Initial increment covers the period during which basic requirements must be adequately defined and the design approach mature enough to proceed with detailed design, i.e., through completion of the Shuttle System Preliminary Design Review.

(b) Record period proceeds from the end of the above increment through the Critical Design Review and the completion of the design, development, test and engineering effort. This increment extends through the first year or so of flight to assure that the Shuttle system is safe, reliable, and capable of meeting the operational missions.

(c) Third increment includes production and upgrade/retrofit of vehicles for operational use.

(d) Fourth increment is the operational phase.

Rockwell International has the equivalent of approximately 420 persons on their system integration effort. There are some 8 dedicated full-time staff people in the Shuttle Integration Office and 35 persons located on the staff of the Vice-President for Engineering (functional support) dedicated to the integration effort. The remaining personnel are putting effort into integration as required along with their basic work on the Shuttle Orbiter contract. On the whole, then, personnel are essentially borrowed from functional organizations as required. Rockwell supports JSC, Level II, operations in many areas as shown by task assignments in Table III.

Some of the more significant areas being worked on include integrated vehicle analyses such as:

(a) Induced environment definition

(b) Ascent performance optimization

(c) POGO test and analysis

(d) Element separation requirements

(e) Ice-frost prevention

(f) EMC/Lightning protection analysis and requirements

(g) Sneak circuit analysis

(h) They also work on the integrated schematics which provide end-to-end visibility of the functional relationships of all components in a system, and as such provide evidence of integration of all subsystems, e.g. electrical, electronic, fluid, mechanical, etc.

An area of particular interest to the Panel was the system safety activities conducted by the System Contractor. These include safety requirements, program/project reviews, system-level trades, system-level hazard analyses, and test/operations safety. One of the many examples of their work provided to the Panel was the development of a fire/toxicity protection plan and its application across the Shuttle program. The single source document for the Orbiter is SD 74-SH-0223. It was prepared for the designer to use as the medium for achievement of fire/toxicity safety. This document was forwarded to the other element contractors as an example of inputs requested for development of total Shuttle requirements.

Based on the material presented and the discussions conducted during the period of examination, it appears to the Panel that the Rockwell International Space Division has more of a support role to JSC than an independent system integration role. Rockwell International is satisfied with this role. This is not unlike the experience of the Integration Contractor on the Skylab program some years back. On the whole this resulted in an operational mode where the contractor had the opportunity to effectively highlight integration problems but not the responsibility of controlling the activities of other contractors. There has been an obvious effort to separate the Integration and Orbiter efforts at Rockwell International and yet retain the valuable abilities being applied to the Orbiter for use on the integration effort. Advantages are as obvious as the drawbacks e.g., assurance of a knowledgeable but independent check and balance. There appears to be no real problems in making this arrangement work to the advantage of the total program, but sustained attention should be paid to making sure that it does so.

2.1.4 Special Management Items

In any program of this size there are bound to be exceptions to the rule in management techniques because of exceptional conditions of one kind or another. The Solid Rocket Booster project differs from the other Shuttle elements in that MSFC itself is the prime contractor rather than an industrial contractor. Marshall has contracted for the Solid Rocket Motor (SRM) with the Thiokol Corporation (Wasatch Division) while maintaining its in-house responsibilities for the design of the total SRB and the assembly of the total SRB. The major question asked by the Panel with regard to the technical management of the Solid Rocket Booster was "Where would the check and balance function come from that normally exists between NASA Centers and their prime contractors?"

The SRB Project Manager is responsible to the MSFC Shuttle Projects Manager and is subject to the Level II integration controls exerted by JSC as the overall Shuttle manager. Program requirement documents and reporting systems are placed upon the SRB organization just as they are on any prime contractor except that NASA does not have the intermediate step of contracting documentation. On the whole there appears to be at least as great a control and checks and balances on the SRB effort conducted by Marshall as on any other Shuttle element. This is supported by the existence of a special SRB Review Office within the JSC Program Office and the strict adherence to configuration management systems by the MSFC personnel.

The NASA Shuttle Organization conducted a Program Requirements Review during the latter part of 1974 designed to realign the Shuttle program with the available budgets and desired scheduling of activities to meet the needs of the design, development, test and evaluation program. The events in this activity included:

(a) Definition of possible candidates to be delayed, modified, consolidated or deleted. Candidate items involved production, spares, ground support equipment, facilities, test program, operational program, technical management details, training and simulation work.

(b) Thorough review of all the possibilities and their impacts and value (cost effectiveness). Those deemed most worthwhile were presented to NASA Management and they decided whether to accept, reject, or hold these possibilities open for later review.

Twenty-eight items were selected and are being implemented. The Panel's interest centered on any safety impacts caused by these program changes. Typical of the Panel's concern were in (1) deletion of the runway barrier at KSC, (2) the large number of adjustments made to the test program (about 39% of the total) particularly those dealing with vibration and structural testing, and (3) reduction in ground support equipment particularly at the flight test sites.

Program management has assured the Panel that each change received will continue to receive a safety review to ascertain any adverse impacts and to bring them to the attention of the program management. The Panel intends to continue to examine this area to assure compliance with NASA Shuttle Management's intent.

The Orbiter/System Integration contractor's organization includes a staff member covering the Shuttle/USAF B-1 Interface. He reports directly to the President of Rockwell's Space Division. This coverage is useful to both the Shuttle and B-1 programs because of the transfer of both technological and management know-how. As an example, the basic landing gear system design for the Orbiter takes advantage of that developed for the B-1. The Shuttle aft thrust structure is made of titanium/boron epoxy reinforcement and the payload doors use graphite epoxy honeycomb. These are extensions of the B-1 developments.

2.2 Organization

The previous Panel Annual Report described the organization and general management system which has not changed to any great degree since then. Significant changes have been noted in Section 2.1.2 "Space Shuttle Main Engine Controller." Personnel changes were made at the Rocketdyne Division. As noted in Section 2.1.4 "Special Management

Items" during the DDT&E phase of the Shuttle program, the Marshall Space Flight Center has been assigned the responsibility for the integration management of the SRB. It is planned to contract-out for the SRB assembly contractor in Fiscal Year 1977. This assembly contractor will then have the prime contractor's role and responsibilities for the total assembly of the SRB. It is expected that this contractor will be located as near as practical to the launch site operational base.

The contractor team is being augmented as required to meet the maturing design and fabrication posture of the Shuttle elements. The principal contractors and subcontractors are listed in Section 7. 5 of this volume.

The Panel visited NASA Centers and a number of contractors during the period since the last Panel report and for the first time examined the KSC role in the Shuttle program. Because the KSC role for Shuttle differs from that on Apollo, Skylab, ASTP and unmanned space systems, it is discussed here. On previous programs KSC received, assembled, checked out and launched the vehicles by providing basic facilities and support equipment such as the Vehicle Assembly Building, launch control center, launch pads, checkout areas, and launch support ground equipment such as the propellant loading systems, gas systems and environmental control systems. The KSC role in Shuttle is more complex.

KSC has responsibilities for receiving inspection and control, assembly, checkout, and launch on Shuttle as on previous programs. However, in addition they will have responsibility for recovery and retrieval operations for the Orbiter and the Solid Rocket Boosters. This is completely new.

Ground operations similar to previous programs include the sustaining engineering effort, logistics and maintainability. However, the "turnaround" operations to prepare the Orbiters for flight is again completely new.

Basic facilities built for prior manned and unmanned programs will be used with appropriate modification. In addition, the following new facilities and associated ground support equipment will be required: runway and taxi areas, Orbiter Processing Facility, a highly automated launch processing system to preclude errors and speed up the turnaround time, and payload preparation areas.

KSC will also provide support to the NASA Flight Research Center and later on to the Air Force's Western Test Range operation.

As presented to the Panel at the time of its inspection trip to KSC, the KSC Shuttle organization has been fully defined to meet known program requirements and the management control systems have been developed and are being implemented. KSC manages its Shuttle work force through manpower work packages which identify discreet work activities in terms of product and required manpower. These serve as contracts between operating elements, project managers and the Center management.

The many organizations involved in the design, development, fabrication, and testing of the Shuttle elements and the combined system appear to be in place and manned in a manner commensurate with the cost, schedule and performance requirements and expectations. Those changes in organization necessitated by program maturity and directed changes will be examined as required to assure that there is no detrimental impact on ground and flight safety.

2.3 Review System

The Shuttle program review system is a direct descendent of those systems used on Apollo, Skylab and ASTP programs. To hold down costs there is an increasing use of the teleconference method of conducting meetings and reviews.

In reality the Shuttle program review is a continuous process occurring on a daily, weekly and monthly basis at all levels of the program from the drafting boards to the program management. Periodically a major management control function is inserted into the system in the form of a detailed formalized review. These provide a means of determining program progress, problems, problem resolution, and approving the current program posture as a sound basis for continuing to the next program milestone.

The review system can be examined from the point of view of the total NASA Shuttle Program down through each succeeding level of management and/or hardware. Within the overall review system there are so many different vehicles used to conduct reviews that it is possible here to examine only those which the Panel has had the most direct dealings: Systems Requirements Review, Preliminary Design Reviews, and special reviews. The many other on-going reviews include the Element Quarterly Technical Reviews, Systems Integration Review (Panel-SIR), weekly and biweekly configuration control boards at each level of the program (some of these are referred to as the CCB, PRCB, etc.), and Orbiter Management Review (OMR). These illustrate the detailed management oriented review system.

As noted above the Panel's major interest was associated with those program activities that assure that requirements are properly implemented and that the hardware/software is certified as having been designed and built to the correct and safest possible configuration.

Background on these reviews follows:

(a) Purpose of the Program Requirements Review (PRR) was to review and define in detail the management techniques, procedures, agreements, etc. to be utilized by all the Shuttle program participants and the program technical requirements. This review was completed in November 1972.

(b) The System Requirements Review (SRR) updated the program and system requirements to be utilized by the contractors. Such requirements were documented as the NASA Level II baseline and placed under configuration change control. Prior to the SRR the Interface Control Documentation (ICD) responsibilities were defined as were the schedules for ICD completion to support the program. This review was completed in August 1973.

(c) Preliminary Design Reviews (PDR) covered individual Shuttle program elements as well as the overall system. These are technical reviews of the basic design approach to assure compatibility with the technical requirements and the producibility of the design approach. The PDR's result in the appropriate authorization to the contractor and in-house organizations to proceed with further design in accordance with the reviewed design approach, interface requirements, commonality items, etc., and approval or update of the Level III baseline documentation. The depth of these reviews can be decerned from the "Space Shuttle Systems Preliminary Design Review Plan" included in Section 7.6 of this report. These reviews were completed as follows:

o Space Shuttle Approach and Landing Test	Nov. 1974
o Space Shuttle System	Mar. 1975
o Orbiter No. 1 (also called 101)	Feb. 1974
o Orbiter No. 2 (also called 102)	Feb. 1975
o Space Shuttle Main Engine	Sept. 1972
o External Tank	Sept. 1974

- o Solid Rocket Booster Nov. 1974
- o Launch Processing System (Scheduled) Aug. 1975

Several aspects of the Preliminary Design Reviews are of interest because they show the PDR as a real-life, real-time management control device as a part of the "building block" approach used in arriving at an operational system within budget and schedule. Each Element (Orbiter, SSME, etc.) Preliminary Design Review was built on a series of prior reviews which generally included Project Manager's reviews, weekly meetings and program/project periodic reviews used for visibility and control of the project. The "building block" approach resulted in the Shuttle Systems PDR being built on the individual Element PDR's.

All these formal reviews utilize the Review Item Disposition (RID) activity to point up discrepancies. Thus they are indicative of the scope of the PDR's as well as the latitude provided to the "working troops" to have their input known and discussed at management levels. This is elaborated on in Section 7.6 wherein the review operation is described. The RID describes significant discrepancies and inconsistencies as well as distinct problem areas determined by anyone on the project/program. The PDR process usually consists of 10 days or two weeks of full scale team reviews of appropriate data and discussions during which RIDS are written. The RIDS are then provided to a screening group, followed by a pre-board, ending up at the formal board. Orbiter 102 PDR resulted in 978 RIDS and the Systems PDR produced 1,204 RIDS. Due to the large number only the most significant ones could be presented to the formal board. However, the individual Team Leaders for each of the approximately twelve teams of the PDR report to the Formal Board on the team activity and major areas of concern.

There are always some areas which cannot be fully covered during the PDR due to a lack of information. These areas require and receive the necessary emphasis to achieve a sufficient degree of technical and documentary depth so that they may be reviewed within a reasonable length of time after the PDR.

The Orbiter Thermal Protection Subsystem, Thermal Control Subsystem, Environmental Control and Life Support Subsystem and Range Safety Avionics are some subsystems which will be so handled in the August/September 1975 time-frame. In the same vein, lack of definition of the Orbital Flight Test Program prevented evaluation of the system design against the mission requirements so that it too will be covered at a later date.

Material covered and that which has yet to be examined as a part of the PDR process again shows the need to look at the Shuttle review system as a continuum which supports the program and project managers' needs for design/hardware assurance.

At a later date each of the elements and the system will be subjected to a Critical Design Review (CDR) to determine the compliance of the completed design with the technical requirements of the NASA baseline. The CDR should result in authorization to the contractors to proceed with he release of detail design to manufacturing, the approval of test procedures, and the appropriate revision or update of the Level III baseline documentation. The Critical Design Reviews begin in the early Spring of 1976.

3.0 SHUTTLE PROGRAM ELEMENTS

3.1 Orbiter Project

Because of the large number of Shuttle elements and components, Panel efforts have been concentrated on those areas which most impact crew safety and management control of the program elements. The intent in this report is to focus on the subsystems critical to crew safety and to provide data for an understanding of risk assessments. A special section is given over to the Orbiter Thermal Protection System because the Panel feels it is one of the most significant systems which, if not properly and adequately designed, fabricated and maintained, would pose a real crew hazard as well as a Shuttle system operational problem.

However, there are differences between the first two Orbiters which should be identified to understand what follows. The first Orbiter, Number 101, will initially be configured as a test vehicle for the Approach and Landing Test (ALT) Program. It will then be reworked to the operational configuration. The second Orbiter, Number 102, will be built in the orbital flight configuration. Thus there are some items unique to the 101 and there are other items which appear on 102 for the first time. Many of these differences result from the needs for flight test instrumentation at low speeds and low altitudes on 101 versus high speeds and high orbital altitudes on 102. There are also differences because of the different natural and induced environmental effects. For example, on the 101 vehicle there is no Thermal Protection

System (TPS), little if any internal insulation, and no main propulsion system (SSME's). There is an instrumentation boom at the nose and ejection seats.

3.1.1 Subsystems Critical to Crew Safety

For the purposes of this report the Orbiter system is divided into the following subsystems:

(a) Structures - this includes the fuselage, wings, empennage, crew module, purge, vent, drain, payload doors, thermal protection system (TPS), and the internal insulation.

(b) Propulsion - includes the reaction control system, orbital maneuvering system, auxiliary propulsion system and the interface between the Orbiter and the Space Shuttle Main Engines.

(c) Avionics - includes guidance, navigation, flight control, communications and tracking, display and control instrumentation, data processing and software, electrical power distribution and control.

(d) Crew Station - includes all those items, such as fuel cells, batteries, and rotating equipment used to store and generate electrical power. This does not include those items used for distribution and control of the generated power.

(e) Environmental Control and Life Support - these include the atmospheric revitalization subsystem, active thermal control, cryogenics, airlock support and waste management.

(f) Mechanical - includes landing and deceleration gear, separation, actuation devices, payload retention and deployment, hydraulics, and pyrotechnics.

All of these systems and their components may be construed as affecting crew safety.

The Panel chose to focus first on (1) systems extending the technical and fabrication state-of-the-art in the literal sense or in its application, (2) systems which prior program "lessons" have indicated as areas of concern, (3) areas which the Panel members considered most vulnerable to "human error' in defining requirements, designing and fabricating, and (4) areas which cannot be adequately tested or validated on the ground.

Using the above criteria, the following subsystems received particular attention from the Panel:

3.1.1.1 Doors and Vents

3.1.1.2 Thermal Protection System

3.1.1.3 Propulsion

3.1.1.4 Avionics

3.1.1.5 Electrical Power System

These are discussed in terms of systems design and current development status.

Additional subsystems of particular significance for crew safety include:

3.1.1.6 Crew Compartment

3.1.1.7 Hydraulics

3.1.1.8 Separation Mechanisms

3.1.1.9 Structures

Here the comments are more limited for the reasons indicated in each section.

Orbiter weight control has been a major management objective. Currently, the estimated weight is about 2000 pounds below the target of 132K. Reviews continue to find ways to take weight out of existing designs or to find new ways to keep the weight down. Since weight control is an important driver, the Panel in its review of these subsystems has been sensitive to any impact on safety.

3.1.1.1 Doors and Vents

Doors and vents on the Orbiter vehicle must operate reliably to maintain the vehicle's integrity for flight during ascent and reentry, and to avoid risk to the crew.

Because of their significance for crew safety, the following doors were included in the Panel's reviews:

(a) MPS/T-0 Umbilical Attachment Door. This door was recently deleted as a result of the latest aerotherodynamic analyses. Figure 3 and 4 depict the "before" and "after" configuration.

(b) Reaction Control System (RCS) Forward Thruster Doors. These have also been deleted as a result of recent studies. Figure 5 depicts this change.

(c) Startracker Door.

(d) ET/Orbiter Closeout Doors. There are two - left and right side.

(e) Air Data System Probe Doors. There are two - left and right hand.

(f) Landing Gear Doors. There are three sets of fairing doors - one for the nose wheel and one each for the left and right main wheel system.

(g) Personnel Hatches. There are three.

(h) Rendezvous Sensor. Currently no information is available on this item.

(i) Payload Bay Doors. There are two 60-foot long doors.

(j) Payload Preflight Umbilical Door.

(k) Vent Doors. These are discussed under the vent system.

In addition there are doors on the Orbier 101 for use during the Approach and Landing Tests on the first vertical flight vehicle 102 that are not found on the later operational vehicles.

System Design

During ascent, door position is a function of required operation. For example, the startracker door is closed during ascent while the External Tank/Orbiter closeout doors are open until the ET is jettisoned. Regardless of the particular function of individual Orbiter doors, they all have to be closed and secured prior to entry.

The Panel reviewed the basis for confidence in the mechanical design. The doors themselves are considered as structural items, and thus are to be designed to preclude failure by use of adequate design safety factors. Recent aerothermodynamic analyses have led to a re-assessment of Orbiter doors resulting in the deletion of the Launch Umbilical Door and RCS Forward Thruster Doors. The remaining Star-tracker Door and some vent doors are actuated and latched by electric motors driving linkages through gear boxes and mechanical sequencers. The ET/Orbiter closeout doors and Air Data Probe Doors are actuated and latched by power drive units consisting of two electric motors driving linkages through a gear box.

There are personnel hatches at three locations in the Orbiter Orbital flight configuration: (1) crew module ingeess/egress hatch, (2) airlock hatch, and (3) airlock/payload bay hatch. The crew module ingress/egress hatch is a circular hatch with double walls. The hatch outer surface is covered with TPS and seals at the Orbiter outer mold line. The hatch inner surface provides a redundant pressure seal to the crew module pressure vessel. The hatch pressure seals may be checked for leakage by pressurizing the volume between the seals. This leak check capability exists during launch preparations or in-flight, utilizing GSE or flight equipment. Mounted in the center of the ingress/egress hatch is a 10-inch diameter window used for crew observations of external conditions and for the performance of experiments.

Control of the hatch is manual, utilizing a rotary actuator which may be driven from either side of the hatch and Apollo CM-type hatch latches. The airlock hatch is a circular hatch which seals at the airlock entry tunnel separating the crew module from the interior of the airlock. The hatch is closed and latched for Orbiter launch, opened shortly after orbital injection to allow access to the airlock interior, and also is cycled during extra-vehicular activity. The hatch pressure seals also may be checked for leakage by pressurizing the volume between the seals. This leak check capability and hatch control is the same as for the ingress/egress hatch. The airlock/payload bay hatch is also a circular hatch which seals at the airlock exit tunnel. Hatch pressure seal check and hatch control again is similar to the ingress/egress hatch configuration. There are two payload bay doors with an actuation system for each 60-foot half door. The Payload Bay door actuation mechanism has not been finalized as yet but the following subsystem description can be provided at this time. The output motion for door movement is taken off the second ring gear of compound planetary gear boxes. There are six gear boxes along each power path and these are connected by torque tubes to each other and to a main reduction gear box. The main gear is driven by the output of a double differential connecting three electric motors. This arrangement allows system operation for any two motor failures, any one motor failure combined with one electric system failure, or any two electrical system failures. A mechanical disconnect of the motor drive unit is provided and the door actuator gear boxes are designed so they will back drive. This will allow the GSE to open or close the doors.

The Purge, Vent and Drain Subsystem is composed of five elements: (1) structural compartment vent, (2) structural compartment ground purge, (3) structural compartment drain, (4) window cavity conditioning, and (5) hazardous gas detection. The individual systems are not discussed here since the major focus is on the safety impacts associated with these systems. The vent ports insure no violation of the delta pressure limitations of the primary structure and therefore are of primary significance for crew safety. It is the proper mechanical operation of these doors that is critical, not the structural integrity of the doors themselves.

There are some eighteen of these vent doors along with the associated electro-mechanical and mechanical operational devices to move them as required. The other purge, vent and drain units present considerably less risk to the crew. However, malfunctions could lead to mission abort.

The structural compartment ground purge provisions are composed of a GSE-supplied flow of air/GN_2/GHe, which is distributed through an onboard duct network to all required structural compartments. The structural compartment drain provisions are composed of piping and disconnects which, acting together with ground support equipment, minimize the accumulation of moisture within the Orbiter structural compartments. The collection points are so located that effective draining is feasible with the Orbiter in either the horizontal or vertical attitude. The window cavity conditioning provisions allow the introduction of a ground-supplied dry nitrogen purge into the inner and outer window cavities during preflight servicing of the Orbiter. During the approach and landing flight tests and boost to orbit, the gas in the window cavities is vented through lines to overboard. While in orbit they are continuously venting the space. During the entry phase ambient atmosphere flows into the cavities. Appropriate valves act to limit the delta pressure across the window panes in the event of filter or line clogging. The hazardous gas detection provisions utilize a combination of flight hardware and GSE to detect the presence and monitor the concentration of hazardous gases during prelaunch and post-landing operations.

Current Status

Door designs, as described to the Panel, are such that the door itself and the mechanical linkages and gear boxes are considered the same as primary structure, i.e., they are designed with sufficient structural safety margin to preclude failure under any known or suspected load condition.

The door operating mechanisms are quite complex and there are continuing efforts under way to simplify these mechanisms.

In the main the doors are contiguous with the Orbiter Thermal Protection System (TPS) and as such interact from the aerothermodynamic standpoint with the function of the TPS.

Rigging of the external doors is difficult and must be done in the "blind" in many cases. As a result it is difficult to prove that door latches latch and lock properly and the chance for human error is present to a degree that may require more than average detailed operational and inspection controls, or verification procedures. The Panel will review this area as the program evolves.

The ET/Orbiter Separation Cluster Plate Doors and Startracker Door continue to be the subject of studies to determine whether the doors and their associated mechanisms could be eliminated, reconfigured, simplified, or reduced in size thereby reducing or eliminating the crew safety risks associated with improper door operation. The results of these studies will be the subject of further Panel review.

The External Tank/Orbiter Cluster Plate Doors are now about 46" x 62" (actually some 2354 sq. in.) rather than the original 72" x 84" size. The maximum exterior surface temperature of the door when closed during reentry is about 1500^{o} F. It is estimated that without the door local temperatures would be 1.5 to 2.5 times as high due to flow disturbances. These doors are open during launch and ascent until ET separation and it would appear that an extensive test program to assure proper operation in the post-launch environment is warranted.

The Startracker door size is dictated by tracker view angles and the requirement for daylight tracking. Tracker-lines of sight are made more difficult by the thickness of the Orbiter TPS material surrounding the window itself. Maximum temperatures near the Startracker door are expected to be about 825° F. The door mechanism and the alternatives are still under evaluation.

Venting analyses have been conducted to determine the effect on the Orbiter vehicle of internal compartment pressures due to opening the vent doors at different altitudes during reentry. At the time the active vent doors are closed, prior to reentry, the pressure in all of the vented compartments is approximately zero. The Orbiter enters the atmosphere with the doors closed until the "hot" part of the descent is completed. The vent doors are then opened at about 70,000 - 80,000 feet and remain open until the Orbiter is on the ground. If the opening of the doors is delayed to a lower altitude, excessive differential pressures could develop across some of the compartments. Analysis indicates that it takes about 15 seconds to open the vent doors. On the other hand those vent doors which open too soon may produce problems due to the impingement of hot plasma on structural members. The active vent system selection was extensively reviewed and approved by a number of contractor and NASA organizational elements, including the Shuttle System Program Manager. The Orbiter vent system appears to have been sized and analyzed for nominal ascent and reentry trajectories, and no detailed analysis has been made to assure adequate operation of this system during abort or vehicle malfunction conditions. Venting analyses for these conditions are not currently underway, but should be available sometime after July 1976.

Two failure modes of the vent system that have been under study because of significance to crew safety are the failure of the OMS pod vent and wing vents to open. JSC venting analysis showed that the fuselage can tolerate a single system failure, but the wings and OMS pod would fail structurally. The time to troubleshoot such a failure is very short (in seconds) and therefore backup procedures cannot meet the need.

The present Orbiter baseline with regard to Orbiter doors and their functions/criticality are shown in Table IV .

3.1.1.2 Orbiter Thermal Protection Subsystem

Systems Designs

The Thermal Protection Subsystem (TPS) consists of the equipment used to insulate against the external aerothermodynamic or induced heating effects on the Orbiter vehicle. The Thermal Control Subsystem (TCS) maintains appropriate Orbiter thermal conditions. The Panel has examined the TPS in detail and considers it one of the most significant subsystems on the vehicle. While not much attention has been given the TCS, it will be examined more closely during the coming year.

The TPS consists of those materials applied to fixed and moveable surfaces to protect the underlying aluminum structure and heat sensitive equipment. The TPS has undergone an evolution in design. Changes have occurred in tile materials, coatings, and configuration. The system will be reviewed in a PDR this summer.

TPS design for operational vehicles (Orbiter 103+, Subs) includes five different thermal coverings rather than the current design using three types:

(a) Low temperature reusable insulation

(b) High temperature reusable insulation

(c) Reinforced carbon-carbon nose caps

(d) (New) Nomex "E" felt with coating of white silicone oxide

(e) (New) bare surfaces with coating for emissivity/absorptivity

Current configurations are shown in Figures 6 to 8 .

Studies have been underway to try and simplify and reduce the cost and weight of the Thermal Protection Subsystem. Both JSC and Rockwell have been heavily involved in these activities.

The modifications between last summer and the spring of 1975 are due to a change in trajectory which resulted in lower temperatures, lower heating rates and a better tile design, based on a more sophisticated thermal analysis of the tile joint areas.

Areas that have received increasing attention are the aero-surface thermal seals: elevons, rudder/speed brakes, and body flap. These seals must (1) provide thermal protection for the aluminum structure to a maximum of 350° F., (2) restrict flow of air and/or plasma from the high to low pressure areas, to allow aerodynamic control of the vehicle, and (3) have 100-mission life capability in operational vehicles.

Wing elevon seals must provide sealing between the:

(a) Elevon to fuselage

(b) Elevon wing (top and bottom)

(c) Elevon-to-elevon

(d) Elevon wing tip

These are complex seal arrangements and have not yet been fully detailed and analyzed.

The vertical tail seal is a conical tube running the length of the rudder as shown in Figure 9. The body flap seal concept is shown in Figure 10.

Among the objectives in developing tile installation procedures are finding ways to minimize the number of tiles and shapes and to simplify the maintenance removal or repair of tiles. Because of the difficulty in maintaining precise airframe substrate surface tolerances, as well as tile installation height tolerances, Rockwell Space Division has developed the "building-block" approach for installing tile on the so-called "acreage" areas comprising about 80 percent of the Orbiter.

In this approach standard tiles are used in large areas. Special rows of closeout tiles are added to fill in the gaps between adjacent areas.

The remainder of the tiles will have to be shaped and fitted for such multiple curvature situations and penetrations through the TPS subsystem as:

(a) The line between the RCC installations and adjacent tile installations.

(b) Windshield

(c) Forward fuselage hoist point

(d) Actuator access doors

(e) Rear access panels near OMS pod

(f) Structure cavity vents

(g) RCS thruster package doors and opening

(h) Nose gear doors and main gear doors

A part of the installation procedure includes the pre-fit of tiles on the vehicle surface with a hand sanding of the lower tile surface to match the inner mold-line of the Orbiter and hand sanding of the upper surface to match the required outer mold line dimensions in order to control the "step" that exists between tiles. This is shown in Figure 11 an indicates the maximum allowable tolerance to preclude "fouling" the airstream flow over the vehicle surface. Thus a tile-to-tile step of +0.030" to -0.050" is allowable in most instances, and a tile gap of 0.050" nominal is allowed.

Current Status

TPS concerns and issues that have been resolved and those still challenging the designer, which have been of specific interest to the Panel during its reviews of this subsytem, can be summarized as follows:

(a) Experience working with the reusable surface insulation (RSI) or tiles shows it has low resistance to ground handling damage. It has the capacity to sustain damage without catastrophic failure during exposure to induced environment. Installation costs and time requirements are sensitive to the gap and step criteria, tile configuration and installation techniques.

(b) The low temperature tiles appear now to provide more protection than needed, based both on the change in trajectory and the results from recent tests and analyses. This over-protection is also a result of the minimum tile thickness of 0.2 inches. This thickness is derived from the structural properties of the tile and its tendency to crack when any thinner than that. As a result, the use of Nomex "E" felt with a white oxide coating has been tested and found practical as a replacement for some 3,275 $ft.^2$ of surface which achieves a maximum temperature at the outer mold-line of 700° F. or less. Information to date shows the Nomex felt to be acceptable for 100 mission use for temperatures up to 600° F. and very possible to 700° F. There are some 2,000 plus $ft.^2$ of the area meeting the 600 degree requirement. There are even areas on the top of the Orbiter that could be flown without any TPS at all. Arc jet testing conducted in early fall and winter indicated that the Nomex and coating remain elastic and waterproof for 100 mission cycles at 600^{o} F. and for at least 50 cycles at 700^{o} F. A further investigation was initiated 25 January 1975 to resolve some of the remaining challenges. These include the extent of degradation of the coating with exposure to ultraviolet radiation, particulary degradation of the thermal radiative properties of absorbtivity and emmissivity and perhaps elasticity. Although there are no particular structural or vibroacoustic concerns, there is the current unknown of what contamination does to the coating. The program also needs more information on the capability of Nomex to handle temperature dispersions, particularly those over the designed-for values. Rockwell has demonstrated the manufacturing and installation ability of the Nomex felt and indicates a weight savings on the order of 500 pounds if used on the 2000 to 3000 square feet of surface area currently cited.

The Panel has also been monitoring the studies to assess the hazards from: (1) ET insulation ablation products deposition on Orbiter glass surfaces and TPS, and (2) ice and frost breaking away from the ET and striking the Orbiter TPS. Tests and analyses have been conducted to assess the ET/Orbiter interaction. As a result it was confirmed that the abalation products will not flow over the windshields or the top observation windows and does not materially affect the TPS absorptivity and emissivity or its ability to adequately protect the aluminum structure. The possibility of TPS damage resulting from ice and/or frost forming on the ET and then breaking away during and prior to the ascent portion of the mission is still an open item receiving attention. When this is completed, if in fact a problem exists, protection will have to be afforded the TPS during the boost phase. Tests to date are not conclusive. Model tests indicate that ice will not form but frost will.

Natural environment factors such as rain, hail, lightning, and bird impact have been studied relative to their effect on the TPS. To assess rain erosion, precipitation models for KSC and Vandenberg AFB have been developed based on NASA and Air Force data. These models as augmented by tests and analyses indicate the following probabilities of encountering critical rains during ascent and descent at both launch/landing sites:

Flight	Per One Flight	Per 100 Flights
KSC Ascent	0.31%	26.7%
KSC Descent	0.013%	1.26%
VAFB Ascent	0.04%	3.9%
VAFB Descent	0.0011%	0.11%

If required, such data may be developed for Edwards AFB. During ascent, launch constraints can reduce the rain erosion problem. Capability for maneuvering during reentry to avoid rain is quite limited.

As a result erosion has to be accepted and the TPS refurbished as required during the maintenance and turnaround period. Such erosion is not considered a crew hazard as such.

As for ice impact and hail tests have shown that the tile does not exhibit significant resistance to ice impact damage. Atmospheric ice is encountered at altitudes below about 50,000 feet. Hail may occur only within or below thunderstorm cells and is observed very infrequently at the surface at both KSC and Vandenberg AFB. Higher frequencies occur at altitude. Studies indicate that the probability of encountering hail during ascent is about 0.0075% and during descent about 0.015% on an annual basis. Since hail is a thunderstorm phenomena, the probability of hail encountering hail during launch may be reduced to essentially zero by constraining launches. During horizontal flight the ability to perform flight maneuvers are neglible and flight through area thunderstorms cannot be avoided. Hail would not be catastrophic but would certainly require significant refurbishment after landing.

Bird impact data from both civilian and military sources have been analyzed with respect to the Orbiter flight trajectories and expected frontal area subjected to bird strikes. Specific attention was given to the windows as the most significant area of concern and the TPS as secondary. Because the probability of a bird strike is extremely low, the program has deemed it practical to accept such low probability risk.

TPS is obviously subject to "people" or handling damage. Therefore those personnel coming in contact with the Orbiter must be trained and constantly be reminded of the fragile nature of the tiles. Where possible, the ground support equipment should be designed and used in a manner which minimizes any inadvertant damage to the TPS.

Lightning effects on the TPS are continuing to be studied to assess the adverse effects, determine how they can be eliminated or minimized and to define necessary constraints. The current baseline has not designed the TPS for a lightning strike. Without any avoidance measures the probability of a lightning strike would be about 0.008% for all altitudes up to 50,000 feet for launches from KSC.

The probability of a strike at Vandenberg AFB would be considerably less, based on lightning occurrence there. Selective time of launch can reduce the probability of a strike by at least an order of magnitude.

Solid Rocket Booster separation motors in their original configuration would have impacted the TPS when fired. As a result of these analyses the forward SRB separation motors were relocated 120 inches forward. Their thrust was increased from eight units of 12,000 pound thrust to four units of 20,000 pound thrust. The firing time was also reduced from two seconds to a period of not more than 0.75 second.

Tile installation is sensitive to structural buckling caused by thermal stresses along the forward fuselage, mid-fuselage and a few panels on the upper and lower surfaces of the wings. Orbiter specification requirements are that there be no buckling below 115% of limit load on ascent and 100% of limit load on descent. As an example, in the mid-fuselage and wing areas the initial design assumed stringers provided adequate stiffness and spacing to preclude buckle until limit load was reached. Subsequent analysis and testing showed that buckling occurred considerably below the design load. The cause was the transverse skin compression stresses induced by combined thermal and mechanical loads. Such buckling disturbs, if not breaks, the TPS subsystem. The current approach to resolving this problem is to conduct tests to structural ultimate strength and determine ability of the TPS subsystem to accommodate the buckling without failure. Then the program will be in a position to define stiffening modifications and retest of TPS installations.

Another area of concern was the effect of the salt air environment on the chemical stability of the tile coatings at the elevated temperatures anticipated in ascent and reentry. As a result of this concern, a test program was conducted at JSC in the 1.5 megawatt arc jet tunnel facility to evaluate the effects of the salt contamination on the reuse capability of the high temperature thermal protection material. Test results indicate that salt accumulations representative of up to ten years of launch pad environmental exposure have no adverse effects on the reuse capability of the HRSI and its coating for approximately 100 missions.

The high temperature (greater than 2300° F.) thermal protection material is made of reinforced carbon-carbon material. This material consists of pyrolized carbon fibers in a pyrolized carbon matrix with a silicone carbide coating. Extensive development testing and analyses are still in process to determine actual performance characteristics and to confirm the RCC configuration as designed, as well as alternate designs which may be used as the final analyses converge on the final design. A design review for this area is scheduled for the summer of 1975. Two major problems with the RCC material are (1) subsurface oxidation, and (2) inter-laminar failure occurring within the pyrolyzed matrix itself. Sub-surface oxidation results in mass loss which is a function of mission environment pressure and temperature. For example, tests are presently being conducted to determine how best to meet the particularly severe environment where the shock wave off the nose of the Orbiter intersects the wings. The inter-laminar failure problem is one of material processing and now appears to be resolved.

The TPS test program includes (1) material characterization, (2) design development testing, and (3) design verification. The results of the test program to date can be summarized as follows:

(a) Reusable surface insulation (tiles) have been tested for "as fabricated" properties and these test results are being evaluated for determining any future test requirements for material characterization.

(b) Reinforced carbon-carbon test program is approximately 25% complete with scheduled completion in February 1976.

(c) Seals used on moving surfaces are in the very early stages of material characterization testing.

(d) Design development testing covers those tests conducted to confirm analytical methods, support of design configuration selections, and establish verification test methods. For example, a 0.36-scale model wind tunnel test is in process at Ames Research Center to measure effects of TPS on low-speed aerodynamics. Some 120 tests are to be performed on this model in the low-speed 40 x 80 foot wind tunnel. Lost tile tests, structural tests, fatigue tests, flutter tests and lightning tests have been, and continue to be, conducted. Aerodynamic heating in the gaps between the silica TPS tiles is receiving attention through tests to assure that these phenomena are correctly modeled in the analyses used to define the configuration of the TPS.

In summary, the Orbiter TPS is a difficult and complex system to design and understand. None the less, the analyses and testing conducted to date indicate that the design and operational complexities are yielding to the planned development effort. The remaining concerns or challenges include the following:

(a) Improved RCC coating to increase material lifetime.

(b) Decision on use of Nomex felt in lieu of thin tiles.

(c) Thermal protection of penetrations (aerosurface seals and movable doors)

(d) TPS sensitivity to structural buckling.

(e) Tile-to-tile high tolerance to preclude "tripping" or disturbing the airstream.

(f) TPS inspection, maintenance, and handling.

(g) 100 mission reusability.

3.1.1.3 Propulsion Systems

System Design

This section deals with four separate power systems: (1) Auxiliary Power Unit, **(2) Forward and Aft**, (3) Reaction Control, and (4) Oribtal Maneuvering Subsystem. The main propulsion system for the Shuttle integrated system is covered under Section 6.6 of this report. The portion contained in the Orbiter vehicle, the three main engines, is covered in Section 3.2.

The Auxiliary Power Unit Subsystem consists of three independent APU's, each having pressurized fuel storage and distribution, an APU, lube oil cooling, and exhaust, vent and drain provisions. Each APU provides mechanical shaft power to one main hydraulic pump of the