Delays in Receiving and Testing SSME Components

What is the nature of these problems? What is the impact on the NSTL test program?

Answer:

The SSME Project is experiencing delays in the manufacture of hardware similar to that experienced on previous engine development programs. The delays are indicative of the complexity of the various manufacturing processes involved and the development learning cycle. However, at this time approximately three specimens have been made of all hardware items, except for the 77:1 nozzle scheduled for completion in early CY76. The initial specimen experience and the hardening of the tooling continually improves the hardware schedule visibility. The testing of components and the engine system is not being driven by the hardware schedules and adequate hardware exists to perform the tests as the test facilities and engineering planning allow.

SSME Controller

When do you expect to have the necessary information on the problems with the current Controller to make a decision on the backup unit? What kinds of information will be considered?

Answer:

The test experience with the first prototype controller (PP-1) and the ISTB experience with the rack mounted controller (EM-1) and its software, have eliminated the need for further backup controller planning. While some changes are being considered to reduce sense line noise and to reduce fabrication problems with the Master Interconnect Board (MIB), considerable experience has been accumulated through functional and environmental tests of PP-1 and through the ISTB tests conducted to date at NSTL. While long duration testing at environmental extremes is still to be completed over the next few months, the functional and short test duration thermal and vibration data accumulated to date indicates that the present controller can be made to function within the engine program constraints. Closure of the backup controller contingency planning effort is presently being staffed between Level II and Level I.

(The November 1974 Contingency Plan for SSME Controller identified a target date of early July 1975 for making a decision on this subject based on projected availability of testing experience and procurement lead times. At the time of our review with the Panel, late April, the test and manufacturing experience accumulated with PP-1 indicated that backup controller effort would not be required.)

TABLE 3-1

FACTORS OF SAFETY FOR SSME

AT FULL POWER LEVEL VS. RATED POWER LEVEL

	Factor Of Safety (Calculated)	
SSME HARDWARE ITEM	FPL	RPL
Low Pressure Oxidizer Turbopump		
Housing	1.50	1.67
Inducer	1.50	1.67
Turbine Blades	4.40	4.90
Turbine Stator Vanes	1.42	1.58
Shaft	1.69	1.69
Low Pressure Fuel Turbopump		
Turbine Housing	2.12	2.29
Pump Housing	1.53	1.64
Inducer	2.74	2.90
Shaft	1.91	2.02
High Pressure Oxidizer Turbopump		
Second Stage Turbine Blades	1.76	2.03
First stage Turbine Disc	1.48	1.71
First stage Turbine Nozzle	2.27	2.50
Turbine bellows	1.69	1.97
Turbine Fairing	2.28	2.67
Turbine Exhaust Struts	1.50	1.75
Turbine Inlet Housing	1.65	1.93
Pump Housing-Inlet	1.62	1.89
Discharge	1.62	1.70
Diffuser Vanes	1.41	1.50
Preburner Volute	1.59	1.70
Main Shaft	1.50	1.75
High Pressure Fuel Turbopump		
Second Stage Turbine Blades	1.40	1.49
Second Stage Turbine Disks	1.40	1.49
First Stage Turbine Nozzle	1.83	1.96
Second Stage Turbine Nozzle	1.55	1.66
Turbine Bellows	1.53	1.64
Turbine Bearing Thermal Shield	1.76	1.89
Turbine Bearing Support	2.66	2.86
Shaft System	1.46	1.53
Pump Housing-Mount'g flange	1.50	1.61
Discharge	1.82	1.94
Diffuser Vanes	2.12	2.26
Pump Inlet vanes	2.00	2.20
Third Stage Impeller	1.79	1.91
First Stage Diffusers	1.50	1.61

TABLE 3-1 (continued)

	FPL	RPL
Valve Actuators		
Connection Flange	1.40	1.40
Pressure Cylinders	2.00	2.00
Gimbal Bearing		
Body	1.48	1.57
Shaft	1.64	1.64
Seat	1.47	1.47
Hot Gas Manifold		
Shell	1.42	1.56
Injector Weld	2.08	2.29
Fuel Preburner Weld	1.55	1.70
Oxidizer Preburner Weld	1.45	1.59
Fuel-Side Collector Liner	9.-	9.-
Fuel-Side Transfer Tube Liners	1.75	1.75
Oxid-Side Collector Liner	2.90	2.90
Oxid-Side Trans. Tube Liners	4.22	4.22
Heat Exchanger Weld	2.70	3.00
Main Combustion Chamber		
Actuator Struts	1.41	1.41
Inlet Manifold	1.41	1.48
Discharge Manifold	1.47	1.55
Longitudinal Welds	1.40	1.50
Liner- Electro Deposit Ni	1.60	1.79
- Narloy-Z	2.29	2.54
Acoustic Cavity	2.61	2.83

TABLE 3-2

REDUNDANCY MANAGEMENT DEFINITION

- REDUNDANCY - REFERS TO HOW OFTEN A FUNCTION IS REPLICATED
- REDUNDANCY MANAGEMENT - REFERS TO HOW MONITORING & CONTROL OF REDUNDANT FUNCTIONS ARE PERFORMED
- FAIL OPERATIONAL (FO) - MISSION OBJECTIVES CAN BE ACCOMPLISHED AFTER A SINGLE FAILURE
- FAIL SAFE (FS) - SAFE VEHICLE & CREW RECOVERY AFTER SINGLE FAILURE
- FO/FS - FO AFTER FIRST FAILURE & THEN FS FOR ANY SUBSEQUENT FAILURE WITHIN THE SAME SUBSYSTEM
- FDI - FAULT DETECTION & IDENTIFICATION (AND ANNUNCIATION)

TABLE 3-3

DESIGN VERIFICATION SPECIFICATIONS
(DVS)

Specification Title	Specification Number
Engine System	
Main Engine (Vols. 1,2)	SSME #101
Gimbal Bearing Assembly	102
POGO Suppression System	106
Avionics	
Controller Assembly (Hardware Vol. 1, Software Vol. 2)	201
Electrical Harness	202
Instrumentation System	203
Flowmeters	204
Ignition System	205
Combustion Devices	
Thrust Chamber Assembly	303
Hot-Gas Manifold	304
Fuel and Oxidizer Preburner Assemblies	305
Turbomachinery	
Low Pressure Oxidizer Turbopump Assembly	401
Low Pressure Fuel Turbopump Assembly	402
High Pressure Oxidizer Turbopump Assembly	403
High Pressure Fuel Turbopump Assembly	404
Valves and Interconnects	
Check Valves	508
Pneumatic Control Assembly	510
Flexible and Hard Duct and Line Assemblies	511
Hydraulic Actuation System	512
Heat Exchanger	513
Static Seals	514
Propellant Valves	515
Fuel and Oxidizer Bleed Valve Assemblies	516
POGO Suppression System Valve Assemblies	517

TABLE 3-4

COMBUSTION DEVICES - TESTING SUMMARY
(THROUGH APRIL 1976)

	TESTS COMPLETED	TESTS PLANNED TO CDR	
ASI	28 TO FPL 700 ENG. START	FULL DURATION	4 TESTS
OPB & FPB	19 TO FPL	2ND UNIT PERF. & DURABILITY (MAX. CONDITIONS) STABILITY	32 TESTS
TCA	17 TO FPL	BOMB DEVELOPMENT (PHASE B TCA)	5 TESTS
		STABILITY & DURABILITY (MAX. CONDITIONS)	11 TESTS
		2ND UNIT PERF. & DURABILITY (MAX. CONDITIONS)	10 TESTS
40K	102 CYCLES RPL (MCC)	40 ADD'L CYCLES ON INJECTOR	28 TESTS
NOZZLE	17 TO FPL (35:1)	77.5:1 FPL OPERATION (MAX. CONDITIONS)	3 TESTS
HEAT EX.		PERF., DURABILITY & FLOW STABILITY	10 TESTS

FIGURE 3-1

SPACE SHUTTLE MAIN ENGINE PROGRAM

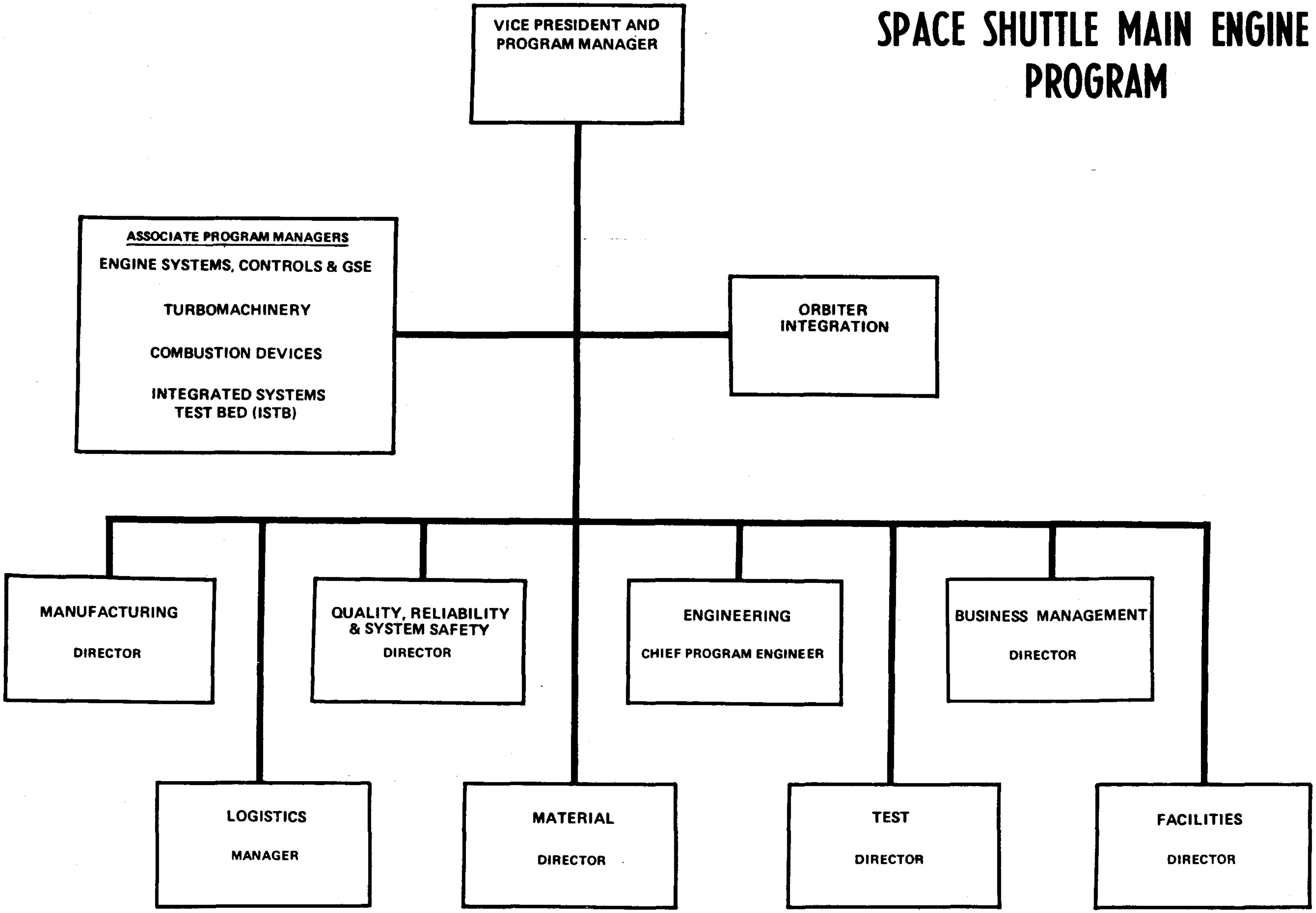


FIGURE 3-2

SPACE SHUTTLE MAIN ENGINE PROGRAM

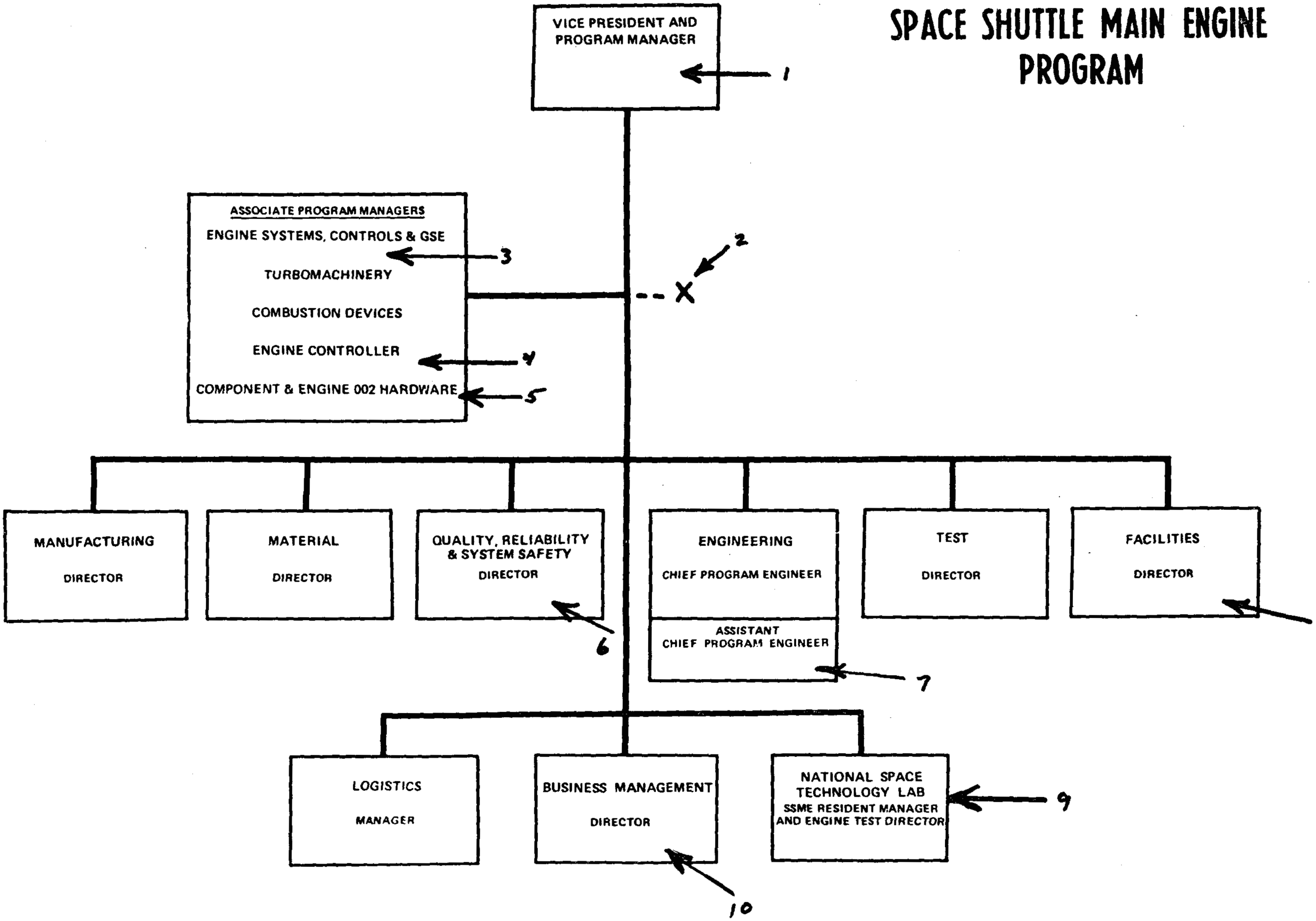


FIGURE 3-3

MAIN PROPULSION SUBSYSTEM SCHEMATIC (FLUID)

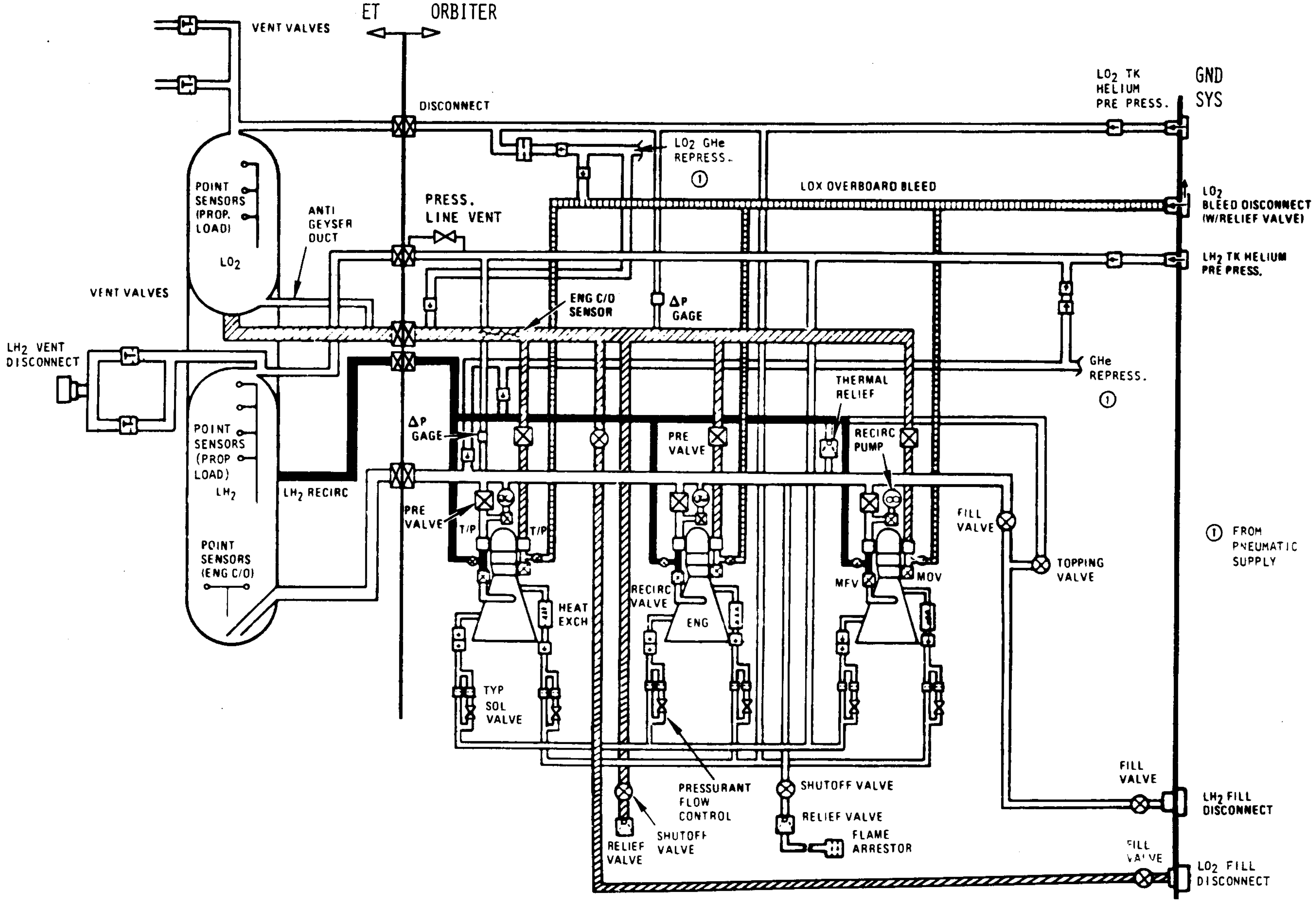
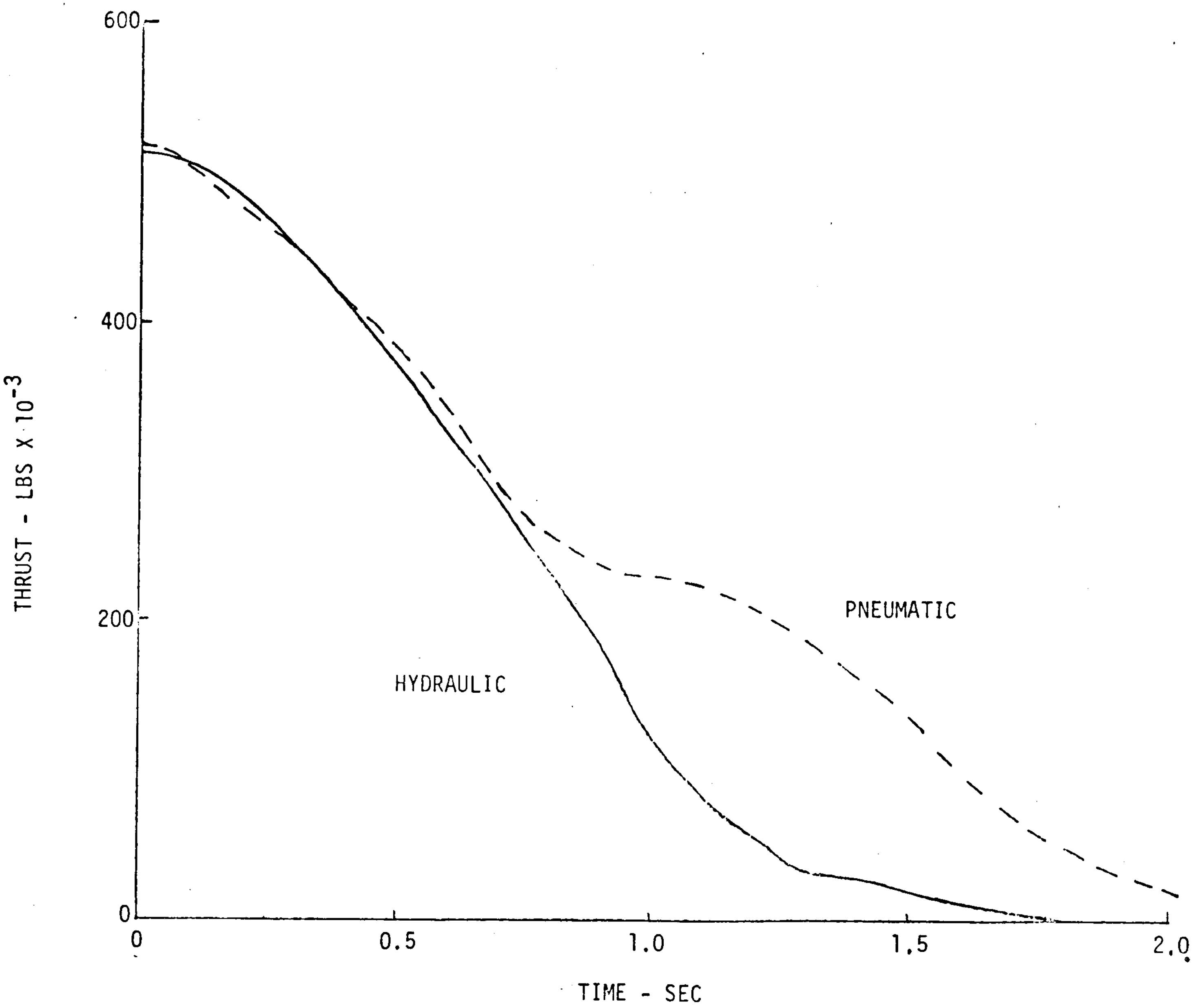


FIGURE 3-4 HYDRAULIC VS PNEUMATIC SHUTDOWN



4.0 ORBITER THERMAL PROTECTION SUBSYSTEM

4.1 Introduction

The Orbiter 101 Critical Design Review and the Orbiter 102 Preliminary Design Reviews have resulted in a reasonably firm baseline of the Orbiter Thermal Protection Subsystem (TPS). As a result, detailed drawing releases, fabrication of hardware, detailed tests, have all begun. The Panel reviewed both the management systems and their implementation as well as the technical adequacy of the TPS. Given this new technology, the Panel wants to assure an adequate basis of confidence in reliability of the TPS and therefore crew safety.

The Panel has had this critical Shuttle hardware system under review during the past two years as shown in Table 4.1. The Orbiter TPS is, of course, a many-faceted system of the Orbiter. It is affected by many factors: aerodynamic pressures; structural deflections on the Orbiter; and the External Tank and Solid Rocket Booster elements of the Shuttle Cluster. Given this complexity it was apparent that the Panel could not provide detailed scrutiny of all these aspects. Therefore the Panel and the Task Team focused on (a) the technical requirements for the TPS during phases of the Shuttle mission, (b) those features of the TPS most affected by unique mission requirements, operational restrictions, resource reductions, (c) challenges created in using new technology, and (d) flight test requirements not previously experienced on manned space flights.

The Panel examined the management systems in terms of its inherant capability for handling (a) communications between technical personnel and through senior levels of management, (b) the hazards identified and their resolution and risk assessment, (c) such major technical problems and interface effects as design, test, fabrication, logistics, maintenance, and assembly. Technical areas covered in these discussions covered materials and processes, thermal analyses, structural adequacy, systems integration, TPS and Orbiter hardware properties affected by aerothermodynamics of ascent and reentry.

Many parts of the program impacting the TPS are under review by the Task Teams for such areas as the Shuttle Major Ground Test Program, Approach and Landing Test Program, the Orbital Flight Test Program, Development Flight Instrumentation, External Tank and Solid Rocket Booster Programs, and Risk Assessment.

The fact-finding began with detailed preliminary data collection and analysis resulting in a discussion with appropriate program personnel to establish the specific areas of interest, the personnel that should be involved and the best sites for the discussions. Then the team undertook on-site reviews with various levels of working and management personnel and examined as appropriate the hardware/software, tests, and documentation.

The team then reviewed the program response to their action item and subsequent baseline reviews and test results. This report is based on such activities.

4.2 Observations

4.2.1 Organization

There have been no measureable changes in the management organization of personnel since the Panel's last report to the Administrator dated June 1975. Based on discussions with NASA and contractor personnel the organization appears to be operating well and is producing the necessary communication between all levels. Top management has visibility of the overall status of the TPS program. The Panel will continue to review the ability of the various TPS organizational elements to respond quickly to changing program needs when they are defined at the Orbiter 102 Critical Design Review and as a result of the updated "loads programs."

4.2.2 Review System

The Orbiter Thermal Protection Subsystem Design Review conducted from mid-July through mid-August 1975 was an extension of the Orbiter 102 Preliminary Design Review (PDR). Since this is a good example of the depth and scope of such a review, the following particulars on the process are cited:

July 28th	Data Packages after having been checked and assembled were sent to

	participants for critique at the following locations: JSC, KSC, ARC, LaRC, NASA Headquarters, SAMSO.
July 28 - August 8	The data was reviewed and Review Item Dispositions (RID's) were submitted as a result of this critique.
August 12-13	The Screening Group reviewed all RID's, resolved the technical or management questions where appropriate and identified those items to be brought before the full, formal Review Board.
August 14	The TPS Formal Review Board reviewed the actions of the screening group, resolved the issues which required their management authority and assigned the actions to be taken in ensuing months.

The distribution of RID's across the TPS technical areas is indicative of where the remaining challenges were found:

Structures (reuseable Carbon-Carbon leading edge, reuse-Surface Insulation-Tiles and Nomex, Thermal Control Subsystem-Internal, Stress/Loads, Materials/Processes)	83
Development Flight Instrumentation and Avionics	14
Aero Sciences	27
Systems Integration	1
Test Program	22
Reliability/Safety	2
Quality Assurance	4
Manufacturing	4

The risk management system for the Orbiter TPS was also reviewed.

The system is continuing to produce hazard assessments. For example, the NASA document "Space Shuttle Safety Concerns Summary Report," JSC 09990, dated December 15, 1975 covers the following:

a. Damage to the Orbiter TPS from the ice shed from the External Tank.

b. Possible impact of the External Tank and Orbiter after initial separation.

c. Damage to the Orbiter by the motor plume from Solid Rocket Booster after separation.

Based on the material presented to the Panel and the discussions between Panel members and NASA and contractor personnel it appears that the review system as applied to the Orbiter TPS is working reasonably well at all levels.

4.2.3 Documentation

The Panel selectively reviews TPS related documents covering the various aspects of the design, test, and fabrication of the Orbiter TPS. Table 4-2 is a partial listing of the documentation reviewed by the Panel since its last report to the Administrator.

4.2.4 Design Progress

Since the basic Orbiter TPS has been described in both prior Panel documents and many NASA and contractor program documents, it is assumed that the reader is acquainted with the TPS subsystem or has access to the material noted above. Observations as presented here cover several areas: (a) significant changes to data reported in the Panel's last Annual Report to the Administrator, (b) new information developed during Panel reviews and task team activities, and (c) observations of other Panel Task Teams that relate to the developing basis of confidence in the Orbiter TPS' ability to support a successful Orbital mission.

4.2.4.1 Mass Properties

The new Felt Reuseable Surface Insulation (FRSI) replaces a portion of the low temperature tiles (LRSI). This change reduces the TPS accountable weight by some 300 pounds. A description of this newest addition to the TPS is provided in Paragraph 4.2.4.3. However, there are a number of items that are expected to lead to weight increases. These items include definition of the penetrations and closeout, beef-up of the reinforced carbon-carbon panel, the outer moldline fairing, the high pressure gradient flow barrier, the aero-surface seal requirements, LRSI coating thickness and optical property change.

4.2.4.2 TPS Material Distribution

The distribution and configuration of the five (5) different types of TPS materials used to cover the Orbiter surface are as shown in Figure 4-1.

4.2.4.3 Felt Reuseable Surface Insulation (FRSI)

Studies conducted in the last months of 1974 showed that the minimum gage LRSI tiles overprotected the structure in many areas. The temperature of the structure in these areas was below 350° F. so that it might be possible to have a "bare top surface." This was, however, considered an unacceptable risk for the first orbital flight. The concentrated test and analysis program covered many materials and material systems and finally selected the Nomex felt. Therefore, the LRSI tiles covering areas with surface temperatures of $\leq$ 700° F during entry and at 750°F or less during ascent have been replaced with DC92-007 silicon paint coating on Nomex felt. There is a continuing effort to extend the use of this coated Nomex material to further reduce weight and complexity of the TPS. The only major concern in changing from tile to Nomex was that there might be a "flutter" interaction. Therefore, a two-foot by four-foot specimen is presently being tested at the Ames Research Center to determine the "flutter" characteristics of this assembly. Table 4-4 describes the FRSI material.

4.2.4.4 Orbiter 101

There is a concern regarding the simulated tiles on the Orbiter 101 for the Approach and Landing Test program vehicle. These are made of polyurethane foam covered with Hypalon coating. The concern is with the foam material and its compatibility with various Orbiter fluids, e.g., hydraulic fluid, APU propellants, etc. There is a potential fire hazard due to this incompatibility. NASA and the Orbiter contractor are examining this area and expect to have a resolution available shortly.

4.2.4.5 TPS Issues

At the time of the Panel's review the following technical challenges were being worked so each is discussed in the following paragraphs:

a. HRSI and LRSI tile coatings.
b. Unique shaped tile
c. Tile-to-tile steps
d. Airframe panel buckling
e. Static door thermal barriers
f. High pressure gradient barriers
g. Use of densified fused silica
h. Use of minimum thickness LRSI tile
i. Body flap, rudder speed brake, elevon aerothermal seals

4.2.4.5.1 Tile Coatings and Unique Shaped Tiles

There is an intensive and detailed materials development program for the tile coating. The program has been conducted by NASA at the Ames Research Center, Johnson Space Center, Rockwell International, and the Lockheed Missile and Space Company. In trying to meet the RSI tile coating goals, the program has been having problems with cracks in the coating on the sidewalls of the High Temperature Reuseable Surface Insulation. The Low Temperature tiles (LRSI) coating is still undergoing demonstration tests on the mechanical adequacy and characterization of its material properties.

The goals for the RSI coating are to:

a. Minimize devitrification during thermal exposure.

b. Minimize thermal expansion coefficient (about 3 x 10^{-7} in./in./$^{\circ}$F).

c. Minimize morphological (form and structure) changes during thermal exposure.

d. Maintain imperviousness to water.

e. Optimize optical properties; $\varepsilon \geq 0.8$, HRSI $\frac{\alpha}{\varepsilon} \leq 1.0$, LRSI $\frac{\alpha}{\varepsilon} \leq 0.4$

f. Meet dimensional tolerance requirements.

g. Provide as much as possible resistance to ground handling and impact damage.

Based on the latest information available to the Panel the program has an approach to resolving the tile coating problem. The present coating (identified as #0050) consists of silicon carbide and cobalt oxide emissivity agents. The basecoat is slip cast fused silica with a basic borosilicate glass as the coating. The test program to resolve the #0050 coating problems involves Lockheed, Rockwell, Ames and JSC support during the first portion of 1976. At the same time there is a program to evaluate the reaction cured glass coating process developed by Ames Research Center. The so-called reaction cured glass coatings are produced by blending the components, then affixing them by spray or paint on the substrate and finally heating the coated tile rapidly to the reaction temperature for the reciprocal action of the ingredients on each other. The result is a three-layered coating with an outer layer of Boron Oxide rich glass, a center layer of Borosilicate glass + Tetraboron Silicide, and an inner layer against the tile of borosilicate glass. When the tests and analyses are completed it is expected that a final decision on the coating material will be made in mid-1976.

In addition to the effort to produce un-flawed coatings, Rockwell International is evaluating the impact of flaws on mission performance. This seems worthwhile since the coating cracking problem appears to be applicable to the LRSI as well as the HRSI; the tiles are subject to damage by any impact, human or natural; and there is presently no viable test method of detecting the sidewall flaws.

For the total TPS tile program, NASA approved material characterization plan specifies that:

> "The mechanical properties, as described under test programs are divided into three catagories to prevent unnecessary and redundant testing.
>
> Category 1: The approach is to test enough specimens in one or more critical properties to verify gaussian distribution in a population of specimens taken from multiple batches of material that has not been well characterized previously. Where similar materials have been well characterized or where generous margins are predicted, fewer test specimens are required. A demonstration of a 1.5 safety margin, using material properties degraded by 100 mission thermal history, will satisfy any requirements for further testing of that property.
>
> Category 2: With only a minimum number of data points scheduled in Category 1, some unsatisfactory margins may result. In these cases, Category 1 results will be assessed, and additional testing will be performed. In addition, certain tests will be conducted when information is required but does not result in a design allowable. Category 2 tests cannot be completely de-

fined until Category 1 testing is complete.

Category 3: After satisfactory allowables are generated, other conditions that could affect the useful life of the TPS will be evaluated. These are not yet completely defined but include evaluation of the effect of natural environments, working fluids, temperature overshoot, permeability, and waterproofness."

Only Category 1 tests are defined in the current issue of the test document RI SD74-SH-0156.

4.2.4.5.2 Tile-To-Tile Steps

To assure an undisturbed airflow over the Orbiter tile surfaces the program must assure that the height of adjacent tiles be held within very tight limits. Figure 4-2 shows the 10-mil "forward step" criteria which is an installation problem covering about 17% of the TPS area. Other areas may permit a somewhat greater step difference as shown, i.e., 30-mil forward and 50-mil backward steps in non-critical aerothermo-dynamic areas.

4.2.4.5.3 Airframe Panel Buckling

The problem with possible cracking of thin tiles as a result of structural deflections was noted in the Panel's last annual report. Currently this could be a problem in some 1800 square feet of surface compared to an original estimate of a little more

200 square feet. Therefore, it is an issue which continues to receive attention. The program is considering such proposed solutions as use of softer strain isolator pad (SIP), smaller tiles, strengthening of the structure, and the reduction in thin tile area by using Nomex (FRSI). Trade-off studies indicate at this time that the most cost-effective solution is to revise the structure rather than modify the TPS with the exception of using FRSI.

4.2.4.5.4 High Pressure Gradient Barriers

There are a number of locations, comprising fairly large surface areas, where there are high to low pressure gradients along the tile gaps resulting in increased gap heating and possibly flow-tripping. Such regions where such connections between high and low pressure flow can exist include chines and trailing edges in particular. The problem is to preclude the flow of gas through the gaps with barriers of some type. The manner in which these flow stoppers could be manufactured and installed are still under study.

4.2.4.5.5. Use of Minimum Thickness RSI Tile

This area of concern has been discussed in the previous sections on the possibility of replacing very thin tiles with Nomex Felt; the effect of flutter and structural deflections; and hot gas flow due to high pressure gradients. Thin tiles have a thickness not exceeding about 0.3 inch. They cover some 2000 to 3000 square feet of Orbiter surface and are susceptible to breakage during handling and launch preparations. Their distribution is as follows:

Straight flat tiles	1000 ft^2 (approx.)
Single curvature tiles	500 ft^2 (approx.)
Double curvature tiles	1000 ft^2 (approx.)

The straight flat tile obviously represent the least problem and can most likely be accommodated by simple methods. However, the single curvature tiles have not demonstrated that they have sufficient strength to be handled in a manner like the flat tiles. Even less is known about the handling qualities and requirements for the double curvature tiles. In any case, it is necessary to demonstrate the techniques that can adequately handle these tiles without undue damage.

4.2.4.5.6 Use of Densified RSI and Thermal Barriers for Doors

Densified RSI is a silicon carbide impregnated RSI for use in those areas where improved dimensional stability and high temperature service are necessary. Applications of this material is currently found in localized areas where static seals are required, around the landing gear doors, the elevon and aft Orbiter/ET umbilical doors. The definition of environmental and dimensional requirements are still in the process of being refined.

The thermal barrier designs for the Orbiter doors and other critical areas have been completed and will be examined analytically to see what testing should be done to prove the adequacy of the design. One area of continued concern is the surface smoothness requirements over doors and other areas using seals and thermal barriers. If the current smoothness requirements were to be relaxed it could very well result in flow transition from laminar to turbulent at an earlier time in the mission that is used in the design and sizing of the TPS. For example, if the requirements on the nose landing gear door area were changed resulting in an early tripping to turbulent flow, the TPS weight might well have to be increased as much as 2900 pounds to handle the situation.

4.2.4.5.7 Leading Edge Structure

The leading edge thermal protection design uses an all-carbon system protected against oxidation by a coating of reinforced carbon-carbon (RCC). The general design and installation is shown in Figure 4-2. The RCC system covers about 410 ft^2 of leading edge surface on the Orbiter fuselage, wings and empennage. The 3,020 pounds associated with this system is made up of some 1600 pounds of the RCC panels themselves and about 1420 pounds of installation hardware and internal insulation in these areas. The material is subjected to temperatures ranging from about 2300° F. to more than 2600° F. This material will be applied to two specific areas on the Orbiter 101 and extensively used on the Orbiter 102 for its Orbital flights.

The on-going studies assess the capability of the leading edge structural subsystem to withstand cyclic aerodynamic and aerothermal stresses (fatigue properties). This work will be reported upon during the Orbier 102 Design Review scheduled for the April/May 1976 time period. There are the number of Review Item Dispositions (RIDSs) remaining open from prior reviews that can be expected at this stage of the development program. All of these items are being worked. A summary of the RID activity through the first of December 1975 is provided in Table 4-3.

The interface between the RCC installation and the adjacent high temperature tiles (HRSI) has been designed with essentially complete layout drawings as well as completed stress and thermal analyses. Significant areas include the RCC attachments themselves and the thermal barriers internal to the protected surface. Thermal barriers are to be included in the development test program currently underway, i.e., "Wing Leading Edge System" and "RCC/RSI Interface - Nose Cap" tests. Additional updates are expected in the coming months to the analyses used in the current design work.

It has been noted that the Inconel 718 metal in the fittings used to attach the LESS is very susceptable to cracking where small flaws existed and there is an air environment of 1000° F. or more.

This concern was discussed in some detail in the Spring of 1975 by both Rockwell and JSC. It was noted that on all released detail drawings that a reasonable margin of safety has been assured through the use of decreased material values (e.g., tensile strength, etc.) which accommodate possible cracks in the same manner as stress-corrosion is accounted for in the design of such items.

4.2.5 Test Program

The Thermal Protection Subsystem Test Program is extensive. It is being conducted at such locations as:

a. Johnson Space Center - Technical management and development activities.

b. Ames Research Center - Coatings development, material characterization, system development tests.

c. Langley Research Center - Development test activities.

d. Lockheed, Sunnyvale, Ca. - Development of tiles and coating and the production of tiles.

e. Rockwell, Downey, Ca. - Development of total TPS system including the assembly and installation, design and development, maintenance and replacement procedures, etc.

f. Johns-Manville - Basic tile material fibers.

g. Globe-Albany, Maine - Supplier of Nomex felt.

For our purposes this status report focuses on material characterization tests, development tests, and certification tests.

The current test status shows the following position at this time:

a. Material selection tests are approximately 75% complete with final completion scheduled for June 1976.

b. The material characterization test work required for the Orbiter 102 PDR is some 90% complete. This phase of the work is expected to be completed around July 1, 1976. Testing will, of course, be continued as required to meet any changes made to either the requirements or the material used in the TPS.

c. Design development testing will be continuous through at least most of 1977. Verification testing is expected to begin sometime in the last half of 1977.

d. A plan has been developed to assess the inherent capability of the TPS to withstand such natural environments as rain and hail bird strikes. A major objective is the determination of that launch and landing constraints that must be considered in mission planning.

e. The effects of a "lost tile" being examined in detail through testing at the Ames Research Laboratory. The objective of these tests is to determine the survivability of adjacent tile installations and their resistance to the so-called "zippering" effect because of entry aerothermodynamic forces. This work continues because the earlier test results were not conclusive.

The depth of the test program can be seen from the following examples of work being conducted at the Langley Research Center:

a. Assessment of the leading edge carbon-carbon material to assess mass loss verify the mission life capability of this material and design.

b. Assessment of the nose gear door thermal barrier to evaluate the design concepts for the thermal performance, leakage rates, and reusability.

c. Determination of the thermal response and gas leakage characteristics of the interface between the leading edge high temperature carbon system and the reuseable tile system which adjoins it.

d. Evaluation of the thermal performance of reuseable surface insulation (tiles) to off-nominal high shear environments.

e. Determination of the effects of tolerance buildup on the TPS performance under nominal (turbulent) flow environment.

f. Evaluation of the effects of the sequence and/or combination of mission environments on the TPS tile acoustic fatigue life.

g. Assessment to correlate damaged tile erosion rate with flow shear, and determine influence of damaged tile on primary structure temperatures during entry.

h. Definition of the design allowables for Orbiter leading edge reinforced carbon-carbon material by determining the synergistic effects of stress, temperature, and pressure on mission life.

At the time of the Orbiter TPS review in August 1975 a number of issues were considered:

a. The methods of dissemination of materials property data by letter followed by revision to the materials handbook was reviewed and is considered acceptable.

b. Materials test plans have been reviewed and the following points made: (1) a plan is required and will be made available for the evaluation of crystobalite formation in fused silica materials (high strength/density) used in high temperature areas of the Orbiter; (2) a plan is being prepared to define the RSI defect and crack acceptance and/or rejection criteria which is necessary for proper Orbiter refurbishment and logistics; and (3) a test plan has been developed to consider the possible effects of launch site environment on the mission life of tiles. This test will be implemented starting in May 1976 and there will be analytical studies conducted concurrently.

c. The planned NASA technology study has been established to continue the investigation of "lost tile" effects. This is mentioned above as a part of the Langley Research Center program in support of the TPS development and operational understanding work. Previous testing had indicated that tile "zippering" would not occur if a single tile were missing from the TPS pattern. However, there was some question about the effects from the loss of two or more tiles adjacent along the airflow path. Langley tests indicate that if flow reattaches on the bottom of the cavity wall where the tile is missing, unzippering is more likely to occur. This is due to the flow field undercutting downstream tiles and erosion of the underlying Strain Isolator Pad (SIP-Nomex Felt).

d. The scope of the acoustic fatigue testing program has been reevaluated to assure that this program is adequate and timely in supporting design development. This was of particular interest to the designers of the aerothermal seals. There is a feeling that such acoustic fatigue tests should in fact contain a sequence of tests that used combined environments to assure that the seals are adequate to pass certification. This is another of the tests noted under the Langley Research Center support programs.

e. The need for tests of the forward external tank/orbiter attachment region was reviewed. Thermal testing was not considered necessary because: (1) the attach/separation mechanism assembly is replaced after each flight, hence damage to this assembly during entry has no next-flight consequence; (2) analysis indicates the substructure in the attachment region will not be overheated; and (3) the TPS surrounding the penetration is mounted on a removable carrier-plate that can readily be inspected and serviced after each flight.

f. There have been questions regarding the certification plan for the TPS because of the use of prototype pre-production hardware tiles in development test articles that may be used in support of certification and the adequacy of the planned testing procedures, especially in the area of acoustic fatigue. To assure an adequate certification test program it had been decided that prototype hardware may be used and if similarity exists with flight hardware and is approved by NASA. The acoustic fatigue test program will be agreed upon sufficiently in advance of the tests themselves.

4.2.6 Fabrication and Assembly

In its 1975 Annual Report the Panel noted two areas requiring continued attention. The Space Shuttle Program office responded to these questions about design and quality control on the TPS and the procedures, instructions and training requirements for installation of it. (See Attachment 4-1 and 4-2).

The TPS is still in the development stage; therefore, the detailed information regarding the process for installation and verification is also under evolution. Some of the statements provided at the TPS Design Review put this aspect of the program into perspective .

a. Non-standard tile shapes are required to accommodate close-out requirements, tile orientation to reduce gap heating effects and the man penetrations, such as doors, windows, access panels, vents, etc.

b. Tile shape and carrier strip geometry has been standardized wherever possible. Layouts, of course, are in various degrees of completion. Differences in assembly must be ironed-out as the design fully develops.

c. The number of tools or arrays to be used in installing the TPS on the Orbiter is estimated as follows:

Mid-fuselage	88
Wings	50
Vertical Stabilizer	83
Upper Forward Fuselage	44
Lower Forward Fuselage	130
Aft Fuselage, Lower	33
APS Pod	64
RCS Pod, Upper Forward Fuselage	26
TOTAL	517

Such installation arrays are being defined as soon as the engineering layouts become available.

d. The TPS inspection plans (15 May 1975) do not rely on visual inspection alone as the initial method of damage inspection. Demage, of course, can occur during assembly or as a result of the mission environment. The intent of the visual inspection is to identify both those vehicle areas where there is obvious damage as well as those areas which warrant more detailed assessment because of the external appearance of the tile or similar data. This visual technique is an effective process to identify areas of refurbishment. Detailed discussion of available NDE (Non-Destructive Evaluation) tests and future plans for such are contained in Rockwell International Letter 044-250-75-080, dated 5 August 1975.

e. An example of the attention being focused on the installation problem at this time is the assignment of twelve quality engineers to work directly with the design group during the current phase of the program. NASA has also assigned a quality engineer to monitor the effort on a full-time basis. In addition, a TPS development shop is located adjacent to the design area to assure continuity between the development testing and the design and quality verification efforts.

4.2.7 Logistics and Maintenance

Much of what has been stated above for the fabrication and assembly portion of the TPS program applies to the logistics and maintenance areas as well. These areas are receiving increasing attention as the design moves forward. For example, Rockwell Internationa is responding to a KSC request for a proposal to develop Space Shuttle thermal protection system refurbishment techniques, which consists of three basic tasks: (1) tile removal and replacement, (2) tile repair, and (3) thermal tile tests at KSC to verify repair methods.

These tasks started in October 1975 and will be completed on or about October 1976.

Handling and packaging specifications and procedures are to be prepared so that the documents covering the TPS handling, storage, transportation, inspection, bonding, machining and coating, and waterproofing will be published and ready in time to support the TPS facilities activation at the Palmdale assembly plant.

TPS tile identification methods are under active consideration with a goal of identifying the tiles with an applicable Rockwell International part number and serial number on the bottom surface of the tile.

4.3 Current Posture

Although basically a new system, the program considers the Orbiter TPS concept appears to be both practical and workable. Design and development testing appears to support this judgment. An example of the maturation of the TPS design is the large reduction in the number of thin (0.20") tiles resulting from the refinement of entry aerothermal loads and the development of coated Nomex felt for those Orbiter surfaces having expected temperatures below the 650-700° F. range.

Based on the data available to the Panel, the following is the status of TPS development:

a. It is expected that 95% of the layout drawings would be completed by April 1976.

b. The TPS design, fabrication, installation and test activities should meet the Orbiter 102 program milestone requirements.

c. The TPS system design reviews are effective in surfacing those kinds of problems requiring the attention of management and the working levels to assure the TPS meets the requirements on Orbiter 102.

d. The Solid Rocket Booster separation rocket engine plumes do not appear to present an impingement problem.

e. The basic TPS materials have been selected and the "acreage" configuration have been baselined. The interface configuration between the leading edge RCC system and the basic tile system has been finalized.

Specifications and test plans need to be completed as follows:

a. The Lockheed Missile and Space Corporation specification on "heat-up" and "cool-down" rates to assure the tile materials meet

Orbiter requirements requires further definition.

b. The material property data in Rockwell International handbooks used by design and test personnel needs to be updated.

c. The TPS Design Specification, SD72-SH-0101-6, is to be updated and completed on or about July 1, 1976 by Rockwell International.

d. Requirements for acoustic fatigue tests need to be verified.

e. There needs to be a demonstration of a full 100 mission life for the carbon/carbon leading edge material (RCC), especially for that section of the wing leading edge where the shock wave off the Orbiter nose intersects the wing.

f. Aerodynamic heating in the gaps between TPS tiles is a problem where much effort is being expended at this time. This is most severe in those portions of the tile system where a large pressure gradient is present causing increased local flow rates, such as on the wing glove area at high angles of attack.

g. A test and analysis program must be defined to prove that the coated tiles can meet the waterproof requirements necessary for re-use. Coating development activity indicates that this is a difficult area and resolution is expected in mid-1976.

h. The requirements for Development Flight Instrumentation

(DFI) for the TPS are fairly well-defined. The program is in the process of deciding the type and number; the location of sensors in regards to edges, tile gaps, structural members; redundant installations and effects of data point drop-out. The organizational responsibilities for various aspects of DFI must also be defined.

4.4 Addendum

The program has just completed a major baseline review and made number of significant decisions.

4.4.1 Tile Coating

The Ames Research Center "RCG" coating has been selected for the high temperature tiles (HRSI) based on the most recent test results and detailed studies. This black coating should eliminate the coating cracking problem experience during the past months. The original grey-colored coating will be used on the low temperature tiles (LRSI) which has not experienced the cracking problem. The thermal properties (emissivity/absorbtivity) appear to meet requirements.

4.4.1 SSME Heat Shields

The thermal protection system design for SSME base heat shield is shown in Figure 4-3. This shield protects the Orbiter and engine structure from heat transfer during the ascent and entry portions of the mission. It has been estimated that one-half of the shield on a single engine may have to be replaced every four or so flights.

4.4.3 Thermal Seals

The Orbiter body flap and wing/elevon lower cove aerothermal seals require failsafe design. As presently designed these may present a single point failure condition which can be considered a crew safety hazard. Furthermore these seals as designed are dynamic systems so that safe-life cannot really be proven and inspection for failures is extremely difficult. Although these seal systems include springs, hinges, linkages, rubbing plates they are not subjected to the form of failure mode and effects analyses (FMEA's) used on other mechanisms because they are considred to be structures. The contractor has noted that reliability trade studies have been conducted to support the design and development and the test program.

The test and analysis program for the seals is directed toward demonstrating that:

a. Sufficient structural and performance margins exist so that there is no credible single point failure in the seal system.

b. Sufficient access and ground test provisions have been provided to permit inspection and tests to prove flight readiness.

c. Where structural and performance margins cannot be demonstrated the design shall incorporate sufficient thermal protection to accommodate a safe single entry by means of insulation, heat sinks, etc. To assure hat the current design approach meets the requirements the contractor has been directed to review the following areas and develop a plan and a schedule to (1) determine if the present design can be made failsafe for all flights, (2) reassess maximum gap size allowables, (3) determine if additional test program will increase confidence, (4) investigate the inspection and maintenance concepts for increasing the ability to meet turnaround times, and (5) Investigate potential modifications to early test missions to enhance the fail-safe concept.

Other areas of thermal seals still being analyzed include the following:

a. The impact of accommodating early boundary layer transition with particular attention given to the forward landing gear door and the external tank/Orbiter/forward attachment points.

b. Use of redundant seal systems based on the results of the activities noted above under the elevon and body flap seals.

c. Payload Bay Door areas.

d. The External Tank Umbilical Door seal.

e. Mechanical properties of thermal brush systems used in the seal and barrier systems.

f. Door rigging on those doors that might have significant deflections during the mission.

4.4.4 Thermal Barriers

In addition to the thermal barrier materials used in the seals around doors and the like, there is also a need for thermal barriers or "gap fillers" between tiles and between tiles and adjacent structures such as windows, the elevon trailing edge, the wing glove and chine, etc. Results from wind tunnel tests clearly indicate that gap heating is significantly increased when flow is driven by a high pressure gradient. The amount of heating increase is dependent upon the magnitude of the gradient. For example, a gap temperature of 1490° F. is experienced at a surface temperature of 1400° F. while a gap temperature of some 2000° F. resulted at a surface temperature of 1600° F. General areas of the TPS where pressure gradients exist and where gap fillers are required have been identified.

Concepts devised to meet this problem include:

a. Thermal brush bonded to tile sides.

b. Glass fabric shapes bonded to tile sides.

c. Saffil fibers encapsulated in Irish Refrasil material and bonded to the filler bar currently in use.

d. Saffil fibers plus a knitted wire mesh spring encapsulated in a high temperature fabric (AB 312) and bonded to the filler bar.

Since the bonding of the tile and coating has not been satisfactory to date, the program is considering the use of Saffil fibers made into a brush (Saffil = silica fibers) or encapsulated and bonded to the filler bar rather than the tile coating.

These designs are being tested both thermally and structurally at this time.

4.4.5 Tile Step and Gap Effects

There appears to be a great deal of difficult in maintaining the small/step and gap required between tiles to prevent early boundary layer transition. For instance the nose landing gear door thermal barrier arrangement produces a 0.025-inch step at forward and aft door edges compared with present requirements for not more than 0.017-inch step. The gap between thermal tiles at the same door edges are in excess of the requirement for 0.034-inch width and 0.034-inch depth. Analytical and test work continues in such areas to bring the step and gap problem within allowable bounds.

4.4.6 Structural Thermal Analyses

The approach to the structural thermal analysis is such that it supports the development of structural and TPS designs that are interdependent. The time that it takes to do a complete thermal and stress analysis calculation or iteration on a previous calculation is quite long. These programs are large, complex 3-dimensional mathematical models requiring considerable manpower and computer usage. These programs do not include all three-dimensional effects that influence the structural temperature gradients because Orbiter design schedules preclude that level of detail. Those three-dimensional effects provided as given inputs are parameters that vary longitudinally as well as transversely, e.g., TPS thickness, heat loads, primary structure, and TCS insulation. The Contractor's TPS minimum weight thermal design and analysis philosophy is to establish RSI thickness requirements and vehicle temperature response based on nominal thermal analyses for aborts as well as normal WTR and ETR missions. All these analyses are planned to be accomplished at a level of detail consistent with Shuttle program funding and schedules. Final vehicle overall thermal and structural capability is to be determined through a progressive flight test program. Predicated on flight test results, design modifications can be effected if required to maintain adequate vehicle operational capability.

ATTACHMENT 4-1

The design and quality control for the doors, Thermal Protection System penetrations and thermal seals should be closely monitored by management to assure that the reliability necessary to satisfy safety will be achieved.

Response: The criticality of reliable designs for doors and other penetrations through the TPS and the associated static and dynamic seals is recognized by management. The closing and latching mechanisms for the doors and hatches were identified as SFP's in the FMEA as leading to failure to close and potential category 1 effects. These critical mechanisms and related thermal seals have also been identified in the Orbiter Hazards Analysis. Concern was expressed about the immaturity of design of this part of the thermal protection system during the TPS PDR for vehicle 102 conducted in early August. Schedule milestones have been established for near term adjustments in the design effort to assure satisfactory margins. The Program Director has been apprised of the status and accomplishment of the milestones will be monitored.

It should also be noted that the overall Space Shuttle design has been reviewed with the objective of minimizing the number of TPS penetrations. For example, as a result of a review of doors actuated in flight, the forward RCS installation was modified to eliminate the doors.

ATTACHMENT 4-2

The procedures, instructions, and training requirements for installation and quality control of the Thermal Protection System components should be reviewed by program management to assure the aero/thermodynamic requirements are met.

Response: The TPS (Thermal Protection System) is still in the development stage; therefore, the detailed information regarding the process for installation and verification of the TPS is also under development. Significant attention is being focused on this area by both the contractor and NASA. For example, to assure timely and adequate development of quality criteria for the TPS installation and verification process, the contractor has assigned 12 quality engineers to work directly with the design group during the design and development phase of the effort. NASA has assigned a quality engineer to monitor the effort on a full time basis. A TPS development shop is located adjacent to the design area to assure continuity between the development testing and the design and quality verification efforts. NDE (nondestructive evaluation) techniques are currently being developed and tested to assure detection of delamination of tile bonds, material voids, cracks, etc., following installation and flight. Personnel training and certification requirements are being developed concurrent with the installation and inspection processes.

The TPS is an area of great concern to management and it is because of this concern that the action was taken to assign design, quality engineering, and manufacturing personnel to develop the necessary verification processes concurrent with development of the design. Frequent reviews are conducted by both the contractor and NASA management to maintain full visibility of progress and problems encountered in the TPS development.

TABLE 4-1

ORBITER THERMAL PROTECTION SYSTEM ACTIVITIES

DATE	LOCATION	SUBJECT
Feb 1974	JSC	Review of significant shuttle decisions and status
Aug 1974	ARC Lockheed	Test and materials development review and examination of materials characterization/fabrication
Sep 1974	RI	Orbiter TPS
Jan 1975	JSC	Level II (Systems Integration) aspects of TPS
Mar 1975	KSC	Inspection, repair, maintenance aspects of TPS
May 1975	RI	More detailed fact finding associated with TPS testing, installation, maintenance, safety impacts
Jul 1975	JSC	TPS design, installation, tests, safety implications associated with door and vent protection
Aug 1975	RI Palmdale	TPS assembly for Orbiter 101 and 102 Participate in TPS Design Review
Oct 1975	RI	Results of Orbiter 101 CDR and input to 102 PDR
May 1976	JSC	Results of Orbiter 102 PDR relating to TPS

TABLE 4-2

DOCUMENTS ASSOCIATED WITH ORBITER TPS

1. Orbiter Thermal Protection Subsystem (TPS) Design Review Board Minutes. 14 August 1975.

2. TPS Design Review summary briefings, system description briefing, team board briefings, Review Item Disposition Summary, RID and team minutes; all published in RI document SSV75-24-1 dated 14 Aug 75.

3. Typical RI Internal Letters relating to TPS:
   "TPS Evaluation of Updated Design Trajectory Mission 3B" April 30, 1975
   "TPS Evaluation of AOA Trajectory-Nominal WTR" June 16, 1975
   "Thermal Evaluation of OML Faired TPS Thickness for OV 102" July 24, 1975
   "TPS Evaluation of ETR Trajectory With Dispersions" August 1, 1975

4. "Shuttle Orbiter OV-101 CDR Safety Analysis Report Volume I-Management Summary" 15 September 1975, SD75-SH-0135-001.
   "Shuttle Orbiter OV-101 CDR Safety Analysis Report Volume II-Structures" 15 September 1975, SD75-SH-0135-002.
   "Shuttle Systems Safety Analysis Report" June 15, 1975, SD75-SH-0064A
   "Space Shuttle Safety Concerns Summary Report" 5 September 1975.
   "Shuttle Orbiter 102 PDR Safety Analysis Report (Update), SD74-SH-0323, dated July 1, 1975.

TABLE 4-3

Review Item Disposition (RID)

From Previous Reviews

Still Open

LESS/HRSI Gap/Step Tolerance

LESS structural and Dynamic Analysis

LESS/HRSI Internal Insulation

RSI Attachment Around Windows

Thermal Deflection of RCC Expansion Seal

LESS Designs for Baseline Trajectory

(These indicate the areas of some concern from a standpoint of design completion and understanding of the problems involved if not resolved)

Table 4-4

Felt Reuseable Surface Insulation (FRSI)

1. This is Nomex or "E" felt coated with white silicone oxide (DC92-007)

2. The use of this material in lieu of tiles saves about 345 pounds

3. Physical Properties

- Maximum allowable temperature for one mission	900°F
- 100 Mission Life Maximum allowable temperature	700°F
- Density, lbs/ft^2 with thickness of 0.4 inches	0.24
- Coating thickness (DC92-007)	0.0075 inches
- Area covered, ft^2	2800

4. Manufacturing process
Nomex felt is heat treated to 700°F for 30 minutes, then it is treated at a raised temperature of 750°F for another 30 minutes. This accomplishes the pre-shrinkage step. After application of the coating (DC92-007) there is a post cure for 15 minutes at 650°F.

FIGURE 4-1 ORBITER THERMAL PROTECTION SUBSYSTEM