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SUMMARY

REFURBISHMENT COST STUDY

OF THE

THERMAL PROTECTION SYSTEM

OF A

SPACE SHUTTLE VEHICLE

PHASE II

BY D.W. HAAS

PREPARED UNDER CONTRACT NO. NAS1-10990
MCDONNELL DOUGLAS ASTRONAUTICS COMPANY-EAST
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ABSTRACT

Labor costs and techniques associated with the refurbishment of representative TPS and their attach concepts suitable for Space Shuttle application have been identified on the basis of experimental tests. Ablative and reusable surface insulation (RSI) TPS configurations were designed, fabricated, and tested on a full-scale mockup. The TPS attachment methods investigated included pi-strap, multiple mechanical fasteners, key/keyway, and direct bond concepts. Techniques for performing installation, inspection, repair and replacement of TPS components were studied by examining a variety of shop procedures. Major problem areas associated with these procedures and the designs to which they were applied were analyzed for several significant parameters such as handling, gaskets between joints, repair techniques, ablator plugs, etc. Results of time and motion studies of specific maintenance tasks, simulating operational procedures, were obtained. Using these data, refurbishment labor cost projections were generated for a representative Space Shuttle orbiter. Study results show that refurbishment labor costs and maintenance techniques are sensitive to heat shield material type and attachment method.

INTRODUCTION

This document summarizes Phase II of a Refurbishment Cost Study of the Thermal Protection System (TPS) of a Space Shuttle Vehicle performed for the National Aeronautics and Space Administration - Langley Research Center (NASA-LRC) by the McDonnell Douglas Astronautics Company - East (MDAC-E), under Contract NAS 1-10990. Detailed results of the Phase II effort are contained in NASA reports CR-112034 and CR-112034-1 (Supplemental report on direct-bonded ablators). A summary and detailed results of the Phase I activities, performed under Contract NAS 1-10093, are contained respectively in NASA reports CR-111833 and CR-111832.

Overall study objectives were:

identification of labor costs associated with inspection, repair and replacement of TPS components suitable for Space Shuttle orbiter application and

development of techniques for performing a variety of refurbishment or maintenance operations

Specifically, Phase II consisted of designing selected TPS components suitable for installation of a full-scale mockup (furnished by NASA-LRC), fabrication and assembly of components, monitoring specific maintenance task functions simulating operational procedures, and evaluating these maintenance task functions from both cost and technique standpoints. The design, fabrication, and test evaluation portions of the program were performed at the MDAC-East facility, St. Louis, Missouri, while the experimental testing was conducted at NASA-LRC, Hampton, Virginia.

TPS TYPE AND ATTACHMENT METHOD

Each TPS concept considered was composed of a heat shield, support structure, and associated attachment hardware. The heat shield types considered were ablative and RSI. The ablative heat shield was an elastomeric material consisting of a combination of phenolic microballoons and silicone resin in a honeycomb matrix. The RSI, in this case, were tiles of hardened compacted fibers (HCF). The HCF material consists of a layer of rigidized inorganic mullite fibers with a high temperature reradiative surface coating and efficient insulative properties. Both materials have been produced in the density range from 192 to 240 kilograms per cubic meter (12 to 15 pounds per cubic foot).

One of the concepts considered in the study was the ablator pi-strap attach concept shown in figure 1. The ablator heat shield consists of a fiberglass honeycomb core bonded to a plastic laminate facesheet with a hard film adhesive. The plastic laminate consists of a thermosetting resin-impregnated woven glass fabric. The honeycomb core cells are filled with a mixture of phenolic microballoons and silicone elastomeric resin. On the ablator side of a facesheet, steel bolts with enlarged hex heads were bonded to the surface with a room-temperature-cure paste adhesive. The bolts were arranged in a grid pattern with spacing requirements determined by the predicted differential pressure between the heat shield and the support panel. Around the ablator heat shield edges, a molded elastomeric gasket was bonded with a room-temperature-cure silicone elastomeric adhesive.

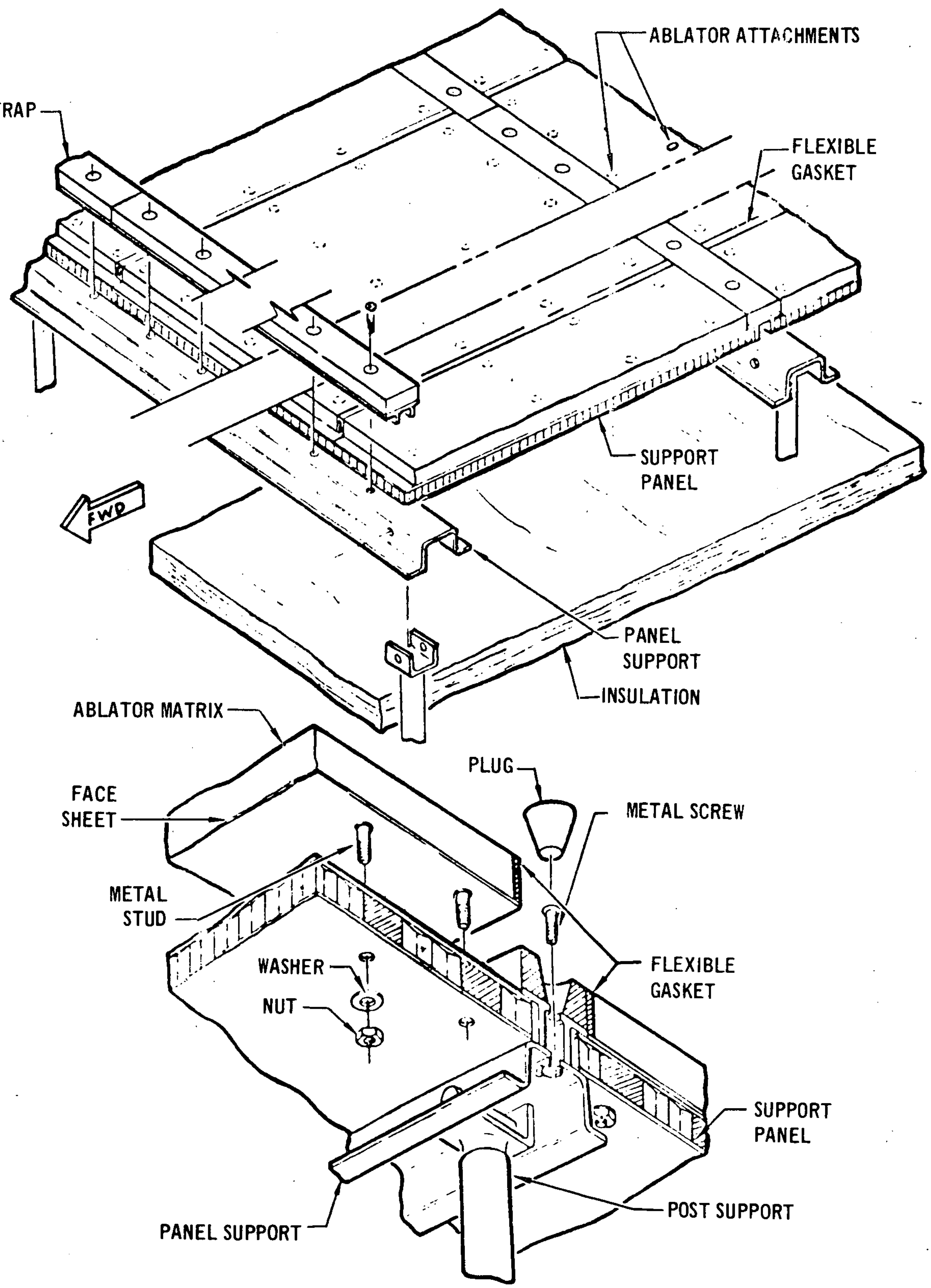

FIGURE 1 PI-STRAP FASTENER ATTACH CONCEPT

The support panel consisted of a fiberglass phenolic honeycomb core bonded between plastic laminate facesheets with a hard film adhesive. Holes were drilled in the honeycomb sandwich to match the bolts located in the ablator heat shield. Local support for the ablator heat shield bolts in the support panel was accomplished by filling the area around the holes with a room-temperature-cure paste adhesive/ potting compound. During final assembly, the ablator heat shield and support panel were joined by attaching a washer and nut to the protruding bolts on the underside of the support panel. An option to this design approach would be to bond the heat shield directly to the support panel. This attachment approach would require stripping the ablator from the support panel during refurbishment.

The combined ablator heat shield/support panel assembly was attached to a panel support beam by means of a pi(π)-shaped retainer. With the support panel resting on the support beam, the pi-shaped retainer was positioned over the lip of the support panel along two edges and firmly attached to the panel support beam by mechanical fasteners. Sills supported the other two edges of the panel. After installation of the mechanical fasteners, the holes in the ablator were filled with premachined ablator plugs which were bonded in place with a soft silicone elastomeric adhesive.

Another ablator heat shield panel considered in this study was the multiple mechanical fastener attach concept shown in figure 2. The ablator heat shield and support panel for this concept are similar to those of the ablator pi-strap attach concept. Molded elastomeric gaskets were bonded to the ablator heat shield edges.

The ablator heat shield was attached to the support panel after the support panel was secured to the TPS support structure. The support panel was first attached to lateral hat sections of the TPS support structure by flush-head screws. The ablator heat shield was then positioned and securely fastened with the bolts. The mounting bolts are inserted through predrilled holes in the ablator composite and secured by means of threaded inserts imbedded in the support panel. The bolt heads are encased in the ablator composite and bear against the heat shield facesheet. After installation, the holes in the ablator composite were filled with ablator plugs which were bonded in place in a manner similar to that employed for the pi-strap concept.

The HCF key/keyway attach concept considered in this study is shown in figure 3. This attach concept is also applicable for use with ablative type heat shields. The HCF heat shield material was formed into tiles which are bonded to a support panel with a room-temperature-cure silicone elastomeric adhesive. The edges of each tile were stepped-machined, as shown. Two intersecting edges of each tile were machined with the extended lip along the outer (top) surface of the tile, while the opposite edges had the extended lip along the inner (bottom) surface.

The support panel for this concept was again, for purposes of illustration, a honeycomb sandwich-type structure. The sides of the panels were provided with solid L-shaped edge members. At the lower surface of each edge of the panel, where two adjacent panels intersect, a silicone "O" ring was provided to prevent hot-gas inflow and water absorption. The temperature at this location is expected to be low enough to permit acceptable gasket reuse.

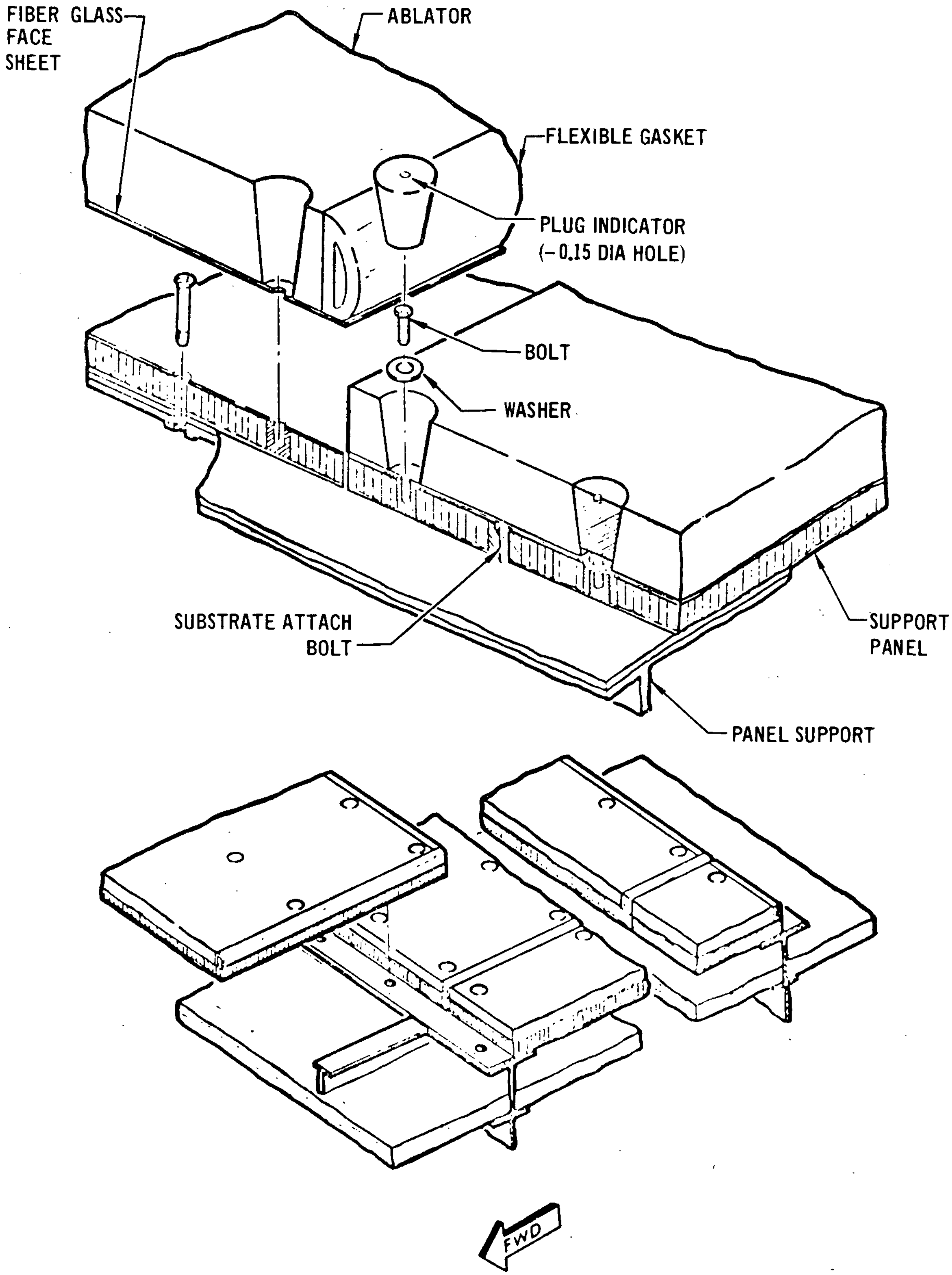

FIGURE 2 MULTIPLE MECHANICAL FASTENER ATTACH CONCEPT

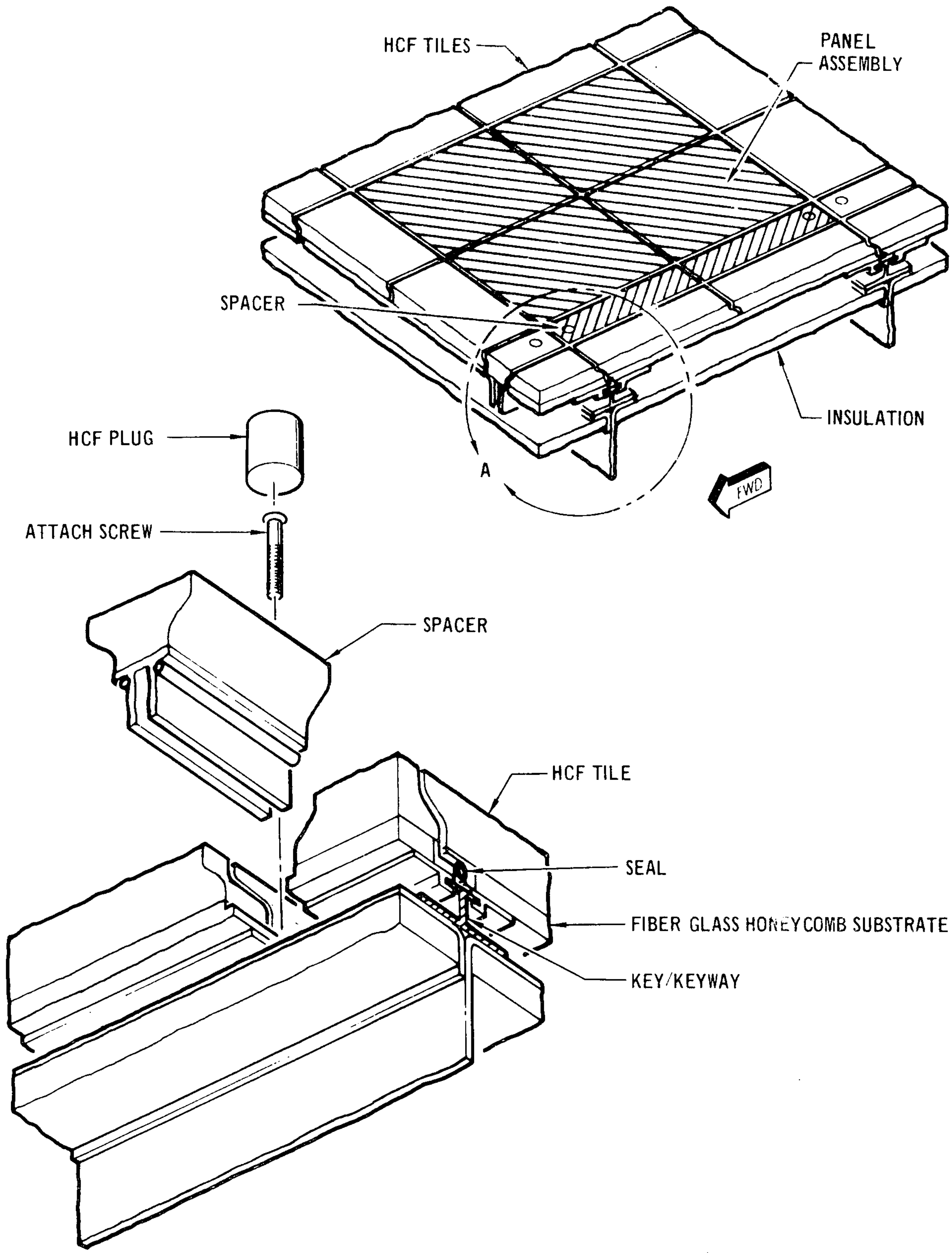

FIGURE 3 KEY/KEYWAY ATTACH CONCEPT

The HCF tiles/support panel composite are supported and attached along two opposite edges by a key/keyway mechanism. The keyway, or female part, having a channel cross sectional area, was attached to opposite edges of the support panel. A rail-shaped key, the male part (which also serves as the panel support sill), was attached to the TPS support structure and spaced to mate with the panel keyways. Intermittent notches were machined into the key and keyways allowing the panel to drop over the key, after which the panel was moved along the key approximately 1.91 centimeters (0.75 inch) to achieve a mechanically attached assembly.

A pi-strap spacer is positioned after every second or fourth panel, allowing selected panels to be removed without requiring removal of a series of panels starting at the end of a row. Each spacer is secured to the TPS support structure by mechanical fasteners. The fasteners are inserted through predrilled holes in the HCF spacer tiles. After attachment, the holes are filled with prefitted HCF plugs.

An approach to TPS attachment proposed by MDAC for the Space Shuttle orbiter involves bonding RSI and/or ablators to the structural skin of the vehicle, as shown in figure 4. The RSI and/or ablators in the form of flat or contoured panels are bonded to the primary structure skin, either directly or with an intermediate silicone sponge pad. The sponge pad permits the use of buckling skins and protruding head rivets on the primary structure, minimizing structural weight and fabrication costs. In the case of RSI, the sponge serves as a required strain isolator. Both the direct bond and intermediate sponge pad approach were investigated in this study.

Prior to bonding, vehicle skins are thoroughly cleaned to provide a "water-break" free surface which cannot be allowed to oxidize between final cleaning and the first bonding operation. The term "water-break" free surface implies a true wetting of the surface in which the water forms a film on the surface without any breaks in the film or formation of beads. After the vehicle surface is cleaned, a thin silicone primer coating is brushed or sprayed on the structural skin. The primer is allowed to hydrolize (time depending on the relative humidity and temperature in the application area). For the adhesive bond to be reliably effected, acceptable humidity and temperature conditions must be maintained to assure proper primer hydrolysis.

After primer cure, a thin layer of silicone adhesive is applied to the primed surface with an automatic mixer/application head, which proportions and (air-free) mixes the two adhesive components immediatley prior to application. Once the adhesive is applied to a given work area, the sponge pad is installed and held in position under a uniform pressure for a minimum of 24 hours to allow the adhesive to cure. The load can be applied mechanically or by using differential atmospheric pressure.

Once the sponge pad is securely bonded to the vehicle skin, the same process of adhesive application is repeated to the outer moldline of the sponge pad for subsequent application of the ablator panels or HCF tiles. After panel/tile installation, uniform pressure is then reapplied and held for 24 hours. A vehicle as large as the Space Shuttle orbiter presents obvious manufacturing problems, in that TPS installation will require extensive multilevel work stands. These must enable placement of panels, as well as application of contact pressure during adhesive cure.

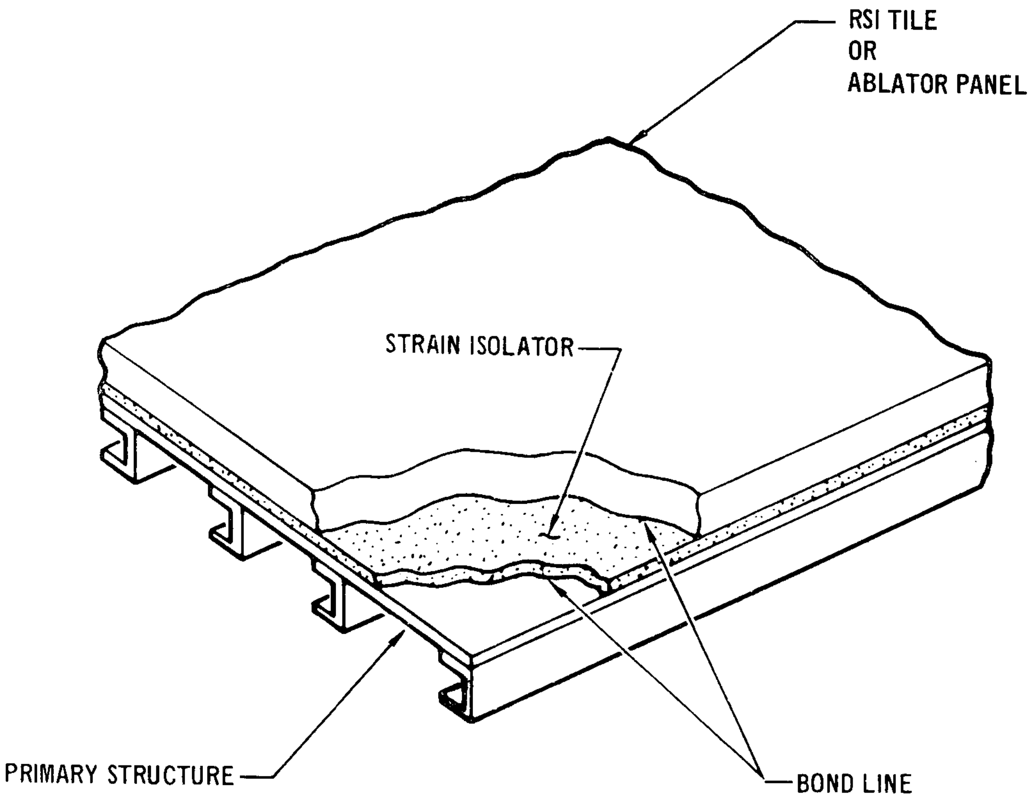

FIGURE 4 DIRECT BOND-ON ATTACH CONCEPT

TEST PROGRAM

Refurbishment testing of the various TPS concepts just described took place on the full-scale mockup shown in figure 5. This mockup served to simulate, in configuration only, a portion of the vehicle primary structure (such as the propellant tank wall). The major portion of the mockup features a cylindrical segment with an approximate 200 square foot plan form area. Each end of the simulated tank wall structure was trunion mounted at the mid-chord to an A-frame structure. A drive mechanism rotates the section and can be used to simulate vehicle fuselage positions (i.e., top, side, and bottom). Tubular links in a post arrangement were used to locate the TPS panels some distance from the basic mockup structure. At the time the panels were designed one of the candidate orbiter configurations being studied had a modified trapezoidal body cross section. Thus, only flat panels of each concept were considered. All the panels were installed and removed in an overhead position simulating the bottom portion of the vehicle fuselage. The panels were attached to beams located on the support posts.

The program test phase consisted of conducting a time and motion study of specific maintenance functions for each of the TPS concepts noted previously. Historically, human performance evaluation methods have been restricted to one-shot visual observations, direct interviews with participating personnel, checklists, and questionnaires. Realizing that such methods were not adequate for evaluating tasks as complex as Space Shuttle TPS maintenance, video tape monitoring equipment was employed. Using a video tape recorder, we captured and retained

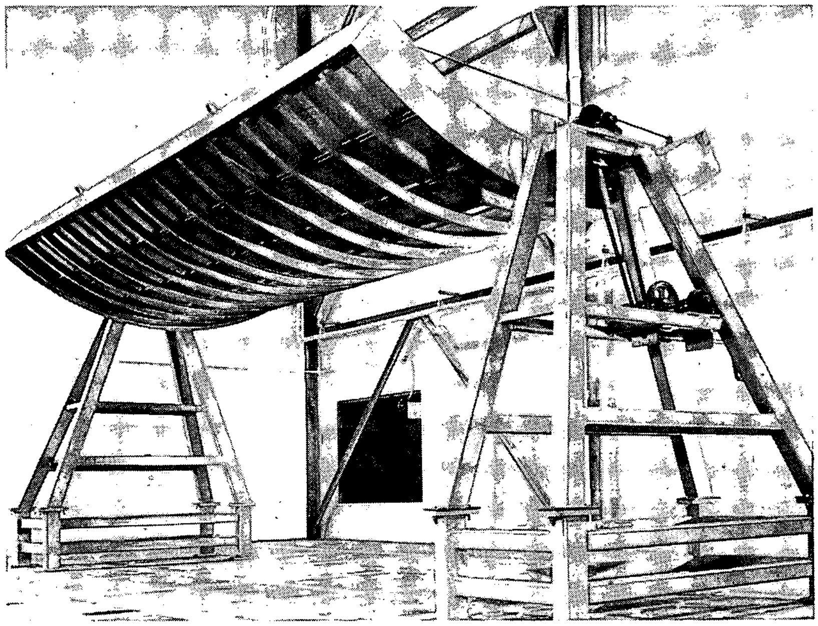

FIGURE 5 NASA FULL SCALE MOCKUP CONFIGURATION

the entire test as a permanent record for viewing as often as necessary, permitting a detailed analysis of the particular refurbishment operation being performed. The relative position of the mockup and recording equipment used in the tests is shown in figure 6.

The prime objective of the test program was to measure the task duration and active productive time requirements associated with the maintenance functions of installation, inspection, removal, replacement, and repair of representative TPS. This was accomplished by testing a series of panels of the same design. The format used to record test data is shown in the sample maintenance task schedule of figure 7. These schedules provided the details of the individual refurbishment activities associated with the particular maintenance function under consideration. In addition, the schedules included provisions for recording individual task duration time, individual subtask productive time, total subtask productive time, a comparison between actual and estimated cumulative productive time, and a summation of subtask duration. Finally, a general comments column was provided in order to document salient procedural function features.

REFURBISHMENT LABOR AND PERFORMANCE REQUIREMENTS

The possible operational refurbishment situations analyzed are best classified as scheduled and unscheduled maintenance. Scheduled maintenance, as defined here, would involve those refurbishment activities associated with vehicle maintainability after the vehicle has experienced its normal flight environment. In the case of ablator TPS, scheduled maintenance would normally occur after each flight. In the case of HCF heat shields, scheduled maintenance would normally take place only after a number of flights because the anticipated use-life of the HCF material is greater than one flight (i.e., up to 100 flights).

Unscheduled maintenance, on the other hand, involves partial removal and replacement of the TPS prior to flight-environment exposure. Those activities

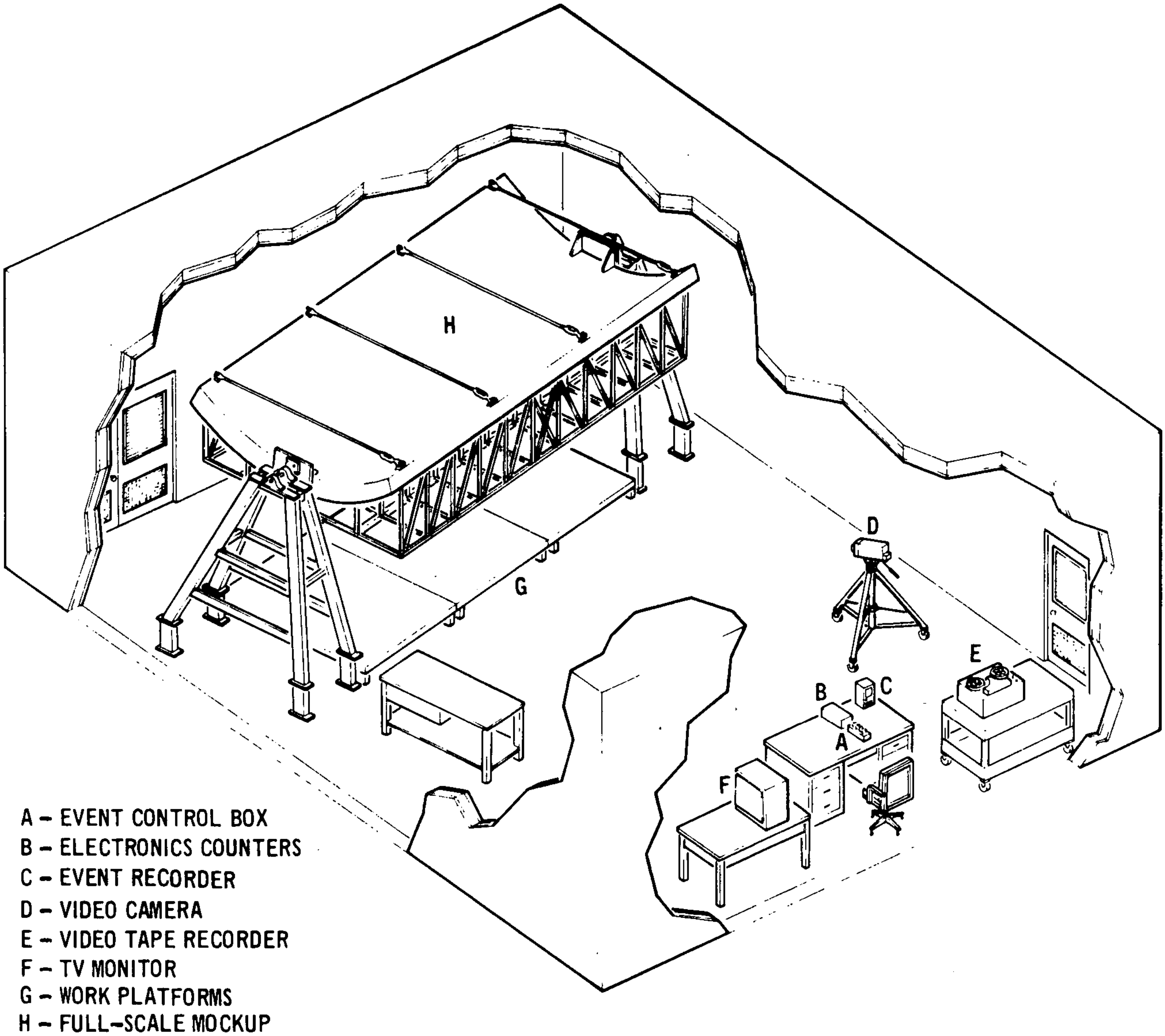

FIGURE 6 TEST SETUP

which would affect unscheduled maintenance include handling, transportation, prelaunch operations, and abort. While this study could not cover all the possibilities which might occur in the maintenance of a vehicle's TPS, enough basic information concerning refurbishment is given that the reader can understand his own particular situations and formulate estimates for similar or related systems.

Total scheduled removal and replacement task duration time and manpower requirements for each of the various concepts considered are presented in figure 8. Data for task duration time are stated in terms of hours per square meter while the manpower requirements are given in terms of manhours per square meter. These data represent a situation based on the assumption that the TPS has gone through an entry environment which has rendered the heat shield assembly not reuseable, necessitating replacement. In the case of the ablator multiple fastener attach concept, the support panel, under scheduled maintenance conditions, would remain on the vehicle. Access to internal equipment in this instance would not be

MAINTENANCE TASK SCHEDULE

- TASK FUNCTION: REMOVE AND REPLACE (TILE NO. 1)
- HEAT SHIELD TYPE: HCF
- ATTACH CONCEPT: BONDED
- PANEL SIZE: 25 X 25 CENTIMETERS (10 X 10 INCHES)

TASK NO.	TASK DESCRIPTION	INDIVIDUAL TASK TIME							CUMULATIVE PRODUCTIVE TIME (MAN-HR)		CUMULATIVE TASK DURATION +CURE TIME (HR)	TOOLS, EQUIPMENT, MATERIAL AND OR PARTS REQUIRED	GENERAL COMMENTS
		TASK DUR (SEC)	MAN NO. 1 (SEC)	MAN NO. 2 (SEC)	MAN NO. 3 (SEC)	MAN NO. 4 (SEC)	Σ PRODUCTIVE TIME (MAN-HR) ACTUAL	Σ PRODUCTIVE TIME (MAN-HR) EST	ACTUAL	EST			
	<u>Remove HCF Tile No. 1 from Test Fixture.</u> <u>NOTE:</u> In Removing HCF material from the support panel, the use of protective goggles/eyeshields, breathing masks and vacuum is mandatory safety equipment.												
1.	Using a putty knife, remove HCF tile from the center of the test panel. Remove all HCF material and adhesive to the metallic surface. Vacuum all loose particles.	2342	2342	2342	-	-	1.301	.350	1.301	.350	.651	2 Protective Goggles or Eyeshields 2 Breathing Masks 1 Vacuum 2 Protective Caps 2 Pair Elastic Gloves 1 Putty Knife 1 Metal Scrapper	Man No. 1 Removed the HCF Material Man No. 2 Vacuumed Loose Particles
	<u>NOTES:</u> (1) Gloves are required in handling the HCF tile. (2) Excercise care in handling the HCF tile to prevent damage to the exterior surface.												
2	Inspect structural support panel for obvious damage and cleanliness.	57	-	-	57	-	.016	.050	1.317	.400	.667	1 Flashlight	
3	Inspect the HCF tile for obvious damage and cleanliness.	28	-	-	28	-	.008	.050	1.325	.450	.675		
4	Trial fit HCF tile.	33	33	-	-	-	.009	-	1.334	-	.684		
5	Clean metal surface of support panel with clean cheese cloth dampened with methyl ethyl ketone.	90	90	-	-	-	.025	.050	1.359	.500	.709	Cheese Cloth Methyl Ethyl Ketone TT-M-261	
6	Apply a thin film of DC 1200 primer to the metallic surface of the support panel. Allow primer to dry for a period of 60 minutes.	88	88	-	-	-	.024	.050	1.383	.550	.733	DC 1200 Primer 1 Brush	

FIGURE 7 SAMPLE MAINTENANCE TASK SCHEDULE

possible unless the support panel was removed. In both the ablator pi-strap, and ablator and HCF key/keyway attach concepts, both the heat shield and the support panel would be removed from the vehicle. The time required to remove the heat shield from the support panel in these latter concepts is not included, since this function would probably take place at a later time and possibly at a different location. Replacement would be either with new or reconditioned TPS components. It should be noted that the ablator key/keyway attach concept values are based on extrapolation of test data, since this configuration was not tested during the program.

From the data presented in figure 8 one can see that a sizable difference exists not only among the attach concepts having a common heat shield material but also among identical attach concepts having different heat shield materials. As indicated, performance time is 7 percent more and manpower requirements are 50 percent more for the ablator multiple fastener attach concept than for the ablator key/keyway attach concept. Comparing the ablator multiple fastener attach data with the ablator pi-strap attach data, it is seen that performance time and manpower requirements for the multiple fastener attach concept are increased by 2 and 17 percent respectively. When comparing the two key/keyway attach concepts, we find that performance time and manpower requirements for the HCF material are higher than for the ablator by 53 and 60 percent, respectively. On a scheduled removal and replacement basis the ablator key/keyway attach concept is the lowest maintenance cost approach; whereas the ablator direct bond-on concept is the highest maintenance cost approach, the difference being over 1000 percent.

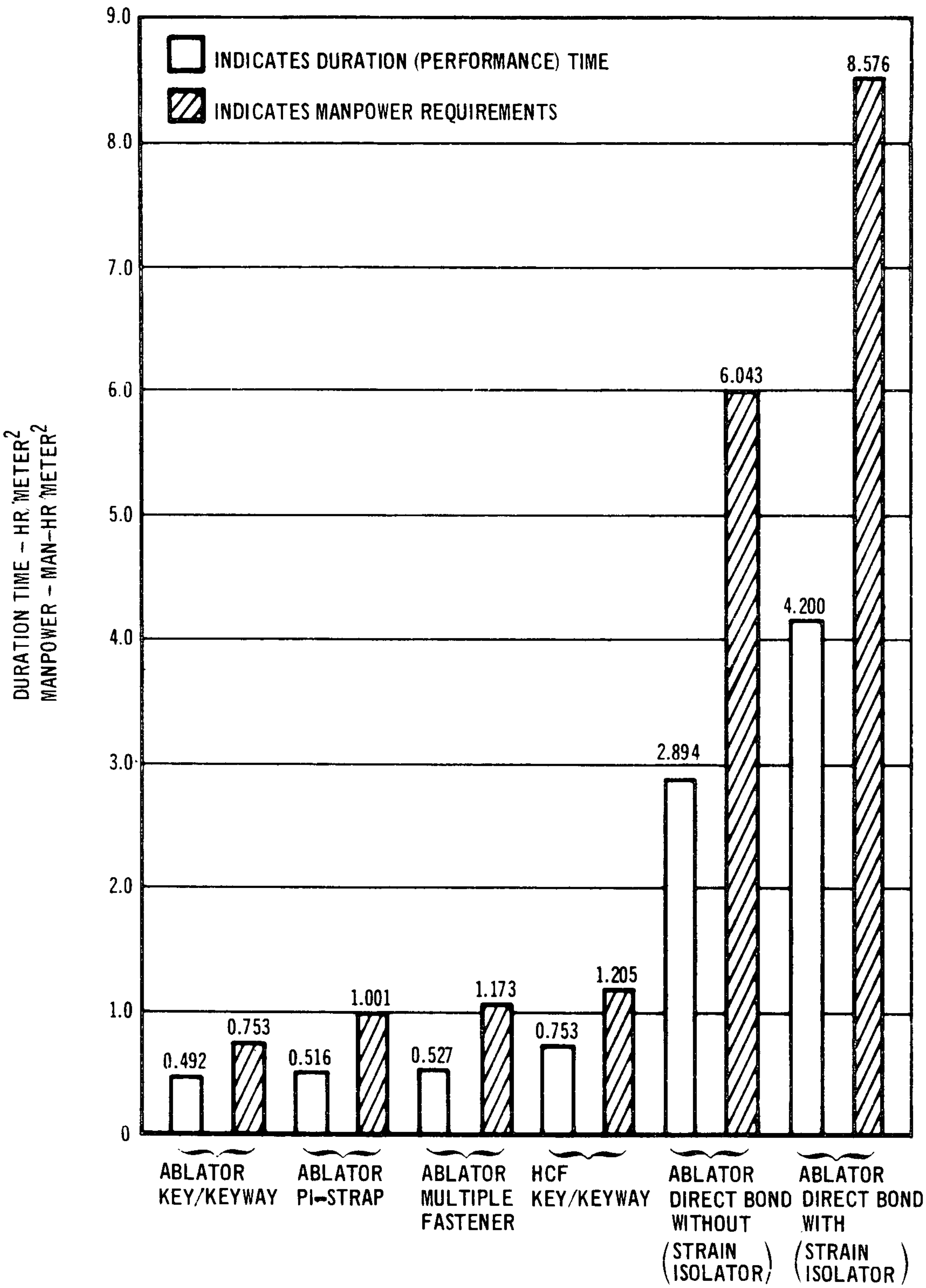

FIGURE 8 SCHEDULED REMOVAL AND REPLACEMENT ATTACH CONCEPT COMPARISON

Total unscheduled removal and replacement task duration time and manpower requirements for each of the various concepts considered are shown in figure 9. These data represent situations in which a random TPS panel would be removed and replaced prior to flight for one, or a combination, of the following reasons:

Damage has occurred to the basic heat shield and/or support panel.

Access to internal insulation or equipment is required.

Damage has occurred to TPS support structure.

The data cited in figure 9 give the requirements for removing and replacing a selected heat shield assembly surrounded by similar components of the same design. In this instance, the primary difference between the scheduled and unscheduled situations lies in the boundary conditions between panels at the time of removal and/or replacement. In the case of the scheduled removal and replacement exercise, successive removal of the panels is made easier by eliminating one or more edge constraints of the previously removed panel. On the other hand, during the unscheduled maintenance situation, panels must be removed or fitted in place between all four adjacent panels.

Comparison among the unscheduled removal and replacement duration times and manpower requirements for the individual attach concepts indicates great differences. As the figure indicates, performance time and manpower requirements for the ablator pi-strap attach are increased by 22 and 14 percent, respectively, versus the ablator multiple fastener attach. This is just the reverse of the results obtained for scheduled maintenance, during which the ablator pi-strap attach required less time and manpower. Comparing a common attach concept (key/keyway) with different heat shield materials, it is again clear that the HCF requires considerably more effort than the ablator key/keyway method. In addition, it was found that it takes considerably more time and effort to remove and replace the direct bonded ablator panels or HCF tiles than for those attached by mechanical fasteners via a removable panel assembly (which can be replaced with a new panel). In this instance the time for the ablator and HCF direct bond-on approach are both greater than the ablator multiple fastener attach concept time (by approximately 750 and 2550 percent, respectively). The HCF direct bond time is greater than the ablator direct bond time primarily due to the added care which must be taken in handling HCF because of its more fragile nature.

SPACE SHUTTLE REFURBISHMENT

To show the possible impact and variation of TPS refurbishment on operational program costs, a representative Space Shuttle vehicle was configured and cost analyzed. This was done for the various TPS concepts considered in the study using the removal and replacement data presented in figures 8 and 9.

One orbiter configuration being considered for the Space Shuttle Phase C/D program is the delta wing vehicle shown in figure 10. This configuration is designed to accommodate a 4.57-meter (15-foot) diameter by 18.3-meter (60-foot) long payload. The 33.4-meter (109.4-foot) long vehicle with its 24-meter (78.6-foot) wing span has a total wetted area of 1076 square meters (11,570 square feet).

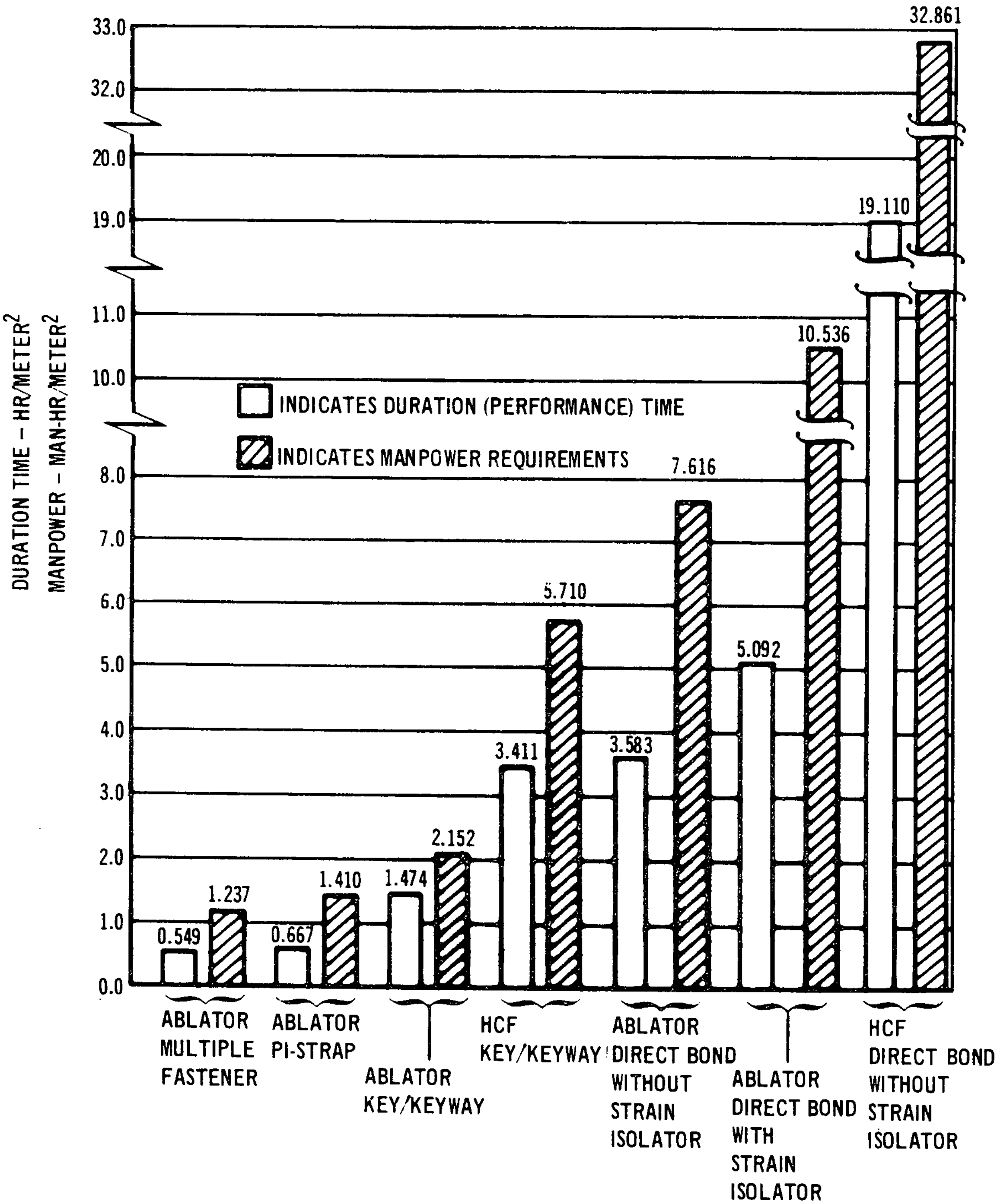

FIGURE 9 UNSCHEDULED REMOVAL AND REPLACEMENT ATTACH CONCEPT COMPARISON

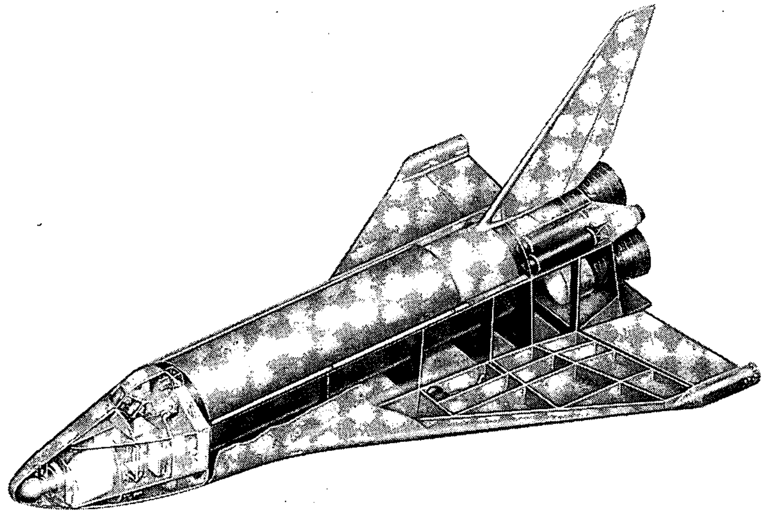

FIGURE 10 DELTA WING SHUTTLE ORBITER

The maximum temperatures experienced by the vehicle outer surface during entry are indicated in the orbiter temperature profile shown in figure 11. The magnitude of these temperatures, coupled with the characteristics of the candidate TPS materials and desired flight life, determine TPS type and thickness.

Using the temperature data given in figure 11, material distributions were constructed for the orbiter as shown in figure 12. The term "charred" ablator refers to that portion of the vehicle which would require refurbishment after every flight. The term "noncharred" ablator refers to that portion which would not experience temperatures greater than 675°K (750°F) and would, therefore, have a use-life greater than one flight. In the case of the noncharred ablator and HCF material, variable use life estimates were assumed. In one instance it was assumed that the materials would have a use-life equal to the life of the vehicle, namely 100 flights. In addition, data were derived assuming total refurbishment once every 100 flights and twice every 100 flights.

In the case of an all-ablator heat shield vehicle, 57 percent of the total surface area would be refurbished after every flight, while the remaining 43 percent would be covered with a non-charring ablator to be totally refurbished in accordance with the use-life assumptions quoted previously. For the vehicle covered with HCF material, all those surfaces not exceeding 675°K (750°F) would also be covered by ablator material identical to the all-ablator concept. In addition, a portion of the nose section and the leading edges of the wing and tail surfaces, would also use ablator. In this instance approximately 52 percent of the total area would be covered with HCF, 43 percent with noncharring ablator, and 5 percent with charring ablator. Refurbishment labor costs for the highly curved nose section, and for the leading edges of the wing and tail surfaces (area A) were not calculated since all test data were derived from flat panels and, as such, are not applicable to these areas.

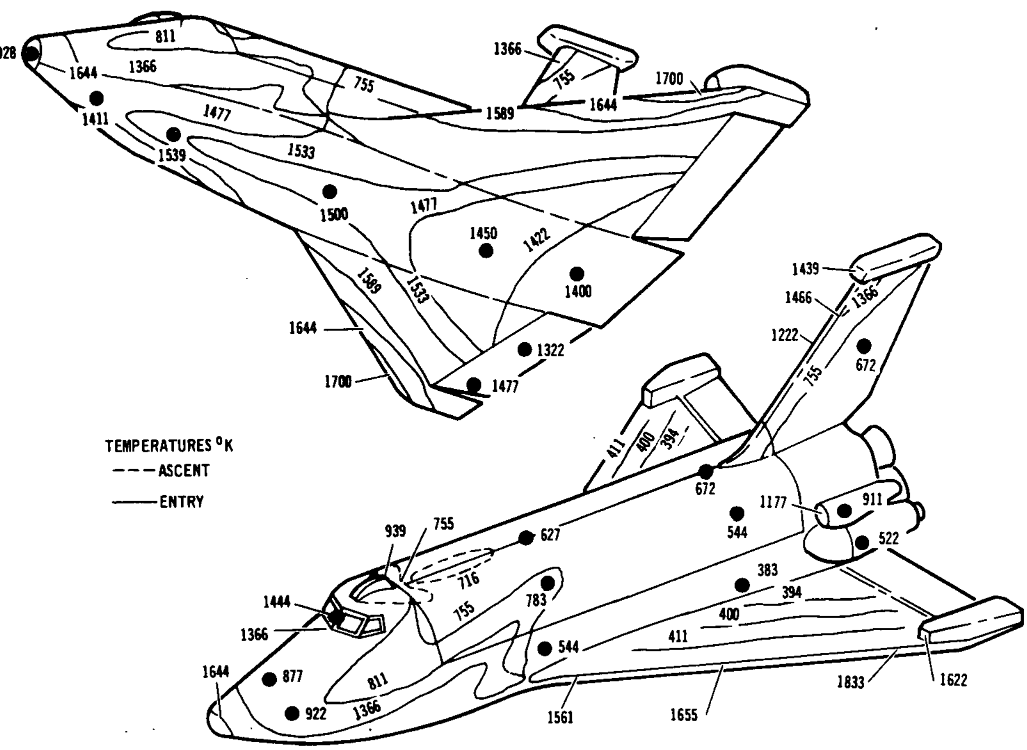

FIGURE 11 ORBITER TEMPERATURES
(Maximum)

In the case of those areas of the vehicle covered with ablator, unscheduled maintenance factors of 1 and 3 percent of the areas were assumed. The 1 percent applies to the unscheduled maintenance required due to damage of the virgin material during normal ground operations attendant upon initial installation and complete refurbishment of the area, while the 3 percent factor is applied every flight for use-life values greater than one (non-charred areas). The same maintenance philosophy was adopted with regard to the unscheduled maintenance of those areas covered with HCF. However, in this instance a range of percentage factors was used because the uncertainties associated with the HCF material are greater than with ablators.

In the case of the HCF attach concepts, factors of 1.5, 2.5, and 5 percent were used to account for the unscheduled maintenance required during initial installation and complete refurbishment, while factors of 3, 5, and 10 percent were used for unscheduled maintenance after every flight for use-life values greater than one. The combination of these factors are cited in tables 1 and 2. It should be noted that percentage factors quoted are purely estimates and are not based on any historical data. Such factors can only be verified after sufficient experience has been obtained on operational hardware.

The significance of the total maintenance labor cost for each vehicle area, except area A, is shown by comparing the various TPS concepts on an average $/square meter ($/square foot) and $/flight basis as shown in tables 1 and 2. Area A cost was not projected because flat panel test data are not applicable to these highly curved regions of the vehicle. These data are the results of a combination

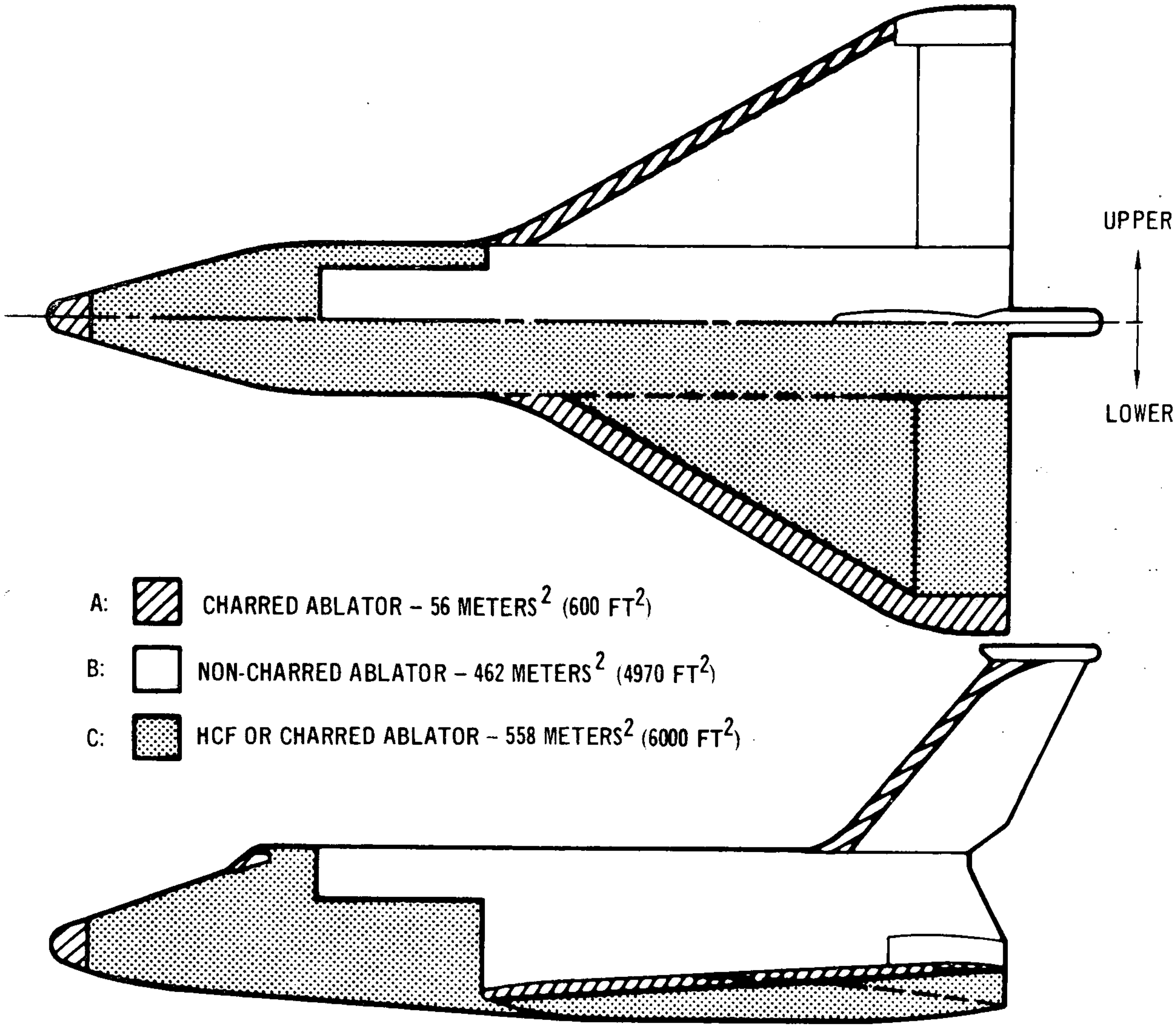

FIGURE 12 ORBITER TPS DISTRIBUTION

of several important parameters, such as the labor cost per square meter (square foot) to remove and replace the various TPS components, total area which must be refurbished after each flight, and the expected use-life of the basic heat shield material.

In deriving these data, the following cost model was used:

$$C_F = (A_F)\ (M)\ (L_R)\ (P)\ (Y)$$

where: C_F = average cost/flight (\$)

A_F = average area/flight replaced measured in meters squared (feet squared)

M = refurbishment manhours/meters^2 (feet^2)

TABLE 1

NON-CHARRED ABLATOR ATTACH CONCEPT COST DATA COMPARISON
Area B = 462 M^2 (4970 Ft^2)

(VEHICLE LIFE = 100 FLIGHTS)

TPS ATTACH CONCEPT	AVERAGE COST WITH TPS FLIGHT LIFE OF:					
	100		50–99		34–49	
	\$/M^2 (\$/FT^2)	\$/FLIGHT	\$/M^2 (\$/FT^2)	\$/FLIGHT	\$/M^2 (\$/FT^2)	\$/FLIGHT
ABLATOR PI-STRAP	1.22 (0.11)	562	1.46 (0.14)	673	1.69 (0.16)	783
ABLATOR MULTIPLE FASTENER	1.16 (0.11)	535	1.44 (0.13)	666	1.72 (0.16)	796
ABLATOR KEY KEYWAY	1.71 (0.16)	791	1.89 (0.18)	871	2.06 (0.19)	952
ABLATOR DIRECT BOND-ON (WITHOUT STRAIN ISOLATOR)	6.48 (0.60)	2,994	7.95 (0.74)	3,674	9.42 (0.88)	4,354
ABLATOR DIRECT BOND-ON (WITH STRAIN ISOLATOR)	8.97 (0.83)	4.146	11.07 (1.03)	5.114	13.16 (1.22)	6,081

L_R = labor rate @ \$15/manhour

P = productivity factor equal to 1.53

Y = planning and engineering support at 1.07

Therefore:

$$C_F = (A_F)\ (M)\ (15)\ (1.53)\ (1.07)$$

The factor Y is used to account for the required effort of planning and engineering personnel to support the maintenance personnel during the refurbishment activity. The factor P is used to account for unproductive time incurred during installation and removal of the TPS panels. Examples of unproductive time would include having the personnel available but not able to perform their function due to parts or equipment delay, equipment breakdown, failure to complete on time a prerequisite task, etc. Included in the refurbishment of each area are the initial installation costs and the costs for both scheduled and unscheduled maintenance functions.

In reviewing the maintenance labor cost data for the noncharred ablator (area B) shown in table 1, it is noted that the average direct bond ablator concept costs are approximately 525 percent higher than those concepts employing a removable panel. When reviewing the maintenance labor cost data for the ablator attach concept for area C, table 2, we see that there is an order of

TABLE 2

MAINTENANCE LABOR COST COMPARISON

Area C = 558 M^2 (6000 Ft^2)

(VEHICLE LIFE = 100 FLIGHTS)

TPS ATTACH CONCEPT	AVERAGE COST WITH TPS FLIGHT LIFE OF:							
	100		50–99		34–49		1	
	$\$/M^2$ ($\$/FT^2$)	\$/FLIGHT	$\$/M^2$ ($\$/FT^2$)	\$/FLIGHT	$\$/M^2$ ($\$/FT^2$)	\$/FLIGHT	$\$/M^2$ ($\$/FT^2$)	\$/FLIGHT
ABLATOR KEY/KEYWAY	–	–	–	–	–	–	18.96 (1.76)	10,582
ABLATOR PI-STRAP	–	–	–	–	–	–	24.67 (2.31)	13,864
ABLATOR MULTIPLE FASTENER	–	–	–	–	–	–	29.05 (2.70)	16,210
ABLATOR DIRECT BOND-ON (WITHOUT STRAIN ISOLATOR)	–	–	–	–	–	–	152.24 (14.16)	84,949
ABLATOR DIRECT BOND-ON (WITH STRAIN ISOLATOR)	–	–	–	–	–	–	216.27 (20.11)	120.679
HCF KEY/KEYWAY								
• 1.5 AND 3%*	4.50 (0.42)	2,509	4.78 (0.45)	2,669	5.07 (0.47)	2,830	–	–
• 2.5 AND 5%*	7.33 (0.68)	4,090	7.60 (0.71)	4,242	7.88 (0.73)	4,395	–	–
• 5 AND 10%*	14.41 (1.34)	8,041	14.65 (1.36)	8,173	14.89 (1.38)	8,306	–	–
HCF DIRECT BOND								
• 1.5 AND 3%*	25.61 (2.38)	14,293	28.18 (2.62)	15,726	30.75 (2.86)	17,158	–	–
• 2.5 AND 5%*	41.66 (3.87)	23,248	44.15 (4.11)	24,636	46.64 (4.33)	26,023	–	–
• 5 AND 10%*	81.78 (7.61)	45,634	82.27 (7.82)	46,909	86.35 (8.03)	48,184	–	–

*UNSCHEDULED REFURBISHMENT

magnitude difference between ablator key/keyway and direct bond (with strain isolator) attach concepts. Comparing the RSI (HCF) attach concepts for area C, it is clearly evident that the direct bond maintenance labor costs are greater than those for the key/keyway attach concept by between 450 and 500 percent.

Comparison among the various TPS attach concepts considering the refurbishment of the entire vehicle surface area is shown in table 3. From these data it is clearly evident that of all the variables considered, use-life of the heat shield material is by far the most significant. State-of-the-art ablators have, for the most part, a use-life of one flight. However, if the ablator material does not experience temperatures above 675°K (750°F) it is assumed that its use-life could be extended to 100 flights. The goal in the development of HCF is a use-life of at least 100 flights. If such a goal is obtained the use of HCF, in combination with a removable panel attach concept, could prove to be most cost effective from a maintenance labor point of view. If, on the other hand, the HCF is bonded directly to primary structure, then ablator panel attach concepts become competitive with HCF even though the ablators have a use-life of one flight.

TABLE 3

MAINTENANCE LABOR COST COMPARISON
Area B + C = 1020 M^2 (10,970 Ft^2)

(VEHICLE LIFE = 100 FLIGHTS)

TPS ATTACH CONCEPT	AVERAGE COST WITH TPS FLIGHT LIFE OF:					
	C = 1, B = 100		C = 1, B = 50–99		C = 1, B = 34–49	
	\$/M^2 (\$/FT^2)	\$/FLIGHT	\$/M^2 (\$/FT^2)	\$/FLIGHT	\$/M^2 (\$/FT^2)	\$/FLIGHT
ABLATOR KEY/KEYWAY	11.15 (1.04)	11,373	11.23 (1.04)	11,453	11.31 (1.05)	11,534
ABLATOR PI-STRAP	14.14 (1.32)	14,426	14.25 (1.33)	14,536	14.36 (1.34)	14,647
ABLATOR MULTIPLE FASTENER	16.42 (1.53)	16,745	16.55 (1.54)	16,876	16.67 (1.55)	17,006
ABLATOR DIRECT BOND-ON (WITHOUT STRAIN ISOLATOR)	86.22 (8.02)	87,943	86.89 (8.08)	88,623	87.55 (8.14)	89,303
ABLATOR DIRECT BOND-ON (WITH STRAIN ISOLATOR)	122.38(11.38)	124,825	123.33(11.47)	125,793	124.27(11.56)	126.760
	B & C = 100		B & C = 50–99		B & C = 34–49	
HCF KEY/KEYWAY						
o 1.5 AND 3%*	3.01 (0.28)	3,071	3.28 (0.30)	3,342	3.54 (0.33)	3.612
o 2.5 AND 5%*	4.56 (0.42)	4,652	4.82 (0.45)	4,915	5.08 (0.47)	5.178
o 5 AND 10%*	8.43 (0.78)	8,603	8.67 (0.81)	8,846	8.91 (0.83)	9,089
HCF DIRECT BOND						
o 1.5 AND 3%*	14.56 (1.35)	14,856	16.08 (1.49)	16.398	17.59 (1.64)	17,941
o 2.5 AND 5%*	23.34 (2.17)	23,811	24.81 (2.31)	25,308	26.28 (2.44)	26,806
o 5 AND 10%*	45.29 (4.21)	46,196	46.65 (4.34)	47.581	48.01 (4.46)	48,967

*UNSCHEDULED REFURBISHMENT

In order to evaluate fully the impact of maintenance labor costs on total program costs, one must consider material replacement costs, hardware manufacturing costs, and TPS development costs. Material replacement and manufacturing costs will depend, for the most part, on material use-life and on the amount of scheduled and unscheduled maintenance required after each flight. As stated previously, ablators are largely state-of-the-art and it is anticipated that their development costs for Shuttle application would be low. Development costs for HCF, on the other hand, are expected to be higher.

Since it was not the intention of the study to consider all the factors involved in TPS costing, one can see that numerous trade studies must be performed before the optimum TPS can be configured and released to hardware status. With the data gathered in this program one of the missing links in the chain of parameters, namely refurbishment labor costs, has been identified. This information, along with related data from other studies, should provide a good data base from which future program costs associated with Space Shuttle TPS can be predicted with greater confidence.

CONCLUSIONS

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

Externally removable heat shield panels are a viable approach to achieving minimum maintenance costs.

Fabrication and handling characteristics of large size TPS panels (i.e., up to 1.02 by 1.78 meters (40 x 70 in.)) are practical.

Increasing panel size reduces removal and replacement requirements.

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

Current RSI materials are fragile and damage prone and as such special handling operations are required.

Dust contamination resulting from removal of direct-bonded RSI tiles and ablator panels may prove to be a serious problem to personnel and sensitive equipment.

Removal and replacement maintenance labor costs of mechanically attached systems were considerably lower than predicted.

TPS panel concepts are more amendable to low cost maintenance than the direct bond approach.

Heat shield material use life greatly affects total labor maintenance costs.

State-of-the-art does not yet encompass totally reliable nondestructive evaluation (NDE) techniques to detect bond anomalies.