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SUMMARY
REFURBISHMENT COST STUDY OF THE THERMAL PROTECTION SYSTEM OF A SPACE SHUTTLE VEHICLE

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INTRODUCTION

This document summarizes Phase I of a Refurbishment Cost Study of the Thermal Protection System of a Space Shuttle Vehicle performed for NASA-LRC by McDonnell Douglas Astronautics Company-East (MDAC-East), under Contract NAS1-10093. Detailed results are contained in NASA CR-111832. Phase I was performed in an eight month period beginning June 1970. The purpose of Phase I was to identify labor costs associated with inspection, repair, and replacement of components of representative thermal protection systems (TPS) for space shuttle orbiter application. Those TPS considered included ablative, metallic, and nonablative, nonmetallic heat shields. In particular Phase I consisted of defining primary load carrying structural arrangements (Task 1), defining TPS attachment techniques (Task 2), generating operational labor costs estimates (Task 3), evaluating design and cost uncertainties (Task 4), and design TPS component parts for a full-scale mockup and formulating a detailed experimental test plan (Task 5). Phase II, when funded, will consist of performing various maintenance tasks to establish test data on refurbishment costs and to develop efficient refurbishment techniques.

Several significant conclusions may be drawn from this study. These include the following:

Primary and support structure has little effect on scheduled TPS maintenance.

TPS panel joints and seals are critical to concept feasibility and refurbishment.

Maintenance labor costs are sensitive to TPS type and method of attachment.

Design and cost uncertainties are primarily due to lack of maintenance experience on space shuttle type TPS.

An experimental test program on actual or simulated TPS components is best approach to resolve uncertainties and verify labor cost estimates.

A test program incorporating, as a minimum, environmental temperature simulation is desirable for complete maintenance definition.

Study results could significantly effect NASA space shuttle TPS trade studies and baseline TPS selection.

TPS maintenance material and support costs should be determined for complete maintenance cost projections.

The assessment of key problem areas and what should be done in the near future to resolve uncertainties is discussed in subsequent paragraphs.

Mr. D. W. Haas, study manager, was responsible for overall technical direction of the study. In support of the study manager were other members of the McDonnell Douglas engineering staff, including Mr. V. M. Gerler, Mr. E. J. Carroll, Mr. J. Komeshak, Mr. H. S. Zahn, and Mr. J. K. Lehman.

Mr. C. W. Stroud, of the Materials Division, Langley Research Center, Hampton, Va., was the technical monitor for the study.

OVERVIEW

The economic feasibility of a space shuttle vehicle hinges on the ability to reuse a vehicle from 50 to 100 times with minimum refurbishment or more precisely, minimum maintenance. Thus the success of any highly reusable system depends in large part on achievement of low operating costs. A significant fraction of the total operational cost is the vehicle's thermal protection system (TPS) cost. Therefore, this is an area where the achievement of cost goals is imperative. Operational costs include all recurring labor and material costs required to support the flight program from initial operational capability (IOC) through program completion.

Within the operational activity, inspection and scheduled and unscheduled maintenance labor cost predictions of candidate TPS are limited. In this study only the cost of labor on a unit basis to perform the required refurbishment tasks were estimated since these costs are primarily independent of vehicle configuration and program definition. Costs associated with material requirements were not calculated since they are mainly configuration and program dependent.

Arrangement of orbiter primary structural components to which TPS are attached were identified. Extensive use was made of those structural concepts developed by MDAC in its continuing R&D activities during NASA Phase A and current Phase B shuttle studies. To supplement this activity, a review of space shuttle Phase A studies conducted by other contractors was performed to identify representative structural arrangements. Typical examples of the primary structures investigated are shown in Figure 1.

In our examination and definition of primary and support structure for the various TPS concepts indications are that these type structures have little, if any, effect on scheduled maintenance of an externally removable TPS panel concept. This assumes that the deflections experienced by the primary and support structure under repeated loading conditions are always within design limits and surface continuity is maintained at all times. Any adverse loading conditions which would tend to distort the structure could complicate panel removal by binding mechanical fasteners. This would come under the category of unscheduled maintenance.

From our review of related study efforts indications are that arrangement of primary and support structure do not dictate the type and attachment method of TPS. Properly designed the primary and support structure can accommodate a variety of approaches such that replaceability and/or interchangeability of panels can be accomplished with nominal effects on the refurbishment cycle.

Study results indicate that the externally removable heat shield panel concept for a space shuttle TPS is most efficient for near optimum system reusability/refurbishability. The panel concept offers minimum weight (primarily due to structural-temperature allowables) and shorter vehicle recertification turnaround times, since the whole vehicle need not be involved in the refurbishment cycle.

Certain TPS attachment methods evolved as prime candidates for space shuttle application. These include the bonded, simple mechanical fastener, pi-strap, multiple mechanical fastener, and key/keyway concept for ablative and nonablative, nonmetallic type heat shields and the flush fastener and pi-straps for metallic heatshields. These concepts are illustrated in Figure 2. Refurbishment task analyses of these concepts clearly indicate maintenance labor costs to be sensitive to the type and method of attachment of the particular TPS being considered. Past experience in cost predictions indicates that RDT&E and investment costs are less sensitive to TPS configuration. Since the results of this study show that operational labor costs are sensitive to configuration, the magnitude of the design and cost feasibility uncertainties must be established before realistic cost projections can be made.

PRIMARY STRUCTURE CONCEPTS

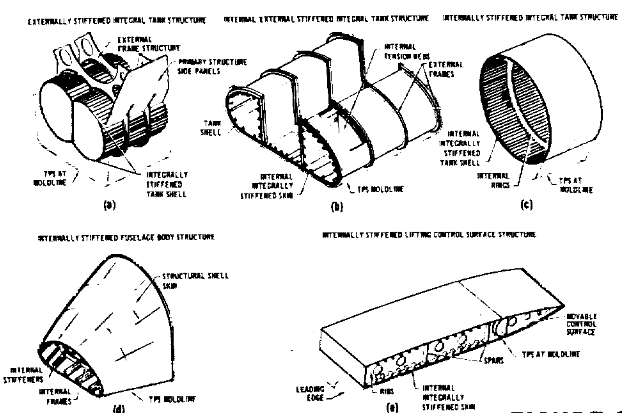

FIGURE 1

HEAT SHIELD ATTACHMENT TECHNIQUES

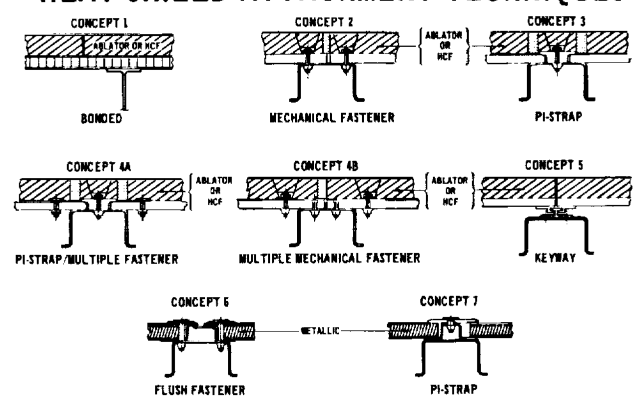

FIGURE 2

Problems encountered in estimating the refurbishment costs are best described as being either technological or economical. Problem severity, both from a design and cost viewpoint, is difficult if not impossible in some cases to assess in a paper type study. This is due primarily to the lack of sufficient operational maintenance experience on shuttle type TPS. Such experience can only be obtained by experimentation with actual or simulated hardware.

Probably the most significant factor effecting refurbishment labor costs is panel size. Table 1 gives estimated manpower requirements for each principal attachment concept in terms of manhours per square foot of exposed TPS area and elapsed time in hours to complete the entire refurbishment cycle. These data were plotted versus panel size as shown in Figures 3 and 4 to show trends involved with parameter variation. Indications are that labor costs decrease as panel size increases, whereas elapsed time requirements increase as panel size increases. In the case of the removal and replacement of the ablative and hardened compacted fibers (HCF) heat shield systems there appears to be little operational cost advantage in refurbishment of panels greater than 20 square feet. In the case of metallic heat shield systems the near minimum cost point seems to be between 40 and 60 square feet. The degree of uncertainty in these cost estimates lies in the exact tradeoffs between the number of men and type of support equipment needed to handle and install a panel as the panel size increases. Since no spacecraft built to date has employed a significantly large panel (i.e., greater than 20 by 20 inches) maintenance data is indeed limited or nonexistent.

REMOVAL AND REPLACEMENT TRENDS ABLATIVE AND HCF

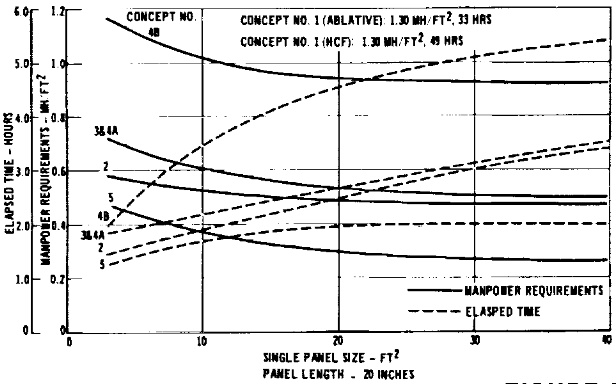

FIGURE 3

REMOVAL AND REPLACEMENT TRENDS METALLIC

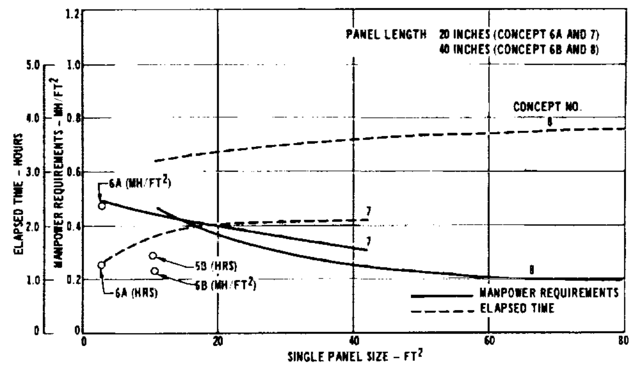

FIGURE 4

Removal and replacement requirements for special areas of the vehicle such as leading edges, body chines, and internal insulation, are given in Table 2. In these cases, manpower requirements are the total manhours to perform refurbishment of a given segment length or insulation area.

Typical repair problems associated with various types of heat shield systems were investigated and a task analysis prepared for representative material defects. Results of this investigation are given in Table 3. Existing procedures, written from the manufacturer's viewpoint, were used when possible.

REMOVAL AND REPLACEMENT REQUIREMENTS

HEAT SHIELD ATTACH CONCEPT		MANPOWER (MHR/FT^2)			ELAPSED TIME (HOURS)		
		PANEL SIZE			PANEL SIZE		
NO.	DESCRIPTION	SMALL	MEDIUM	LARGE	SMALL	MEDIUM	LARGE
	ABLATIVE OR HCF						
1	Bonded	1.30	-	-	33.1 (ablative) 39.1 (HCF)	-	-
2	Mechanical Fastener	0.58	0.49	0.47	1.45	2.30	3.35
3	Pi-strap	0.72	0.54	0.50	1.85	2.50	3.50
4A	Pi-strap/multiple fastener	0.72	0.54	0.50	1.85	2.50	3.55
4B	Multiple mechanical fastener	1.17	0.95	0.92	1.95	4.25	5.40
5	Keyway	0.47	0.31	0.26	1.25	1.80	1.95
	METALLIC						
6A	Flush fastener	0.47	-	-	1.25	-	-
6B	Flush fastener/middle support	0.23	-	-	1.45	-	-
7A	Pi-strap	0.49	0.41	0.31	1.25	1.95	2.10
7B	Pi-strap/middle support	0.47	0.28	0.20	3.20	3.50	3.75
	INTERNAL INSULATION	-	0.60	-	-	3.15	-

TABLE 1

REMOVAL AND REPLACEMENT REQUIREMENTS - SPECIAL AREAS

CONCEPT	MANHOURS	ELAPSED TIME (HOURS)
Carbon/carbon leading edge (20 inch segment)	1.30	1.20
Ablative leading edge (20 inch segment)	2.15	2.10
Ablative chine (40 inch segment)	1.90	1.85
Insulation (20 by 100 inches)	8.30	3.15

TABLE 2

REPAIR REQUIREMENTS

CONCEPT	MANHOURS	ELAPSED TIME (HOURS)	DESCRIPTION
Ablative	2.10	11.10	1 to 3 in dia
HCF	2.60	28.60	1 to 3 in dia
Carbon/carbon	0.50	3.50	Surface scratches
Metallic	3.35	7.65	Coating

TABLE 3

Inspection requirements for various types of heat shield systems were derived. Estimates shown in Table 4 are for exterior surface visual inspection only and are based on a common panel size of 20 by 20 inches.

INSPECTION REQUIREMENTS (PANEL SIZE: 20 x 20 INCHES)

CONCEPT	MANHOURS	ELAPSED TIME (HOURS)
Ablative	0.08	0.08
HCF	0.10	0.10
Carbon/carbon	0.08	0.08
Metallic (C_B)	0.15	0.15

TABLE 4

To show possible variation in refurbishment labor costs between various heat shield attachment concepts investigated in this study, a representative orbiter TPS configuration was considered. The TPS area considered was the planform surface of a representative orbiter vehicle (5000 ft^2).

Using manpower requirement data presented in Table 1 and a labor rate of $15 per manhour, for medium size panels, data presented in Figures 5 through 7 were generated. For examples given, general areas of discontinuities were not considered since these areas are highly configuration and program oriented. The curves show differences in refurbishment costs between concepts and the rate of increase in labor costs with increasing number of flights, based on various use life estimates per panel.

Uncertainties exist concerning fastener installation and removal; the latter appearing to be the most critical. In the case of an ablative or HCF heat shield system, fastener removal involves locating the fastener and removal of either the used or conditioned insulating material down to a depth which exposes the mechanical fastener. Location of the fastener may or may not be a serious problem. If the technique of using small pilot holes in the insulating material proves to be a workable scheme, removal will be relatively straightforward. However, if after thermal environment exposure these holes become obscure due to the products of ablation or fusing of the coatings, time consuming and costly refurbishment techniques would be involved. Depending

LABOR COST PROJECTIONS - ABLATIVES

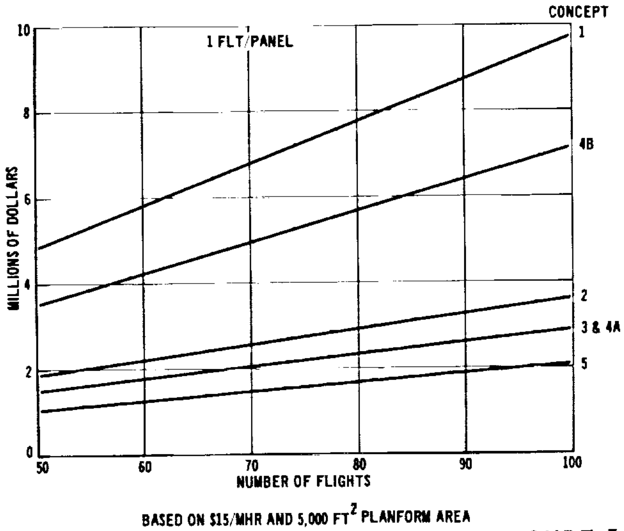

FIGURE 5

LABOR COST PROJECTIONS - HCF

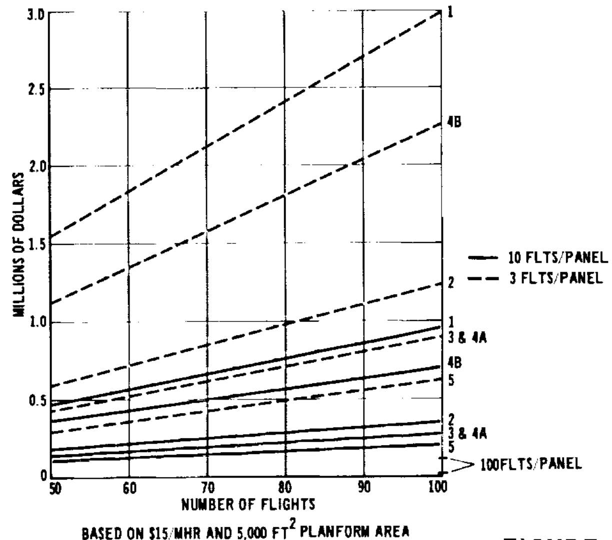

FIGURE 6

LABOR COST PROJECTIONS - METALLICS

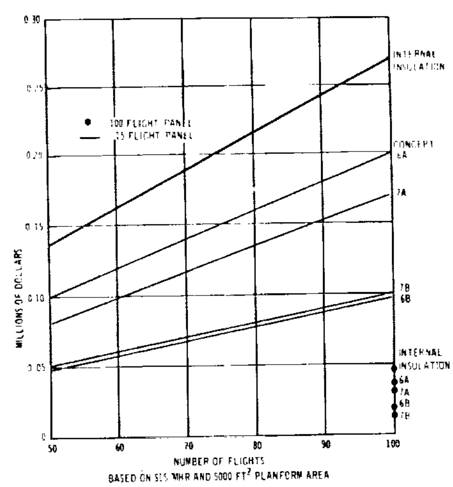

FIGURE 7

on the number of fasteners used, this one factor could make a particular attachment concept noncompetitive. Unfortunately there is not sufficient data available at this time to assess its severity. In the case of metallic fasteners, the problem also exists but with potentially less severity. In this instance the problem consists of flowing of the coatings into the attach points causing fasteners to freeze up, making removal more difficult.

Another critical problem area involves maintenance operation adequacy to make panel repairs while the panel is attached to the vehicle. This may involve nothing more than reconditioning surface scratches, up to complete replacement of material. The ability of the maintenance crew to inspect the damaged part, assess the degree of repair, and then to make the repair hinges on the location of the repair on the vehicle and the tools and equipment needed. These latter items range from only light hand tools to complicated jig fixtures.

The advantage of repair in place is that it eliminates or minimizes time consuming removal operations of a complete panel assembly. This of course helps to achieve low operating costs.

In the area of heat shield attachment, the most critical feasibility and related maintenance design aspect concerns joints and seals between adjacent panels. In this area incompatabilities exist. On the one hand gaps between panels must be provided to allow for the normal expansion and contraction of the panels under various environmental extremes. Yet these same gaps have to be minimized, if not eliminated, to prevent the inflow of hot boundary layer gases and water. Gaps are caused by a variety of conditions the most critical of which are attributable to cryo tank shrinkage, primary structure thermal gradients, body deflection during boost separation, panel expansion during entry and manufacturing tolerances.

The problem is not as acute with some heat shield types, as with others. In the case of ablative heat shields, elastromeric type seals, provide sufficient flexibility to resolve the problem. The same problem is solved in the case of metallic heat shields by simply overlapping panel joints. However, with HCF type heat shields, the problem is more critical due to the low shear strength capabilities of the material, causing edges to be particularly suspectible to damage. In this instance the goal of the designer is to provide a joint and/or seal which is compatible with the anticipated use life of the basic heat shield material (i.e., 100 flights) so as to minimize refurbishment. Silastic seals in this case have limited application because of their reusability aspects. Overlapping the joints with other high strength temperature metals or ceramics in combination with various stepped geometry is a possible solution.

In those instances where accurate cost estimation was difficult, or where technical or practical feasibility of a concept was questionable, detailed experiment plans were developed to resolve uncertainties. These plans call for fabrication and experimental testing of component parts of selected TPS for use on a full scale mockup (Figure 8) at NASA-LRC during Phase II. The

NASA LRC FULL SCALE MOCKUP

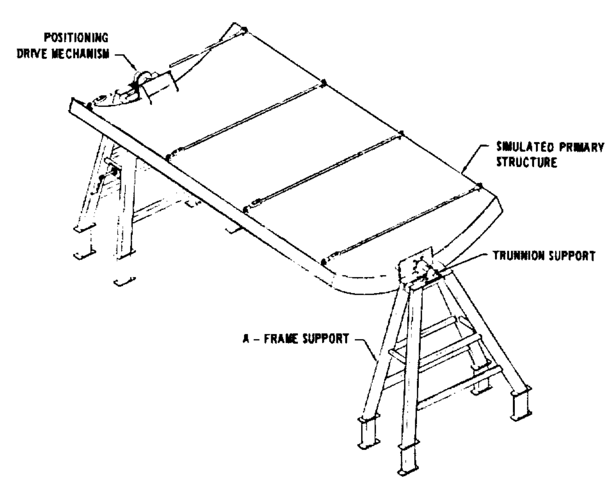

FIGURE 8

component parts include selected heat shield panels and associated attachments, the panel support structure between TPS panels and the basic mockup, and TPS panel arrangement and mockup installation. Pertinent aspects of these components are shown in Figures 9 through 14.

TPS PANEL SUPPORT ASSEMBLY

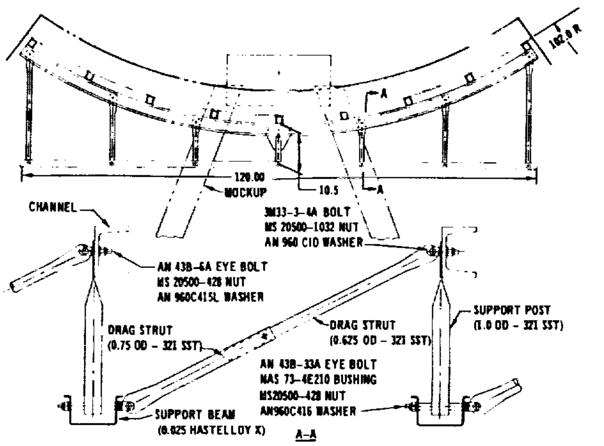

FIGURE 9

ABLATOR PANEL ASSEMBLY - PI-STRAP ATTACH

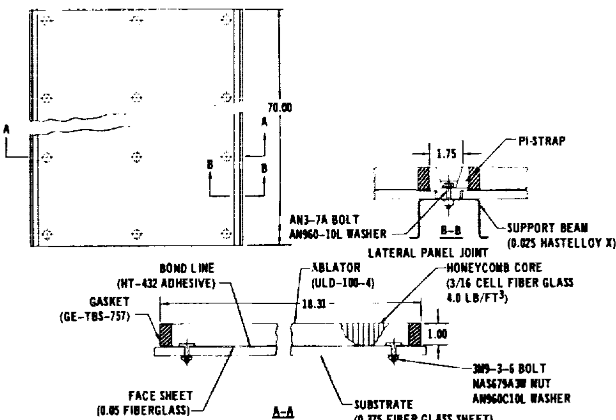

FIGURE 10

ABLATOR PANEL ASSEMBLY

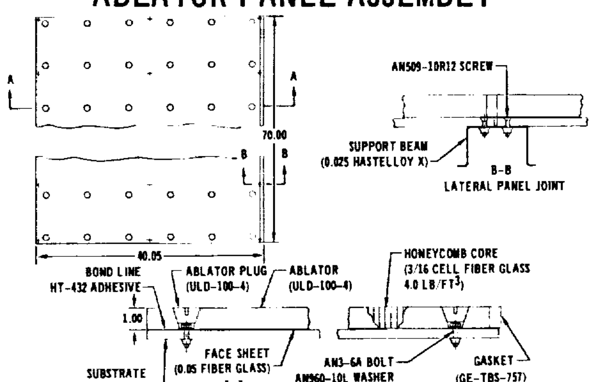

FIGURE 11

HCF PANEL ASSEMBLY - KEYWAY ATTACH

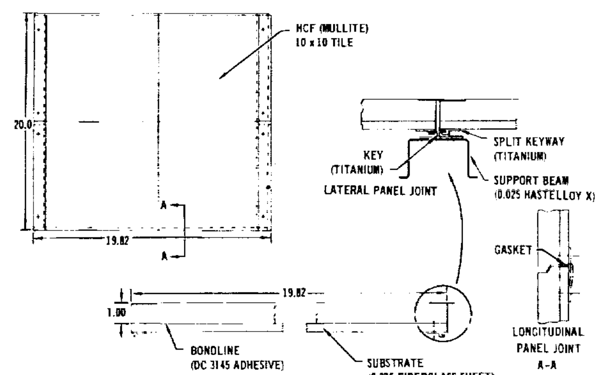

FIGURE 12

METALLIC PANEL ASSEMBLY - EDGE FASTENER ATTACH

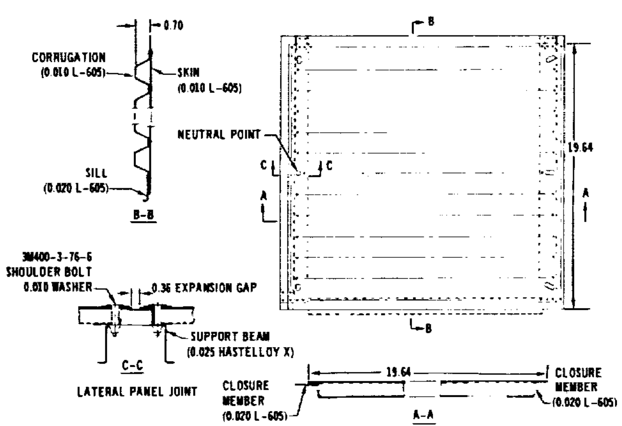

FIGURE 13

METALLIC PANEL ASSEMBLY - PI-STRAP ATTACH

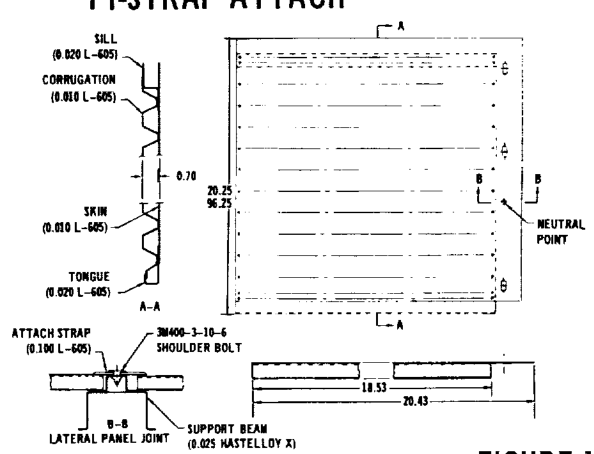

FIGURE 14

The proposed test matrix is shown in Figure 15. The location of the specified TPS configurations on the mockup is shown in Figures 16 . Six different tests are outlined which can be performed individually or in combination with each other. Major activities and significant milestones for the overall program plan are shown in Figure 17.

TEST PLANS

TEST NO.	TPS CONCEPT	PANEL SIZE (INCHES)	PANEL QUANTITY	MATERIALS
1	ABLATOR PANEL ASSEMBLY - PI-STRAP ATTACH	19 x 70	3	ELASTOMER ABLATOR/ SOLID FIBER GLASS SUBSTRATE
2	METALLIC PANEL ASSEMBLY - PI-STRAP ATTACH	20 x 20	12	L-605
3	ABLATOR PANEL ASSEMBLY	39 x 70	4	ELASTROMER ABLATOR/ SOLID FIBER GLASS SUBSTRATE
4	METALLIC PANEL ASSEMBLY - PI-STRAP ATTACH	20 x 96	3	L-605
5	HCF PANEL ASSEMBLY - KEY/KEYWAY ATTACH	20 x 20	12	MULLITE HCF/SOLID FIBER GLASS SUBTRATE
6	METALLIC PANEL ASSEMBLY - EDGE FASTENER	20 x 20	12	ALUMINIDE COATED L-605

FIGURE 15

TPS PANEL INSTALLATION ASSEMBLY

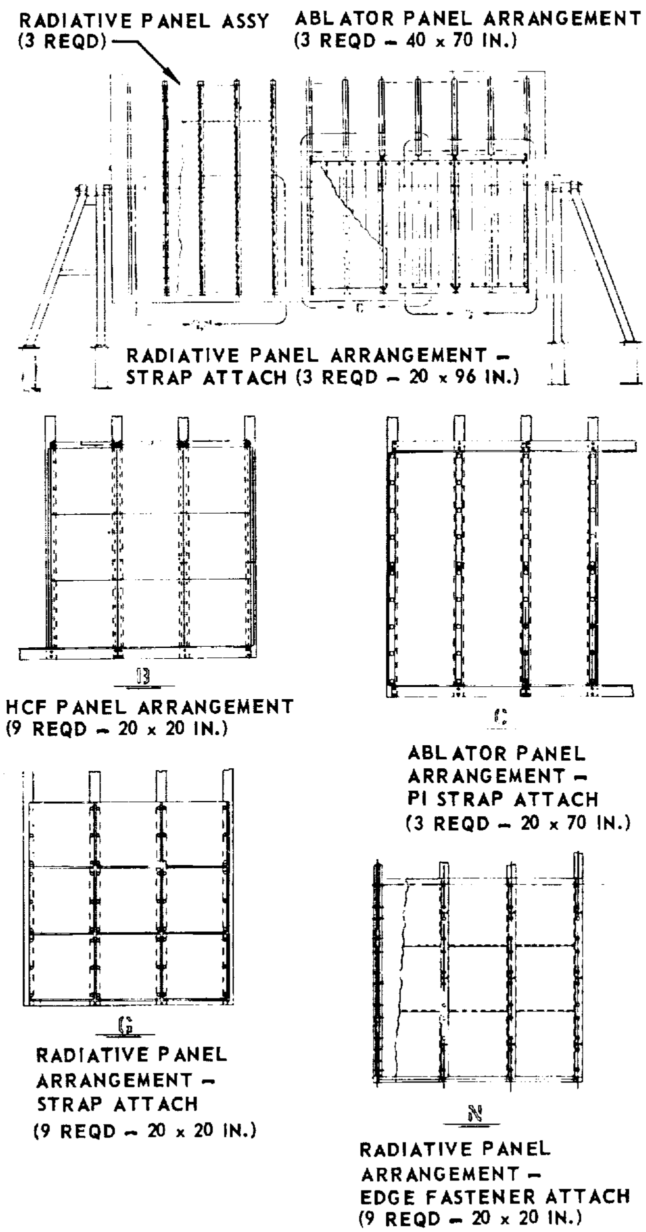

FIGURE 16

MASTER TEST PLAN SCHEDULE

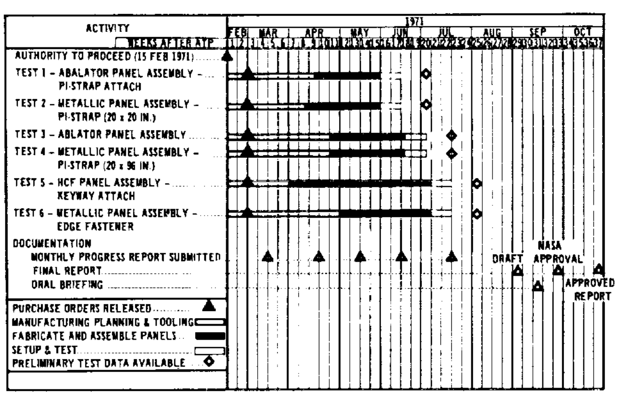

FIGURE 17

The sequence of tests called for under each test plan are referred to in the classification of the particular maintenance task function under consideration. These include initial installation, initial inspection, removal and replacement of a simulated damaged panel, simulated damaged panel repair in place on mockup, environmental testing, and removal and replacement of used or heated TPS panels.

For each maintenance task or simulation test called for, reference is made to a maintanance task schedule similar to the one shown in Figure 18.

MAINTENANCE TASK SCHEDULE

MAINTENANCE TASK SCHEDULE- A-1

- TASK FUNCTION ... INSTALLATION
- HEAT SHIELD TYPE ABLATIVE
- ATTACH CONCEPT PI-STRAP (MDAC DWG. 64T020003)
- SINGLE PANEL SIZE 20 x 70

FUNCTION - TASK DESCRIPTION	CUMULATIVE MANHOURS	ELAPSED TIME IN HOURS (1, 2)	TOOLS AND EQUIPMENT PARTS AND MATERIAL
Installation of Ablative TPS Test Panels			
1. Procure (3) substrate panels size 20" x 70" from storage.	0.20	2	3 panel support - 64T02003-7
2. Procure (3) ablative composites size 20" x 70" with associated attaching nuts, bolts, and washers from storage.	0.40	2	3 ablators 64T020003-9 99 nuts - NAS 679A32 99 washers - AN960C10L 99 bolts - 3M9-3-6
3. Visually inspect 20" x 70" substrate panels for obvious damage, cleanliness, and deterioration.	0.45	1	1 flashlight 1 inspection mirror
4. Visually inspect 20" x 70" ablator composites for obvious damage and deterioration.	0.50	1	1 flashlight 1 inspection mirror
5. Align and install an ablative composite to a panel substrate.	0.55	1	1 panel support - 64T020003-7 1 ablator - 64T020003-9 1 facesheet AMS 4918
6. Install the (33) nuts and washers to the (33) bolts on the bottom side of the panel substrate.	0.85	3	3/8" sockets and 3 pneumatic wrenches 33 nuts - NAS 679A3W 33 washers - AN960C10L 33 bolts - 3M9-3-6
7. Torque the (33) nuts on the panel substrate.	1.15	3	3/8" socket (3) torque wrenches (3)
8. Visually inspect the completed ablator panel assembly for obvious damage and proper system assembly.	1.20	1	1 flashlight 1 inspection mirror 1 ablator panel assy - 64T020003-1

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FIGURE 18

These schedules give details of individual refurbishment activities associated with the particular maintenance function and equipment to perform the particular refurbishment activity. This format of test conduct serves two purposes. It establishes when personnel and equipment are needed, and it serves as a checklist of duties much like that of an operational plan maintenance manual. Each test plan also contains provision for test data measurement and evaluation, documentation, and a fabrication and test milestone schedule.

CONCLUSIONS

Economical development of TPS requiring easily performed, routine inspection and a minimum level of unscheduled repair and replacement will occur only if those refurbishment activities to achieve low-cost goals are identified and related to appropriate system design features before the designs are committed to production. The resolution of key design and cost uncertainties, if obtained in a timely fashion, could have a major impact on NASA's current and future space shuttle activities. Such impact is already showing its effect in that the Phase I results of this study are currently being considered by MDAC personnel in their TPS trade studies being performed for the NASA Phase B shuttle activities.

In particular Phase I milestone commitments and study results were instrumental in; establishing the baseline metallic TPS configuration for the Phase B orbiter design and supplementary test program, laying the ground work for a feasible HCF panel joint configuration, providing a data base upon which all operational maintenance labor cost estimates were made for the shuttle, and pin-pointing key design problem areas associated with heat shield attachment which enhanced orbiter TPS design trade studies. The timeliness and effect which the TPS Refurbishment Cost Study (Phase I) has had on the NASA Phase B shuttle program and that which Phase II could have on the NASA Phase B follow-on options are shown in Figure 19.

PROGRAM SCHEDULE IMPACT

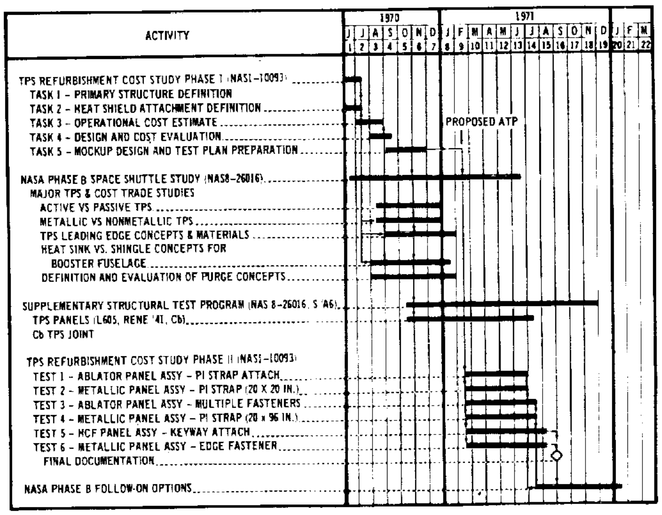

FIGURE 19

Since the results of this study have shown that maintenance labor costs are particularly sensitive to TPS design, refurbishment techniques may be a significant factor in selecting a baseline TPS for the shuttle. Unfortunately not all aerospace companys agree as to the magnitude of the maintenance labor costs since there is no historical data to use as a reference. Thus, it is imperative that these estimates be verified as soon as possible.

The most efficient method of resolving key problems is through experimental examination of specific refurbishment tasks on actual or simulated hardware. The proposed test program will accomplish these objectives. The program is aimed towards examining those concepts which exhibit desirable individual characteristics insofar as minimizing refurbishment activities associated with future space shuttle maintenance, and those concepts which when combined in an experimental program cover the full spectra of anticipated refurbishment problems.

The proposed test program is geared to obtaining maximum data for minimum cost. To accomplish this fabrication and assembly, activities will be closely monitored and controlled through cost-effective administrative systems. TPS panels fabricated for mockup use need not be flight quality, which minimizes quality controls. The key to a successful test program lies in the manner in which the data is obtained, the accuracy of the data and methods by which the data are presented. For these reasons a field tested video tape recording system, used previously by MDAC on related programs, provides the best method of measuring human performance. A significant factor effecting TPS reuse/refurbishment is its physical change after exposure to ground and flight environments. Thus, a certain amount of temperature testing is desirable in order to create a realistic maintenance environment. Timely initiation and completion of the phase II effort will greatly enhance the overall aspects of TPS design and cost predictions for future space shuttle activities.

A factor not considered in this study is that of weight. Thus a particular concept which shows low cost maintenance potential may not necessarily be the lightest weight design or vice versa. Therefore, weight/cost trade-off studies should be performed on candidate system as soon as possible before any one scheme is committed to detail development and subsequent production.

Establishing realistic refurbishment procedures and attendant labor costs is only one aspect of the overall maintenance of a space shuttle vehicle TPS. Costs associated with material procurement, shipping, transportation, and related support equipment will also influence overall maintenance. Further analysis of the costs associated with these items should be determined in order to establish the real cost drivers.

Supporting research and technology contracts such as the one reported on herein greatly enhance main stream shuttle activity. For this reason MDAC provides for a close working relationship between the personnel of both activities in order to achieve the highest value to cost ratio, which is the ultimate goal of the overall shuttle program.