NASA CR-111830

FINAL REPORT FOR REFURBISHMENT COST STUDY OF THE THERMAL PROTECTION SYSTEM OF A SPACE SHUTTLE VEHICLE

Prepared under Contract NAS 1-10094 by
LOCKHEED MISSILES & SPACE COMPANY
Sunnyvale, California 94088

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By Robert J. Peterson

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FOREWORD

This report is the final technical documentation of all work performed under Contract NAS 1-10094.

Work was performed at the Lockheed Missiles & Space Company (LMSC) at Sunnyvale, California, and was administered under direction of the Materials Division, Langley Research Center, Hampton, Virginia, with Mr. C. W. Stroud acting as Technical Monitor.

Mr. Robert J. Peterson of LMSC was Program Manager. Acknowledgement is made to Mr. Robert W. Goldin for his support in Costing Methodology and Mr. Kenneth Urbach for his assistance in Field Operations.

This report presents the technical basis for selection of test activities which warrant further evaluation. Predicated on high cost, technological uncertainty, and design feasibility considerations, a test program has been formulated where these factors can be assessed using the Langley Mockup. Justification for selected tests will result from the potential savings in Operations costs that might be realized if the factors of concern can be resolved.

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Section 1

INTRODUCTION AND SUMMARY

1.1 Introduction

The economic feasibility of a manned space shuttle hinges on the ability to reuse a vehicle from 50 to 100 times with minimum refurbishment. In a multiple reuse system of this kind, the thermal protection system refurbishment cost can be a significant fraction of the total operational cost.

These thermal protection system costs consist of inspection and repair costs, cost of replacement of parts that are not reusable, and amortization of the initial cost of reusable components. The purpose of the Refurbishiment Cost Study (RCS) is to identify the costs associated with inspection, repair, and replacement of components, and to develop efficient techniques for performing these operations.

Three basic thermal protection systems (TPS) are considered: ablative metallic and non-metallic heat shields. The ablative heat shield is a phenolic glass honeycomb filled with elastomeric ablator. Metallic shields consist of a superalloy or coated refactory metal on the outer surface. The reradiating outer surface protects a low-density insulation layer. Non-metallic, non-ablative shields consist of a layer of rigidizied inorganic fibers in the 12 to 15 lb/ft^3 class. The material is bonded to a supporting surface consisting of either the primary structure, a backface surface sheet or metal/honeycomb subpanel when the shield stands off from the primary structure.

Each TPS is capable of transmitting loads encountered during flight through the attachment points to the primary structure of the vehicle. Fastening methods are selected to be consistent with the structural configuration and any requirement to prevent crycpumping. TPS thickness is established through sizing studies by applying typical thermal loads to areas where heat shields are to be used. Joint designs are capable of preventing hot gas inflow during reentry and facilitate refurbishment tasks.

The study is implemented in phases. Phase I, a definition and planning program, is presented in this document. Phase II will consist of detail experimental studies of specific refurbishment problems relative to particular thermal protection systems. These detailed studies will use a 200-square foot mockup of a section of the space shuttle. The mockup has been constructed and is located at Langley Research Center.

Phase I is partitioned into five task groups. The first two review existing space shuttle reports. Task I involves identification of primary structural components since attachment methods will vary with their structural arrangements. Methods by which heat shields are attached to different primary structure components are identified in Task II. Detailed operational cost estimates are developed in Task III for various attachment methods, TPS material systems, and primary structure configurations. Based on the resulting costs, candidate systems are selected for further study. Task IV involves identification of items in the preceding task for which cost estimation was difficult or where technical/practical feasibility is questionable. In particular, questions which can be resolved only by the application of full-scale panels to large structures are delineated. In Task V, candidate TPS systems, selected by the Government are designed. Each system is compatible with the full-scale mockup, and all associated mounting hardware is provided. In addition to the design activity, a test plan is provided to conduct experimental studies designed to clarify the unknowns associated with each candidate system. This plan will be implemented during Phase II and is as economical as possible consistent with study objectives.

1.2 Summary

The Phase I RCS program investigated the refurbishment function of Operations. Refurbishment tasks and TPS material subsystems matrices were developed for five TPS system configurations using a delta body orbital vehicle.

Value judgments have been made for each task/subsystem element. Both a nominal value and an uncertainty factor are assigned. The magnitude of this value measures the effort required to perform a task using some nominally accepted technical approach. The size of the uncertainty factor measures the extent of technological unknowns presented by a spectrum of possible technical approaches. Estimates originate with operational specialists who can relate their experience and training to the problem at hand and arrive at value judgments. Uncertainty values are selected to cover the variation in each estimate resulting from differences in opinion as to technological difficulties occurring between individual estimators. Thus each opinion is a considered part of every estimate.

Operational costs are determined using normal pricing procedures to arrive at a common basis for comparing alternative operational methods and techniques, as well as to indicate the effect of TPS material variations on cost. System level costs are developed from a mission model which specifies a ten-year-life system, composed of eight vehicles flying 75 missions a year.

At the system level, the effect of refurbishment cost on Production and DDT&E can be evaluated. Major TPS subsystem and operational task cost drivers and associated uncertainties are identified. From this information, priority lists which differentiate between operational tasks and TPS material subsystems are developed using high cost and high uncertainty as selection criteria.

From the priority list of operational tasks and TPS subsystem materials, those elements that can be evaluated effectively on the Langley Mockup have been identified. Having identified what technological problems best can be tested on the mockup, the material systems, and tasks, a test plan is provided.

The test plan is made up from Test Requirement Sheets (TRS) developed by experienced operations people. Task activities were selected from the operational analysis according to the problems encountered in cost estimating or where technical feasibility was a matter of concern. In the test plan, a test program is presented to lay up panels from each TRS material system. Test labor cost and panel fabrication costs are presented.

In the sections that follow, the Phase I study is discussed more fully. Appendices are provided at the end of the report for reference and detail support.

Section 2

VEHICLE STRUCTURE EVALUATION

Design objectives established for the Space Shuttle vehicle system will strongly influence the refurbishment costs ultimately realized by the operational system. For this reason, it is important that Operations be given an opportunity to establish and specify design requirements for operationally efficient thermostructural systems. The Langley Mockup can be the means by which this is accomplished.

In particular, TPS refurbishment costs will depend on the structural details envisioned at the outer mold line of the vehicle configuration chosen. TPS structure can be simple or complex in design depending upon the nature of the primary structure to which it attaches, aerodynamic and thermodynamic properties of the materials selected, and environmental hazards encountered while performing a mission. Payload optimization studies will ultimately determine the TPS performance requirements having taking into account each of these factors. The resulting TPS subsystem will be a cost effective structure capable of minimizing refurbishment costs while maximizing thermal protection performance.

Since one of the study objectives is to select design options for evaluation on the Langley Mockup, a review of Space Shuttle documentation was considered appropriate to determine what is available and pertinent to operational refurbishment. The information to be sued in determining those hardware items and operation activities that can be realistically evaluated on the Langley Mockup - considering the present level of design maturity.

2.1 DESIGN MATURITY

Existing Space Shuttle reports; recently compiled bibliographies applicable to such Space Shuttle functions as materials, processes, and the thermal protection system; and individual libraries assembled by Space Shuttle personnel, as well as their own expertise, have been reviewed. This effort has identified documentation that is useful to the Refurbishment Cost Study program and provided an excellent perspective regarding the documentation status of attachment methods and primary structural components. References are listed in Appendix A.

2.1.1 Documentation Coverage

It is clear that available Space Shuttle documentation does not specifically address the subject of attachments or primary structure alternatives. Detailed thermostructural designs, which meet operational requirements for feasibility and cost effectiveness, are not available. The literature lacks either coverage or depth in the following categories:

1. Studies specifically oriented toward TPS panel installation and attendant design and operational problems.
2. Detailed evaluation of the special structural problems associated with complex contours, leading edges, etc.
3. Studies addressing the problem of panel size, geometry, and orientation versus vehicle configuration.
4. Studies that scale up the ablative information from that developed during the early 1960s on the X-20, HL-10, M2-F2 vehicles to that which meets the needs presently envisioned of vehicles.
5. Studies of metallic TPS systems where attachment design details have been analyzed for thermal, structural stress, loads and dynamics, and materials acceptability.
6. Studies of recent origin that are related to vehicles presently envisioned and directed toward establishing a baseline vehicle configuration.

The likelihood of any improvement in this situation is remote, particularly since the Phase II test program will preempt the Phase B studies and many of the recently awarded Support Research and Technology contracts.

2.1.2 Documentation Summary

The following is a summary of information which is available to the RCS study for use in the technical evaluation and for Phase II planning purposes:

1. Attachments, attachment methods, and primary structural concepts have changed radically from those used on the X-20, M2-F2, HL-10 vehicle configurations to those that are envisioned on present vehicles.

2. Ablative TPS systems are the best illustrated and most widely documented. Little or no metallic TPS system documentation exists that is significant to the RCS study and the same is true for non-metallic systems.

3. Documentation is explicit in expressing a need for detailed consideration on such TPS system subjects as (1) panel sizing, fabrication, and installation needs, and (2) procedures and operations requirements. However, the substance of the coverage is still too general for useful operational design details to have been produced. To date, concern has been with material characterization and associated processes rather than with the practical problems of fabrication and installation of selected TPS thermostructural panels. Where operational experience does exist, it has not been developed sufficiently to be influential in establishing operationally feasible TPS designs.

4. Product Assurance and Operations documentation dealing with such problems of reusable TPS systems, as Fail-Safe or Safe-Life concepts, are as yet not sufficiently well defined for timeline analyses. Inspection techniques will be strongly affected by this information since postflight, in-process maintenance, and preflight inspection and verification are directly concerned.

These findings, regarding the status of documentation on attachment methods, primary structural components and operational concepts, indicate that a baseline system must be established for purposes of technical evaluation. They further indicate that for Phase II planning purposes, only representative TPS subsystem and operational techniques would be considered feasible for test program development.

It is apparent that Space Shuttle development activities have not yet reached a point of maturity where operationally efficient designs are a consideration. At the same time, if operations waits until this maturity is reached, it is doubtful that requirements for operationally efficient structures would be satisfied. Consequently, there is a need for some activity in this period of low-level design maturity to begin the process of Operation System Engineering. The function of this group would be to establish initial operational design requirements for inclusion in TPS system structural designs. The Langley Mockup is an excellent vehicle for just such an activity and a reasonable point from which to start.

2.2 PRIMARY STRUCTURE OPTIONS

Primary structure design options vary according to vehicle configurations. In general, however, thermostructural systems will be attached directly to a load carrying shell or some form of ring assembly. In either case, these TPS interfacing elements are supported by a complex structural system which distributes the static and dynamic loads transferred to them through the TPS system. In Figure 2-1 these primary structure options are identified as follows:

	Options	Heat Shield Support
Primary Structure	Skin over rings	Primary Structure
	Skin under rings	TPS Subpanel
	Standoffs under rings	

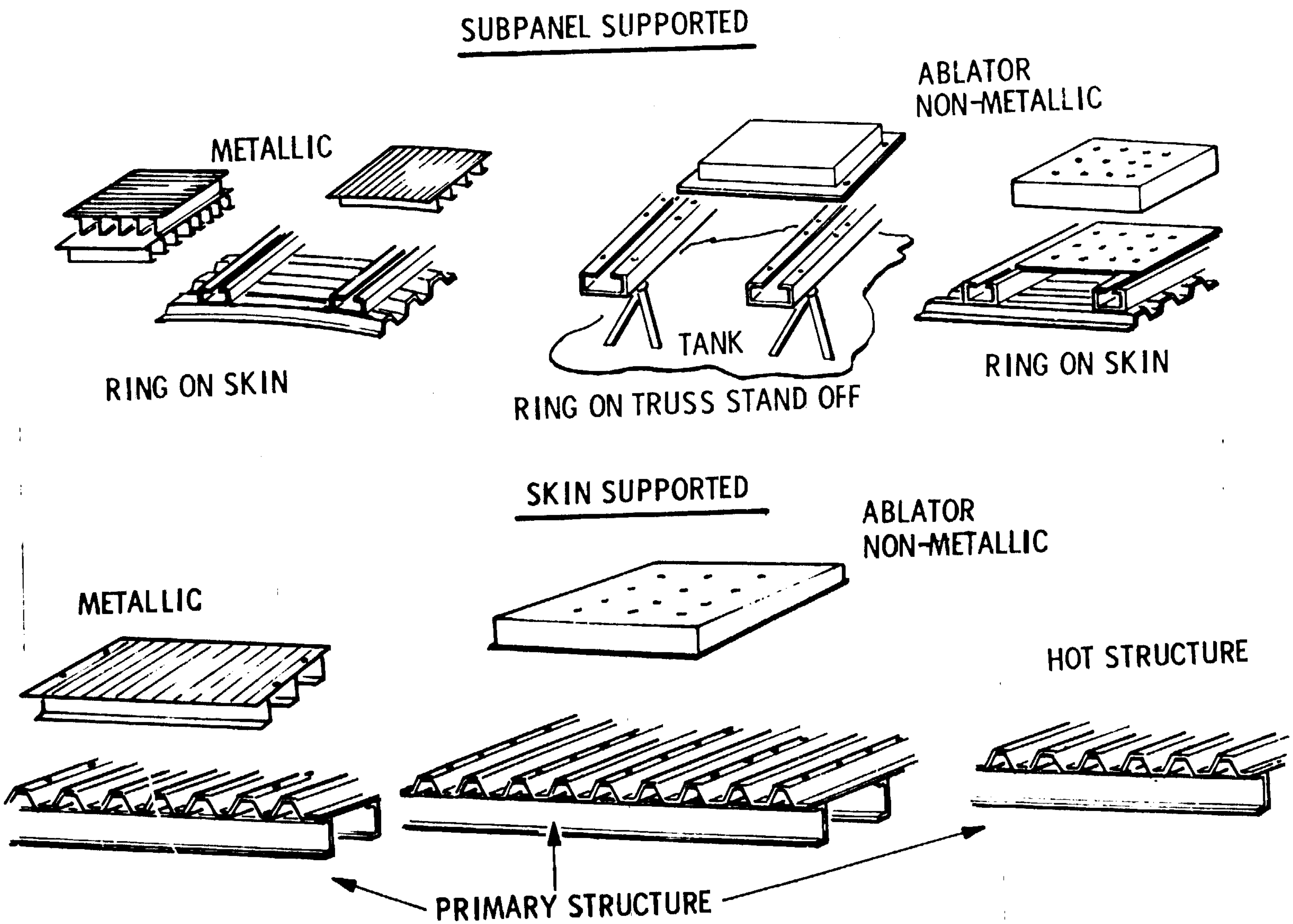


FIGURE 2-1 - PRIMARY STRUCTURE OPTIONS

Panel structure design will be either load carrying TPS metallic skin or skin supporting any one of the three (3) TPS systems, or designs where subpanels bridge rings to support metallic, non-metallic and ablative systems.

Each of these variations is a possible design candidate in vehicle sizing determinations. Selection of the proper structural approach will depend upon payload optimization studies where structural weight minimization will be a design objective. The importance of primary structure to TPS design is in panel size determination and panel structure design. Where there is a load carrying skin to which a thermostructural system can be attached, the structural features of the panel are less complex. As an example, the skin itself may be the TPS system as well as principal load carrying member of the vehicle structure. When rings are used as primary structure, panels become more complex in their design because subpanels are required to mechanically support the heat shield and to transfer air loads to the primary structure.

In general, it is operationally desirable to have wide ring spacing which would afford large panel sizes. At present, panel size determination must await payload/vehicle structure optimization studies before actual panel designs can be made available. Initial sizing studies indicate that panel dimensions might range from 24" x 24" to 48" x 48" with odd sizes occurring at several locations due to surface geometry. These results would indicate that primary structure design has not materialized sufficiently for thermostructural point designs to be available and that only representative panels can be exercised on the Langley Mockup.

2.3 ATTACHMENT OPTIONS

Methods of attaching TPS panels to primary structure whether made directly to a skin or rings all use mechanical securing methods. In addition, the interchangeability design objective and refurbishment requirements, dictate that panel attachment points be serviceable from positions external to the vehicle.

Attachment options are as follows:

	TPS Material	Attach Location	Attach Bolt Insulators	Securing Method
Attachment	Rigid and Non-metallic	Subsurface	With	Mechanical
			Without	Mechanical
	Metallic	Surface	With	Mechanical
		Subsurface	With	Mechanical
			Without	Mechanical

TPS structure attachment is made either at the surface of the heat shield or at a location beneath the TPS material surface. Both methods have advantages and disadvantages. When at the surface, attach bolts are subject to heat shorts and may require insulators, preload is difficult to maintain, and head exposure can be a problem. However, accessability is a desirable refurbishment feature. Refurbishment is more difficult when the attach bolts are below the surface of the heat shield, however, protection afforded from the thermal environment is an advantage.

External access to TPS panels implies that attachment methods must be independent of the primary structure to which they interface. Because many panels will be used to surface a vehicle, then it also follows that the method of panel lay-up must be independent of primary structure options. This feature is essential to minimizing TPS refurbishment costs and should be a design requirement for operational efficiency.

2.4 CLOSURE OPTIONS

Closure methods represent one of the key refurbishment problems of operations. Closure concepts together with the surfacing methods selected for panel lay-up determine removal and replacement time expenditures. Design concepts to affect closure and the environmental factors that determine their configuration are not widely understood for the surfacing methods envisioned on Space Shuttle vehicles.

Closure and lay-up options are categorized as follows:

	Closure Method	TPS Subsystem	Lay-up: Surfacing Method	Lay-up: Joint Option
Closure	Plug	Metallic	Paneling	Open
		Non-metallic	Paneling	Open
	Filler	Ablative	Paneling	Open
	Structure	Metallic	Shingling	Full
	Structure Plug	Metallic	Shingling	Partial

Joint option refers to the manner in which the panel structure directly participates in the closure function. The paneling method of surfacing leaves "open" spaces between panels requiring the use of closure plugs or filler. The shingling method of surfacing involves either a "Full" (four-sided) or "Partial" (two-sided) overlap of the heat shield material.

The Langley Mockup is particularly suited for closure and panel lay-up type operational tasks. Operational demonstrations using representative design concepts to establish operation design requirements would be appropriate at this stage of TPS design maturity. Closure and panel lay-ups which can be demonstrated using the Mockup are illustrated in Figure 2-2.

2.5 BASELINE SYSTEM

A high crossrange orbiter has been selected as the baseline system. Illustrated in Figure 2-3 the vehicle is designed to carry a 50,000 lb payload and capable of operating at crossranges up to 1500 nm. It has a cool body structure using a ring-over skin structural design. Primary skin temperatures are 200°F or less while backface temperatures on the TPS system is held to a 600°F design level.

These designs satisfy the mission performance requirements of the general system specification while meeting design requirements for operationally efficient panels. The spectrum of TPS subsystem material types for selected orbiter temperature ranges is illustrated in Figure 2-4.

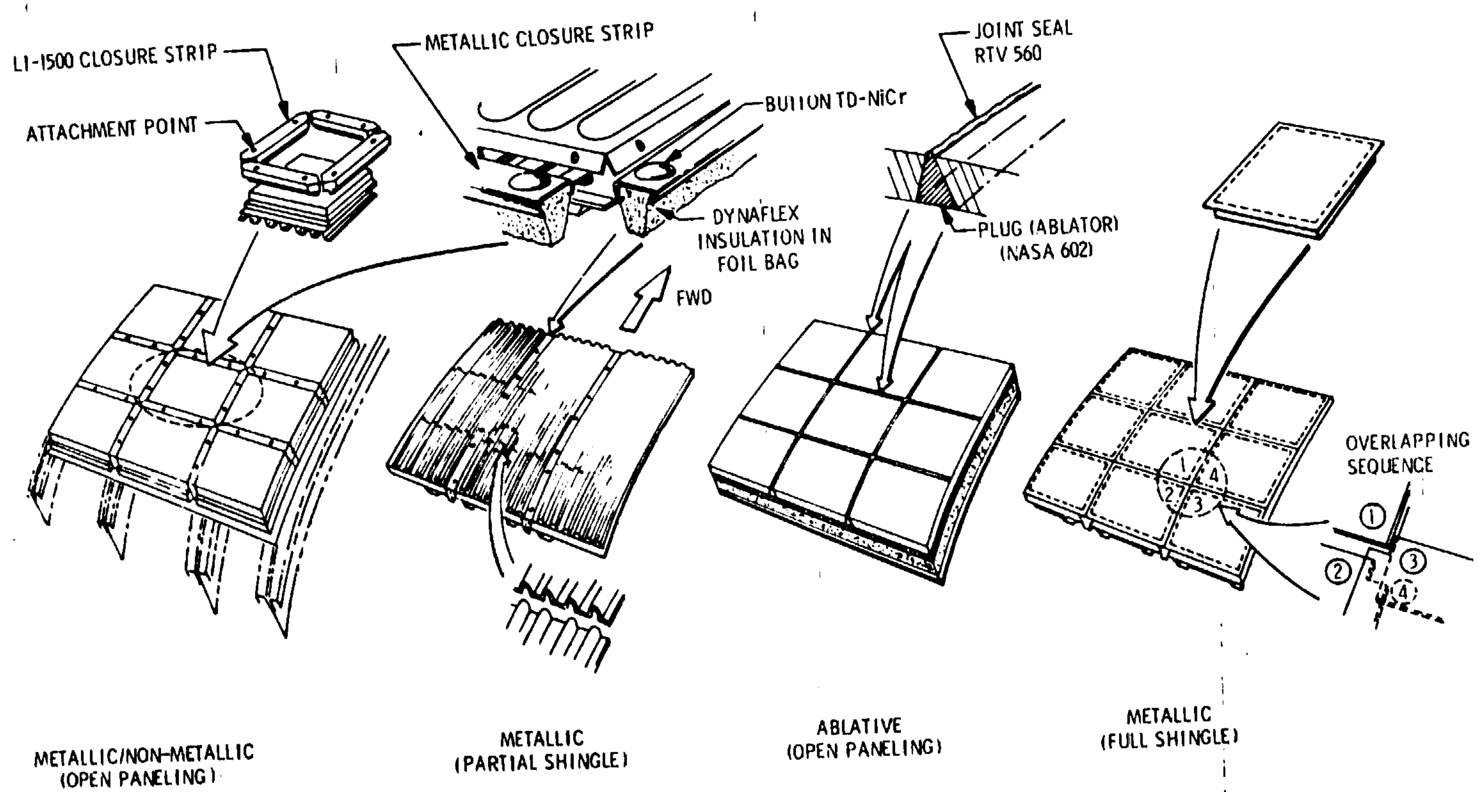


FIGURE 2-2 PANEL CLOSURE AND LAY-UP ALTERNATIVES

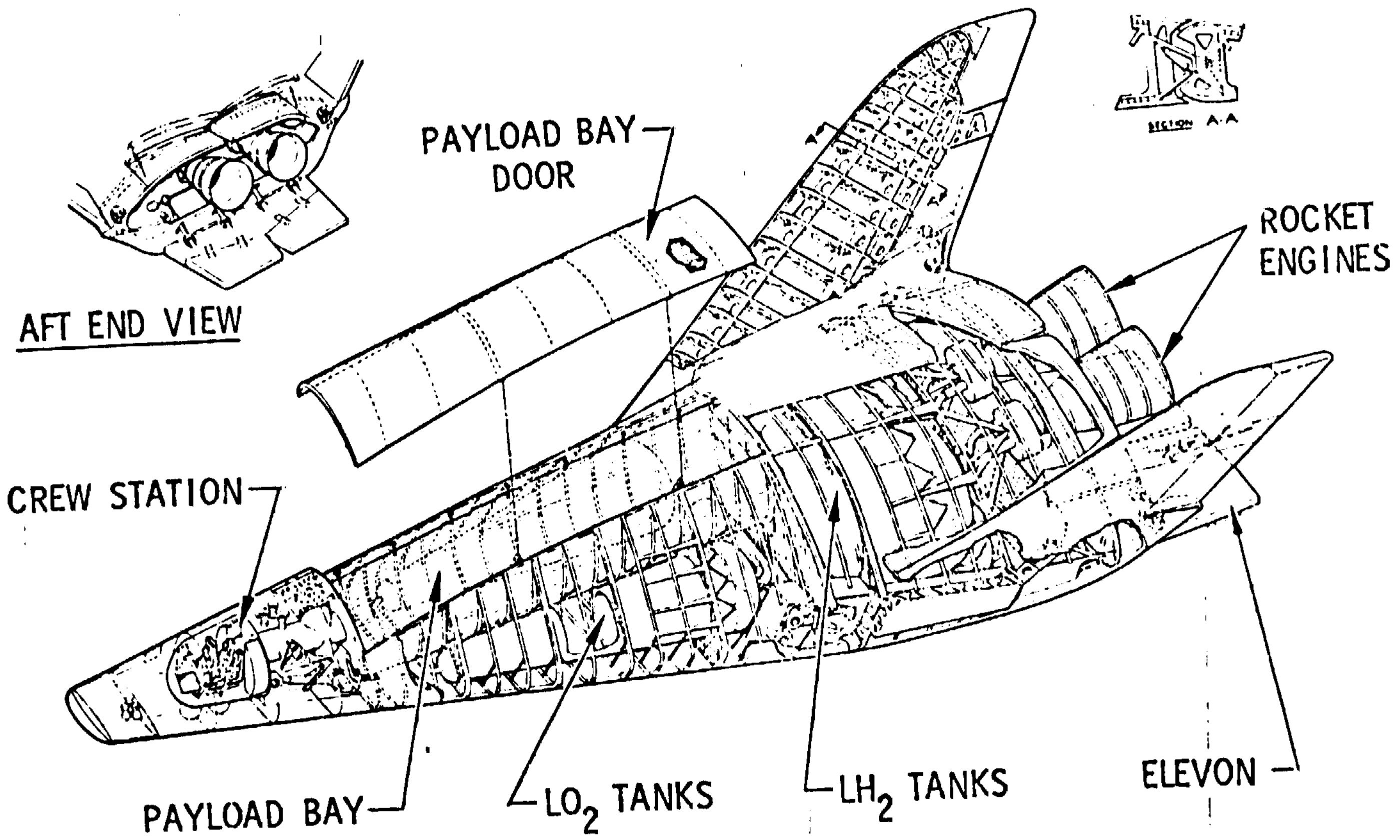


FIGURE 2-3 - HIGH CROSSRANGE ORBITER

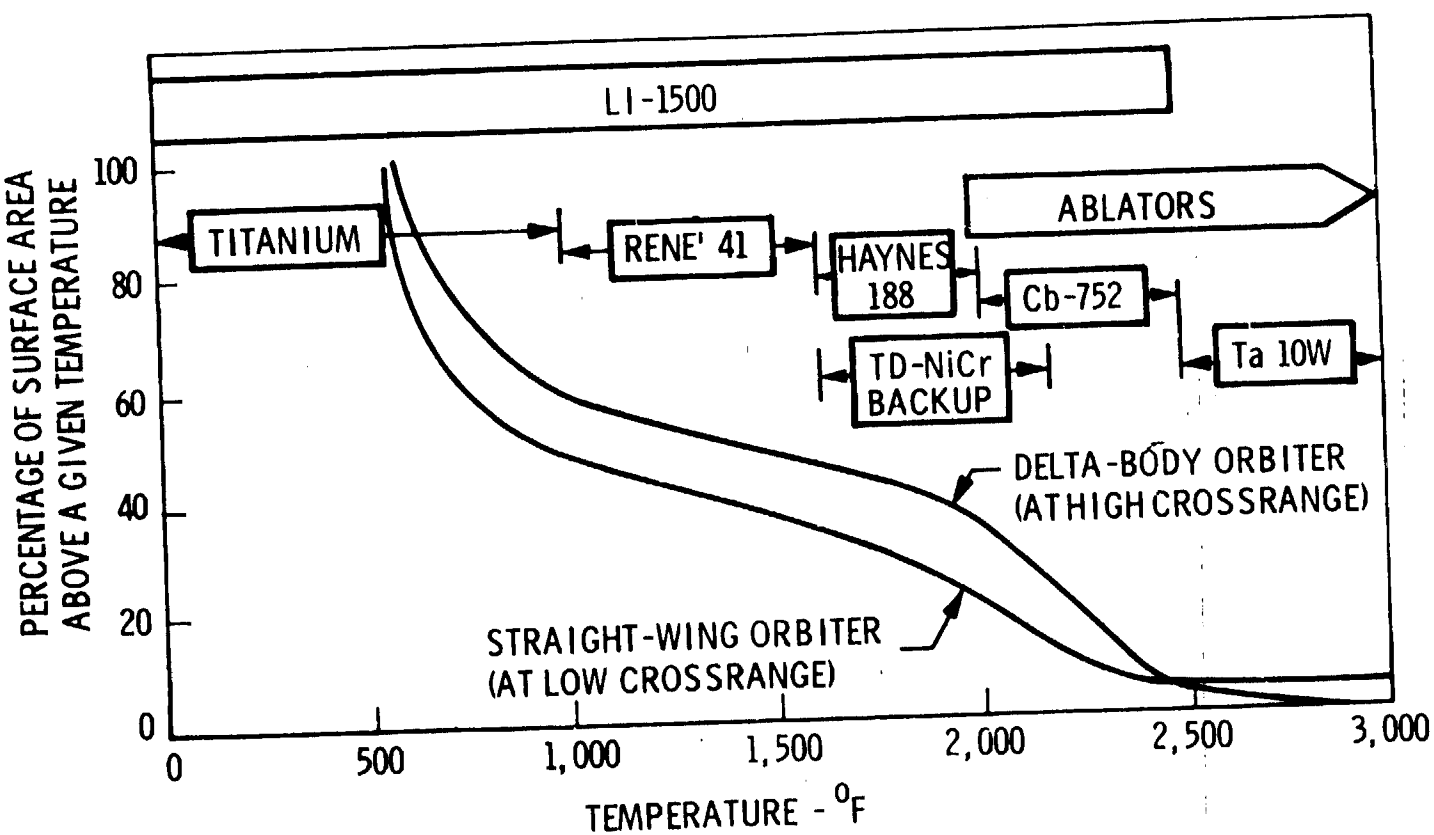


FIGURE 2-4 - ORBITER TEMPERATURE RANGES AND HEAT SHIELD MATERIALS

The total wetted area for the baseline vehicle is provided in Table 2-1 for critical temperature regimes and key locations on the vehicle. TPS materials will cover 16,311 ft^2 of vehicle surface, 73 percent of which involves the body structure, 16.4 percent the fin and rudder assembly, and the remaining 10.6 percent is devoted to miscellaneous areas. Several locations will require substantial TPS coverage: The top 5,166 ft^2; the bottom, 3,381 ft^2; the side, 2,709 ft^2; and the chine, 1,195 ft^2.

Initial payload optimization studies indicate that a higher payload efficiency is realized with a ring-on skin primary structure in contrast to the skin supported design. This is due to the lighter gauge materials needed for the lower temperature skin and direct skin loading. Metallic, non-metallic, and ablative TPS structure will use a subpanel support concept where the subpanel is used to transfer the air loads from the heat shield to the primary structure. Typical non-metallic and metallic TPS subsystems are shown in Figures 2-5 and 2-6 with closure and attachment options depicted. In the event further studies favor a primary structure with an outer shell or skin, then the non-metallic or ablative TPS subsystem illustrated in Figure 2-7 will be possible candidates.

The safe-life design objective for the orbiter is 100 missions before a major refurbishment activity is expected.

The operational system will consist of eight (8) vehicles flying 75 missions a year. Operating life for the system is 10 years. Operations has established panel interchangeability as a design requirement. It has further specified that all refurbishment activities must be accomplished from work positions external to the vehicle primary structure.

TABLE 2-1 - TOTAL WETTED AREA OF BASELINE VEHICLE

(Delta Body 1500-nm Crossrange 50,000-lb Payload)

LOCATION		TEMPERATURE REGIME (°F)	AREA (ft²)		AREA DISTRIBUTION								
					BODY				FIN/RUDDER			OTHER	
NOMEN-CLATURE	POSITION		A	%	TOP	SIDE	BOTTOM	CHINE	LEAD-ING EDGE	TOP	BOTTOM	NOSE CONE	BASE SHIELD
Nose Cone	Front	2500°-3000°	70	0.4								70 0.4%	
Body	Bottom Chine	2000°-2500°	4,576(a) to 5,431(b)	28.0 to 33.5			3,381 20.7%	1,195 7.3%	- to 855				
Fin Body	Lead Edg Bottom Side	1600°-2000°	2,132(a) to 1,277(b)	13.0 to 7.8		1,029 6.3%			855 to -		248 1.5%		
Rudder Body	Bottom Side	1000°-1600°	1,845	11.3		1,180 7.2%					665 4.1%		
Rudder Fin Body	Top Top Top	< 1000°	6,078	37.3	5,166 31.7%					912 5.6%			
Base Shield	Back	-	1,610	10.0									1,610 10.0%
			16,311	100.0	5,166 31.7%	2,209 13.3%	3,381 20.7%	1,195 7.3%	855 5.2%	912 5.6%	913 5.6%	70 0.6%	1,610 10.0%
					7,375 45%		4,576 28%		2,680 16.4%			1,680 10.6%	
					11,951 73%				4,360 27%				

(a) Area for metallic TPS system.
(b) Area for non-metallic TPS system.

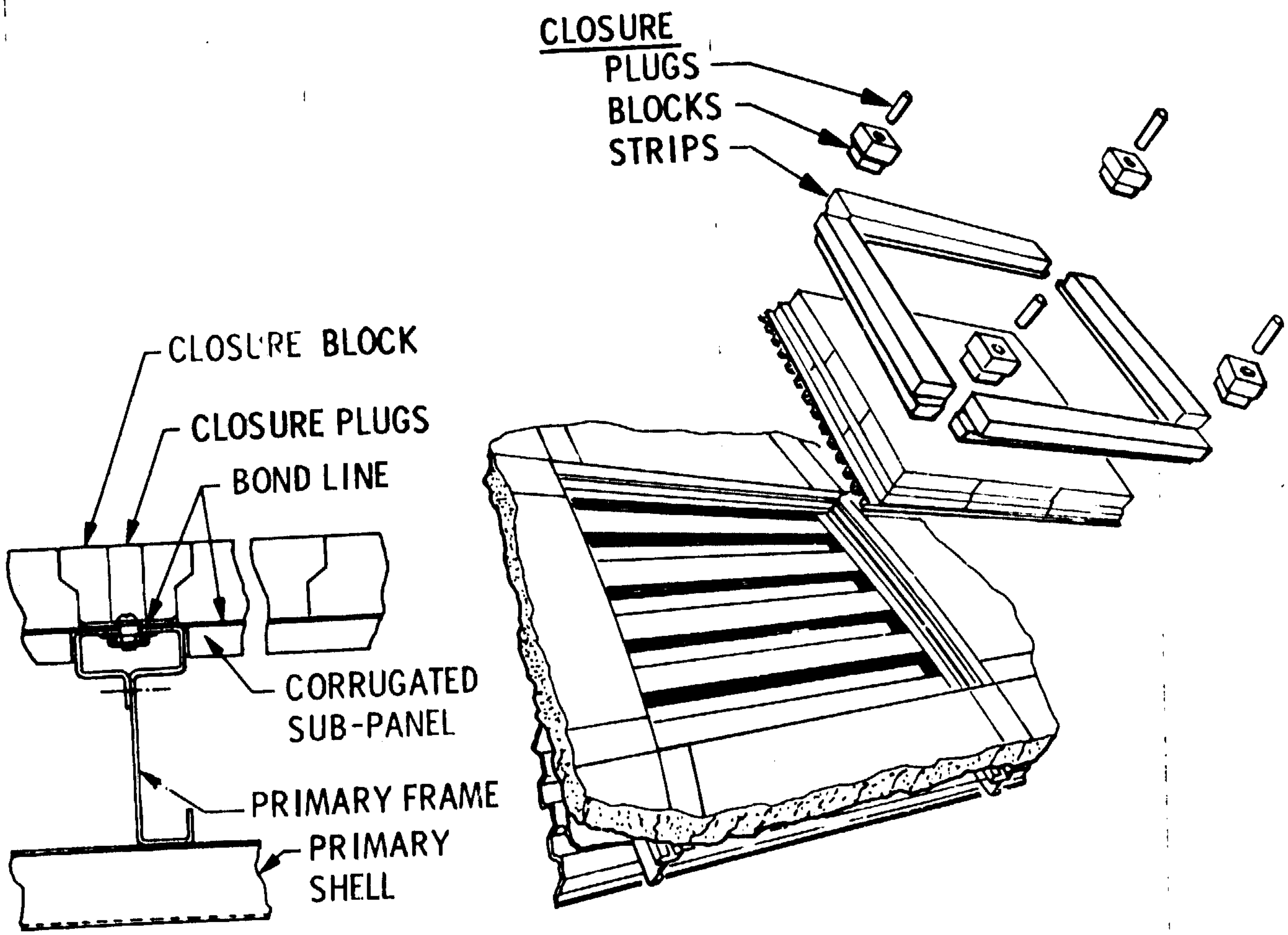


FIGURE 2-5 - NON-METALLIC TPS SUBSYSTEM

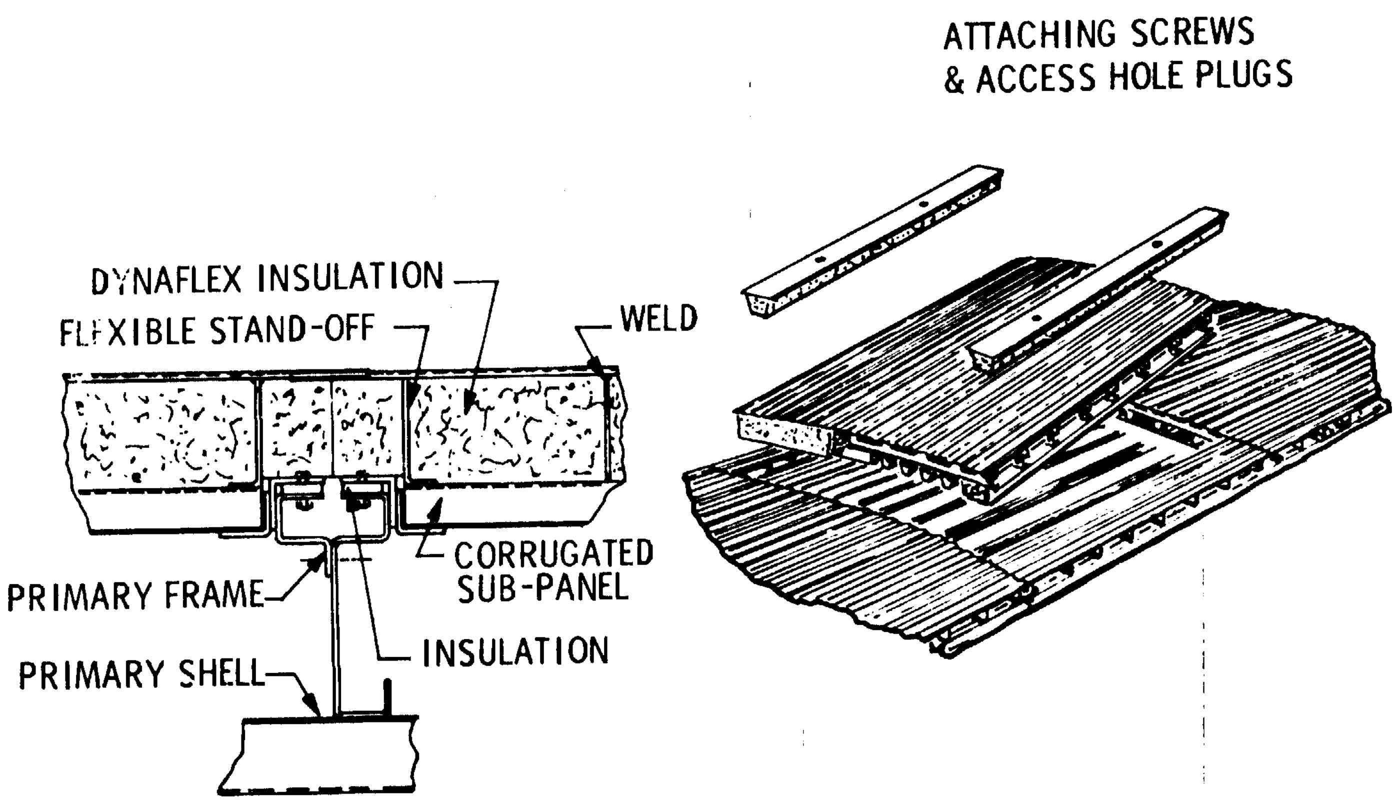


FIGURE 2-6 - METALLIC TPS SUBSYSTEM

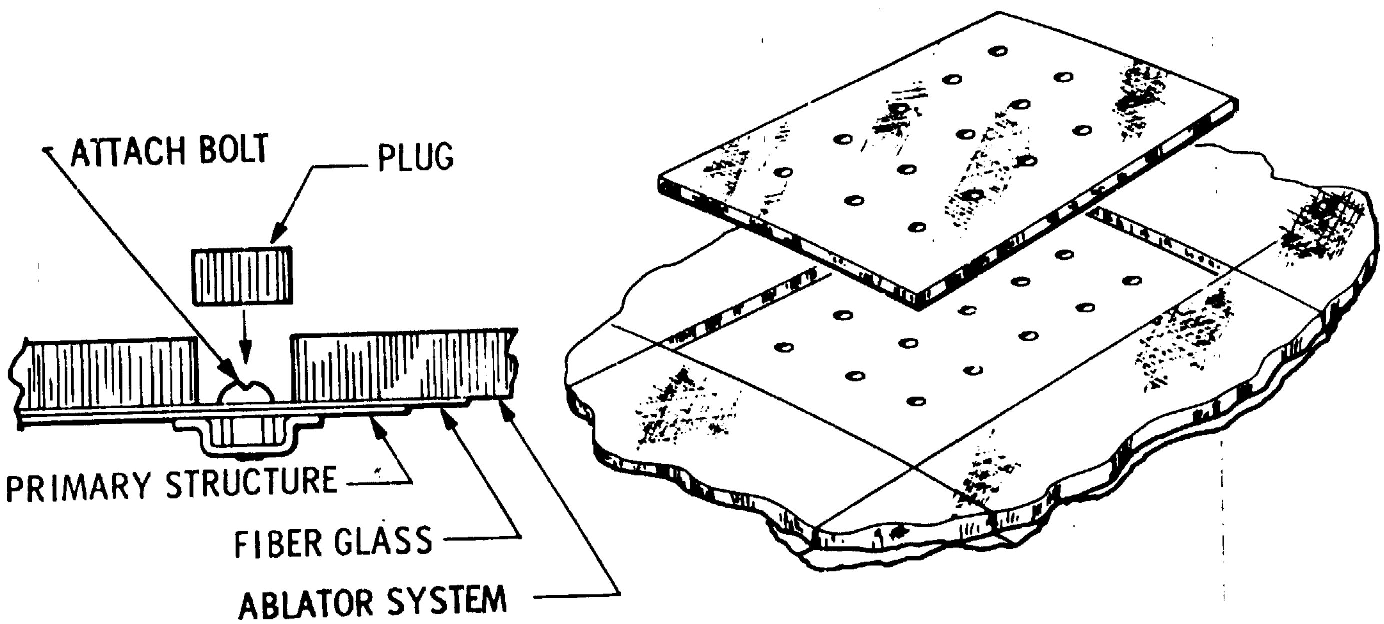


FIGURE 2-7 - NON-METALLIC/ABLATIVE TPS SUBSYSTEM

2.6 OPERATIONS AND MAINTENANCE

For the most part, proven techniques for the maintenance and repair of thermal protection systems have not been developed. This is understandable since there are very few TPSs or heat shield materials currently in use, and only a limited number of these on which enough data exists on repair and maintenance to be of value.

Questions which need resolution, typically, are the identification and development of low-cost, fast, and efficient inspection techniques; the effects of multiple-flight thermal and structural stress on panel removel and replacement problems; efficient mechanical fastening techniques; handling and storage problems associated with coated metallic heat shields and with non-metallic TPS subsystems; adequate access to the shuttle, due to its large size, for maintenance and repair activities; criteria for maintenance and repair in place; criteria for panel refurbishment for reuse.

Figure 2-8 shows the typical Space Shuttle mission cycle. At the end of the mission the Orbiter lands, proceeds to the cooling, clean and purge stations where it is "safed", and then it is taken to the maintenance hangar. At the maintenance hangar , after preparatory hookup of ground support and safety items, and positioning of GSE inspection equipment, the TPS will receive a gross visual inspection, followed by special inspections to a more refined degree. A special inspection could consist of an overall emissivity inspection by radiometer, then more detailed inspections of critical areas (such as areas of stress concentration) both visually and by radiometer to see whether temperatures have approached design limits. Suspect panels will then receive a more thorough inspection which will result in determination of the maintenance actions required to correct the problems found.

Panels would be repaired in-place if feasible. Experience with titanium panels on SR-71 aricraft indicates that such repair is possible. Application of similar techniques may apply to the titanium panels on the Space Shuttle, as well as to some of the other metallic TPS. Other repair-in-place techniques need to be developed.

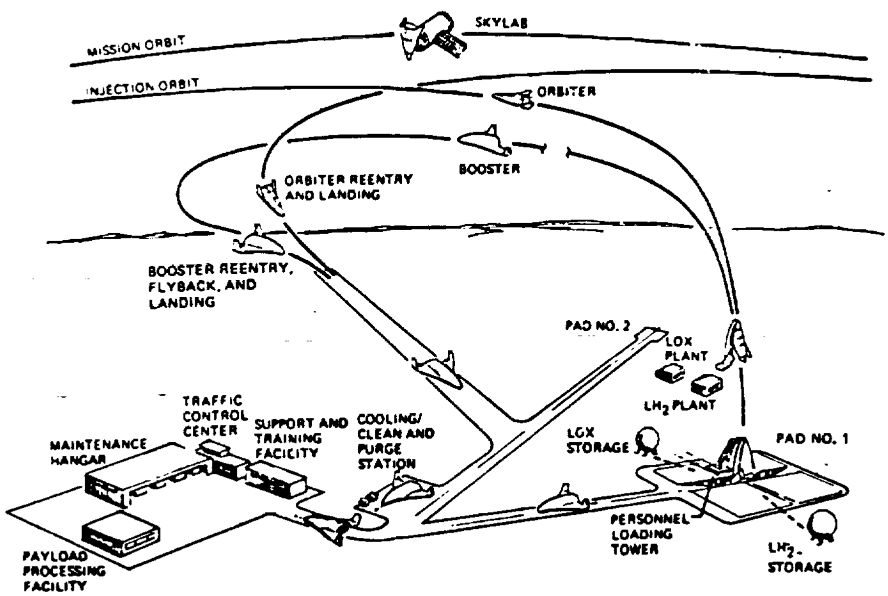


FIGURE 2-8 - TYPICAL SPACE SHUTTLE MISSION

When repair in place is not possible or when the life cycle of a TPS panel has been exhausted, it will be removed and another panel substituted for it. The panel that has been removed will be either cycled through the factory for repair, or it will be designated as scrap. As TPS maintenance and repair activities are completed, the work will be inspected and the vehicle recertified for flight.

In this study a differentiation is made between maintenance and refurbishment tasks within operations. Maintenance will pertain to those activities directly related to restoring degraded panels to a flightworthy status. Repair-in-place and remote repair tasks fall under maintenance. Refurbishment will include all activities associated with vehicle servicing and making it ready for flight validation. Activities that will be considered a part of refurbishment are panel removal, reinstallation, packaging and handling, transportation, and inspection. The combined efforts of both maintenance and refurbishment will be considered operations.

Section 3

TECHNICAL EVALUATION

3.0 The technical evaluation is conducted in two parts: (1) A total system economic evaluation, and (2) An operational cost analysis. The total system economic evaluation establishes the relative cost relationship between the major functional cost drivers, i.e., Manufacturing, Operations, Engineering, and Quality Assurance. In the operational cost analysis, time line techniques were used to establish the relative cost between operational functions using methods and techniques for accomplishment envisioned for the Space Shuttle operations. For assumptions and premises used in these exercises, see Appendix C.

Both provide comparable data; however, their orientation is different. The former has as its objective the creation of a baseline economic model for a total system acquisition which establishes the economic worth of all system functions and measures the resources that should be allocated to each function in satisfaction of performance requirements. The latter analysis stresses the practical ramification of satisfying performance requirements within the functional areas subject to the economic constraints as dictated by that functions importance to the system. Here, each function has available a tool which permits continuous economic assessment of design options. The cost tradeoffs conducted are an integral part of the design selection process. Designs which satisfy a spectrum of possible methods and techniques are compared and selected subject to good design practice, system technical performance requirements and cost performance.

3.1 System Economic Cost Evaluation

The total system economic cost evaluation uses as a baseline vehicle system the 1500 nm crossrange, 50,000 lb. payload, delta body orbiter. The data in Table 3-1 illustrates various hardware system options considered in the economic evaluation.

TABLE 3-1 - SUBSYSTEM VARIATION OPTIONS

DESCRIPTION	OPTIONS	
Vehicle Configuration	Delta Body	
TPS Systems	Metallic, Ablative, Non-metallic	
TPS Subsystem (Material/Temp)	Columbium	
	Haynes 188	
	René 41	
	Tantalum	
	LI-1500 (3 temp regimes)	
	TTNiCr	
	Beryllium	
	Ablators	
	Dynaflex-Insulation	
	Titanium	
	Fail Safe LI-1500	
Crossrange	1,500 nm	
Generalized Area (ft^2)	Nose Cone	70
	Base Shield	1,610
	Fin/Rudder	
	Leading Edge	855
	Top	915
	Bottom	913
	Body	
	Chine	1,195
	Bottom	3,381
	Side	2,209
	Top	5,166
	TOTAL	16,311

To achieve balanced trade-studies, the cost data are required in a matrix which includes the cost value and cost-uncertainty for each of the categories shown in Table 3-2 .

TABLE 3-2 - ECONOMIC DATA CATEGORIES

ORGANIZATION/ FUNCTION	• Nine Functional Areas	Engineering Materials Analysis/Test Engineering Thermo Analysis/Test Engineering Loads & Criteria Analysis/Test Engineering Stress Analysis/Test Engineering Weights Analysis/Test Engineering Design/Mockup Manufacturing Quality Assurance Operations
COST PRESENT-ATION	• Three Program Phase Groups	Non-recurring DDT&E Recurring Production Recurring Operations
HARDWARE END ITEMS	• Five to Fifteen TPS Subsystems*	Nose Cap Base Shield Leading Edges Cooling System Lower-Surface Heat Shields (2 to 6 types) Upper-Surface Heat Shields (2 to 4 types)

*For any particular Orbiter, the number of subsystems varies from one configuration to another.

The functional area breakdown (9 elements) provides for suitable detail in the most basic elements of cost collection, namely, labor hour estimates.

Within each of the functional-area elements, a breakdown is made to at least one other level. This additional detail is needed to identify the operation tasks of each specific key development-program activity area. Each functional area then relates the work projected for the orbiter TPS to similar work done on actual hardware programs, in formulating the estimated man-hours, test article, material, etc. requirements.

The three program phase elements are cited below for convenience.

Non-recurring Costs (DDT&E). The definition of non-recurring cost is provided in NASA NHB9501.2, Procedures for Reporting Cost Information from Contractors, March 1967.

Recurring Costs (Production). Are defined as the costs associated with producing flight hardware up through acceptance of hardware by the Government, which includes all costs associated with: (1) The fabrication and assembly of flight hardware, (2) Ground test and factory checkout of flight hardware, (3) Spares to support airborne hardware during flight operations, (4) Maintenance of GSE and spares for GSE, (5) Maintenance of tooling and special test equipment, and (6) Sustaining engineering in support of hardware production.

Recurring Costs (Operations). Are defined as the costs associated with those activities occurring subsequent to Government acceptance of the flight hardware, and are further identified as:

a. Launch Operations: The costs of receiving the flight hardware, static firings, refurbishments of static test stand, assembly of the vehicle, checkout, prelaunch test and checkout, servicing, launching, and refurbishment of the launch pad.

b. Flight Operations: The cost of mission control, mission planning, flight crew training, and simulation and aids required for crew training (not to include the costs of those identified as test articles).

c. Refurbishment Costs: The costs of those activities required to restore a previously flown reusable system to a flight readiness condition.

The TPS subsystem category allows a logical lower-level hardware breakdown for the work breakdown structure (WBS), beneath the total TPS, as shown in Table 3-3. The heat shield type listed for TPS materials encompass a spectrum of material candidates. These candidates are determined from trajectory evaluations using temperature profiles similar to those illustrated in Figure 3-1 The list of candidate subsystems are each identified by a number for convenience during trade-study analysis. The "10" digit is assigned to a material, and the "1" digit identifies a highest temperature regime or a peculiar vehicle location. Also, it serves the vital trade-study function of dealing with a variety of heat shield designs, including a crosscheck of weight-versus-cost characteristics as these designs are applied in different orbiter/mission configurations.

Results of the total economic evaluation study will assist accomplishment of the following:

- Establish the relative economic importance of Refurbishment Operations to other system functions.
- Establish the TPS material subsystem which contributes most to System and Operation cost and uncertainty.
- Identify the operational tasks which produce the largest operational cost and uncertainty.
- Identify the effect of maintenance rate resulting from mission hazards, on the cost and uncertainty of operations.

With this information, it will be easier to relate the relative worth of refurbishment operations to the system as a whole and to show the economic importance of tests conducted on the Langley Mockup. These will be expressed in a priority table using cost and uncertainty to establish the priority.

TABLE 3-3 - RADIATION TPS SUBSYSTEM CODING

CODE NO.	MATERIAL	TEMPERATURE RANGE	LOCATION*
010	Ablator	2500° to 3000°	Nose Cone
011	Ablator	2000° to 2500°	Bottom
012	Ablator	1600° to 2000°	Bottom/Side
013	Ablator	1000° to 1600°	Side
020	Tantalum	2500° to 3000°	Nose Cone
030	Columbium	2000° to 2500°	Bottom/Chine
040	LI-1500	N.S.	N.S.
041	LI-1500	2000° to 2500°	Bottom
042	LI-1500	1600° to 2000°	Bottom/Side
043	LI-1500	1000° to 1600°	Side
044	LI-1500	N.S.	Base Shield
050	TDNiCr	2000° to 2200°	Bottom
060	Haynes 188	1600° to 2000°	L. Edge/Side
070	Rene' 41	1000° to 1600°	Side
080	Titanium	Under 1000°	Top
090	Beryllium	Under 1000°	N.S.
100	Dynaflex Insulation	N.S.	N.S.
101	Dynaflex Insulation	N.S.	Flap Shield
110	**FS-1500	N.S.	N.S.
111	FS-1500	2000° to 2500°	Bottom
112	FS-1500	1600° to 2000°	Bottom/Side

*N.S = Not specific, until configuration is defined.
**F S. = Fail Safe LI-1500 design.

1500 NM CROSSRANGE, $T = 2{,}500^{o}F$
TEMPERATURES IN ^{o}F ($\epsilon = 0.8$)
RHO-MU TURBULENT HEATING METHOD
GRADUAL TRANSITION $R_{et} = 1\text{-}2 \times 10^6$
MARGINS INCLUDED
LMSC DRAWING LO-2069
TRAJECTORY RE-150

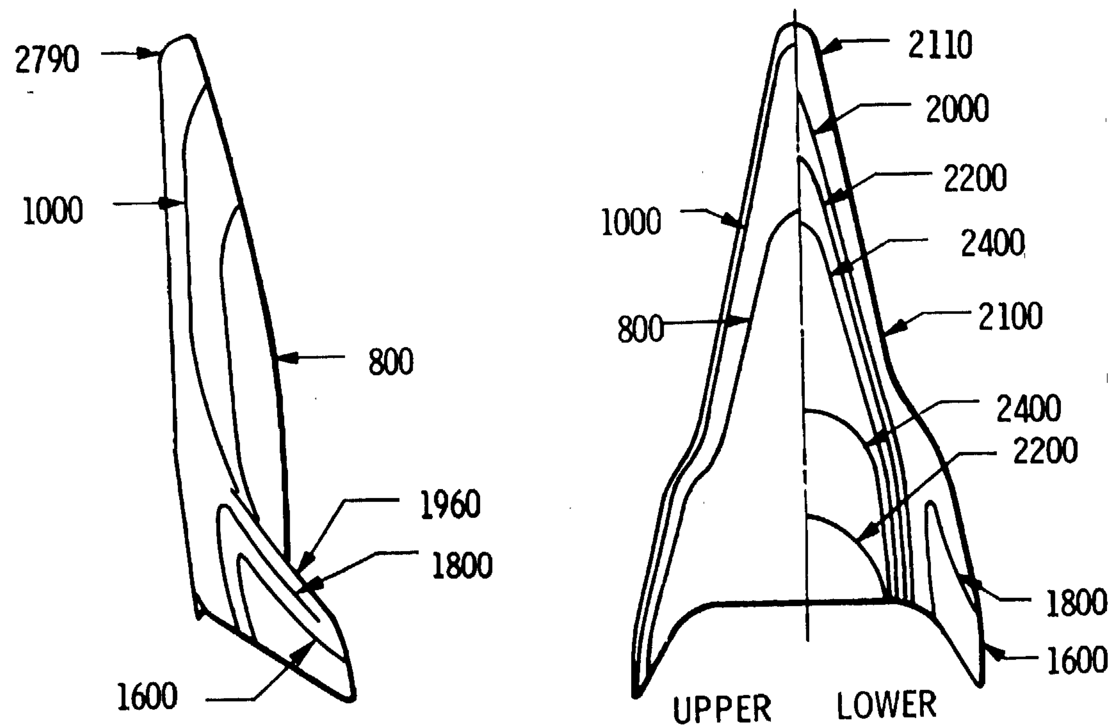


FIGURE 3-1 - DELTA BODY ISOTHERMS

3.2 Evaluation Methodology

The elements of the cost estimating approach are depicted in Figure 3-2. There are thirteen (13) steps required in developing total system cost:

1. TPS Sizing Data for Baseline Vehicle
2. End Item Summary Sheet - Operations
3. Production Panel Model
4. Maintenance Rate Sheet
5. Operations Expenditures - Hours
6. Operations Expenditures - Material
7. Vehicle Level Operations - End Item
8. Vehicle Level Operations - Operation Task
9. System Level Operations - End Item
10. System Level Operations - Operation Task
11. System Cost of Operations by Phase and TPS Subsystem
12. System Costs by Phase and Operational Task
13. System Costs by Phase and Function
14. System Cost Uncertainty by Phase

A general survey covering each step follows. Detailed information is available in Appendix B.

<u>TPS Sizing for Baseline Vehicle</u>

Each TPS material subsystem is structurally depicted and sized. TPS surface area (A) weight (W), and average unit weight per subsystem and vehicle are provided.

Material and panel geometry are considered as a function of the temperature regimes over the vehicle surfaces. While surface geometry and location on the vehicle are listed parameters, they are not at this time carried as factors in the total system cost analysis.

The data contained in the sizing exercise is used for calculating the number of panels (N) of a given material type. In this evaluation, a panel is approximately fourteen (14) square feet in area. Further use of the data is made in the <u>Production Panel Model</u> where area and weight are the principal cost-generating factors.

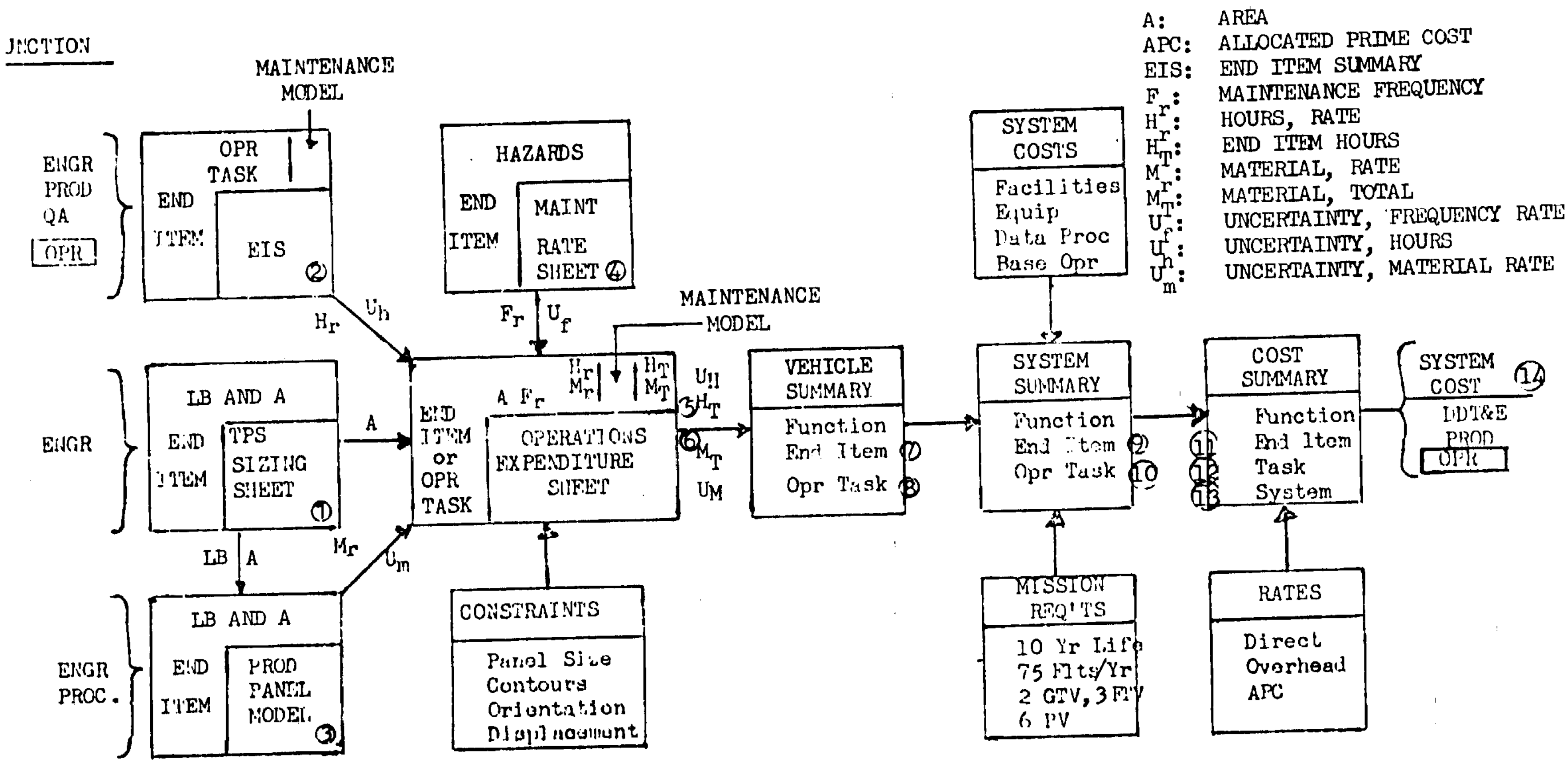


FIGURE 3-2 - OPERATIONAL COST ESTIMATING APPROACH

End Item Summary (EIS)

An End Item Summary Sheet (EIS) is used as the basic cost estimating document on which all original data regarding operations is recorded. Operations personnel have selected six (6) operation tasks for which a given material subsystem, End Item, can be expected to produce a cost impact. These are presented as:

- Panel Installation
- Panel Removal
- In-Process Inspection
- Packaging and Handling
- Storage
- Maintenance

Various methods and techniques are considered for accomplishing each of these tasks and hourly rates (H_r) assigned commensurate with the degree of effort required. The nominal hourly estimates are based on performing similar type operational tasks on a known baseline material, which in this evaluation is titantium. The uncertainty assigned to each End Item/Operation Task element (U_h) indicates the degree to which selected methods and techniques are well enough understood to be in fact accomplished in the time indicated.

End Item totals and Operation task totals are used in the Operational Expenditures calculation where they are modified by the Maintenance Factors to produce a vehicle refurbishment labor cost.

Production Panel Model

Panel structural design varies with material type, temperature regime, location on the primary structure and design approach taken on the vehicle structure.

Production panel weight (W) and area (A) values are obtained from the TPS sizing exercise. They are represented in a format where those costs which are a function of weight can be separated from those that are a function of area. Cost per pound and per square foot are provided by Procurement Material estimators. The production panel model provides material cost rates (M_r) and uncertainty (U_m).

Production panel costs are used in the Operational Expenditures calculation where they are modified according to Maintenance Factors to produce logistic maintenance material costs.

Maintenance Factors

The combined effect of all mission hazards encountered by a TPS system while flying a selected mission profile will determine the nature and extent of operational refurbishment. Inspection, maintenance, and logistic TPS activities (and costs) are essentially a direct function of the operations that must be undertaken as a result of the hazards experienced.

A matrix of TPS Maintenance Frequencies provides values that indicate the degree to which a selected TPS subsystem will respond to a given hazard. Materials Engineering has selected six (6) environmental factors which affect operational costs and established maintenance frequencies for each. These are presented as:

- Temperature Exposure
- Combined Temperature/Load
- Combined Temperature/Pressure
- Combined Temperature/Pressure/Load
- Packaging and Handling
- Environment (Operations)

Integrating the spectrum of hazards over the mission profile provides a maintenance rate (F_r). Maintenance rates are interpreted as "the expected number of flights a TPS subsystem will experience before some maintenance action is required". Both rate (F_r) and uncertainty (U_f) are iteratively developed measures derived from existing documentation and best engineering judgments.

The end item maintenance rates are used in the Operational Expenditures calculation where they are used to determine the numbers of panels replaced per TPS subsystem and from this the vehicle labor hours and materials.

Operation Expenditures

Operational Expenditure calculations are made to determine the vehicle labor and material cost subject to the data just described in the previous step and operation premises.

Number of panels (N) and maintenance rate (F_r) are used to calculate the expected number of panels maintained (P_r). Hourly panel rates (H_r) developed in the EIS exercise and material costs (M_r) calculated by the panel model are combined with factors from the maintenance model to arrive at end item hours (H_T) and material (M_T).

These results are summarized in a series of manipulations which convert every cost factor to dollars, beginning with Vehicle Level Operations.

Vehicle Level Operations

Vehicle costs are summarized by end item and operation tasks using data obtained from the Operation Expenditure effort. Maintenance, Inspection, Material and Equipment costs are displayed as recurring or non-recurring for those costs that were determined from the Operation Expenditure analysis, as well as, those prorated costs which are not estimated at the end item level. Base Inspection falls into this latter category and is prorated to the subsystem level on an end item area basis.

The consolidation of all recurring and non-recurring end item and operation task costs on one summary sheet is in preparation for the application of mission life cycle requirements in determination of System Level Operations costs.

System Level Operations

System level operation costs are summarized by End Item and by Operation Task. Values are obtained by multipying the vehicle level operations data by the number of missions flown over the life of the program by a given fleet of vehicles. In this evaluation, there are eight (8) vehicles in the fleet. This group will fly 75 missions a year for 10 years, which will require 750 refurbishments over the life of the program. The total expenditures for labor, material and equipment are provided.

Equipment is often required to perform system type activities. As such, it is a system level cost and applies across the whole vehicle fleet for the life of the program. For cost comparison purposes the cost is prorated to the subsystem on the basis of end item area.

System Cost by Phase and TPS Subsystem

Total system cost is first developed at this step in the evaluation. Rates and normal price estimating procedures are applied to develop a total system cost by Phase, Recurring, Non-recurring and TPS Subsystem. The results provide a system level look at end item cost drivers.

System Cost of Operations by Phase and Operational Task

System costs for Operations are developed by Operation Task. Like the previous effort performed for end item cost, the data is reoriented to provide cost by Operation Task and Phase.

System Cost by Phase and Function

Total system cost is broken down into its six (6) functional areas and two (2) summary cost groups for the three (3) program phases.

Together the three (3) System Cost categories give a composite picture of the major end item, operation task, and function cost drivers.

System Cost Uncertainty by Phase

Nominal costs to perform the DDT&E, Production, and Operation phases reflect the depth of informational detail available to all functional groups. The estimates developed in the preceding exercises are based on a mix of subjective judgment, "similar to" knowledge, and definitive information. The extent to which definition is lacking will appear in the magnitude of associated uncertainty factors.

The importance of this information is twofold: (1) It provides perspective which allows the establishment of priorities for further development activities that will effectively lead to uncertainty reduction and definitive costing, and (2) the data can be directly related to a function, activity, or end item, permitting critical appraisal of design and system tradeoffs and maintenance of program objectives.

A total economic evaluation was performed on five (5) TPS material systems. Each exercise is referred to as an "Iteration" because in the normal evolution of a development program the costs would be continually modified in an iterative manner as new and better design information is made available. Results of each iteration are discussed in the material that follows.

3.3 System Cost Evaluation

A system cost summary is presented in Figure 3-3 for the five (5) TPS system iterations. System cost is greatest for ablators varying from 4.1 to 5.6 times more costly than those exhibited by its competitors. This high cost results from the large number of ablative panels (627) that must be replaced after every flight as opposed to metallic and non-metallic panels whose replacement rates range from 32 to 39 panels per flight.

Cost difference between each TPS iteration are listed in Table 3-4 for DDT&E and Production. These entries were developed as a part of a continuous effort at LMSC to establish space shuttle system cost estimating baselines. The high material replacement requirement of ablative systems and the resultant logistic impact it has on production account for the high production cost of this functional area.

There are two significant features of an ablative system that are favorable to its use. While operational costs are nominally large, there is sufficient uncertainty regarding the reusability of ablative materials to indicate that operational costs could be significantly less than nominal ($424 million). This, when coupled with the fact that performance of ablative systems in the hostile environment of entry is well documented, would tend to substantiate the likelihood of realizing lower operating costs. The second favorable item stems from the fact that DDT&E cost (Table 3-4) is less for non-reusable ablators than for the other TPS systems. Less expensive ablator materials and simplified design requiring less development are the apparent reasons.

TABLE 3-4 - PRODUCTION, DDT&E SYSTEM COSTS

ITERATION	TPS SYSTEM	COST IN MILLIONS		
		DDT&E	PRODUCTION	TOTAL
4	ABLATOR	$ 52.6	$ 760.5	$ 813.1
2	METALLIC (Cb)	82.4	193.2	275.6
6	METALLIC (TDNiCr)	80.9	183.1	264.0
5	NON-METALLIC (FS-1500)	69.5	183.0	252.5
3	NON-METALLIC (LI-1500)	59.6	151.4	211.0

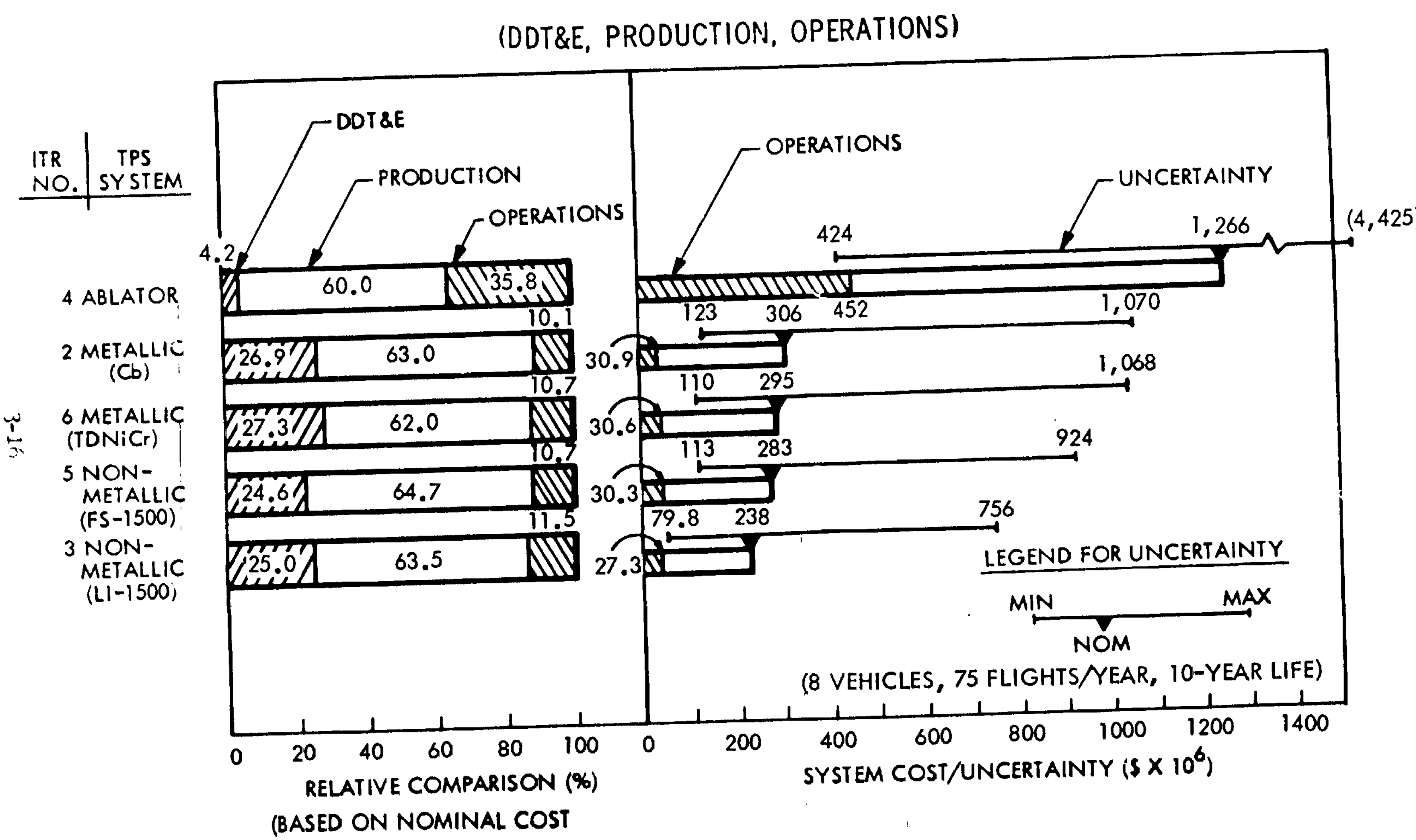


FIGURE 3-3 - SYSTEM COST SUMMARY

The one overriding fact still remains that until reusable ablative concepts are developed, operational costs will constitute the largest portion of system acquisition expense, which in this evaluation is 35.8%.

Metallic TPS systems, whether columbium or TDNiCr, have essentially the same total system cost and uncertainty. Technological uncertainty suggests that total system costs could amount to approximately $1,070 million for either system. Operation costs average 10% of total system cost, amounting to $30.9 million for columbium and $30.6 million for TDNiCr.

Non-metallic systems cost the least of the three TPS systems. This is due to material costs being much less than for metallic, so that the differential cost is enough to offset the impact of the slightly lower maintenance rate. Fail Safe LI-1500 costs exceed those for LI-1500 because of higher development and production costs associated with securing a more complex material system.

In summary, the system cost summary shows that for an eight vehicle fleet, flying 75 flights per year over a ten year period, metallic and non-metallic TPS system have the potential for significant savings in resources as compared with an ablative system. However, technological uncertainty is large enough that these systems can cost as high as 1,068 to 1,070 million dollars while an ablative system can cost as low as 424 million dollars. On the basis of existing ablative knowledge and contracts presently underway, the chances of realizing a major portion of the 424 million dollars cost may be achievable. However, the alternative can force the total acquisition cost as high as 4,425 million dollars.

3.4 Maintenance Rate Summary

Material costs are a function of unit price ($/ft^2) or ($/lb) and total material usage. Consequently, the total system cost of a high-unit-cost material may be less than that for a low-unit-cost material because of its low relative usage. This interplay between unit material costs and TPS subsystem usage occurs in labor costs as well. Difficult subsystems to fabricate and maintain will have high hourly unit costs but the impact on total labor will vary with the total material subsystem requirement.

A third and principal cost driver is maintenance rate. Operationally efficient TPS panel designs may be realized but if the maintenance rate is low, as it is so graphically evidenced with ablators (F_r=1). Such efficiencies will serve only to minimize an already large operational cost because the total operational cost will be driven up by the large number of panel replacements.

Expected maintenance rates of each TPS system and associated subsystems are displayed in Figure 3-4. Metallic materials are expected to fly more missions (29.3 to 41.0) than non-metallics (22.6 to 35.8) before some maintenance action is required. An exception occurs with the tantalum nose cone (020) where, because of the severe environment experienced, the maintenance rate is lower (10.7). Ablators can fly only one (1) mission.

With the exception of tantalum (020) and ablator subsystems, indicates that no TPS subsystem should have a rate less than 40 and that this can go as high as 90 for metallic and 94 for non-metallic materials. On the other hand, the various subsystem rates can range as low as 15 for non-metallic and 28 for metallic materials. Table 3-5 shows the expected number of refurbishments per 100 missions that each TPS subsystem will experience.

(DELTA BODY, 50,000 LB PAYLOAD, 1,500 NM CROSSRANGE)

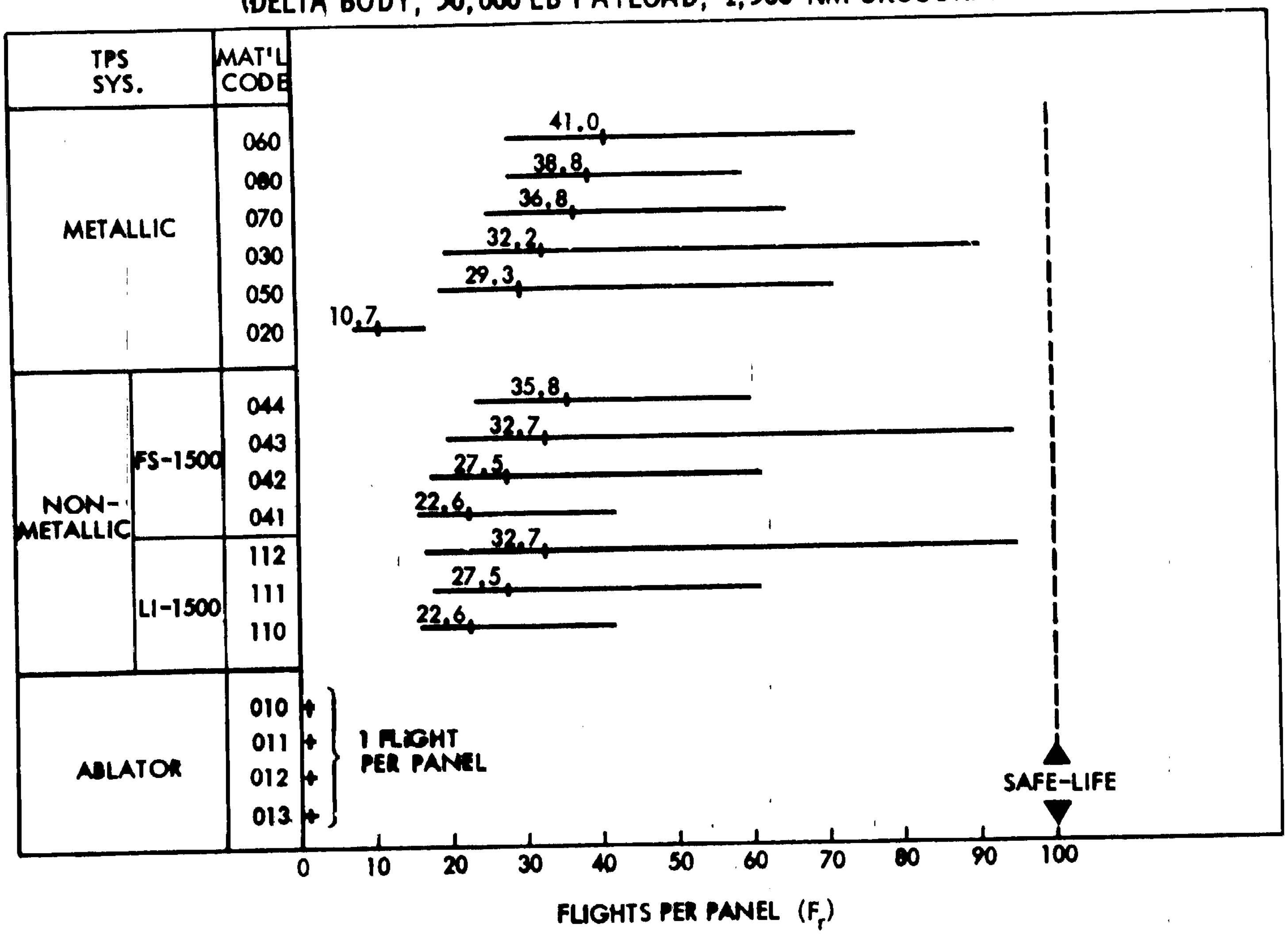


FIGURE 3-4 - MAINTENANCE RATE SUMMARY

TABLE 3-5 - TPS SYSTEM REFURBISHMENTS

TPS SYSTEM	CHANGES PER 100 MISSIONS
METALLIC	2.5 to 3.5
NON-METALLIC	2.8 to 4.5
TANTALUM (020)	10
ABLATOR	100

A vehicle with a 100 mission safe life requirement (no major refurbishment in less than 100 missions) is not yet achievable with existing or near term materials technology. Much more effort is needed in the area of safe life testing, if these results are representative. This would indicate that expenditures for material development should be reassessed to determine their adequacy.

3.5 Operational Costs Uncertainty

It is important in assessing refurbishment activities to have knowledge about the relative cost of Operations to Production, and DDT&E. In particular, this information will serve to indicate what monetary emphasis should be placed on securing efficient operations and panel designs.

Operational costs and uncertainties for each material system and five (5) study iterations are displayed in Table 3-6. As previously discussed under System Cost Evaluation, operations will constitute from 10.1 to 11.5 percent of total system costs for metallic and non-metallic systems, while ablators will be 35.8 percent of total system acquisition.

Technological uncertainty is less for ablators than for metallic or non-metallic systems. Non-metallic systems exhibit the highest uncertainty although the disparity between TPS system uncertainties is not large. This is attributed to the panel design concept used in this study and interchangeability features of all panels which tends to make each material system panel operationally similar. Methods and techniques used in performing time line operation tasks are the factors contributing to uncertainty.

TABLE 3-6 - OPERATIONAL COST UNCERTAINTY SUMMARY
(RECURRING)

COST UNCERTAINTY FACTORS AND COST RANGE	TPS SYSTEM				
	ABLATOR	METALLIC		NON-METALLIC	
	Iteration #4	Iteration #2	Iteration #6	Iteration #5	Iteration #3
HIGH UNCERTAINTY FACTOR	3.59	4.76	4.87	4.84	5.25
LOW UNCERTAINTY FACTOR	$\left(\frac{1}{3.10}\right)$	$\left(\frac{1}{3.92}\right)$	$\left(\frac{1}{4.00}\right)$	$\left(\frac{1}{3.36}\right)$	$\left(\frac{1}{4.06}\right)$
HIGHEST TPS COST	$1,617 M	$146.3 M	$148.9 M	$146.1 M	$143.7 M
NOMINAL TPS COST	453 M	30.9 M	30.6 M	30.3 M	27.3 M
LOWEST TPS COST	146 M	7.9 M	7.7 M	9.0 M	6.7 M
PERCENT OF TOTAL SYSTEM COST (%)	35.8	10.1	10.7	10.7	11.5

NOTES:
- UNCERTAINTY FACTORS ARE SUMMATION VALUES REFLECTING ALL COST ELEMENT UNCERTAINTY ESTIMATES.
- THE HIGH & LOW FACTORS ARE MULTIPLIERS TO BE USED WITH NOMINAL COSTS TO OBTAIN ESTIMATED HIGH & LOW COST LIMITS.
- THESE DATA REFLECT A TYPICAL TPS COST ESTIMATE FOR A DELTA BODY ORBITER, 1500 NM CROSS RANGE.
- LOGISTIC SPARES ARE NOT INCLUDED IN THESE VALUES.

3.6 Operational Cost for TPS Materials

In Figure 3-5 the operational cost per square foot of TPS material applied to a delta body orbiter is presented. Thus normalized, each material system and subsystem can be compared. For a given material subsystem (material Code), the dollars represent the cost of maintaining a uare foot of that material over a 10 year life of the system.

Albators have the highest cost per square foot, approximately $50,000, except for the nose cone which amounts to $85,000. No one metallic or non-metallic subsystem is uniformly less expensive to maintain over the temperature regimes shown. Operating costs do tend to diminish as temperature goes down. This is because low-temperature operation extends periods between refurbishment. Furthermore, it decreases the amount of material required, hence, reduces cost. Table 3-7 presents the cost range for TPS system and temperature regime along with the high and low cost material subsystem.

TABLE 3-7 - TEMPERATURE EFFECT ON OPERATIONAL COST

TEMPERATURE	OPERATIONAL COST RANGE ($/FT^2)*		
	METALLIC NON-METALLIC ($)	ABLATIVE ($)	LOCATION AREA (ft^2)
Over 2500	14,500 Ta	85,000	Nose Cone 70
2000 to 2500	2,000 to 2,800 Cb LI-1500	50,CCC	Bottom Chine 4,576 to 5,431
1600 to 2000	1,350 to 1,950 FS-1500 Haynes	52,00C	Leading Edge Side 1,277 to 2,132
1000 to 1600	1,300 to 1,550 FS-1500 LI-1500	52,000	Bottom Side 1,845
Under 1000	1,300 to 044 080	-	Top 6,078

*Based on Nominal Costs

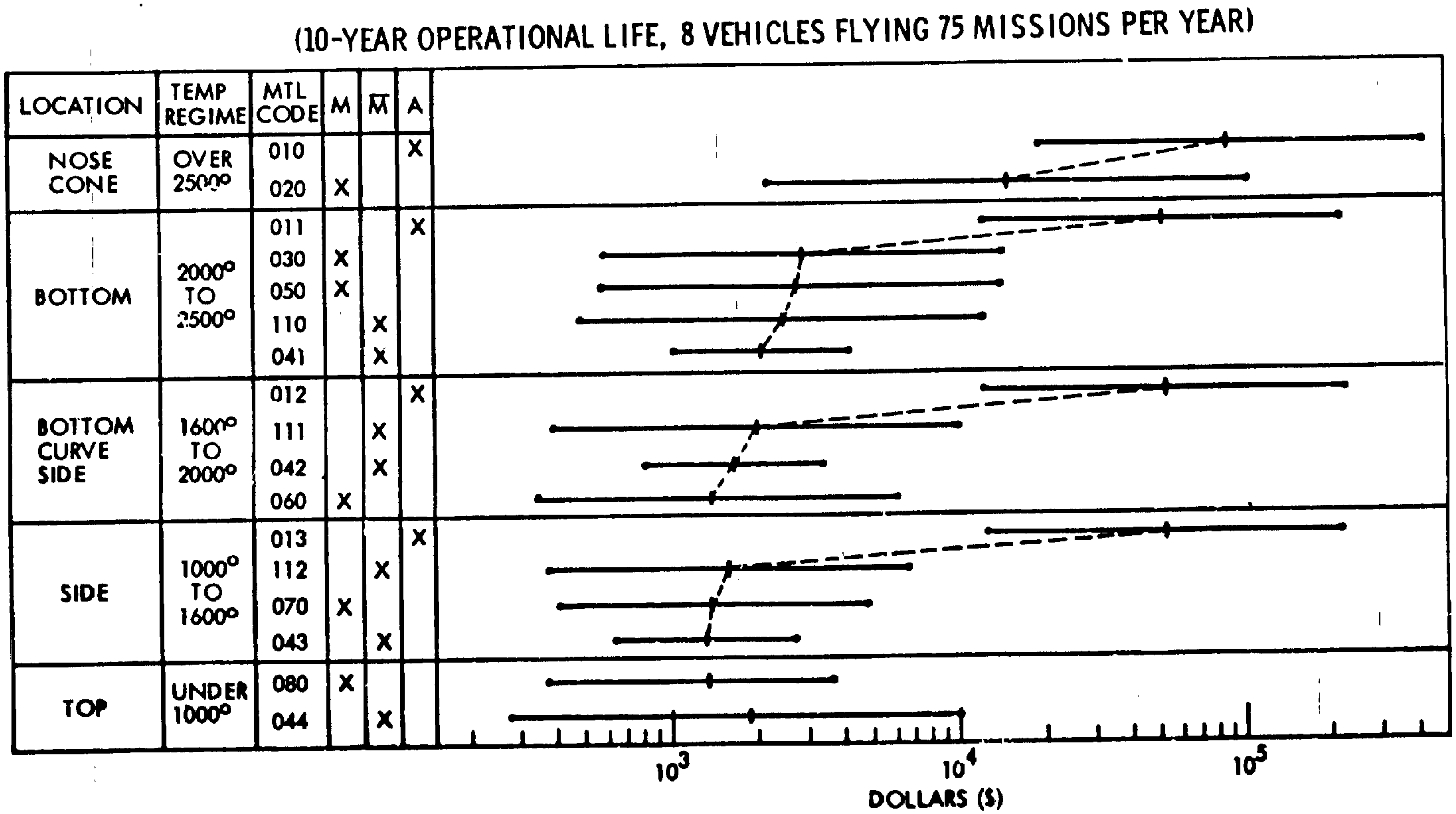


FIGURE 3-5 - OPERATIONAL COST PER SQUARE FOOT OF TPS MATERIAL (10 YEAR OPERATIONAL LIFE, 8 VEHICLES FLYING 75 MISSIONS PER YEAR)

It is evident from this table that temperature effects will produce operational costs that range from $1300 to $2800 per square foot for metallic and non-metallic TPS system, and $50,000 to $52,000 for ablative TPS over the total surface of the Orbiter, except for the nose cone where material and maintenance rate effects become more pronounced.

From a vehicle design standpoint, these results indicate that a low operational cost vehicle system would be one which had the material distributions illustrated in Table 3-8.

TABLE 3-8 - POSSIBLE LOW OPERATING COST TPS SYSTEM

LOCATION	TPS * MATERIAL	MATERIAL CODE
Nose	Ta	020
Bottom	LI-1500	041
Bottom Side	Haynes	060
Sides	LI-1500	043
Top	Titanium	080
Base Shield	LI-1500	044

*Base on Nominal Costs

Refurbishment studies conducted on the Langley Mockup can involve materials such as these indicated in Table 3-8 if real TPS materials are used for panels.

3.7 Operational Tasks

Operational tasks which are performed during vehicle system maintenance vary significantly between tasks as illustrated in Figure 3-6. Again, ablator and metallic/non-metallic TPS systems are widely separated in cost. However, TPS subsystem variations result in relatively small changes between iterations within the metallic/non-metallic category. This is illustrated in Table 3-9 where the range of nominal cost for each of the six (6) operation tasks is presented.

TABLE 3-9 - OPERATION TASK COST RANGE

OPERATION TASK	COST RANGE (MILLIONS OF DOLLARS)	
	METALLIC/NON-METALLIC ITERATIONS 2, 3, 5, 6	ABLATOR ITERATION 4
Maintenance	13.5 to 19.0	213
Panel Installation	6.4 to 8.4	147
Panel Removal	2.0 to 2.6	49
Inspection	2.3 to 2.4	22
Packaging & Handling	.55 to .65	11.9
Storage	.44 to .58	10.6

Maintenance is defined here as repairs of level one (1) and higher. Repair-in-place activities as well as repairs performed away from the vehicle are considered under Maintenance. Both labor and material incurred while restoring panels to a flightworthy condition are charged to this task area. Logistic spans resulting from scraping panels are chargeable to Manufacturing as a recurring production cost. Maintenance uncertainty is large. On the high side, both metallic and non-metallic systems overlap ablative maintenance cost. The magnitude by which maintenance cost deviates from nominal is indicative of the general lack of knowledge that exists regarding maintenance problems. Should a low maintenance uncertainty result, panel installation could replace maintenance as the major cost driver.

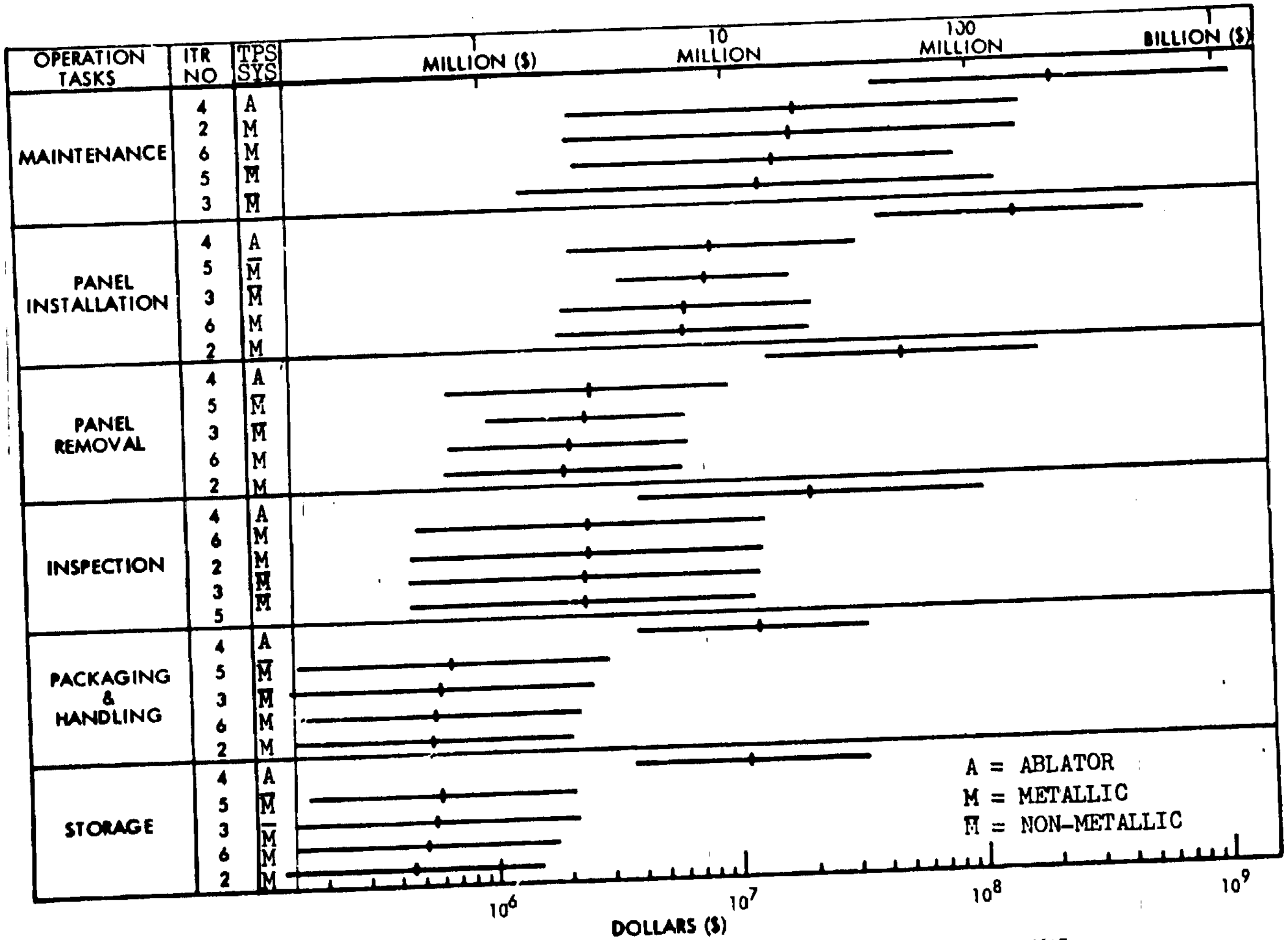


FIGURE 3-6 - COST/UNCERTAINTY COMPARISON FOR OPERATIONAL TASKS

The maintenance task is not within the general interest area of the RCS program, although certain controlled tests might be performed in this area if real materials are secured for testing purposes.

Panel installation is both costly and uncertain. Uncertainty occurs because of difficulties that are expected to occur in replacing panels after the vehicle has performed a mission. This concern is reflected in the higher nominal cost to install panels as opposed to removing them where care in handling may not be as stringent.

Panel removal and inspection have comparable nominal costs but the magnitude of the inspection uncertainty is larger. The Quality Assurance function is just not clear as to the scope of this activity or sufficiently knowledgeable as to what methods and techniques will be applied. For this reason, having a qualified Quality Assurance man on the Phase II Test Team is recommended.

Packaging/Handling and Storage tasks are minor contributors to total system cost. Asssociated uncertainties are of interest because of the magnitude. Concern has been expressed regarding the susceptibility of these operational tasks to the materials handled and stored. If the materials must be handled with great care and protected from physical and/or environment conditions, then costs will be high.

In summary, the ranking of operation tasks shown in Table 3-9 represents the order in which emphasis should be placed in selecting methods and techniques for developing a test program on the Langley Mockup. Inspection and panel removal tasks are not mutually exclusive and so should be conducted jointly. It would appear that a test program should involve panel replacement and removal tasks with inspection overseeing the operation. Packaging/Handling and Storage tests can be conducted aside from the primary test, if representative physical characteristics exist with the panels being tested.

3.8 Refurbishment Costs

Refurbishment includes all operational tasks except maintenance. Because refurbishment costs are of primary interest in this study, the labor cost for each material system has been determined and summarized in Table 3-10.

TABLE 3-10 - REFURBISHMENT UNIT COSTS

ITERATION	MATERIAL SYSTEM	COST ($) (1)	PANELS REPLACED (2)	COST PER UNIT AREA ($/FT²) (3)
4	Ablator	239.7	460,000	35.50
5	FS-1500	14.6	29,000	34.30
3	LI-1500	13.9	29,000	32.60
6	TDNiCr	12.3	25,000	33.40
2	Cb	11.9	24,000	35.40

(1) Cost in millions.
(2) 750 flights over 10 years.
(3) Panel area = 14 ft^2.

Total refurbishment labor cost for an ablative system is approximately twenty (20) times that for metallic or non-metallic systems. This situation is typical of any non-reusable system even though the cost per square foot to refurbish the system is comparable to the other material systems. Because the panel design concept is the same for all TPS material systems, unit area cost should be essentially the same and is.

Recurring logistic costs required for refurbishment are provided in Table 3-11 along with initial production expenditures.

TABLE 3-11 - REFURBISHMENT LOGISTIC COST*

ITERATION	LABOR ($)			MATERIAL ($)			TOTAL ($)
	INITIAL PROD	RECURRING PROD	LABOR TOTAL	INITIAL PROD	RECURRING PROD	MATERIAL TOTAL	
4	23.0	545.3	568.3	5.4	186.8	192.2	760.5
5	28.5	120.0	148.5	6.6	27.8	34.4	182.9
3	23.5	98.6	122.1	5.6	23.7	29.3	151.4
6	30.3	107.8	138.1	9.9	35.1	45.0	183.1
2	32.5	112.0	144.5	10.9	37.7	48.6	193.1

*Cost in millions.

It is evident that the cost to purchase materials and fabricate panels for refurbishment is much greater than the initial expenditure for TPS in the production vehicles. This is in sharp contrast to the logistics unit costs shown in Table 3-12.

TABLE 3-12 - LOGISTICS UNIT COSTS

ITERATION	LOGISTIC COST*	PANELS REPLACED	COST PER UNIT AREA ($/FT^2)**
4	760.5	460,000	118.00
5	183.9	29,000	450.00
3	151.4	29,000	373.00
6	183.1	25,000	524.00
2	193.1	24,000	575.00

*Cost in millions.
**Panel area = 14 ft^2.

The relative cost of producing panels may favor the ablative systems, however, its non-reusable feature negates any cost advantage that might be realized in the total system cost.

Refurbishment tasks are compared with operations and total system cost in Table 3-13.

TABLE 3-13 - REFURBISHMENT COMPARISON BETWEEN OPERATIONS AND TOTAL SYSTEM COSTS

ITERATION	OPERATIONS (%)	TOTAL SYSTEM (%)	REFURBISHMENT ($)*
4	52.8	17.3	239.7
5	48.2	5.2	14.6
3	49.0	5.8	13.9
6	40.3	5.2	12.3
2	38.4	3.9	11.9

*Cost in millions.

Refurbishment costs represent from 38.4 to 52.8 percent of operations; the remainder is expended by maintenance. Compared with total system cost, refurbishment will expend 3.9 to 17.3 percent of this cost over the ten (10) year life of the system.

3.9 CER and Bottom-Up Cost Comparisons

Concurrent with bottom up costing, an independent CER (Cost Estimating Relationship) estimate was made to make comparable cost data comparisons. The CER approach uses the IDA model as modified by LMSC System Engineering to fit present Space Shuttle support programs.

The CER costs are tabulated in Table 3-14 for only those functions which would make a cost contribution to a total TPS cost. The total TPS cost of 610.6 million dollars represents 9% of the total system cost, 6,767.6 million dollars.

TABLE 3-14 - CER SYSTEM COST ANALYSIS
METALLIC TPS (TDNiCr)

ALL ENTRIES IN MILLIONS OF DOLLARS

DESIGNATION	SYSTEM	ORBITER	TPS
NR (DDT&E)	$ 5,512.4	$ 2,498.5	$
STRUCTURE		719.0	345.2
TEST HARDWARE (Labor)		310.6	149.0
(Matl)			
FLIGHT OPS	86.0		
Refurbishment	10.5	(5.25)*	(2.625)**
NR Total	$ 5,512.4		$496.825
R (PRODUCTION)	$ 501.7	305.6	$ 55.6
(OPERATION)	753.5		
Launch Ops			
Flight Ops	315.3		
Refurbishment	232.7	(116.35)*	(58.175)**
R Total	$ 1,255.2		$ 113.775
TOTAL	$ 6,767.6		$ 610.600

* Cost shared 50/50 between booster and orbiter.
** Cost shared 50/50 between TPS refurbishment and other orbiter refurbishment activities

Operation refurbishment is estimated to cost 58.2 million dollars which is 0.9% of the total system cost and 7.7% of the total operations cost of 753.5 million dollars over the ten (10) year life of the system. These results are summarized in Table 3-15 according to the position of TPS operational refurbishment in the hierachy of system costs.

TABLE 3-15 - TPS OPERATION REFURBISHMENT RELATIONSHIPS

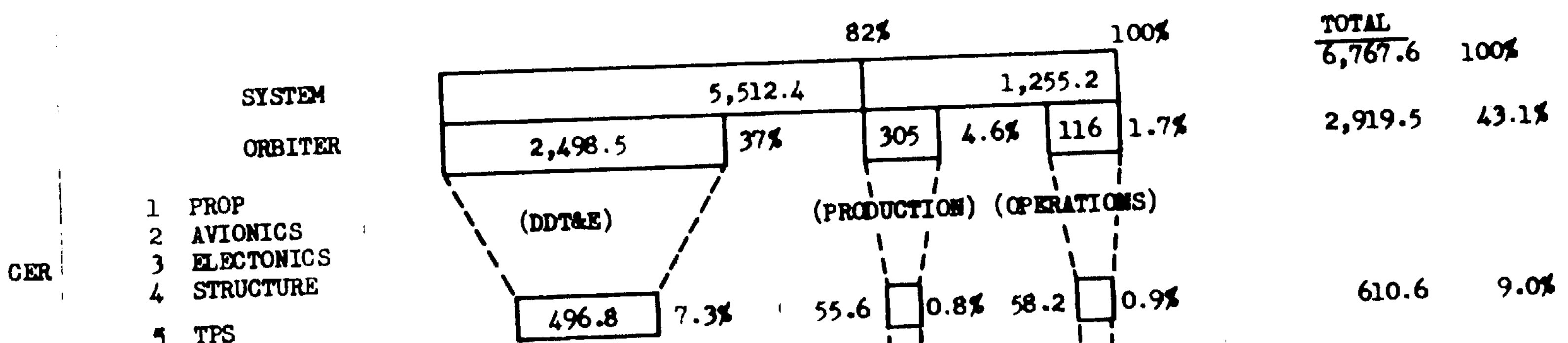
COST CATEGORY		ECONOMIC WEIGHT *		
		Level	Total ($)	%
SYSTEM	TOTAL SYSTEM COST	1	6,767.6	100.00
	SYSTEM OPERATIONS	2	753.5	11.10
	FLIGHT OPERATIONS	3	315.3	4.65
	REFURBISHMENT	4	232.7	3.42
ORBITER	ORBITER	5	116.0	1.72
	TPS SYSTEM	6	58.2	.9

*All entries in millions of dollars.

It is significant to note that the operational uncertainties that can be addressed on the Langley Mockup fall in the sub-categories of methods and techniques which time line study shows would be below the sixth (6th) level. This would indicate that such costs are quite possibly of little consequence in the overall problem of reducing operating costs. This latter point is further emphasized when it is realized that 92.3% of the System Operations cost is going to be spent in areas other than TPS.

In Figure 3-7, CER and bottom-up costs are compared. Bottom-up estimates for Operations compare favorably with the 58.2 million CER value, particularly since the uncertainty values encompass the CER value. However, the DDT&E and Production costs differ significantly. DDT&E bottom-up values are less than the CER value of 496.8 million dollars by a factor of six times for comparable metallic systems. The variance is the result of insufficient definition of

(ALL ENTRIES IN MILLIONS OF DOLLARS)



BOTTOM UP

COST ITERATION	TPS SUB-SYSTEM	DDT&E	U	PROD	U	OPS	U	TOTAL	U
2	COLUMBIUM	82.4	299 30	193.2	456.0 110.0	30.9	146 7.9	306.5	1,070 123.5
3	LI-1500	59.6	165 15	151.4	317.0 89.6	27.3	143.7 6.7	238.3	756.0 79.8
4	ABLATOR	52.6	180 18	760.5	1,950.0 403.0	453	1,617 146	1,266.1	4,425.0 424.0
5	FS-1500	69 6	207 21	183.0	457.5 124.5	30.2	146.1 9.0	282.9	924.0 113.1
6	TDNiCr	80.9	301 28	183.1	445.0 96.9	30.6	148.9 7.7	294.6	1,068.0 110.0

U = UNCERTAINTY

FIGURE 3-7 - CER/BOTTOM-UP COST COMPARISON the development program for good cost estimating to be accomplished by the Engineering function. While they express their concern over this problem in the uncertainty values, it is apparent that the bottom-up high uncertainty values still do not encompass the CER value. In the iterative process of system development, more work is required on system definition in order to resolve this cost estimation deficiency.

Production costs developed from bottom-up estimates are three times larger than the 55.6 million predicted by the CER value. A possible reason for this outcome can be observed in Table 3-16 where initial production costs and logistics spares requirements are displayed. The CER value of 55.6 million dollars and the nominal values for initial production are comparable in magnitude, with the CER value lying well within the uncertainty bounds estimated for initial production. However, the CER estimate does not account for logisitc spares lying well below the lower uncertainty values for total production. This outcome is largely due to a better definition of logistic spares requirements at the time bottom-up estimates were made.

TABLE 3-16 - INITIAL AND LOGISTICS SPARES PRODUCTION

ITERATION	INITIAL PRODUCTION		LOGISTICS SPARES	TOTAL PRODUCTION
	NOMINAL	UNCERTAINTY		
2	43.5	103.0 25.0	149.7	193.2
3	29.1	60.0 17.2	122.3	151.4
4	28.4	162.0 33.0	732.1	760.5
5	35.2	88.0 24.0	147.8	183.0
6	40.2	98.0 21.0	142.9	183.1

Here the concept of uncertainty shows itself to be a powerful tool because, had the CERs for DDT&E and Production been designed to handle uncertainty factors, the high and low overlap between the CER and bottom-up approaches would be a better measure of the significance in the deviation between estimates.

3.10 Operational Analysis

Operational analysis (Appendix D) shows that refurbishment activities involve only 33 percent of the total elapsed time expended in one turnaround period. It will be in this segment of the turnaround period that operationally efficient TPS panel design will have its largest impact on manpower skill, procedures and task time. In effect, skilled TPS personnel will be working 33% of the time. During the remaining 67% of the refurbishment period they will be sitting around. System level tradeoffs must be conducted to solve this problem of manpower optimization. However, within the period that crews are gainfully employed, something can be done to improve efficiency either through methods improvements or TPS panel design performance improvements. It is in this area that the Langley Mock-up will be effective.

Time line studies indicate that the concept of panel interchangeability results in the same nominal time to refurbish panels. However, the TPS material system selected does introduce differing uncertainties. A metallic TPS system has a larger uncertainty than that for either non-metallic or ablator systems, principally in those operational task areas involved with panel replacement. A priority list of operation tasks is shown in Table 3-17 for a shuttle system having a two (2) week turnaround operations cycle. Each operational event is ranked in descending order of nominal cost magnitude subject to the condition of high uncertainty.

The duration and uncertainty values for each time line event were estimated by maintenance personnel familiar with flight operations Underlined information highlights the total duration and weighted uncertainties for each operational step. Step IV involves refurbishment activities which are expected to take six hours but this can vary from 2.5 to 19 hours depending on the degree of difficulty encountered and methods of accomplishment. The remaining four steps are of shorter duration and with the exception of postflight inspection their uncertainties are less. Postflight inspection uncertainty is large because credible methods of quickly and effectively inspecting a vehicle after completion of a mission are not known.

TABLE 3-17 - PRIORITY LIST OF OPERATIONAL TASKS

PRIORITY	TIME LINE EVENT	TIME LINE EVENT DESCRIPTION	DURATION/UNCERTAINTY		
			NOM TIME	UNCERTAINTY H	UNCERTAINTY L
1.0	STEP IV	Conduct Refurbishment	6	3.19	1/2.34
1.1	4.7	Clean and Inspect	0.75	8	1/8
1.2	4.9	Position Panel and Check Fit	0.75	5	1/5
1.3	4.10	Attach Panel	0.5	4	1/4
1.4	4.46	Remove Panel	0.1	5	1/5
1.5	4.12	Clean and Inspect	0.5	2	1/2
	4.2	Remove Plugs	0.5	2	1/2
	4.1	Locate Panel and Plugs	0.5	2	1/2
1.6	4.3	Remove Closure	0.25	4	1/4
	4.11a	Install Plugs	0.25	4	1/4
1.7	4.4a	Detach Panel	0.4	2	1/2
1.8	4.11b	Install Closure	0.25	2	1/2
1.9	4.8	Unpack and Inspect New	0.25	1	1
2.0	STEP I	Post Flight Inspection	4	8	1/8
3.0	STEP V	Final Operations	4	2	1/2
4.0	STEP II	Scheduling	2	2	1/2
	STEP III	Preparation	2	2	1/2

Time line studies conducted on removing panels which are in close proximity or widely dispersed, show that the refurbishment time may vary from 4.4 to 6 hours per panel, respectively. The Langley Mockup would be effective in establishing the correctness of this nominal outcome.

Cost estimating was difficult in all areas of TPS refurbishment because a baseline operational system does not exist. Operations personnel could establish reasonable operational tasks but they were not in a position to state what methods and techniques would be most effective in accomplishing the tasks Nominal values and uncertainties assigned to each event are measures of this difficulty. These results indicate that it will be difficult to write a reasonable test program for the Langley Mockup until definitive test procedures are established. Without the explicit delineation of tasks, methods and techniques described in a baseline operational system, considerable judgment by experienced Operations personnel will be necessary. During the planning activity for Phase II, emphasis should be placed on securing such people and having them formulate definitive procedures.

Section 4

TEST PROGRAM PLAN

4.1 PURPOSE

This plan describes the series of tests recommended for the first of a progressive series of incremental steps phased to the development of the NASA Space Shuttle Program. These particular tests have been selected to provide reference data for evaluating the time and cost estimates for panel removal and replacement. This is the largest element of recurring TPS refurbishment cost; hence, improvements in this area can have the biggest impact on development cost, schedules, and operational costs.

4.2 SCOPE

This Phase II, Step 1 test program shall encompass the test operations described in the following Test Requirements Sheets, performed in sequence:

TRS No. NM 7 - PANEL LAY-UP AND REMOVAL (NON-METALLIC TPS)
TRS No. ME 7 - PANEL LAY-UP AND REMOVAL (METALLIC TPS)
TRS No. AB 7 - PANEL LAY-UP AND REMOVAL (ABLATIVE TPS)

The three (3) Test Requirement Sheets are provided at the end of this Section.

4.3 TEST FACILITIES AND EQUIPMENT

The test facilities and equipment to conduct the initial Phase II Test Program consist of the NASA-Langley Mockup, work access platforms, TPS panel-handling equipment, rigging, hand tools, and an enclosed work area of approximately 32' x 50', serviced by a 2-ton bridge crane. Other handling equipment, special tools, and devices which are peculiar to a given test are identified on individual Test Requirements Sheets. Special environmental and cleanliness controls are not specified for the test area due to an assumption that the tests defined for TPS panels and techniques to be evaluated in these tests should be capable of being performed without special attention to these factors. It is assumed that a design goal for the TPS system for the Shuttle vehicle would be to perform turnaround refurbishment in ambient atmosphere with minimum shelter requirements.

The tests will be performed on the NASA-Langley Mockup (M/U) located in a Government laboratory at the LRC. The M/U facilities and utilities are GFE for this test program; all other facilities and support equipment required by LMSC will be provided under the contract.

4.4 TEST OBJECTIVES

The basic objective of these tests is to identify means for reducing refurbishment costs. A corollary objective, therefore, is to establish reference times for evaluation of TPS refurbishment estimates and potential cost savings. Secondary objectives are to determine the operational adequacy of the preliminary TPS design concepts and the identification of operational procedures, processes, and special support equipment, so that requirements may be interjected into the Space Shuttle development cycle.

4.5 TEST ITEMS

Table 4-1 summarizes typical test panel weights. Options A-2 and B-2 are recommended test panels. Ablative panels are fabricated to NASA specifications and supplied by NASA. Panel drawings, test assembly, drawings, and layout drawings are included in Appendix E.

The test items consist of the following:

- Ablative, metallic, non-metallic panels fabricated from candidate materials and designs in selected sizes.
- Substructures and attachment hardware for attaching the TPS panels to the mockup in a manner comparable to that proposed for the Space Shuttle vehicle.
- Closure strips and other hardware required to simulate finished exterior surface of the shuttle vehicle.

TABLE 4-1 - HEAT SHIELD WEIGHT SUMMARY

DESIGN CONDITION

Substrate Temp: $600^{\circ}F$
Span Length: 25 in

Crushing Press: +2.5 psi
Bursting Press: -1.6 psi

HEAT SHIELD MATERIAL			SUB-PANEL	OPTION	OUTER PANEL Gage in	OUTER PANEL Unit Wt psf	CLIPS Height in	CLIPS Unit Wt psf	SUBPANEL Unit Wt psf	INSUL UnitWt psf	ADHES UnitWt psf	25"x25" Panel lb
METALLIC (Corrugated)	REAL	Cb	Ti	A-4	.015	.924	2.5	.48	.89	1.312		15.65
		TDNiCr	Ti	A-3	.010	.51	2.5	.45	.89	1.312		13.74
	SIMULATED	Al	Al	A-2	.012	.179	2.5	.69	.58	Filler Required		(**) 6.28
		Steel	Wood	A-1	.012	.52	2.5	.97	1.62	Filler Required		13.51
NON-METALLIC	REAL	LI-1500	Ti	B-7	2	2.50			1.07		.15	16.15
	SIMULATED	LI-1500	Steel	B-6	2	2.50			1.44		.15	17.78
		LI-1500	Wood	B-5	2	2.50			.96		.15	15.68
		(*) Mix	Steel	B-4	2	2.50			1.44		.15	17.78
		(*) Mix	Wood	B-3	2	2.50			.96		.15	15.68
		Foam	Steel	B-2	2	2.50			1.44		.15	(**) 17.78
		Foam	Wood	B-1	2	2.50			.96		.15	15.68

(*) Mix includes a panel combination of Foam and LI-1500
(**) Recommended Test Panels

4.6 TEST DOCUMENTATION

A test report shall be prepared at the conclusion of the test program to document the purpose, procedures, materials, operational times, and particular difficulties of each of the three TPS material systems. The time study data from successive iterations of test operations for each system shall be analyzed to detect learning trends and estimate nominal average times that might be expected for the operational phase of Space Shuttle, and the uncertainty associated with the estimate. The overall test program shall be analyzed to identify areas of technology, design, and support that should be considered for further development or testing.

The test report for this program is estimated to require approximately 150 pages, including 20 illustrations. Additional documentation of the tests, in the form of a silent movie, is suggested as a valuable record of a unique test program, a helpful aid to program planners and designers, and a useful training aid for future Space Shuttle TPS development test programs.

4.7 TECHNICAL DISCUSSION

The usefulness and validity of the test results depend upon the accuracy with which operational conditions are simulated or weighting factors for non-simulated conditions or activities determined. Application of learning curve techniques, to determine Nth unit time requirements is a well known practice but demands continuous production and, typically, extrapolates from data for the 20th or 50th units to predict performance on the 200th or 500th unit. Obviously, such data for the Space Shuttle is years off, but the basic technique can be used as an approximation if sufficient reference data is obtained to provide a starting point. Studies of maintenance operations of large airlines (TWA and United), a small airline (PSA), and military transports (C-130, C-141, C-5A, and P-3A) do not reveal any flight-line or "overnight" maintenance similarity to TPS, and only slight application of Class D (block overhaul) techniques to the conditions and type of construction and materials being considered for Space Shuttle TPS. Hence, sufficient testing on a mockup must be done to provide the reference time base for operational estimates.

Reference times are necessary for operations involving a group of panels and for individual panel replacement since typical shuttle maintenance is expected to involve both situations. A "test iteration" designed to accumulate data for both cases has therefore been specified. The iteration consists of applying an arbitrary number of TPS panels (9) to the Mockup in a 3 x 3 pattern, then removing one of the panels (preferably the center one because it is most typical of a vehicular installation, being completely surrounded by other panels), cleaning and inspecting the cavity, reinstalling the panel, and then removing the group of panels. Figure 4-1 shows a typical arrangement. The simulation should include such in-process inspection activities as checking fits, surface matching, correct part numbers, proper torques, etc. The "iteration" could have started with the "group removal" operation, more true-to-life, but would have necessitated an extra "group installation" cycle for each TPS material system at the beginning, and an extra "group removal" cycle at the end of each test series. The compromise in sequence will not affect the validity of the reference data obtained. A typical lay-up sequence for nine (9) non-metallic panels and closures is shown in Figure 4-2.

A minimum of two complete iterations for each simulated "vehicle area", namely the mockup vertical (side of the vehicle) and the mockup horizontal (bottom of the vehicle), are considered necessary to provide a basis for extrapolation. The more iterations that are performed the greater will be the confidence in the projections. It is important that the test operations not be prejudiced by activities or constraints that are not typical of an operational maintenance base environment. One complete iteration of the first material system to be tested, in this case, the non-metallic system, should be performed to familiarize the crew with the work area, source of minor supplies, the support equipment and tools, the Mockup, and the techniques and working conditions. This iteration permits the Time Study Analyst to lay out his work sheets and to identify meaningful discrete measurement points in the process. The Mockup and the test hardware

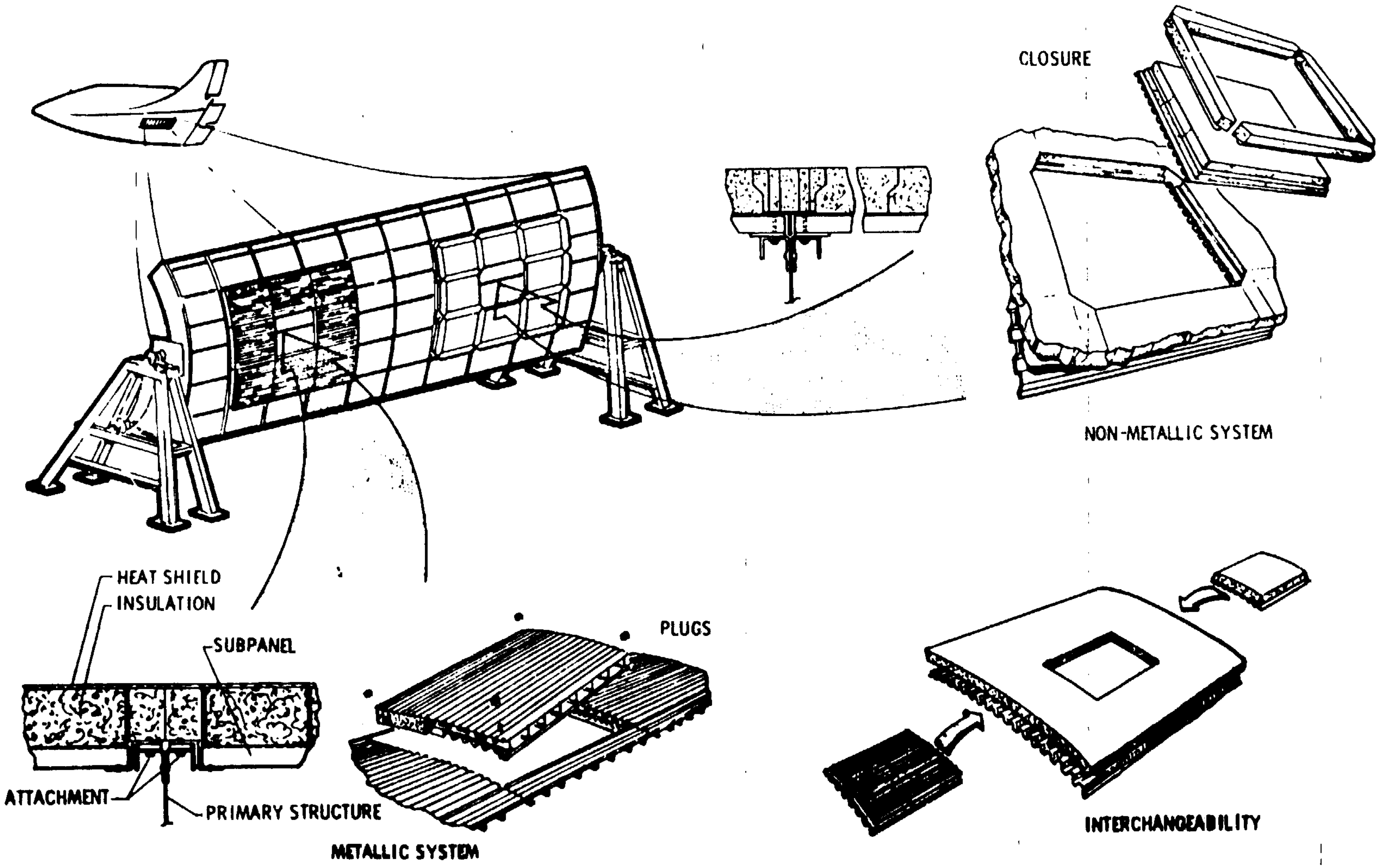
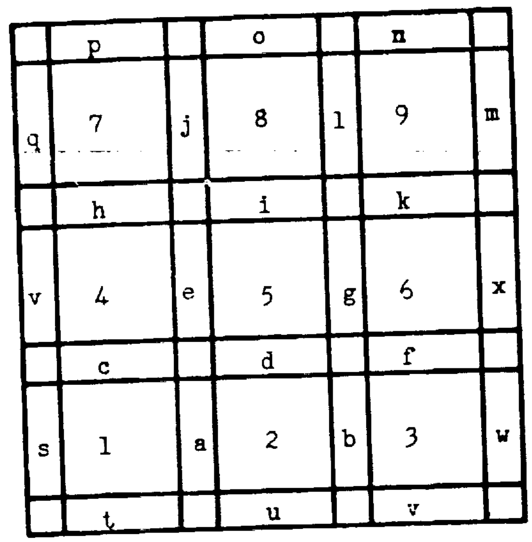


FIGURE 4-1 - LANGLEY MOCKUP WITH PANELS

Non-Metallic Lay-up Configuration



Typical Event Sequence

Item	Event
1.	Position and attach panel 1
2.	Position and attach panel 2
3.	Insert closure strip (a)
4.	Position and attach panel 3
5.	Insert closure strip (b)
6.	Position and attach panel 4
7.	Insert closure strip (c)
8.	Position and attach panel 6
9.	Insert closure strips (d) and (e)
.	
.	
.	
.	
17.	Position and attach panel 9
18.	Insert closure strips (k, l, m, and n)
19.	Insert closure strips (o) through (x)

FIGURE 4-2 - TYPICAL LAYUP SEQUENCE

(simulating the vehicle primary structure to which the TPS mounts) is proven by this initial "non-typical" iteration. The support equipment used may be simple but must be of a type suitable for repetitive operational use. Aircraft work stands, scissors-type manlifts (6' x 10' platform size), pickup trucks or "baggage train" tractor and dollies are typical, whereas fixed-scaffolding, folding-step ladders, cherry pickers or crane-suspended platforms would not be representative. Work areas are also important. There must be access all around the vehicle (and the Mockup) to bring up and position the support equipment and to move other equipment and supplies around without having to stop work and move the work platforms out of position. The Mockup work area requirements are shown in Figure 4-3. A 32' x 50' area is recommended to provide on-site storage for tools, support equipment, spares, and three (3) sets of test TPS material. However, if storage space is provided near by, it is possible to get along with a 28' x 40' test area and still have a reasonable simulation of the operational environment; anything less than this complicates the test operations and adjustment or interpretation of reference times.

Test results will be documented by descriptions of the processes and/or procedures for installation and removal, tables of times required, graphs of trends and projections, drawings or photographs of the test articles, and a motion picture of a typical iteration for each TPS material system. The picture has been planned as a separate test series after the conclusion of the basic series, because the concurrent production would introduce non-typical activities and delays that would render time studies invalid. Further, with completion of the basic series, the most critical operations and productive techniques are known and can be emphasized.

The Non-metallic and Ablative TPS designs employ expendable plugs to protect the attachment bolts in the current concepts. Logistic spares are therefore required in sufficient quantities to support the number of test iterations planned. Additional allowance must be made for breakage or damage during normal handling, installation, and removal operations. Allowance has been

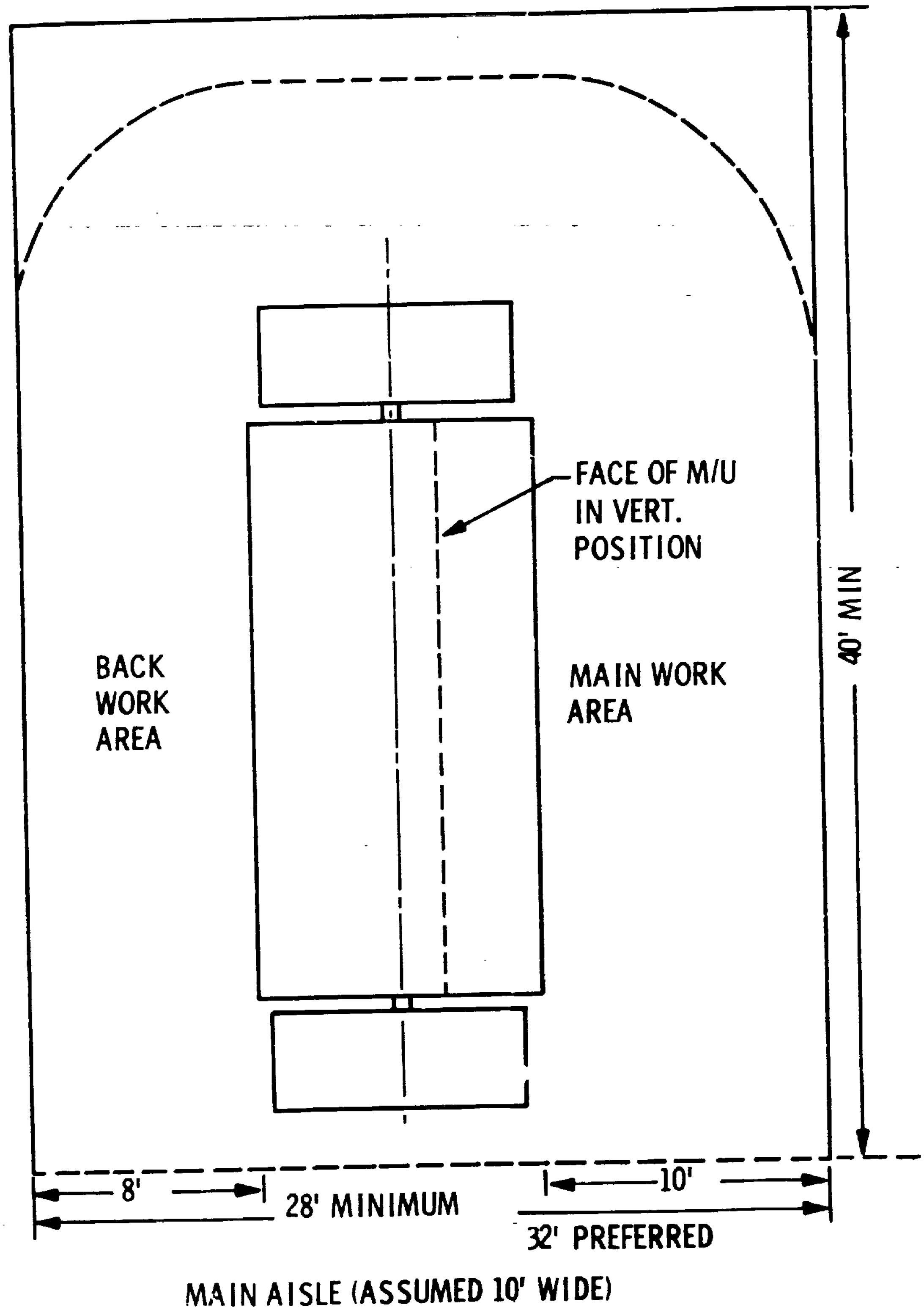


FIGURE 4-3 - MOCKUP WORK AREA

made in the planned fabrication of test panels and associated parts for spares and supplies to support the test program previously described.

4.8 TEST SCHEDULE AND MANNING

A thirty-one week program schedule has been developed to accomplish the test objectives on three TPS material systems previously described. The first fifteen weeks are allotted to procurement and fabrication of test articles and test hardware and the packaging and air-shipment to Langley. (Air-shipment has been selected to save approximately two weeks of project time.) One week has been allocated to pre-test activities which include arranging for rental of additional support equipment, obtaining and checking out GFE, unpacking material and equipment shipped from Lockheed, installing the simulated vehicle primary structure on the Mockup to precise dimensions, and preparing for the actual test program. Nine weeks have been estimated for the three test series: 15 work days for the non-metallic system, including an extra "first time only" iteration, 13 work days for the metallic system, and 17 work days for the ablative system. At the conclusion of the basic test activity, two weeks have been assigned to a documentary movie—approximately three days of shooting an ablative, metallic, and non-metallic TPS operations in that order. Post-test operations, which include cleanup, return of rental or borrowed equipment, packaging and shipping of Lockheed-owned equipment, and the transfer to Langley of residual items built or purchased specifically for the test program, require a week. It should be noted that there is no provision for the refurbishment of test articles, test hardware, or the Mockup in this program. An additional three weeks is then required to complete and deliver the final report, including the silent documentary movie. It has been assumed that Langley personnel will continuously monitor the test program and participate in discussions with the Project Leader, providing appropriate direction and guidance, so that submission of a draft report is unnecessary. Figure 4-4 shows the proposed schedule described above.

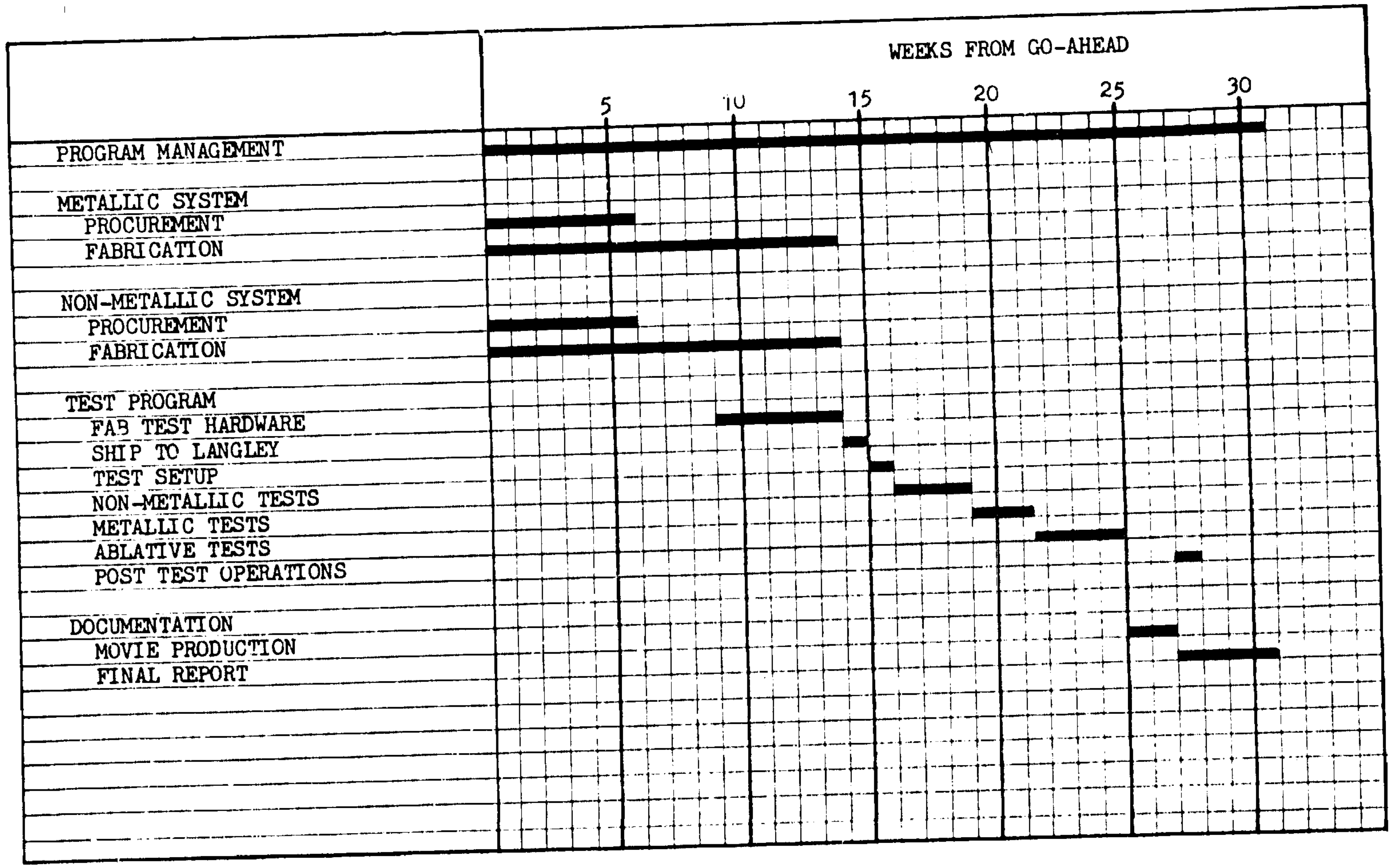


FIGURE 4-4 - PROGRAM SCHEDULE

Particular attention has been given to the Test Manning Requirements and the selection of personnel. This test series is believed to be unique in its place so early in the Space Shuttle program schedule; this will permit the results to be used to influence design for operational considerations - a goal often voiced but rarely implemented. The development of aerospace hardware is a complex process with many conflicting and competing requirements at every level. All too often the impact of operations on systems cost is ignored until after designs are frozen and production is committed. Lockheed has recognized this problem in their Space Systems Manufacturing Operations and employs the methodology illustrated in Figure 4-5 to ensure that designs are economical to manufacture and to maintain. Interaction is required between design functions and the manufacturing operations from the beginning. The initial concept is reviewed and analyzed by experienced manufacturing operations and methods engineers. Questions of suitability for intended use, economy of manufacture, choice of methods, etc. are resolved by analysis or experimental investigations. Data obtained from the design feasibility investigation are fed into the preliminary design; several iterations may be required. Both preliminary design data and the results of the feasibility investigations form a starting point for the operational process development studies, which involve frequent exchange between the final design group and the process development.

Final design release normally must be made prior to complete definition of the process, with significant alterations effected by means of engineering change orders. Actual controlling documents and specifications are generated by responsible functional groups utilizing the information available from both design and operational development studies. These documents are typically of three types. The first consists of Engineering Specifications defining both the materials and the engineering requirements with which the process must comply. The second is an Operational Process Specification, which will delineate the step-by-step activities of the operators. The third is a Quality Assurance Standard which dictates the methods and occasions for inspection in-process to assure compliance with the engineering requirements.

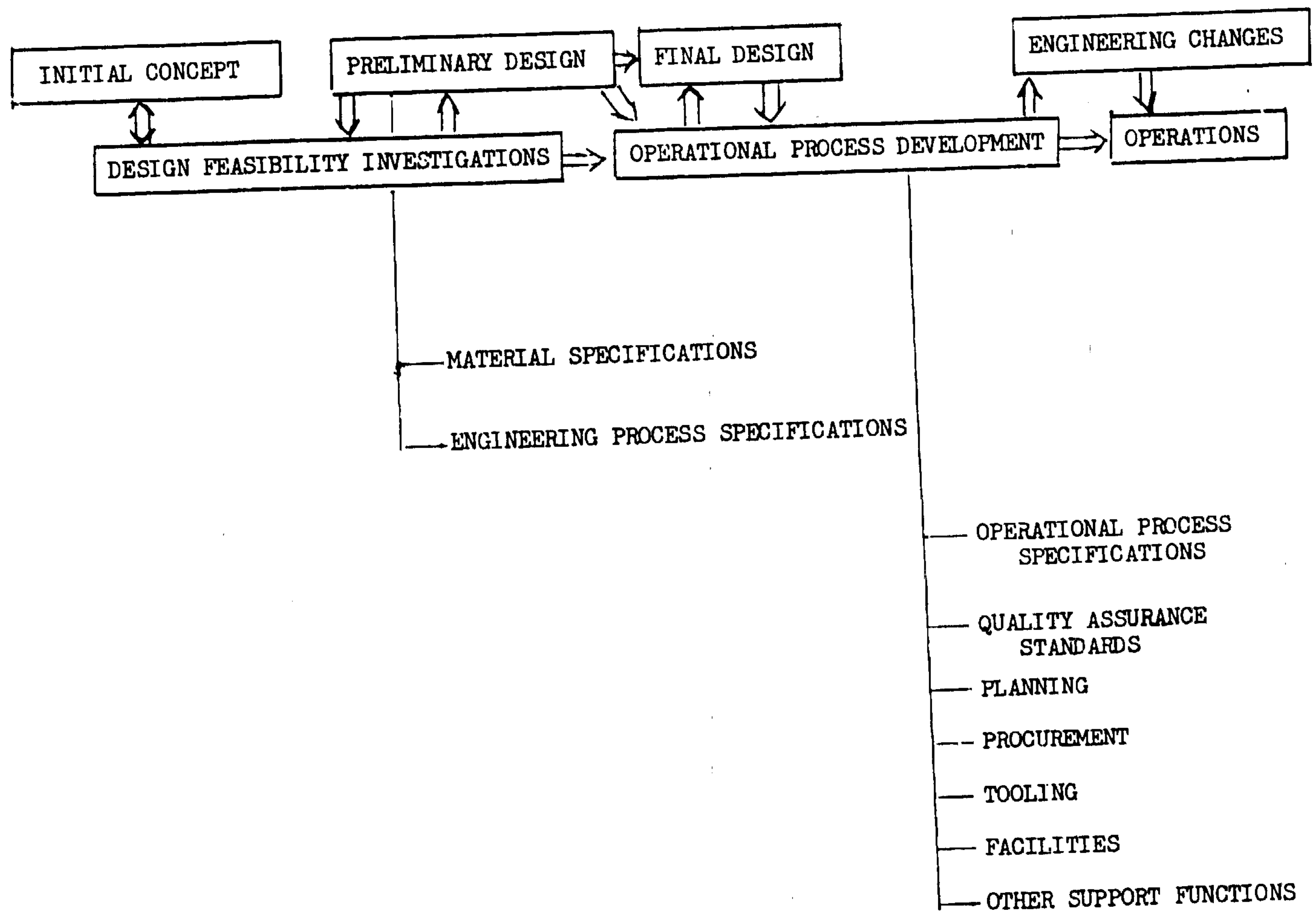


FIGURE 4-5 - MANUFACTURING DEVELOPMENT METHODOLOGY

Upon release of the design, many affiliated support actions are initiated. Tool planning and fabrication, production control, procurement, and many other functions must be accomplished in a timely manner to meet production schedules. To implement such activities does, however, require working with conceptual designs rather than with flight-test proven items, and with procedures developed on paper but not previously tried. For these reasons, it is considered necessary that the test crew be made up of highly versatile engineers, each with broad experience rather than either highly specialized technicians or semi-skilled labor. (Once procedures and designs have been fixed and proven, it is expected that semi-skilled technicians may be trained to handle the routine operations involved in the removal and replacement of TPS.) Table 4-2 shows the allocation of personnel to the various tasks.

The Project Leader provides overall supervision of the test program and direct interface with the Langley COR. He has been selected for his familiarity with Thermal Protection Systems, industrial engineering experience, analytical ability, and leadership.

The Inspection Engineer develops and analyzes manufacturing/assembly processes and determines the controls and inspection requirements. For this job, he will be a direct participant in the test activities, identifying in-process inspection requirements and injecting appropriate steps or interruptions into the installation sequences. When not wearing his "inspection" hat, he will assist in assembly and support tasks.

The Methods Development Engineer acts as lead man for the assembly crew, developing and modifying assembly sequences and techniques and performing the operations. A broad background in handling and assembling mechanical hardware for aircraft and spacecraft under production and launch base conditions is considered desirable in establishing efficient and realistic operations.

The Assembly Process Engineer supports and complements the Methods Engineer in skills and experience. Practical experience in vehicle assembly and maintenance operations is a prime requisite for this key crew member.

TABLE 4-2 - MANPOWER DISTRIBUTION

	PROJECT LEADER	INSPECTION ENGINEER	METHODS DEVELOPMENT ENGINEER	ASSEMBLY PROCESS ENGINEER	TIME STUDY ENGINEER	PHOTOGRAPHER	MANUFACTURING	TECH. EDITING AND ART	TOTAL HOURS
PROGRAM MANAGEMENT	560								560
METALLIC SYSTEM FAB							2564		2564
NON-METALLIC SYSTEM FAB							3031		3031
TEST PROGRAM									3192
TEST HARDWARE FAB							592		
TEST SETUP	40	40	40	40	40				
NON-METALLIC TESTS	145	145	145	145	145				
METALLIC TESTS	129	129	129	129	129				
ABLATIVE TESTS	166	166	166	166	166				
POST TEST OPERATIONS	40	40	40	40	40				
									640
DOCUMENTATION						120			
MOVIE PRODUCTION								200	
FINAL REPORT	120	80	20	20	80				
TOTAL DIRECT HOURS	1200	600	540	540	600	120	6187	200	9987

These people constitute the basic "minimum" cr ;, and are assisted by the other crew members in oper-tions requiri-; additional help. (Three are required for many operatic s and a fourth man may be needed in some situations.)

The Time Study Engineer is the official observer and recorder of actual test operations and time spans. He requires considerable experience in this facet of industrial engineering and a good understanding of field conditions and mechanical assembly operations to properly identify the significant steps. When actual tests are not being performed, he will assist in support operations or in the preparation of analyses and data for the test report.

4.9 TEST SUPPORT COST

Phase II management cost, test labor expenditures, and documentation cost for the three (3) TPS systems are summarized in Table 4-3.

TABLE 4-3 - TEST SUPPORT PRICE SUMMARY

ITEM	COST ELEMENT	TEST	REPORTS/ DOCUMENTATION	PROGRAM MANAGEMENT	TOTAL
	Engineering Hours	1,143	520	560	2,223
	Manufacturing Hours	2,049	120	-	2,169
	TOTAL HOURS	3,192	640	560	4,392
1	Material	$ 1,631	$ -	$ -	$ 1,631
2	Material Overhead	302	25	-	327
4	Engineering Labor	10,659	3,698	5,712	20,069
5	Engineering Overhead	8,195	3,728	4,015	15,938
6	Manufacturing Labor	13,176	866	-	14,042
7	Manufacturing O'head	15,429	904	-	16,333
8	Other Costs	26,104	395	64	26,563
9	Subtotal	$75,496	$ 9,616	$ 9,791	$ 94,903
10	G&A Expense	5,181	1,039	909	7,129
13	Subtotal	$ 80,677	$10,655	$10,700	$102,032

The non-metallic system will be tested first, followed by the metallic system and concluding with the ablative system. Five (5) test iterations will be performed on the non-metallic foam/steel panels; the first will be conducted for crew familiarization and general test shakedown. Aluminum/Aluminum metallic panels will have four (4) test iterations performed on them as will the ablative system. Crew size will vary from two (2) to four (4) personnel. They will be involved in layup, inspection, data recording and observation activities. A typical task and manpower breakdown for a non-metallic system is provided in Table 4-4.

TABLE 4-4 - TYPICAL OPERATIONAL TASK AND MANPOWER SEQUENCE

SEQUENCE	PERSONNEL		TASK
	WORKER	SUPPORT	
Layup Panels	2	Observer	Pickup, layup, position
Bolts Panels	2	Inspector	Hand installion, hand tighten, torque
Layup Closure	1	Inspector	Pickup, drop in place, position
Layup Closure Blocks	1	Inspector	Pickup, drop in-place, adjust
Bolt Closure Blocks	1	Inspector	Install, hand tighten, torque
Insert Closure Plugs	1	Inspector	Cement, insert, position

Both the observer and inspector will perform additional support duties such as getting material ready and assist in handling them during testing.

4.10 TEST PANELS

Low-cost TPS structural materials and fabrication methods have been identified for a number of metallic and non-metallic TPS system options (Appendix E). It has been determined for simulated systems that such physical characteristics as size, structure, and weight, and handling features are not significantly different from those exhibited by real panels. What variations do exist will not seriously jeopardize TPS design objectives or credibility of the resulting operations data. Consequently, it is recommended that simulated TPS systems be selected for the Phase II test program.

Another factor which merits consideration in the final selection process is the general status of the space shuttle design effort and its likely effect on the information obtained from the Phase II test program Adequate space shuttle baseline design criteria have not been formulated as yet. The low level of design maturity is evidenced in the layout drawings and sketches in the literature and the particular lack of point design effort in the TPS subsystem area. Because of this situation, it is both practical and expedient to use materials which reduce the ultimate cost of the Phase II test programs. Simulated TPS systems which are considered to be the best technical representation of metallic and non-metallic systems and are relatively inexpensive to fabricate can be identified as follows:

TPS System	Component
Metallic	Al/Al
Non-metallic	Foam/Steel

Neither system is the least expensive but the desirability of using metallic subpanels resulted in their selection. Wood subpanels were discarded because they were not considered sufficiently durable The price to fabricate nine (9) panels, closures and associated test assembly hardware are provided in Table 4-5.

TABLE 4-5 - TEST PANEL — PRICE SUMMARY

ITEM	COST ELEMENT	OPTION A-2 (Al/Al) METALLIC SYSTEM	OPTION B-2 (FOAM-STEEL) NON-METALLIC SYSTEM
	Engineering Hours	470	558
	Manufacturing Hours	2,094	2,473
	Total Hours	2,564	3,031
1	Material	$ 271	$ 901
2	Material Overhead	50	167
4	Engineering Labor	2,844	3,376
5	Engineering Overhead	3,370	4,001
6	Manufacturing Labor	10,658	12,588
7	Manufacturing Overhead	15,768	18,622
8	Other Costs	2,808	3,317
9	Subtotal	$ 35,769	$42,972
10	G&A Expense	4,161	4,919
13	Subtotal	$ 39,930	$47,891

TEST REQUIREMENTS SHEET

TRS NO. ME 7

TITLE: PANEL LAY-UP AND REMOVAL (METALLIC TPS)

OBJECTIVES:
1) Determine adequacy of installation design concept.
2) Obtain a "reference" time for installation of group of panels.
3) Obtain a "reference" time for removal & replacement of a single panel.
4) Identify operations having prospects for significant improvements by development of procedures, processes or special support equipment.

TEST ITEMS: 9 panels, 2' x 2', single curvature, typical of corrugated metallic TPS, 6 Closures, 24 Cover Plates, 12 Insulation Pillows, associated fasteners, plus logistics spares for expendables (depending on No. of operations).

FACILITIES: TPS Mock-up Structure with "primary vehicle structure" attached.

Enclosed 32' x 50' area with 2-ton bridge crane having a 20' hook height, shop air, standard utilities and motor vehicle access.

SUPPORT EQUIPMENT:
Aircraft-type adjustable service stand.
Telescope Work Platform, 4 to 12 ft. height range (Scissors Manlift or equiv.)
Assorted small hand tools

EST. TEST MANNING:
Test Leader/Industrial Engineer
Inspection Requirements Engineer
Methods Development Engineer
Mechanical Assembly Technician
Time Study Analyst

EST. TEST TIME: 13 working days *

NOTES: *Assumes first test on M/U has been done for another system and test personnel are familiar with facilities, equipment and basic techniques. Test itself then consists of two iterations with M/U vertical and two iterations with M/U horizontal, simulating bottom of Space Shuttle. One iteration consists of complete installation of 9 panels, removal and replacement of one panel (preferably the center one), and removal of the 9 panels. During each iteration inspection activities and interruptions typical of the actual operational phase requirements shall be simulated, and time spans for each type of activity or process shall be recorded.

NAS 1-10094

TEST REQUIREMENTS SHEET

TRS NO. AB 7

TITLE: PANEL LAY-UP AND REMOVAL (ABLATIVE TPS)

OBJECTIVES:

1) **Determine adequacy of installation design concept.**
2) **Obtain a "reference" time for installation of group of panels.**
3) **Obtain a "reference" time for removal & replacement of a single panel.**
4) **Identify operations having prospects for significant improvements by development of procedures, processes or special support equipment.**

TEST ITEMS: 6 panels, 4' x 6' and 3 panels, 2' x 6', single curvature, typical of Ablative TPS, 180 Plugs, RTV, associated fasteners, plus logistics spares for expendables (depending on No. of operations).

FACILITIES: **TPS Mock-up Structure with "primary vehicle structure" attached.**

Enclosed 32' x 50' area with 2-ton bridge crane having a 20 ft hook height, shop air, standard utilities and motor vehicle access.

SUPPORT EQUIPMENT:
Aircraft-type adjustable service stand.
Telescoping Work Platform 4 to 12 ft. height range (Scissors Manlift or equiv.)
Assorted small hand tools

EST. TEST MANNING:
Test Leader/Industrial Engineer
Inspection Requirements Engineer
Methods Development Engineer
Mechanical Assembly Technician
Time Study Analyst

EST. TEST TIME: 17 **working days ***

NOTES: *Assumes first test on M/U has been done for another system, and test personnel are familiar with facilities, equipment and basic techniques. Test itself then consists of two iterations with M/U vertical and two iterations with M/U horizontal, simulating bottom of Space Shuttle. One iteration consists of complete installation of 9 panels, removal and replacement of one panel (preferably the center one), and removal of the 9 panels. During each iteration inspection activities and interruptions typical of the actual operational phase requirements shall be simulated, and time spans for each type of activity or process shall be recorded.

TEST REQUIREMENTS SHEET

TRS NO. NM 7

TITLE: PANEL LAY-UP AND REMOVAL (NON-METALLIC TPS)

OBJECTIVES:
1) Determine adequacy of installation design concept.
2) Obtain a "reference" time for installation of group of panels.
3) Obtain a "reference" time for removal & replacement of a single panel.
4) Identify operations having prospects for significant improvements by development of procedures, processes or special support equipment.

TEST ITEMS: 9 panels, 2' x 2', single curvature, typical of Non-metallic TPS, 24 Closures, 16 Blocks, 16 Plugs, associated fasteners, plus logistics spares for expendables (depending on No. of operations).

FACILITIES: TPS Mock-up Structure with "primary vehicle structure" attached.

Enclosed 32' x 50' area with 2-ton bridge crane having a 20' hook height, shop air, standard utilities and motor vehicle access.

SUPPORT EQUIPMENT: Aircraft-type adjustable service stand.
Telescope Work Platform, 4 to 12 ft. height range (Scissors Manlift or equiv.)
Assorted small hand tools

EST. TEST MANNING: Test Leader/Industrial Engineer
Inspection Requirements Engineer
Methods Development Engineer
Mechanical Assembly Technician
Time Study Analyst

EST. TEST TIME: 15 working days *

NOTES: * Assumes first test on M/U is for NM system, with one complete iteration to familiarize test personnel with facilities, equipment and basic techniques and to prove out test fixture. Test itself then consists of two iterations with M/U vertical and two iterations with M/U horizontal, simulating bottom of Space Shuttle. One iteration consists of complete installation of 9 panels, removal and replacement of one panel (preferably the center one), and removal of the 9 panels. During each iteration inspection activities and interruptions typical of the actual operational phase requirements shall be simulated, and time spans for each type of activity or process shall be recorded.

Section 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Mockup Philosophy

The Langley Mockup is a test bed on which studies may be made of structures, materials, methods, and techniques which have significant development and operational cost impact. These studies should ultimately lead to recommendations on materials, operational criteria for structure design requirements, identification of handling equipment characteristics for TPS assemblies, and a yard stick for estimating TPS maintenance time spans and manpower requirements. Studies (or tests) on the Mockup can provide many answers to operational unknowns or uncertainties; they do not answer questions relating to mechanical strain, fatigue, creep, buckling, binding, rupture, peeling absorption, etc. resulting from exposure to real or simulated launch flight entry, landings and ground handling environments. Figure 5-1 portrays elements of a test program that should be planned for the TPS early enough to influence design.

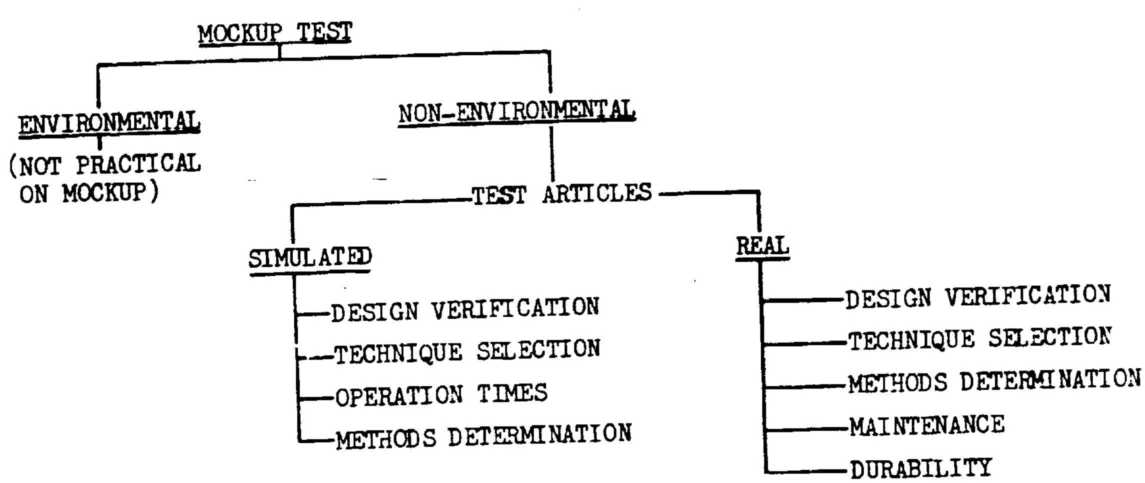


FIGURE 5-1 - MOCKUP TEST PROGRAM

At this stage of Space Shuttle development, the Langley Mockup will function as a Development Test Article (DTA) having considerable growth potential. Figure 5-2 envisions the way in which the mockup will be used during the development phase of the Space Shuttle program. The present status of the program suggests that the phase schedules for system acquisition are not firm. Consequently, the Phase II program should be tailored to this condition by scheduling DTA activities according to the status of design development. In Step 1 the mockup would be used to demonstrate that panels can be laid up, that selected designs can do the job at a cost which is less for some than for others. As TPS system design matures and operational performance requirements become better defined, they can be proof tested on the Mockup during Step 2. During this period, procedures for conducting refurbishment operation can be developed and improved. Now the mockup can take on a much broader role by providing design with operational performance criteria and by giving management and engineering a clearer understanding of operational needs through the technique of demonstration. Further, the Mockup may assume a different appearance both in configuration and number of DTA that are available, and provide more flexible features for accommodating various designs.

As the operational phase approaches, Step 3 would be initiated. Technical training would be given to operational crews using the procedures developed in Step 2. New crew members can be trained and programs to maintain operator proficiency could be initiated. Training aids such as movies and slides could be used in the classroom along with the mockup.

5.2 Technical Evaluation

The results and observations derived from the total economic evaluation and operational cost analysis are important in that they assign the refurbishment function of Operations to its proper economic relationship with total system acquisition cost. In addition, a means is provided for making decisions regarding the selection of TPS material systems and operation tasks for inclusion in a Test Program.

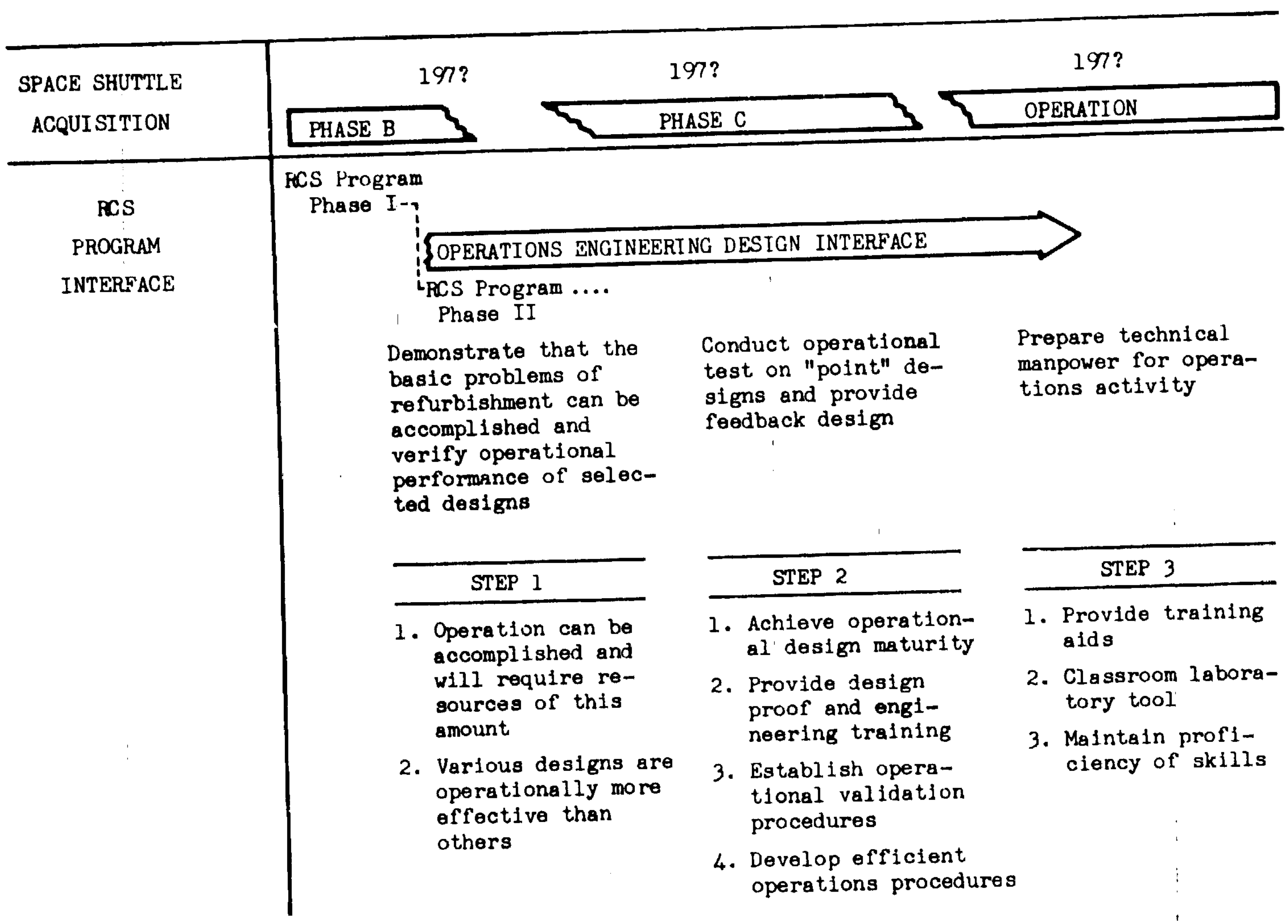


FIGURE 5-2 - RCS PHASE II PROGRAM

5.2.1 Relative Economi~ Importance of Refurbishment Operations. The mission model for the total economic evaluation and operational analysis used on eight (8) vehicle systems, which flies 75 missions a year for the ten (10) year life of the system. Returning Orbiters are refurbished in a two (2) week turnaround period.

Based on CER cost estimates, refurbishment operations (58.2 million) constitute approximately 7.7% of the total operations cost of the system (753.3 million dollars). In terms of total system cost, refurbishment operations represents 0.9% of the estimated 6,767.6 million dollars to acquire and operate the system.

Bottom-up costs estimated for metallic and non-metallic TPS systems show that refurbishment costs can range from 6.7 million to 148.9 million dollars due to technological uncertainty. The nominal cost ranges from 27.3 to 30.9 million dollars which compares with the 58.2 million dollars developed from CER data.

Operational analyses, using time line techniques, indicate that approximately one-third (1/3) of the elapsed turnaround time will be devoted to refurbishment activities while the remaining two-thirds (2/3) must be considered as non-productive or lost time. Consequently, 19 million dollars of the 58.2 million estimated as necessary to perform refurbishment functions will be affected by efficient operational procedures or by achieving improved TPS panel performance.

Operational tasks which have the largest cost and largest uncertainty have been identified in the operational analysis as panel removal, panel replacement, and in-process inspection. They should recieve first consideration in the Phase II test program. Experienced operations personnel should be available during Phase II planning to ensure the selection of representative methods and techniques for each task and to formulate the criteria upon which panel design performance is to be judged.

5.2.2 TPS System/Subsystem Contribution to System Cost. The ablative TPS system is operationally most expensive because of its large refurbishment rate. It is evident that efficient panel design and operational procedures would be desirable to reduce the total cost of refurbishing ablative panels. However, the estimated costs for DDT&E would be impacted if a significant reduction in operating expense is to be achieved and this might still result in ablative systems not being competitive with metallic or non-metallic systems. Only a truly reusable ablator system can begin to compete with the metallic or non-metallic TPS systems.

In order of high cost and uncertainty, ablator, metallic and non-metallic TPS systems would be selected for test consideration. However, it is the low-cost non-metallic system which shows the most promise.

Subsystem materials are largely influenced by the temperature regime in which they reside. Low maintenance rates will exist for such areas as the nose cone, leading edges, chine and bottom of the Orbiter vehicle. TPS subsystems which should receive highest priority are those physically located on the bottom of the Orbiter, since this region will experience the largest number of panel replacements. The cost uncertainty is also highest in this region. TPS subsystems recommended for the Phase II test program are listed in Table 5-1 in order of high cost and high uncertainty.

5.2.3 Operation Tasks Contribution to System Cost. Operation tasks are most expensive and uncertain in the maintenance function where panels are made flightworthy after removal. This function is not one which is considered for Mockup applications, although "repair-in-place" activities might be performed if actual test materials are used. Operation tasks considered for inclusion in the RCS test program as Refurbishment activities are listed in Table 5-2 in order of high cost and high uncertainty.

TABLE 5-1 -- TPS SUBSYSTEM MATERIAL PRIORITY

PRIORITY	MATERIAL CODE	LOCATION	MATERIAL SUBSYSTEM
1	011	Bottom	Ablator
2	013	Side	Ablator
3	012	Leading Edge/Side	Ablator
4	110	Bottom	FS-1500*
5	030	Bottom	Columbium
6	050	Bottom	TDNiCr
7	041	Bottom/Chine	LI-1500
8	080	Top	Titanium
9	010	Nose Cone	Ablator
10	044	Base Shield	LI-1500
11	060	Leading Edge/Side	Haynes
12	112	Side	FS-1500*
13	070	Side	Rene'41
14	111	Leading Edge/Side	FS-1500*
15	043	Side	LI-1500
16	042	Leading Edge/Side	LI-1500
17	020	Nose Cone	Tantalum

*FS = Fail Safe.

TABLE 5-2 — OPERATION TASK PRIORITY

PRIORITY	OPERATION TASK	
1	Maintenance (Not considered for Mock-up applications)	
2	Panel Installation	Refurbishment
3	Panel Removal	
4	In-process Inspection	
5	Packaging and Handling	
6	Storage	

5.2.4 Maintenance Rate Contribution to System Cost. Maintenance rate ranks as the single most important cost driver. Metallic TPS systems experience the lowest number of panel replacements per mission followed by non-metallic and then ablative systems. The Langley Mockup cannot evaluate the general status of panels brought about by conditions experienced during a flight. The postflight inspection task cannot be performed even though it does represent one of the high cost operational tasks and is a most uncertain function. Validation of maintenance rates and uncertainties would be possible if actual materials were first tested on the Mockup and then subject to an environmental test program. This is considered outside the initial scope of the Phase II Test Program.

5.2.5 Application to the Langley Mockup. TPS structure designs for those panels to be tested on the Mockup should come from the bottom region of selected baseline vehicle configurations. The Mockup by design is ideally suited to simulate such a region owing to its relatively shallow single curvature. Operational tasks may be limited to only refurbishment activities, however, this should not be considered as disadvantageous. Design maturity is not well enough advanced in point designs and operational techniques to expect more than demonstration testing of typical operational procedures on representative panels to be accomplished at this time.

5.3 Phase II Program Cost

The recommended Phase II program will involve fabrication and testing of panels representative of the three TPS material systems. Nine metallic, non-metallic and ablative system panels and closures will be tested. Lay-up and removal tasks were determined from operational analysis to be high-cost activities and to possess large technological uncertainties. Five test iterations are planned for the non-metallic system, the first for familiarization purposes and the remainder for data acquisition. Both the metallic and ablator systems will have four test iterations.

The test program will involve individuals skilled in operational activities. Testing will take place at the Langley Research Center over a period of 13 weeks. The final report will be completed 31 weeks after contract go-ahead.

Phase II material and test labor expenditures are provided in Table 5-3. Simulated panels are recommended. Al/Al structure is considered to be representative of metallic systems and foam/steel structure as representative of non-metallic systems. Albator material is GFE. Total program cost is $189,853 excluding fee.

TABLE 5-3 - PRICE SUMMARY

ITEM	COST ELEMENT	OPTION A-2 (Al/Al) METALLIC SYSTEM	OPTION B-2 (FOAM/STEEL) NON-METALLIC SYSTEM	TEST	REPORTS/ DOCUMENTATION	PROGRAM MANAGEMENT	TOTAL
	Engineering Hours	470	558	1,143	520	560	3,251
	Manufacturing Hours	2,094	2,473	2,049	120	-	6,736
	Total Hours	2,564	3,031	3,192	640	560	9,987
1	Material	$ 271	$ 901	$ 1,631	$ -	$ -	$ 2,803
2	Material Overhead	50	167	302	25	-	544
4	Engineering Labor	2,844	3,376	10,659	3,698	5,712	26,289
5	Engineering Overhead	3,370	4,001	8,195	3,728	4,015	23,309
6	Manufacturing Labor	10,658	12,588	13,176	866	-	37,288
7	Manufacturing Overhead	15,768	18,622	15,429	904	-	50,723
8	Other Costs	2,808	3,317	26,104	395	64	32,688
9	Subtotal	$ 35,769	$ 42,972	$75,496	$ 9,616	$ 9,791	$173,644
10	G&A Expense	4,161	4,919	5,181	1,039	909	16,209
11	Subtotal	$ 39,930	$ 47,891	$80,677	$10,655	$10,700	$189,853

APPENDIX A

REFERENCES

References contained in this section are those which proved to be most useful to the RCS program. Their selection was based on:

1. The presentation of attachment and primary structure design concepts and design maturity.
2. The delineation of operational methods and techniques of implementation that would be helpful in establishing an Operations Scenario and for "time line" analysis.
3. The coverage of inspection procedures that would clarify the most likely techniques to be used in refurbishment determinations and subsequent verification activities.

The list of references was reviewed continually throughout the duration of the contract.

This review of the literature has established the nature and extent of TPS design and analysis work conducted to date and further established the degree to which these activities have developed optimum methods for installing TPS on a shuttle vehicle. In general, the literature is extensive in the areas of material characterization and adequately covers small panel structural design, analysis, and test activities, but on the subject of panel installation data are sparse at best with few feasible designs and detail drawings in evidence. In addition, the availability of current information (1969-1970) covering large shuttle type developments is meager.

The literature lacks coverage and depth in the following categories:

1. Studies specifically oriented toward TPS panel installation problems where attachment methods and primary structure interaction are detailed for refurbishment efficiency study.

2. Detailed evaluation of special structural problems associated with complex contours, leading edges, etc., that would be helpful in making operational performance determinations of such designs.

3. Studies addressing the problem of panel size, geometry, and orientation versus vehicle configuration as they affect such operational problems as handling, ground support equipment, and crew-size evaluation.

4. Studies which scale up the ablative information from that developed during the early 1960's on the X-20, HL-10, M2-F2 vehicles to that which meets the needs of vehicles presently envisioned.

5. Studies of metallic TPS systems where attachment design details have been analyzed for thermal, structural stress, loads and dynamics, and materials acceptability.

6. Studies of recent origin (69-70) which establish a baseline vehicle configuration which would be helpful in establishing what will be considered as representative TPS design.

The likelihood of any improvement in this situation during the RCS program is remote, particularly since this program preempts the Phase B studies and recently awarded SRT contracts.

Following is a summary of information which is available to the RCS study for design purposes and for use in developing operational uncertainties:

1. Attachments, attachment methods, and primary structural concepts have changed radically from those used on the X-20, M2-F2, HL-10 vehicle configurations to those that are envisioned on present vehicles.

2. Ablative TPS systems are the best illustrated and most widely documented. Little or no metallic TPS system documentation exists that is significant to the RCS study and the same is true for nonmetallic inorganic systems.

3. Documentation is explicit in expressing a need for detailed consideration on such TPS system subjects as panel sizing, fabrication and installation needs and procedures and operations requirements. However, the substance of the coverage is still too general for useful operational details to have been produced. To date concern has been with material characterization and associated processes rather than with the practical problems of fabrication and installation of selected TPS thermostructural panels. Where operational experience does exist, it has not been developed sufficiently to be influential in establishing operationally feasible TPS designs.

4. Documentation dealing with such problems of reusable TPS systems, as Fail-Safe or Safe-Life concepts are as yet not sufficiently well defined. This will make operation time line analyses very difficult. Inspection is also affected by this situation since post-flight, in-process maintenance, and preflight inspection and verification techniques are directly dependent.

1. Radiative Thermal Protection Systems Development for Maneuverable Reentry Spacecraft. William E. Black, General Dynamics/Convair, San Diego, Calif., Feb. 1969.

2. Refurbishable Thermal Shields for Lifting Entry Vehicles. J. D. Stewart and H. L. Bloom, in AFSC Proc. of ASSET/Advanced Lifting Re-Entry Technol. Symp. Mar. 1966, p. 1239-1260.

3. Prime Vehicle Heat Protection System. J. Meltzer, J. I. Slaughter, and D. V. Sallis, in AFSC Proc. of ASSET/Advanced Lifting Re-Entry Tech. Symp. Mar. 1966, p. 1065-1149.

4. Review of Structural and Heat-Shield Concepts for Future Re-Entry Spacecraft. James W. McCown, American Institute of Aeronautics and Astronautics, Annual Meeting and Technical Display, 5th, Phila., Pa., Oct. 21-24, 1968, paper 68-1127.

5. Influence of Structure and Material Research on Advanced Launch Systems Weight, Performance, and Cost. Phase 3: Design Synthesis of Recoverable Launch Vehicle Structures. J. A. Boddy, Washington NASA CR 1116, Jul. 1968.

6. Lightweight Radiative Heat Shield Development. William E. Black, General Dynamics/Convair, San Diego, Calif., Dec. 1967.

7. Materials and Structures Technology for a Space Transportation System. J. E. Colwell, K. T. Kamber, and C. H. Maines, Presented Feb. 4-6, 1970 at the AIAA Advanced Space Transportation meeting. Preprint 70-272.

8. A Survey of Reusable Non-Metallic and Metallic Thermal Protection Materials for Space Shuttle Applications. Paul E. Bauer and Donald L. Kumer. Presented Feb. 4-6, 1970 at the AIAA Advanced Space Transportation Meeting, Preprint number 70-272.

9. Economic and Manufacturing Considerations for Re-Entry Thermal Protection Systems. Joseph W. Maccalous. Presented Feb. 4-6, 1970 at the AIAA Advanced Space Transportation Meeting, Preprint 70-274.

10. Refurbishable Ablative Thermal Protection System Concepts for a Multi-mission Lifting Entry Vehicle. Calvin M. Dolan, Presented Feb. 4-6, 1970 at the AIAA Advanced Space Transportation Meeting, Preprint 70-277.

11. S V-5D; Prime Reusability. Martin Co., Baltimore, Md. Oct. 1967.

12. Reusable Orbital Transport -- The Detachable Ablative Heat Shield Concept. J. Prunty. General Dynamics/Astronautics, San Diego, Calif., 1966.

13. A Study of Advanced Thermal Protection Systems. Paul D. Sones and Joseph J. Rossi, AIAA and American Soc. of Mech. Engineers, Structures, Structural Dynamics and Materials Conf., 9th, Palm Springs, Calif., Apr. 1-3, 1968, AIAA Paper 68-300.

14. Research Study to Provide Concepts of Panel Attachment Mechanisms Suitable for Refurbishable Panel Application. R. E. Rieckmann, Washington, NASA, Nov. 1966. NASA CR-640.

15. Research on Refurbishable Thermostructural Panels for Manned Lifting Entry Vehicles. A. H. LaPorte, Martin Company. Baltimore, Md., Nov. 1966. NASA CR-638.

16. Orbiter Thermal Protection System Design Analysis, Lockheed Missiles & Space Company, July 10, 1970. LMSC/A972005, SS-546.

17. Delta Orbiter - Structural Material Evaluation, R. J. Bellinfante, LMSC Report, December 3, 1969.

18. Final Report on Structural Heat Shield for Reentry and Hypersonic Lift Vehicles. C. J. Giemza and W. B. Hunter, Aeronca Manufacturing Corp., Middletown, Ohio. January 1965, ML-TDR-64-267.

19. Investigation of Insulative Heat Shield Attachment Systems, S. Shields, Ling-Temco-Vought, Inc., April 1965. AFFDL-TR-65-55.

20. Statement of Work, Space Shuttle System Program Definition, (Phase B), Enclosure No. 4 to RFP No. 10-8423, dated February 1970, NASA/HQ.

21. Data Requirements Description No. ME003M, 16 January 1970; "Program Costs and Schedule Estimations".

22. Space Shuttle Program, Boeing/Lockheed Proposal D2001, March 1970.

23. Preliminary Technical Requirements for Space Shuttle Oriiter Cost Estimation· Lockheed Engineering Memorandum No. L-1-M4, dated 25 April 1970.

24. Orbiter Thermal Protection System Design Analysis, LMSC-A972005, dated 1 April 1970.

25. NASA NHB 9501.2, "Procedures for Reporting Cost Information from Contractors," dated March 1967.

26. NASA CR-111795 "Low Cost Ablative Heat Shield for Space Shuttles", Contract NAS 1-9943, dated November 20, 1970, North American Rockwell, Downey, Calif.

APPENDIX B

TOTAL SYSTEM ECONOMIC EVALUATION

Cost data have been assembled on five (5) TPS vehicle configurations using three (3) TPS system candidates. Each exercise resulted in a cost iteration as illustrated in Table B-1 .

TABLE B-1 - TPS COST ITERATIONS

Cost Iteration	TPS System	TPS Subsystem	Maintenance Rate Table
2	Metallic	Columbium	2
3	Non-Metallic	LI-1500	3
4	Ablative	Silicone Elastomer	4
5	Non-Metallic	Fail Safe LI-1500	5
6	Metallic	TDNiCr	6

Each iteration is discussed in the material which follows. Bottom up costs are assembled in a matrix of nine (9) functional areas, two (2) summary cost groups for the three (3) program phases, and six to eight TPS subsystems.

Bottom up cost estimates and uncertainties are provided by responsible functional groups. Nominal costs are estimated using accepted cost estimating procedures. Uncertainties were assigned based on individual judgment regarding knowledge then in existence on the matrix item in question.

The elements of the cost estimating approach are depicted in Figure B-1. There are thirteen (13) steps required in developing the total system cost:

1. End Item Summary Sheet - Operations
2. TPS Sizing Data for Baseline Vehicle
3. Production Panel Model

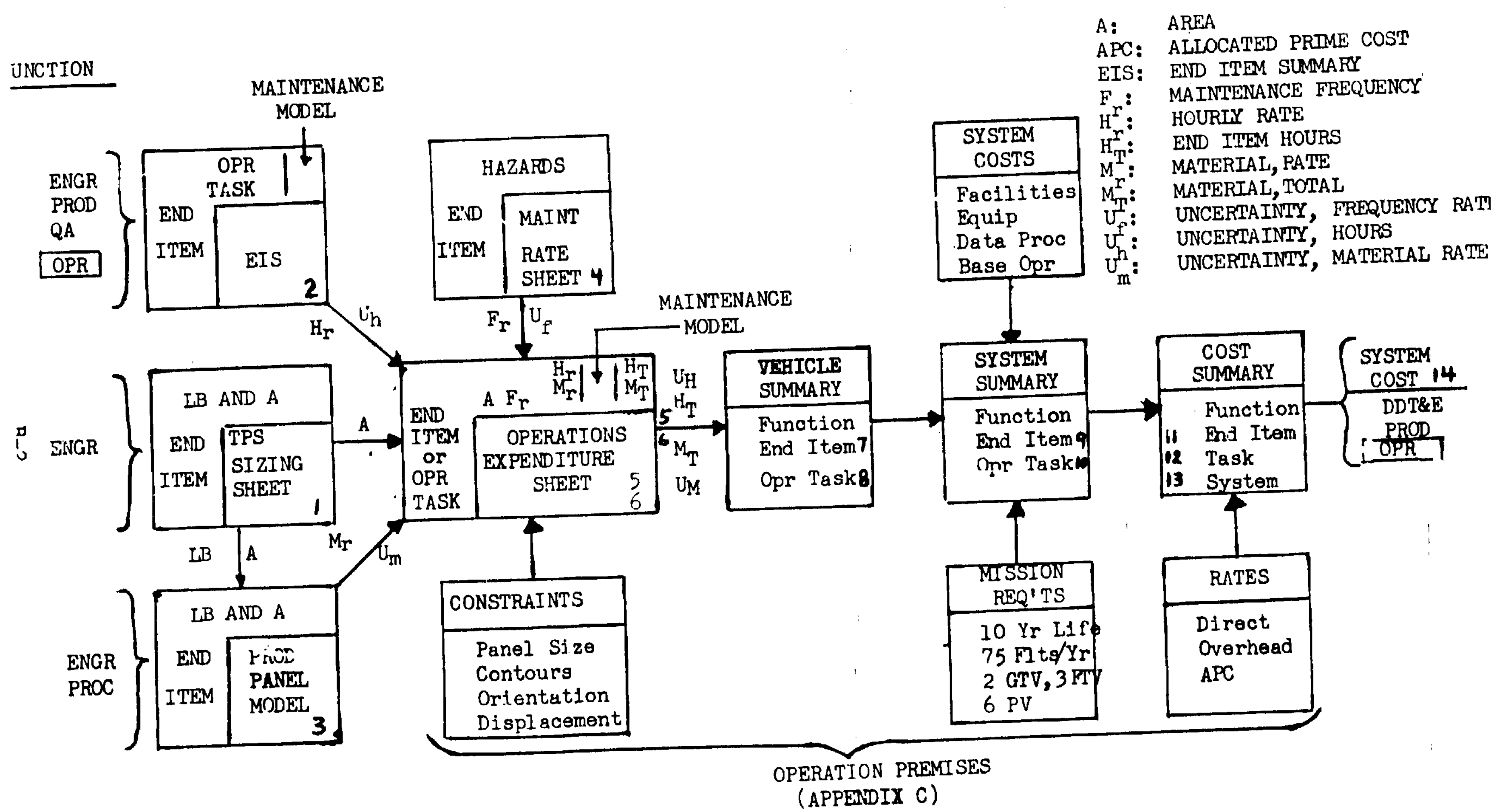


FIGURE B-1 OPERATIONAL COST ESTIMATING APPROACH

4. Maintenance Rate Sheet
5. Operations Expenditures - Hours
6. Operations Expenditures - Material
7. Vehicle Level Operations - End Item
8. Vehicle Level Operations - Operation Task
9. System Level Operations - End Item
10. System Level Operations - Operation Task
11. System Costs by Phase and TPS Subsystem
12. System Costs by Phase and Operational Task
13. System Costs by Phase and Function
14. System Cost Uncertainty by Phase

The material in each Iteration which follows is presented and analyzed in this order.

ITERATION NO. 2

Iteration No. 2 is a metallic TPS system with six (6) subsystem materials selected through computer analysis. Columbium (Material Code 030) is used as the primary subsystem for investigation and sizing purposes.

TPS Sizing For Baseline Vehicle

Each TPS material subsystem is structurally depicted and sized in Table I2-1. TPS covers 17,411 ft^2 of the vehicle surface and weighs 43,098 lbs. for an average unit weight of 2.48 psf.

Material and panel geometry are a function of the temperature regimes listed at the bottom of the table. While surface geometry and location on the vehicle are listed parameters, they are not at this time carried as factors in the total system cost analysis.

The data contained in this table is used for calculating the number of panels (N) of a given material type. In this evaluation 14 ft^2 panels (approximately 45" x 45") are used. Further use of the data is made in the Production Panel Model where area and weight are the principle cost generating factors.

End Item Summary (EIS)

The End Item Summary Sheet (EIS) is the basic cost estimating document on which all original data regarding operations is recorded. Operations personnel have selected six(6) operation tasks for which a given material subsystem, End Item, can be expected to produce a cost impact. These are presented in Table I2-2 as:

- Panel Installation
- Panel Removal
- In Process Inspection
- Packaging and Handling
- Storage
- Maintenance

Various methods and techniques were considered for each of these tasks and hourly weights assigned commensurate with the degree of effort required. The nominal hourly estimates are based on performing similar type operational tasks on a known baseline material which in this case is titantium. The uncertainty assigned to each End Item/Operation Task element indicates the degree to which selected methods and techniques are well enough understood to be in fact accomplished in the time indicated. All values listed in Table I2-2 are for a single panel.

The tantalum nose cone requires the greatest expenditure of time and has the largest uncertainty, followed by (044) LI-1500 on the base shield and then columbium which is applied to the bottom surface of the vehicle.

For the Operation tasks, cost and uncertainty are highest in the maintenance area where repairs are made on removed panels. Panel installation follows next in terms of high cost although the uncertainty is not adversely large.

End Item totals and Operation task totals are used in the Operational Expenditures calculation where they are modified by the Maintenance Factors to produce a vehicle refurbishment labor cost.

Production Panel Model

Panel structural design varies with material type, temperature regime, location on the primary structure and design approach taken on the vehicle structure.

In Table I2-3, the weight and area values obtained from Table I2-1 are represented in a format where those costs which are a function of weight can be separated from those that are a function or area. Cost per pound and per square foot are provided by Procurement Material estimators.

Summary results indicate that a complete TPS system will require a material expenditure of $1,084,985. Columbium has the highest cost per pound and its total cost is greater than that for titantium, even with the much greater weight of titantium. The nose cone has a high cost per pound, but its weight contribution is small relative to all other TPS subsystems.

Production panel costs are used in Operations Expenditure calculations where they are modified according to Maintenance Factors to produce a vehicle refurbishment material cost.

Maintenance Factors

The combined effect of all mission hazards encountered by a TPS system while flying a selected mission profile will determine the nature and extent of operational refurbishment. Inspection, maintenance, and logistic TPS activities (and costs) are essentially a direct function of the of the operations that must be undertaken as a result of the hazards experienced.

In Table I 2-4 a matrix of TPS Maintenance Frequencies provides values that indicate the degree to which a selected TPS subsystem will respond to a given hazard. Integrating the spectrum of hazards over the mission profile provides a maintenance rate (F_r). Maintenance rates are interpreted as "the expected number of flights a TPS subsystem will experience before some maintenance action is required". Both frequency and uncertainty are iteratively developed measures derived from existing documentation and best engineering judgments.

The lowest maintenance rate ($F_r = 10.7$) and highest uncertainty ($\pm$ .033) occur on the tantalum nose cone due primarily to the large temperature/load frequency.

The end item maintenance rates are used in the Operation Expenditures calculation where they are used to determine the numbers of panels replaced per TPS subsystem and from this the vehicle labor hours and materials.

Operation Expenditures

Operation Expenditure calculations are made to determine the vehicle labor and material cost subject to the data just described in the previous step and operation premises (Appendix C).

In Tables I2-5 and I2-6, the results show that thirty-two (32) panels out of 1163 total panels can be expected to require refurbishment, in this case, necessiatating removal and replacement. A labor expenditure of 2,207 hours and a material committment of $8,459 will result.

It should be noted that while the tantalum nose cone had the lowest maintenance rate (Fr = 10.7) of the six (6) TPS subsystems, its contribution to total labor and material cost is almost the lowest for the six subsystems. Its size and single panel feature produce this outcome.

The primary cost driver for both labor and material is columbium with titanium second. The lower maintenance rate for columbium and higher labor and material differential costs produce this outcome.

Cost uncertainty differences between subsystems are not large enough to produce any change in the total labor or material costs of end items. This in spite of the high labor uncertainty for tantalum and LI-1500.

Vehicle Level Operations

Vehicle costs are summarized by end item in Table I2-7 and operation tasks in Table I2-8. Maintenance, Inspection, Material and Equipment costs are displayed as recurring or non-recurring for those costs that were determined from the Operation Expenditure analysis, as well as, those prorated costs which are not estimated at the end item level. Base Inspection falls into this latter category and is prorated to the subsystem level on an end item area basis.

The consolidation of all recurring and non-recurring end item and operation task costs on one summary sheet is in preparation for the application of mission life cycle requirements in determination of System Level Operations cost.

System Level Operations

System level operation costs are summarized by Eni Item in Table I2-9 and by Opertion Task in Table I2-10. Table values are obtained by multipying the vehicle level operations by the number of missions flown over the life of the program by a given fleet of vehicles. In this evaluation, there are 8 vehicles in the fleet. This group will fly 75 missions a year f. 10 years, which will require 750 refurbishments over the life of the program.

The total expenditures for labor, material and equipment are:

Labor	-	1,751,250 hours
Material	-	$6,343,500 (In support of Maintenance operations)
Equipment	-	$1,750,000

Equipment is an Inspection requirement. It is a system level cost and applies across the whole vehicle fleet for the life of the program. For cost comparison purposes its cost is prorated to the subsystem on the basis of end item area.

System Cost by Phase and TPS Subsystem

TPS subsystem expenditures are provided in Table I2-11. End item costs are greatest for columbium with titanium second. While the production costs for both are comparible, there is a 4.5 million dollar differential between columbium and titantium in Operations, and a 17.3 million dollar differential in DDT&E. The relatively lower production cost for LI-1500 is due to its lower material cost. Logistic cost amounts to 149,7 million dollars or 49% of the total system cost. The relative rank in percent of total cost is as follows:

				Uncertainty	
Rank	Material Code	Material	Percent	Mat'l	Labor
1	030	Columbium	36.2	1.20	4.93
2	080	Titanium	25.0	1.17	3.13
3	060	Haynes	12.9	1.15	4.03
4	070	Rene' 41	10.5	1.10	3.47
5	044	LI-1500	7.9	1.20	6.03
6	020	Tantalum	7.5	1.10	6.33

Logistic expenditures are prorated by the initial production cost.

System Cost of Operations by Phase and Operational Task

System costs for Operations are shown in Table I2-12, by Operation Task. Maintenance costs rank highest in total cost followed by Panel Installation and Inspection. Their relative rank in percent of total cost is as follows:

			Uncertainty	
Rank	Operational Task	Percent	Mat'l	Labor
1	Maintenance	58.0	H 1.53 L 1/2.04	8.29
2	Panel Installation	19.1	-	3.29
3	Inspection	14.1	-	5.16
4	Panel Removal	6.1	-	3.06
5	Packaging and Handling	1.4	-	3.69
6	Storage	1.3	-	3.38

Refurbishment operations amount to $11,865,129 or 36% of the total cost.

System Cost by Phase and Function

Total system cost for Iteration No. 2 is $306,504,137. In Table I2-13, this cost is broken down into its six (6) functional areas and two (2) summary cost groups for the three (3) program phases.

Refurbishment costs for the metallic TPS system described in this Iteration, composed of six TPS subsystems and requiring 750 refurbishments over the 10 year life of the program, amount to $30,904,585, approximately 10% of the total TPS system cost. This compares with the other program phases as follows:

Group	Phase	Percent	UNCERTAINTY High	UNCERTAINTY Low
Recurring	Operation	10	4.26	1/3.92
	Production	63	2.36	1/1.74
Non-recurring	DDT&E	27	3.63	1/2.74

The contribution by each of the nine (9) functional groups is summarized as follows:

Function	Percent	
Operation	9	
Manufacturing	50	
Quality Assurance	17	(2% of which is for Operations)
Engineering	24	

Cost estimates for the functions other than Operations were derived in a manner similar to that just described. Due to its volume, the supporting data is not provided.

System Cost Uncertainty by Phase

Nominal costs to perform the DDT&E, Production, and Operation phases reflect the depth of informational detail avaiable to all functional groups. The costs shown in Table I2-14 are based on a mix of subjective judgment, "similar to" knowledge, and definitive information. The extent to which definition is lacking will appear in the magnitude of the uncertainty factor.

The importance of this information is twofold: (1) It provides perspective which allows the establishment of priorities for further development activities that will effectively lead to uncertainty reduction and definitive costing, and (2) the data can be directly related to a function, activity, or end item, permitting critical appraisal of design and system tradeoffs and maintenance of program objectives.

Conditions shown in Table I2-14, indicate that the metallic TPS system can cost 3.49 times nominal or 1070.0 million dollars. Technological uncertainty can result in a 1/2.48 reduction in the nominal cost to 123.5 million dollars for a metallic TPS system.

Operations exhibits the widest range of uncertainty exceeding that for the system. Operations can cost 4.76 times nominal or 146 million dollars, while a 1/3.92 reduction due to technological uncertainty would result in a cost of 7.9 million dollars.

TPS SIZING DATA FOR BASELINE VEHICLE

(ITERATION NO. 2 - TPS METALLIC (COLUMBIUM))

TPS ELEMENT LOCATION & TYPE *	AREA FT^2	INSUL. THICKNESS IN.	OUTER PANEL LBS.	CLIPS	SUB PANEL LBS.	INSUL. LBS.	TOTAL LBS.	PSF
Body - Nose Cone - Ta	70	0.25	412	30	95	452	989	
SUBTOTAL (020)	70	-	412	30	95	452	989	14.10
Body - Smooth - Cb	1195	3.2	1815	336	1028	2008	5187	
Body - Corrugated - Cb	3381	3.2	3125	1559	2903	5680	13267	
SUBTOTAL (030)	4576	-	4940	1895	3931	7688	18454	4.04
Fin - Leading Edge - Haynes	855	2.7	2468	206	734	1212	4620	
Fin - Smooth - Haynes	248	2.3	342	57	214	299	912	
Body - Smooth - Haynes	1029	2.8	1419	251	877	1513	4060	
Body - Corrugated - Haynes	-	-	-	-	-	-	-	
SUBTOTAL (060)	2132	-	4229	514	1825	3024	9592	4.50
Fin - Smooth - Rene	665	2.3	826	141	570	803	2340	
Body - Smooth - Rene	1180	1.5	1466	224	1014	929	3633	
Body - Corrugated - Rene	-	-	-	-	-	-	-	
SUBTOTAL (070)	1845	-	2292	365	1584	1732	5973	3.23
Fin - Corrugated - Ti	912	0.25	468	109	-	120	697	
Body - Corrugated - Ti	5166	0.25	2652	615	-	678	3945	
SUBTOTAL (080)	6078	-	3120	724	-	798	4642	0.76
Body - Base Heat Shield	1610	-	-	188	519	2109	2816	
SUBTOTAL (044)	1610	-	-	188	519	2109	2816	1.75
Lower Flap	1100	-	-	-	-	632	632	
SUBTOTAL (101)	1100	-	-	-	-	632	632	0.57
TOTAL	17411	-	14993	3716	7954	16435	43098	2.48

* Materials:
(020) = Tantalum (2500° to 3000°)
(030) = Columbium (2000° to 2500°)
(044) = LI 1500 Base Shield
(101) = Dynaflex Flap Shield
(060) = Haynes 188 (1600° to 2000°)
(070) = Rene 41 (1000° to 1600°)
(080) = Titanium (Under 1000°)

TABLE I2-1

ORIGINATOR
DUNGAN

DATE: 5/12/70

ITERATION NO. 2 – TPS METALLIC (COLUMBIUM)
(END ITEM SUMMARY SHEET (EIS))

VEHICLE: DELTA BODY

TPS METALLIC CR: 1500 NM

DWG: LO-2069

FIG: 7 ITERATION #2

MAT'L CODE	BASELINE MATERIAL:	PANEL INSTALLATION H_{pi}	PANEL INSTALLATION U_{pi}	PANEL REMOVAL H_{pr}	PANEL REMOVAL U_{pr}	INSPECTION (IN-PROCESS) H_i	INSPECTION (IN-PROCESS) U_i	PACKAGING & HANDLING H_h	PACKAGING & HANDLING U_h	STORAGE H_s	STORAGE U_s	$H\_$	$U\_$	MAINTENANCE REUSE H_m	MAINTENANCE REUSE U_m	TOTAL H_r	TOTAL U_r
020	TANTALUM (Nose)	150	2.50	50	2.50	24	6.00	16	4.00	8	4.00			300	10.00	548	6.825
030	COLUMBIUM	24	5.00	8	5.00	5	5.00	3	4.00	3	4.00			40	5.00	83	4.928
060	HAYNES	18	3.00	6	3.00	1	4.00	1	2.00	2	2.00			32	5.00	60	4.033
070	RENÉ 41	18	1.50	6	1.50	1	1.50	1	1.00	1.5	1.00			36	5.00	63.5	3.465
080	TITANIUM	18	1.50	6	1.50	1	1.50	1	1.00	1	1.00			24	5.00	51	3.127
044	LI-1500	40	7.00	8	7.00	15	5.00	1	5.00	3	4.00			23	5.00	90	6.033
TOTAL	WT AVE.	268	3.295	84	3.059	47	5.340	23	3.696	18.5	3.575			455		895.5	
TOTAL	ARITH AVE.		3.417		3.417		3.833		2.833		2.666				8.297		5.934

TABLE I2-2

ITERATION NO. 2 - TPS METALLIC (COLUMBIUM)

PRODUCTION PANEL MODEL

TPS STRUCTURE	Tantalum 020	Columbium 030	Haynes 060	Rene 070	Titanium 080	LI-1500 044	Insul. 101
Erosion Shield	412	4,940	4,229	2,292	3,170	2,109	
Sub-Panel					7,954		
Clips					3,716		
(Not in Total#) Insulation	(452)	(7,688)	(3,024)	(1,732)	(798)		13,694
Total #	412	4,940	4,229	2,292	14,790	4,109	13,694
$ / #	$50.00	$98.35	$20.00	$10.00	$29.44	$6.90	-
	$20,600	$486,055	$84,580	$22,920	$435,417	$14,552	$13,694
Area (Ft^2)	70*	4,576*	2,132*	1,845*	6,078*	1,610	14,701
$ /Ft^2	-	-	-	-	-	$2.00	$1.20
	0	0	0	0	0	$3,220	$17,641
Total $	$20,600	$486,055	$84,580	$22,920	$435,417	$17,772	$17,641
(With Insulation)	$ 84	$ 5,491	$ 2,558	$ 2,214	$ 7,294	-	(17,641)
TOTAL $	$20,684	$491,546	$87,138	$25,134	$442,711	$17,772	-

TOTAL $1,084,985

TABLE I2-3

IGINATOR
ACEDO/KISH

ITERATION NO. 2 – TPS METALLIC (COLUMBIUM)

MAINTENANCE FACTORS

TE: 5/11/70
HICLE: DELTA BODY
S: Metallic CR: 1500 nm
G: LO-2069
G: 7 Iteration #2

T'L DE	BASELINE MATERIAL:	TEMP EXPOSURE		COMBINED TEMP/LOAD		COMBINED TEMP/PRESS.		COMBINED TEMP/PRESS./LOAD		HANDLING		ENVIRONMENT		COMPOSITE MAINTENANCE FREQUENCY		MAINTENANCE RATE (FLIGHT/PANEL)	
		$F_{\underline{T}}$	U ±	$F_{\underline{TL}}$	U ±	$F_{\underline{TP}}$	U ±	$F_{\underline{TPL}}$	U ±	$F_{\underline{H}}$	U ±	$F_{\underline{E}}$	U ±	$F_{\underline{F}}$	U ±	F	MAX. / MIN.
20	Tantalum (nose)	.0224	.012	.1041	.033	.0565	.020	.1510	.033	.0530	.033	.1093	.033	.0932	.033	10.7	16.611 / 7.924
30	Columbium (Smooth)	.0133	.002	.0377	.020	.0485	.011	.0242	.020	.0204	.003	.0289	.008	.0311	.020	32.2	90.090 / 19.569
30	Columbium (Corrugated)																
60	Haynes (Leading Edge)	.0199	.003	.0316	.007	.0359	.011	.0142	.005	.0185	.003	.0185	.003	.0244	.011	41.0	74.627 / 28.249
60	Haynes (Smooth)																
70	RENE' 41	.0357	.012	.0281	.006	.0304	.009	.0170	.006	.0179	.002	.0291	.006	.0272	.012	36.8	65.789 / 25.510
30	Titanium	.0175	.005	.0327	.007	.0376	.008	.0142	.005	.0198	.006	.0247	.009	.0258	.009	38.8	59.524 / 28.736
44	LI-1500	.0167	.003	.0373	.010	.0299	.010	.0097	.004	.0313	.010	.0324	.011	.0279	.011	35.8	59.172 / 25.707
01	DYNAFLEX (Flap Shield)																
30	Columbium (Lower Flap Sh)	.0133	.002	.0377	.020	.0485	.011	.0242	.020	.0204	.003	.0289	.008	.0311	.020	32.2	90.090 / 19.569
70	RENE' 41 (Upper Flap Sh)	.0357	.012	.0281	.006	.0304	.009	.0170	.006	.0179	.002	.0291	.006	.0272	.012	36.8	65.789 / 25.510
TOTAL	WT AVE.																
	ARITH AVE.																

TABLE I2-4

ITERATION NO. 2 - TPS METALLIC (COLUMBIUM)

(OPERATION EXPENDITURES - - HOURS)

'UNGAN
5/12/70

: DELTA BODY

METALLIC CR: 1500 N/A

: LO-2069

7 ITERATION #2

		TPS SUBSYSTEM: Area (ft^2)	Panel Area (ft^2)	Subsyst. Panels (N)	Maintenance Rate: F_r	Min / Max	Panels Maintained: P_r	Max / Min	Module IV Maintenance Reuse: H_r	Max / Min	H_T	F_rK: Max / Min	H_rK: Max / Min	Worst Case
)20	TANTALUM (Nose)	70	70	1	10.7	7.92 / 16.61	.09	.126 / .060	548	3740.10 / 80.24	51.21		69.05 / 32.58	
)30	COLUMBIUM	4576	14	327	32.2	19.57 / 90.09	10.16	16.71 / 3.63	83	409.02 / 16.84	842.89		1386.93 / 301.29	
)60	HAYNES	2132	14	154	41.0	28.25 / 74.63	3.76	5.45 / 2.06	60	241.99 / 14.88	225.60		327.00 / 123.60	
)70	RENÉ 41	1845	14	132	36.8	25.51 / 65.79	3.59	5.17 / 2.01	63.5	220.03 / 18.33	227.97		328.30 / 127.64	
)80	TITANIUM	6078	14	434	38.8	28.74 / 59.52	11.19	25.10 / 7.29	51	157.48 / 16.31	570.69		770.10 / 371.79	
)44	LI-1500 (Base)	1610	14	115	35.8	25.71 / 59.17	3.21	4.47 / 1.94	90	542.97 / 14.92	288.90		402.30 / 174.60	
		16,311		1163	36.4	24.7 / 69.5	32.0	47.03 / 16.99	895.5	5313.57 / 161.57	2207.26		3583.68 / 1131.80	

TABLE 12-5

ITERATION NO. 2 - TPS METALLIC (COLUMBIUM)

(OPERATION EXPENDITURES - MATERIAL)

NGAN

12/70

VEHICLE: DELTA BODY

TPS METALLIC CR:1500 NM

LO-2069

7 ITERATION #2

		TPS SUBSYSTEM Area (ft²)	Panel Area (ft²)	Subsyst Panels (N)	Maintenance Rate F_r	MIN / MAX	Panels Maintained P_r	MAX / MIN	Model IX Maintenance Reuse M_r $	MAX / MIN			TOTALS M_T $	F_r=K MAX / MIN	M_r=K MAX / MIN	Worst Case MAX / MIN
20	Tantalum (Nose)	70	70	1	10.7	7.92 / 16.61	.09	.126 / .060	30,681	22,752 / 18,804			535.20		744.28 / 356.80	
30	Columbium	4576	14	327	32.2	19.57 / 90.09	10.16	16.71 / 3.63	491,044	575,494 / 419,479			4390.84		7,221.55 / 1,568.78	
50	Haynes	2132	14	154	41.0	28.25 / 74.63	3.76	5.45 / 2.06	87,135	100,209 / 75,772			510.61		740.11 / 279.75	
70	René 41	1845	14	132	36.8	25.51 / 65.79	3.59	5.17 / 2.01	25,134	27,647 / 22,549			164.06		236.26 / 91.85	
30	Titanium	6078	14	434	38.8	28.74 / 59.52	11.19	15.40 / 7.29	442,711	486,982 / 402,465			2739.50		3676.74 / 1784.72	
14	LI-1500 (Base)	1610	14	115	35.8	25.71 / 59.17	3.21	4.47 / 1.94	17,772	21,326 / 14,510			119.06		165.79 / 71.95	
		16,311		1163	36.4	24.7 / 69.5	32.0	47.03 / 16.99	$1,094,983	1,834,410 / 954,179			$8459.27		12,804.72 / 4,153.25	

TABLE I2-6

ITERATION NO. 2 - TPS METALLIC (COLUMBIUM)

VEHICLE LEVEL OPERATIONS

CODE NO.	MATERIAL	RECURRING LABOR HOURS			RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION			
			In-Process	Base		
020	Tantalum (nose)	49	2	3	535	
030	Columbium (smooth)	792	51	56	4,390	
030	Columbium (Corrugated)					
060	Haynes (L. Edge)	222	4	29	511	
060	Haynes (Smooth)					
070	Rene' 41	224	4	17	164	
080	Titanium	559	11	14	2,740	
044	LI-1500	241	48	9	119	
	TOTAL	2,087 hrs	120	128 *	$8,459	
		Total = 2,207 hours				

*Prorated by End Item Area

TABLE I2-7

ITERATION NO. 2 - TPS METALLIC (COLUMBIUM)

VEHICLE LEVEL OPERATIONS

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	1,119	$8,459	
PANEL INSTALLATION	659		
PANEL REMOVAL	207		
INSPECTION			
PRE-FLIGHT	64		
IN-PROCESS	120		
POST-FLIGHT	64		
PACKAGING AND HANDLING	57		
STORAGE	45		
TOTAL	2,207 Hrs	$3,459	

TABLE I2-8

ITERATION NO. 2 - TPS METALLIC (COLUMBIUM)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

CODE NO.	MATERIAL	RECURRING LABOR HOURS MAINTENANCE	RECURRING LABOR HOURS INSPECTION In-Process + Base	RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
020	Tantalum (nose)	36,750	3,750	401,250	38,500
030	Columbium (Smooth)	427,500	39,750	921,750	213,500
030	Columbium (Corrugated)	166,500	40,500	2,370,750	547,750
060	Haynes (L. Edge)	85,500	12,000	185,250	190,750
060	Haynes (Smooth)	81,000	12,750	197,250	204,750
070	René 41	168,000	15,750	123,000	246,750
080	Titanium	419,250	42,750	2,055,000	190,750
044	LI-1500	180,750	18,750	89,250	117,250
TOTALS		1,565,250 Hrs	186,000 Hrs	$6,343,500	$1,750,000*
		TOTAL 1,751,250 Hrs			

*Prorated by End Item Area

TABLE I2-9

ITERATION NO. 2 - TPS METALLIC (COLUMBIUM)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	839,250	$6,343,500	
PANEL INSTALLATION	494,250		
PANEL REMOVAL	155,250		
INSPECTION			$1,750,000
PRE-FLIGHT	48,000		
IN-PROCESS	90,000		
POST-FLIGHT	48,000		
PACKAGING AND HANDLING	42,750		
STORAGE	33,750		
TOTALS	1,751,250 hrs	$6,343,500	$1,750,000

TABLE I2-10

SYSTEM COSTS BY PHASE AND TPS SUBSYSTEM

(ITERATION NO. 2 - TPS METALLIC (COLUMBIUM))

SUBSYSTEM	RECURRING OPERATIONS	RECURRING PRODUCTION	NON-RECURRING DDT&E	TOTAL
020 TANTALUM	$1,040,579	$2,521,298	$8,166,919	$11,728,796
030 COLUMBIUM	12,986,984	15,530,665	27,733,979	56,251,628
060 HAYNES	2,977,831	5,001,928	12,295,494	20,275,253
070 RENE'41	2,548,049	4,110,070	10,489,987	17,148,106
080 TITANIUM	8,329,149	13,377,325	17,330,135	39,036.609
044 LI-1500	3,021,993	2,061,702	6,380,050	12,363,745
TOTAL	$30,904,585	$43,502,988	$82,396,564	$156,804,137
LOGISTICS	-	$149,700,000		149,700,000
TOTAL	$30;904,585	$193,202,988	$82,396,564	$306,504,137

TABLE I2-11

SYSTEM COSTS OF OPERATIONS BY PHASE AND OPERATIONAL TASK

(ITERATION NO. 2 - TPS METALLIC (COLUMBIUM))

OPERATIONAL TASK	HOURS	RECURRING		NON-RECURRING	TOTAL
		LABOR	MATERIAL	EQUIPMENT	
MAINTENANCE	839,250	$10,918,634	$ 8,120,822	$ -	$ 19,039,465
PANEL INSTALLATION	494,250	6,430,193	-	-	6,430,193
PANEL REMOVAL	155,250	2,019,803	-	-	2,019,803
INSPECTION					
PRE-FLIGHT	48,000	624,280	-	582,482	1,206,962
IN-PROCESS	90,000	1,170,900	-	1,075,351	2,246,251
POST-FLIGHT	48,000	624,280	-	582,482	1,206,962
PACKAGING & HANDLING	42,750	556,177	-	-	556,177
STORAGE	33,750	439,087	-	-	439,087
TOTAL	1,751,250	$22,783,763	$8,120,822	$2,240,315	$33,144,900

TABLE I2-12

SYSTEM COSTS BY PHASE AND FUNCTION
(ITERATION NO. 2 - TPS METALLIC (COLUMBIUM))

FUNCTION	RECURRING OPERATION	RECURRING PRODUCTION	NON-RECURRING DDT&E	TOTAL
MANUFACTURING	$ -	$ 21,898,794	$ 17,283,979	$ 39,182,773
OPERATIONS	28,484,725	-	-	28,484,725
ENGINEERING:				
STRESS	-	2,146,461	4,589,141	-
WEIGHTS	-	754,552	3,323,025	-
LOADS & DYNAMICS	-	586,162	2,046,286	-
THERMODYNAMICS	-	1,162,235	4,157,934	-
DESIGN	-	1,482,531	3,262,097	-
MATERIALS	-	8,772,718	39,910,897	-
TOTAL ENGINEERING	-	$14,904,659	$57,289,380	$72,194,039
QUALITY ASSURANCE:				
MANUFACTURING	-	6,699,535	5,582,890	-
OPERATIONS	2,419,860	-	2,240,315	-
TOTAL Q.A.	$2,419,860	$6,699,535	$7,823,205	$16,942,600
TOTAL	$30,904,585	$43,502,988	$82,396,564	$156,804,137
LOGISTICS	-		-	$149,700,000
MANUFACTURING		$115,000,000		
QUALITY ASSURANCE		34,700,000		
TOTAL	$30,904,585	$193,202,988	$82,396,564	$306,504,137

TABLE I2-13

SYSTEM COST UNCERTAINTY BY PHASE
(ITERATION NO. 2 - METALLIC TPS)

COST-UNCERTAINTY FACTORS & COST RANGE	PROGRAM PHASES			TOTAL
	DDT & E	PRODUCTION	OPERATIONS	
HIGH UNCERTAINTY FACTOR	3.63 / 1	2.36 / 1	4.76 / 1	3.49 / 1
LOW UNCERTAINTY FACTOR	1 / 2.74	1 / 1.74	1 / 3.92	1 / 2.48
HIGHEST TPS COST	$299 M	$456.0 M	$146 M	$1,070.0 M
NOMINAL TPS COST	82.4 M	193.2 M	30.9 M	306.5 M
LOWEST TPS COST	30 M	111.0 M	7.9 M	123.5 M

NOTES:
- UNCERTAINTY FACTORS ARE SUMMATION VALUES REFLECTING ALL COST-ELEMENT UNCERTAINTY ESTIMATES
- THE HIGH & LOW FACTORS ARE MULTIPLIERS TO BE USED WITH NOMINAL COSTS TO OBTAIN ESTIMATED HIGH & LOW COST LIMITS
- THESE DATA REFLECT A TYPICAL TPS COST ESTIMATE FOR A DELTA BODY ORBITER, 1500 NM CROSS RANGE

TABLE I2-14

ITERATION NO. 3

Iteration No. 3 is a non-metallic TPS system with (6) six TPS subsystem materials selected through computer analysis. LI-1500 (Material Code 040) is used as the primary subsystem for investigation and sizing purposes.

TPS Sizing For Baseline Vehicle

Each TPS material subsystem is structurally depicted and sized in Table I3-1. TPS covers 17,411 ft^2 of the vehicle surface and weighs 37,750 lb for an average unit weight of 2.17 PSF.

Material and panel geometry are a function of the temperature regimes listed at the bottom of the table. While surface geometry and location on the vehicle are listed parameters, they are not at this time carried as factors in the total system cost analysis.

The data contained in this table is used for calculating the number of panels (N) of a given material type. In this evaluation 14 ft^2 panels (approximately 45" x 45") are used. Further use of the data is made in the Production Panel Model where area and weight are the principle cost generating factors.

End Item Summary (EIS)

The End Item Summary Sheet (EIS) is the basic cost estimating document on which all original data regarding operations is recorded. Operations personnel have selected six(6) operation tasks for which a given material subsystem, End Item, can be expected to produce a cost impact. These are presented in Table I3-2 as:

- Panel Installation
- Panel Removal
- In Process Inspection
- Packaging and Handling
- Storage
- Maintenance

Various methods and techniques were considered for each of these tasks and hourly weights assigned commensurate with the degree of effort required. The nominal hourly estimates are based on performing similar type operational tasks on a known baseline material which in this case is titantium. The uncertainty assigned to each End Item/Operation Task element indicates the degree to which selected methods and techniques are well enough understood to be in fact accomplished in the time indicated. All values listed in Table I3-2 are for a single panel.

The tantalum nose cone requires the greatest expenditure of time and has the largest uncertainty, followed by (044) LI-1500 on the base shield and then titanium which is applied to the 'top' surface of the vehicle.

For the Operation tasks, cost and uncertainty are highest in the maintenance area where repairs are made on removed panels. Panel installation follows next in terms of high cost although the uncertainty is not inadversely large. Inspection shows a low cost but high uncertainty.

End Item totals and Operation task totals are used in the <u>Operational Expenditures</u> calculation where they are modified by the <u>Maintenance Factors</u> to produce a vehicle refurbishment labor cost.

<u>Production Panel Model</u>

Panel structural design varies with material type, temperature regime, location on the primary structure and design approach taken on the vehicle structure.

In Table I3-3, the weight and area values obtained from Table I3-1 are represented in a format where those costs which are a function of weight can be separated from those that are a function or area. Cost per pound and per square foot are provided by Procurement Material estimators.

Summary results indicate that a complete TPS system will require a material expenditure of $565,960. Tantalum has the highest cost per pound with titanium second, however, its total cost is less than that for titantium, because of the much greater weight of titantium. The tantalum cone weight contribution is small relative to all other TPS subsystem. LI-1500 exhibits very good material cost compound with the (2) other material candidates.

Production panel costs are used in Operations Expenditure calculations where they are modified according to Maintenance Factors to produce a vehicle refurbishment material cost.

Maintenance Factors

The combined effect of all mission hazards encountered by a TPS system while flying a selected mission profile will determine the nature and extent of operational refurbishment. Inspection, maintenance, and logistic TPS activities (and costs) are essentially a direct function of the of the operations that must be undertaken as a result of the hazards experienced.

In Table I3-4 a matrix of TPS Maintenance Frequencies provides values that indicate the degree to which a selected TPS subsystem will respond to a given hazard. Integrating the spectrum of hazards over the mission profile provides a maintenance rate (F_r). Maintenance rates are interpreted as "the expected number of flights a TPS subsystem will experience before some maintenance action is required". Both frequency and uncertainty are iteratively developed measures derived from existing documentation and best engineering judgments.

The lowest maintenance rate ($F_r = 10.7$) and highest uncertainty ($\pm .033$) occur on the tantalum nose cone due primarily to the large temperature/load frequency.

The end item maintenance rates are used in the Operation Expenditures calculation where they are used to determine the numbers of panels replaced per TPS subsystem and from this the vehicle labor hours and materials.

Operation Expenditures

Operation Expenditure calculations are made to determine the vehicle labor and material cost subject to the data just described in the previous step and operation premises (Appendix C).

In Tables I3-5 and I3-6, the results show that thirty-nine (39) panels out of 1162 total panels can be expected to require refurbishment, in this case, necessitating removal and replacement. A labor expenditure of 2,229 hours and a material commitment of $4,486 will result.

It should be noted that while the tantalum nose cone had the lowest maintenance rate ($F_r = 10.7$) of the six (6) TPS subsystems, its contribution to total labor cost is the lowest for the six subsystems. Because of the low material cost per pound of LI-1500, (4) four of these subsystems cost less than tantalum. Only the (041) subsystem has a high material cost due to its heavy usage on the bottom of the orbiter.

The primary cost driver for labor is (041) LI-1500 with titanium second. For material the titanium cost is greatest. The lower maintenance rate for LI-1500 and higher differential cost in material produces this outcome.

Cost uncertainty differences between subsystems are not large enough to produce any change in the total labor or material costs of end items. This in spite of the high labor uncertainty for tantalum and (044) LI-1500.

Vehicle Level Operations

Vehicle costs are summarized by end item in Table I3-7 and operation tasks in Table I3-8. Maintenance, Inspection, Material and Equipment costs are displayed as recurring or non-recurring for those costs that were determined from the Operation Expenditure analysis, as well as those prorated costs which are not estimated at the end item level. Base Inspection falls into this latter category and is prorated to the subsystem level on an end item area basis.

The consolidation of all recurring and non-recurring end item and operation task costs on one summary sheet is in preparation for the application of mission life cycle requirements in determination of System Level Operations cost.

System Level Operations

System level operation costs are summarized by End Item in Table I3-9 and by Opertion Task in Table I3-10. Table values are obtained by multipying the vehicle level operations by the number of missions flown over the life of the program by a given fleet of vehicles. In this evaluation, there are 8 vehicles in the fleet. This group will fly 75 missions a year for 10 years, which will require 750 refurbishments over the life of the program.

The total expenditures for labor, material and equipment are:

Labor	-	1,768,500 hours
Material	-	$3,364,500 (In support of Maintenance operations)
Equipment	-	$1,750,000

Equipment is an Inspection requirement. It is a system level cost and applies across the whole vehicle fleet for the life of the program. For cost comparison purposes its cost is prorated to the subsystem on the basis of end item area.

System Cost by Phase and TPS Subsystem

TPS subsystem expenditures are provided in Table I3-11. End item costs are greatest for (041) LI-1500 with titanium second. This follows for Operations and DDT&E, however, titanium production costs are greater than that for (041) LI-1500. The relatively lower cost of (041) LI-1500 results from its much smaller material cost. Logistic cost amounts to 122.3 million dolars or 51% of the total system cost. The relative rank in percent of total cost is as follows:

Rank	Material Code	Material	Percent	Uncertainty	
				Material	Labor
1	041	LI-1500	33.2	1.2	2.00
2	080	Titanium	28.4	1.1	3.13
3	020	Tantalum	10.4	1.1	6.83
4	044	LI-1500	10.3	1.2	6.03
5	043	LI-1500	10.1	1.2	2.04
6	042	LI-1500	7.5	1.2	2.02

Logistic expenditures are prorated by the initial production cost.

System Cost of Operations by Phase and Operational Task

System costs for Operations are shown in Table I3-12 by Operation Task. Maintenance costs rank highest in total cost followed by Panel Installation and Inspection. Their relative rank in percent of total cost is as follows:

Rank	Operational Task	Percent	Uncertainty	
			Material	Labor
1	Maintenance	45.5	H 1.42 L 1/1.66	9.21
2	Panel Installation	26.9	-	2.20
3	Inspection	15.5	-	5.21
4	Panel Removal	8.4	-	2.51
5	Packaging and Handling	2.0	-	4.14
6	Storage	1.8	-	3.86

Refurbishment operations amount to $13,884,923 or 47% of the total cost.

System Cost by Phase and Function

Total system cost for Iteration No. 3 is $238,543,041. In Table I3-13 , this cost is broken down into its six (6) functional areas and two (2) summary cost groups for the three (3) program phases.

Refurbishment costs for the non-metallic TPS system described in this iteration, composed of six TPS subsystems and requiring 750 refurbishments over the 10 year life of the program, amount to $27,315,352--approximately 11% of the total TPS system cost. This compares with the other program phases as follows:

Group	Phase	Percent	Uncertainty High	Uncertainty Low
Recurring	Operation	23.5	5.2	1/4.06
	Production	25.1	2.09	1/1.69
		51.4		
Non-recurring	DDT&E		2.77	1/3.97

The contribution by each of the nine (9) functional groups is summarized as follows:

Function	Percent
Operation	10.5
Manufacturing	57.1
Quality Assurance	10.4 (2.1 of which is for Operations)
Engineering	22.0

Cost estimates for the functions other than Operations were derived in a manner similar to that just described. Due to its volume, the supporting data is not provided.

System Cost Uncertainty by Phase

Nominal costs to perform the DDT&E, Production, and Operation phases reflect the depth of informational detail avaiable to all functional groups. The costs shown in Table I3-14 are based on a mix of subjective judgment, "similar to" knowledge, and definitive information. The extent to which definition is lacking will appear in the magnitude of the uncertainty factor.

The importance of this information is twofold: (1) It provides perspective which allows the establishment of priorities for further development activities that will effectively lead to uncertainty reduction and definitive costing, and (2) the data can be directly related to a function, activity, or end item, permitting critical appraisal of design and system tradeoffs and maintenance of program objectives.

Conditions shown in Table I3-14, indicate that the non-metallic TPS system can cost 3.17 times nominal or 756.0 million dollars. Technological uncertainty can result in a 1/2.99 reduction in the nominal cost to 79.8 million dollars for non-metallic TPS system.

Operations exhibits the widest range of uncertainty exceeding that for the system. Operations can cost 5.25 times nominal or 143.7 million dollars, while a 1/4.06 reduction due to technological uncertainty would result in a cost of 6.7 million dollars.

TPS SIZING DATA FOR BASELINE VEHICLE
(ITERATION NO. 3 - TPS NON-METALLIC (LI-1500 TPS))

TPS ELEMENT LOCATION & TYPE *	AREA FT^2	INSUL. THICKNESS IN.	SUB PANEL LBS.	INSUL. LBS.	TOTAL LBS.	PSF
Body, Nose Cone - Ta	70	-	537	452	989	14.10
SUBTOTALS (020)	70	-	537	452	989	14.10
Fin - 2000° - 2500° Body - 2000° - 2500°	855 4576	2.0 2.2	742 3977	2000 11668	2742 15645	
SUBTOTALS (041)	5431	-	4719	13668	18387	3.40
Fin - 1600° - 2000° Body - 1600° - 2000°	248 1029	1.8 2.2	215 894	528 2620	743 3514	
SUBTOTALS (042)	1277	-	1109	3148	4257	3.35
Fin - 1000° - 1600° Body - 1000° - 1600°	665 1180	1.8 2.2	578 1025	1416 3008	1994 4033	
SUBTOTALS (043)	1845	-	1603	4424	6027	3.27
Fin - Corrug. Ti Body - Corrug. Ti	912 5166	0.25 0.25	577 3267	120 678	697 3945	
SUBTOTALS (080)	6078	-	3844	798	4642	0.76
Body - Base Heat Shield	1610	-	707	2109	2816	
SUBTOTALS (044)	1610	-	707	2109	2816	1.75
Lower Flap	1100	-	-	632	632	-
SUBTOTALS (101)	1100	-	-	632	632	0.57
TOTAL	17411	-	12519	25231	37750	2.17

* Materials:
(020) = Tantalum (2500° to 3000°)
(041) = LI 1500 (2000° to 2500°)
(042) = LI 1500 (1600° to 2000°)
(043) = LI 1500 (1000° to 1600°)
(080) = Titanium (Under 1000°)
(044) = LI 1500 Base Shield
(101) = Dynaflex Flap Shield

TABLE I3-1

ORIGINATOR
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ITERATION NO. 3 - TPS NON-METALLIC (LI-1500)
(END ITEM SUMMARY SHEET (EIS)

DATE: 5/12/70
VEHICLE: DELTA BODY
TPS: LI-1500 CR: 1500 NM
DWG: LO-2077
FIG: 8 ITERATION #3

MAT'L CODE	BASELINE MATERIAL:	PANEL INSTALLATION		PANEL REMOVAL		INSPECTION (IN-PROCESS)		PACKAGING & HANDLING		STORAGE				MAINTENANCE REUSE		TOTAL	
		H_{pi}	U_{pi}	H_{pr}	U_{pr}	H_i	U_i	H_h	U_h	H_s	U_s	H _	U _	H_m	U_m	H_r	U_r
020	TANTALUM (Nose	150	1.40	50	2.0	24	6.00	16.0	4.00	8	4.00			300	10.00	548.0	6.825
041	LI-1500	34	1.60	12	1.60	2	5.00	1.8	5.00	3	4.00			2	2.50	54.8	2.000
042	LI-1500	34	1.60	10	1.60	2	5.00	1.8	5.00	3	4.00			2	2.50	52.8	2.015
043	LI-1500	31	1.60	10	1.60	2	5.00	1.8	5.00	3	4.00			2	2.50	49.8	2.040
080	TITANIUM	18	1.50	6	1.50	1	1.50	1.0	1.00	1	1.00			24	5.00	51.0	3.127
044	LI-1500 (Base)	40	7.00	8	7.00	15	5.00	1.8	5.00	3	4.0			23	5.00	90.0	6.033
TOTAL	WT AVE.	307	—	96	—	46	—	23.4	—	21	—		—	353	—	846.4	
	ARITH AVE.		2.200		2.513		5.446		4.145		3.857				4.207		5.624

TABLE I3-2

ITERATION NO. 3 - TPS LI-1500

PRODUCTION PANEL MODEL

	020 Tantalum	041 LI-1500	042 LI-1500	043 LI-1500	080 Titanium	044 LI-1500	101 Insul
Erosion Shield / Subpanel (Included together [1])	412	13,668	3,148	4,424	3,124 / 8,987 [1]	2,109	
Clips	(452)				(798)		(632)[2]
Insulation (Not in total #)							1,250
TOTAL #	412	13,668	3,148	4,424	12,111	2,109	1,250
$/#	$50.00	$6.90	$6.90	$6.90	$29.44	$6.90	-
	$20,600	$94,309	$21,721	$30,526	$356,548	$14,552	
Area (ft^2)	70[2]	5,431	1,277	1,845	6,078[2]	1,610	(1,100)[2] 6,148
$/Ft^2	-	$2.00	$2.00	$2.00	-	$2.00	$1.20
	0	$10,862	$2,554	$3,690	0	$3,220	$7,378
TOTAL $ (With Insulation)	$20,600 / $ 84	$105,171	$24,275	$34,216	$356,548 / $ 7,294	$17,772	$7,378 / ($ 7,378)
TOTAL $	$20,684	$105,171	$24,274	$34,216	$363,842	$17,772	-
TOTAL	$565,960						

1. All subpanels are titanium.
2. Flap shield insulation omitted.

TABLE I3-3

ORIGINATOR

Macedo/Kish

DATE: 5/11/70

(ITERATION NO. 3 - TPS NON-METALLIC (LI-1500)

MAINTENANCE FACTORS

VEHICLE: Delta Body TPS: LI 1500 CR: 1500 NM DWG: LO-2077 FIG: 8 Iteration #3		TEMP EXPOSURE		COMBINED TEMP/LOAD		COMBINED TEMP/PRESS.		COMBINED TEMP/PRESS./ LOAD		HANDLING		ENVIRONMENT		COMPOSITE MAINTENANCE FREQUENCY		MAINTENANCE RATE (FLIGHT/PANEL)	
		F_T	U ±	F_{TL}	U ±	F_{TP}	U ±	F_{TPL}	U ±	F_H	U ±	F_E	U ±	F_F	U ±	F_r	MAX. / MIN.
MAT'L CODE	BASELINE MATERIAL:																
020	Tantalum (Nose)	.0224	.012	.1041	.033	.0565	.020	.1510	.033	.0530	.033	.1093	.033	.0932	.033	10.7	16.011 / 7.924
041	LI-1500 (2000-2500)	.0182	.003	.0789	.020	.0349	.010	.0117	.004	.0363	.010	.0389	.011	.0442	.020	22.6	41.322 / 15.570
042	LI-1500 (1600-2000)	.0167	.003	.0679	.020	.0299	.010	.0097	.004	.0313	.010	.0334	.011	.0364	.020	27.5	60.976 / 17.730
043	LI-1500 (1000-1600)	.0152	.006	.0569	.033	.0249	.015	.0079	.004	.0263	.015	.0279	.015	.0306	.020	32.7	94.340 / 19.763
080	Titanium	.0175	.005	.0327	.007	.0376	.008	.0142	.005	.0198	.006	.0247	.009	.0258	.009	38.8	59.524 / 28.736
044	LI-1500 (Base Shield)	.0167	.003	.0373	.010	.0249	.010	.0097	.004	.0313	.010	.0324	.011	.0279	.011	35.8	59.172 / 25.707
101	Dynaflex (Flap Shield)																
030	Columbium (Lower Flap Shield)	.0133	.002	.0377	.020	.0485	.011	.0242	.020	.0204	.003	.0289	.008	.0311	.020	32.2	90.090 / 19.569
070	Rene' (Upper Flap Shield)	.0357	.012	.0281	.006	.0304	.009	.0170	.006	.0179	.002	.0291	.006	.0272	.012	36.8	65.789 / 25.510
TOTAL	WT AVE.		—		—		—		—		—		—		—		
	ARITH AVE.																

TABLE I3-4

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5/12/70

ITERATION NO. 3 - TPS NON-METALLIC (LI-1500)
(OPERATION EXPENDITURES - HOURS)

[illegible]: DELTA BODY

TPS LI-1500 C2: 1500 [illegible]

[illegible]: LO-2077

[illegible]: 8 ITERATION #3

[illegible]		TPS SUBSYSTEM Area (ft^2)	Panel Avg Area	Subsys Panels (N)	Maintenance Rate F_r	MIN / MAX	Panels Maintained P_r	MAX / MIN	Module IV Maintenance Reuse H_r	MAX / MIN			H_T	$F_r=K$ MAX / MIN	$H_r=K$ MAX / MIN	Worst Case MAX / MIN
020	TANTALUM (Nose)	70	70	1	10.7	7.924 / 16.611	.09	.126 / .060	548	374.16 / 80.[illegible]			57.21		69.05 / 32.88	
041	LI-1500	5431	14	388	22.6	15.576 / [illegible]	17.17	24.91 / 9.33	54.8	107.66 / 27.4			940.92		1365.07 / 511.28	
042	LI-1500	1277	14	92	27.5	17.730 / [illegible]	3.35	5.19 / 1.19	52.8	106.39 / 26.20			176.88		274.03 / 62.83	
043	LI-1500	1845	14	132	32.7	19.763 / 44.340	4.04	6.68 / 1.40	49.8	101.57 / 24.41			201.19		332.66 / 69.72	
080	TITANIUM	6078	14	434	38.8	[illegible] / 57.524	11.19	15.10 / 7.24	51	159.48 / 16.31			570.69		770.10 / 371.79	
044	LI-1500 (Base)	1610	14	115	35.8	[illegible] / [illegible]	3.21	4.47 / 1.94	90	542.97 / 14.92			288.90		402.30 / 174.60	
		16,311		1162	29.8	54.[illegible] / 20.6	39.05	56.476 / 21.210	346.4	1425.[illegible] / 189.53			2229.79		3213.21 / 678.44	

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5/12/70

ITERATION NO. 3 - TPS NON-METALLIC (LI-1500)

(OPERATION EXPENDITURES - MATERIAL)

	DELTA BODY / LI-1500 2:1500 NM / LO-2077 / 8 ITERATION #3	TPS SUBSYSTEM Area (ft^2)	Panel Area (ft^2)	Subsyst Panels (N)	Maintenance Rate F_r	MIN / MAX	Panels Maintained P_r	MAX / MIN	Model IX Maintenance Reuse M_r	MAX / MIN	M_T	F-K MAX / MIN	M_rF-K MAX / MIN	Worst Case MAX / MIN
MAT'L CODE														
020	TANTALUM (Nose)	70	70	1	10.7	7.924 / 16.611	.09	.126 / .060	20,684	22,754 / 18,805	53520		250.84 / 358.02	
041	LI-1500	5431	14	388	22.6	15.576 / 41.576	17.17	24.91 / 9.33	105,171	126,205 / 87,643	111698		1670.09 / 607.05	
042	LI-1500	1277	14	92	27.5	17.730 / 60.976	3.35	5.19 / 1.19	24,275	29,130 / 20,229	212.14		328.60 / 95.94	
043	LI-1500	1845	14	132	32.7	19.763 / 94.340	4.04	6.68 / 1.40	34,216	41,059 / 28,513	251.33		56.21 / 87.05	
080	TITANIUM	6078	14	434	38.8	21.736 / 59.524	11.19	15.10 / 7.29	363,842	400,226 / 330,765	225126		3031.35 / 1467.10	
044	LI-1500 (Base)	1610	14	115	35.8	25.791 / 57.172	3.21	4.47 / 1.94	17,772	21,326 / 14,810	119.06		165.32 / 72.09	
		16,311		1162	29.8	54.8 / 20.6	34.05	56.476 / 21.210	565,968	646,700 / 500,765	1446.27		6369.41 / 2687.23	

TABLE 13-6

ITERATION NO. 3 - TPS LI-1500

VEHICLE LEVEL OPERATIONS

CODE NO.	MATERIAL	RECURRING LABOR HOURS			RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION			
			In-Process	Base		
020	Tantalum	49	2	3	535	-
041	LI-1500	906	35	63	1,117	-
042	LI-1500	171	7	15	212	-
043	LI-1500	193	8	21	251	-
080	Titanium	559	11	16	2,252	-
044	LI-1500	241	48	10	119	-
	Totals	2,119	111	128*	$4,486	
		Total 2,230 hours				

*Prorated End Item Area

TABLE I3-7

ITERATION NO. 3 - TPS LI-1500

VEHICLE LEVEL OPERATIONS

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	935	$ 4,486	
PANEL INSTALLATION	813		
PANEL REMOVAL	254		
INSPECTION			
PRE-FLIGHT	64		
IN-PROCESS	111		
POST-FLIGHT	64		
PACKAGING AND HANDLING	61		
STORAGE	56		
TOTALS	2,358 Hrs	$4,486	

TABLE I3-8

ITERATION NO. 3 - TPS LI-1500

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

CODE NO.	MATERIAL	RECURRING LABOR HOURS		RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION In-Process + Base		
020	Tantalum	36,750	3,750	401,250	46,550
041	LI-1500	679,500	73,500	837,750	866,775
042	LI-1500	128,250	16,500	159,000	200,550
043	LI-1500	144,750	21,750	188,250	284,025
080	Titanium	419,250	43,500	1,689,000	218,750
044	LI-1500	180,750	20,250	89,250	132,650
	TOTALS	1,589,250 Hrs	179,250 Hrs	$3,364,500	$1,750,000*
		Total 1,768,500 Hrs			

*Prorated End Item Area

TABLE I3-9

ITERATION NO. 3 - TPS LI-1500

SYSTEM LEVEL OPERATIONS

(750 REFURBISHMENTS)

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	701,250	$ 3,364,500	
PANEL INSTALLATION	609,750		
PANEL REMOVAL	190,500		$ 1,750,000
INSPECTION			
PRE-FLIGHT	48,000		
IN-PROCESS	83,250		
POST-FLIGHT	48,000		
PACKAGING AND HANDLING	45,750		
STORAGE	42,000		
TOTALS	1,768,500 Hrs	$3,364,500	$1,750,000

TABLE I3-10

SYSTEM COSTS BY PHASE AND TPS SUBSYSTEM

(ITERATION NO. 3 - TPS NON-METALLIC LI-1500)

SUBSYSTEM	RECURRING		NON-RECURRING	TOTAL
	OPERATIONS	PRODUCTION	DDT&E	
020 TANTALUM	$ 1,040,579	$ 2,559,768	$ 8,402,903	$ 12,003,250
041 LI-1500	10,869,001	8,647,508	19,019,357	38,535,866
042 LI-1500	2,086,747	2,037,816	4,584,467	8,709,030
043 LI-1500	2,407,157	2,905,965	6,496,598	11,809,720
044 LI-1500	3,031,749	2,755,519	6,181,883	11,969,151
080 TITANIUM	7,880,119	10,226,285	14,959,620	33,066,024
TOTAL	$27,315,352	$ 29,132,861	$59,644,828	$116,093,041
LOGISTICS	-	122,250,000	-	122,250,000
TOTAL	$27,315,352	$151,382,861	$59,644,828	$238,343,041

TABLE I3-11

SYSTEM COSTS BY PHASE AND OPERATIONAL TASK

(ITERATION NO. 3 - TPS NON-METALLIC LI-1500)

OPERATIONAL TASK	HOURS	RECURRING		NON-RECURRING	TOTAL
		LABOR	MATERIAL	EQUIPMENT	
MAINTENANCE	701,250	$ 9,123,263	$ 4,307,166	$ -	$ 13,430,429
PANEL INSTALLATION	609,750	7,932,848	-	-	7,932,848
PANEL REMOVAL	190,500	2,478,405	-	-	2,478,405
INSPECTION					
PRE-FLIGHT	48,000	624,480	-	582,482	1,206,962
IN-PROCESS	83,250	1,083,083	-	1,075,351	2,158,434
POST-FLIGHT	48,000	624,480	-	582,482	1,206,962
PACKAGING & HANDLING	45,750	595,207	-	-	595,207
STORAGE	42,000	546,420	-	-	546,420
TOTAL	1,768,500	$23,008,186	$4,307,166	$2,240,315	$29,555,667

TABLE I3-12

SYSTEM COSTS BY PHASE AND FUNCTION
(ITERATION NO. 3 - TPS NON-METALLIC LI-1500)

FUNCTION	RECURRING OPERATION	RECURRING PRODUCTION	NON-RECURRING DDT&E	TOTAL
MANUFACTURING	$ -	$ 15,599,080	$ 13,998,555	$ 29,597,635
OPERATIONS	24,983,209	-	-	24,983,309
ENGINEERING:				
STRESS	-	2,114,190	4,516,755	-
WEIGHTS	-	742,878	3,269,784	-
LOADS & DYNAMICS	-	577,032	2,015,116	-
THERMODYNAMICS	-	1,144,165	4,093,195	-
DESIGN	-	745,800	1,479,330	-
MATERIALS	-	5,898,976	25,971,888	-
TOTAL ENGINEERING	-	$11,223,041	$41,346,068	$52,569,109
QUALITY ASSURANCE:				
MANUFACTURING	-	2,310,740	2,059,890	-
OPERATIONS	2,332,043	-	2,240,315	-
TOTAL Q.A.	$2,332,043	$2,310,740	$4,300,205	$ 8,942,988
TOTAL	$27,315,352	$ 29,132,861	$59,644,828	$116,093,041
LOGISTICS				122,250,000
MANUFACTURING	-	106,500,000	-	
QUALITY ASSURANCE	-	15,750,000		
TOTAL	$27,315,352	$151,382,861	$59,664,828	$238,343,041

TABLE I3-13

SYSTEM COST UNCERTAINTY BY PHASE
(ITERATION NO. 3 - NON-METALLIC TPS)

COST-UNCERTAINTY FACTORS & COST RANGE	PROGRAM PHASES			TOTAL
	DDT & E	PRODUCTION	OPERATIONS	
HIGH UNCERTAINTY FACTOR	2.77	2.09	5.25	3.17
	1	1	1	1
LOW UNCERTAINTY FACTOR	3.97	1.69	4.06	2.99
HIGHEST TPS COST	$165 M	$317.0 M	$143.7M	$756.0 M
NOMINAL TPS COST	59.6 M	151.4 M	27.3M	238.3 M
LOWEST TPS COST	14.9 M	89.6 M	6.7M	79.8 M

NOTES:
- UNCERTAINTY FACTORS ARE SUMMATION VALUES REFLECTING ALL COST-ELEMENT UNCERTAINTY ESTIMATES
- THE HIGH & LOW FACTORS ARE MULTIPLIERS TO BE USED WITH NOMINAL COSTS TO OBTAIN ESTIMATED HIGH & LOW COST LIMITS
- THESE DATA REFLECT A TYPICAL TPS COST ESTIMATE FOR A DELTA BODY ORBITER, 1500 NM CROSS RANGE

TABLE I3-14

ITERATION NO. 4

Iteration No. 4 is a Ablative TPS system with six (6) TPS subsystem materials selected through computer analysis. Ablator (Material Code 010) is used as the primary subsystem for investigation and sizing purposes. The elastomeric honeycomb structure has a density of 25 pcf.

TPS Sizing For Baseline Vehicle

Each TPS material subsystem is structurally depicted and sized in Table I4-1. TPS covers 17,411 ft^2 of the vehicle surface and weighs 47,206 lbs for an average unit weight of 2.71 PSF.

Material and panel geometry are a function of the temperature regimes listed at the bottom of the table. While surface geometry and location on the vehicle are listed parameters, they are not at this time carried as factors in the total system cost analysis.

The data contained in this table is used for calculating the number of panels (N) of a given material type. In this evaluation 14 ft^2 panels (approximately 45" x 45") are used. Further use of the data is made in the Production Panel Model where area and weight are the principle cost generating factors.

End Item Summary (EIS)

The End Item Summary Sheet (EIS) is the basic cost estimating document on which all original data regarding operations is recorded. • Operations personnel have been selected six(6) operation tasks for which a given material subsystem, End Item, can be expected to produce a cost impact. These are presented in Table I4-2 as:

- Panel Installation
- Panel Removal
- In Process Inspection
- Packaging and Handling
- Storage
- Maintenance

Various methods and techniques were considered for each of these tasks and hourly weights assigned commensurate with the degree of effort required. The nominal hourly estimates are based on performing similar type operational tasks on a known baseline material which in this case is titanium. The uncertainty assigned to each End Item/Operation Task element indicates the degree to which selected methods and techniques are well enough understood to be in fact accomplished in the time indicated. All values listed in Table I4-2 are for a single panel.

The ablative nose cone requires the greatest expenditure of time and has the largest uncertainty, followed by (044) LI-1500 on the base shield and then the remaining ablative subsystems. Titanium requires the least expenditure of labor hours and has the smallest uncertainty.

For the Operation tasks, cost and uncertainty are highest in the maintenance area where repairs are made on removed panels. Panel installation follows next in terms of high cost although the uncertainty is not as large as that for inspection.

End Item totals and Operation task totals are used in the Operational Eexpenditures calculation where they are modified by the Maintenance Factors to produce a vehicle refurbishment labor cost.

Production Panel Model

Panel structural design varies with material type, temperature regime, location on the primary structure and design approach taken on the vehicle structure.

In Table I4-3, the weight and area values obtained from Table I4-1 are represented in a format where those costs which are a function of weight can be separated from those that are a function or area. Cost per pound and per square foot are provided by Procurement Material estimators.

Summary results indicate that a complete TPS system will require a material expenditure of $544,097. Titanium is the only TPS subsystem using cost per pound. The other subsystems are costed by dollars per square foot. It should be noted that the combined material cost for ablators ($150,412) is a little less than one-half the cost for titanium.

Production panel costs are used in Operations Expenditure calculations where they are modified according to Maintenance Factors to produce a vehicle refurbishment material cost.

Maintenance Factors

The combined effect of all mission hazards encountered by a TPS system while flying a selected mission profile will determine the nature and extent of operational refurbishment. Inspection, maintenance, and logistic TPS activities (and costs) are essentially a direct function of the operations that must be undertaken as a result of the hazards experienced.

In Table I4-4 a matrix of TPS Maintenance Frequencies provides values that indicate the degree to which a selected TPS subsystem will respond to a given hazard. Integrating the spectrum of hazards over the mission profile provides a maintenance rate (F_r). Maintenance rates are interpreted as "the expected number of flights a TPS subsystem will experience before some maintenance action is required." Both frequency and uncertainty are iteratively developed measures derived from existing documentation and best engineering judgments. The lowest maintenance rate ($F_r = 1.0$) has an uncertainty of ($\pm$ 0.0) which is due to the assumption that ablative panels must be replaced after every flight.

The end item maintenance rates are used in the Operation Expenditures calculation where they are used to determine the numbers of panels replaced per TPS subsystem and from this the vehicle labor hours and materials.

Operation Expenditures

Operation Expenditure calculations are made to determine the vehicle labor and material cost subject to the data just described in the previous step and operation premises, (Appendix C).

In Table I4-5 and I4-6, the results show that 627 panels out of 1162 total panels will require replacement. A labor expenditure of 42,496 hours and a material commitment of $38,557 will result.

Maintenance rate completely dominates cost as the principle cost driver. Material and labor costs are high due to the large number of panels that must be replaced.

No information has been forthcoming from the literature or materials engineering that would suggest the reusability of ablative systems.

NASA has five (5) contracts underway with ablative contractors which may change this situation. However, until then, it will be assumed that the thermal environment experienced by an Orbiter will be well in excess of 700°F temperature at which material degradation becomes irreversible. For this reason, panels will be replaced after every mission.

Vehicle Level Operations

Vehicle costs are summarized by end item in Table I4-7 and operation tasks in Table I4-8. Maintenance, Inspection, Material and Equipment costs are displayed as recurring or non-recurring for those costs that were determined from the Operation Expenditure analysis, as well as, those prorated costs which are not estimated at the end item level. Base Inspection fall into this latter category and is prorated to the subsystem level on an end item area basis.

The consolidation of all recurring and non-recurring end item and operation task costs on one summary sheet is in preparation for the application of mission life cycle requirements in determination of System Level Operations cost.

System Level Operations

System level operation costs are summarized by End Item in Table I4-9 and by Operation Task in Table I4-10. Table values are obtained by multiplying the vehicle level operations by the number of missions flown over the life of the program by a given fleet of vehicles. In this evaluation, there are eight vehicles in the fleet. This group will fly 75 missions a year for 10 years, which will require 750 refurbishments over the life of the program.

The total expenditures for labor, material and equipment are:

Labor	-	31,967,250 hours
Material	-	$28,917,750 (In support of Maintenance Operations)
Equipment	-	$ 1,750,000

Equipment is an inspection requirement. It is a system level cost and applies across the whole vehicle fleet for the life of the program. For cost comparison purposes its cost is prorated to the subsystem on the basis of end item area.

System Cost by Phase and TPS Subsystem

TPS subsystem expenditures are provided in Table I4-11. End Item costs are greatest for (011) Ablator which is applied on the bottom of the Orbiter. Together with the logistic requirements, the ablator subsystem constitutes 96% of the total system acquisition cost, amounting to 1,216 million dollars out of the total of 1,266 million dollars for the system. Logistic cost amounts to 732.1 million dollars or 58% of the total system cost. The relative rank in percent of total cost is as follows:

RANK	MATERIAL CODE	MATERIAL	PERCENT	UNCERTAINTY MAT'L	UNCERTAINTY LABOR
1	011	Ablator	56.0	1.6	4.17
2	013	Ablator	19.7	1.6	4.17
3	012	Ablator	13.8	1.6	4.17
4	080	Titanium	6.9	1.1	3.13
5	044	LI-1500	2.3	1.2	6.03
6	010	Ablator	1.3	1.6	5.00

Logistic expenditure are prorated by the initial production cost.

System Cost of Operations by Phase and Operational Task

System costs for Operations are shown in Table I4-12 by Operation Task. Maintenance costs rank highest in total cost followed by Panel Installation and Removal. Their relative rank in percent of total cost is as follows:

Rank	Operational Task	Percent	Uncertainty Mat'l	Uncertainty Labor
1	Maintenance	42.4	H 1.02 L 1/1.02	9.03
2	Panel Installation	35.0	-	3.58
3	Panel Removal	11.9	-	3.63
4	Inspection	5.4	-	5.08
5	Packaging and Handling	2.8	-	3.16
6	Storage	2.5	-	3.00

Refurbishment operations amount to $239,700,078 or 53% of the total cost.

System Cost by Phase and Function

Total system cost for Iteration No. 4 is $1,266,077,530. In Table I4-13, this cost is broken down into its six (6) functional areas and two (2) summary cost groups for the three (3) program phases.

Refurbishment costs for the ablator TPS system described in this Iteration, composed of six TPS subsystems and requiring 750 refurbishments over the 10 year life of the program, amount to $452,913,848, approximately 35.8% of the total TPS system cost. This compares with the other program phases as follows:

Group	Phase	Percent	Uncertainty High	Uncertainty Low
Recurring	Operation	35.8	3.59	1/3.10
	Production	60.2	2.57	1/1.89
Non-recurring	DDT&E	4.0	3.42	1/2.87

The contribution by each of the nine (9) functional groups is summarized as follows:

Function	Percent
Operation	34.2
Manufacturing	44.5
Quality Assurance	17.8 (4.0% of which is for Operations)
Engineering	3.5

Cost estimates for the functions other than Operations were derived in a manner similar to that just described. Due to its volume, the supporting data is not provided.

System Cost Uncertainty by Phase

Nominal costs to perform the DDT&E, Production, and Operation phases reflect the depth of informational detail avaiable to all functional groups. The costs shown in Table I4-14 are based on a mix of subjective judgment, "similar to" knowledge, and definitive information. The extent to which definition is lacking will appear in the magnitude of the uncertainty factor.

The importance of this information is twofold: (1) It provides perspective which allows the establishment of priorities for further development activities that will effectively lead to uncertainty reduction and definitive costing, and (2) the data can be directly related to a function, activity, or end item, permitting critical appraisal of design and system tradeoffs and maintenance of program objectives.

Conditions shown in Table I4-14, indicate that the ablative TPS system can cost 3.50 times nominal or 4,425 million dollars. Technological uncertainty can result in a 1/2.98 reduction in the nominal cost to 424 million dollars for an ablative TPS system.

Operations exhibits the widest range of uncertainty exceeding that for the system. Operations can cost 3.59 times nominal or 1,617 million dollars, while a 1/3.10 reduction due to technological uncertainty would result in a cost of 146 million dollars.

TPS SIZING DATA FOR BASELINE VEHICLE
(ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC))

TPS Element Location and Type*	Area (ft2)	Insulation Thickness (in.)	Sub-Panel (lb)	Insulation or Ablator (in.)	Total (lb)	PSF
Nose Cone	70	2.15	537	320	857	12.24
SUBTOTALS (010)	70	-	537	320	857	12.24
Fin - 2000° - 2500°	855	1.75	742	3206	3948	
Body - 2000° - 2500°	4576	1.75	3977	17160	21137	
SUBTOTALS (011)	5431	-	4719	20366	25085	4.62
Fin - 1600° - 2000°	248	1.65	215	878	1093	
Body - 1600° - 2000°	[illegible]	1.65	894	3643	4537	
SUBTOTALS (012)	1277	-	1109	4521	5630	4.41
Fin - 1000° - 1600°	665	1.50	578	2141	2719	
Body - 1000° - 1600°	1180	1.50	1025	3800	4825	
SUBTOTALS (013)	1845	-	1603	5941	7544	4.09
Fin - Corrugated Ti	912	0.25	577	120	697	
Body - Corrugated Ti	5166	0.25	3267	678	3945	
SUBTOTALS (080)	6078	-	3844	798	4642	0.76
Body - Base Heat Shield	1610	-	707	2109	2816	
SUBTOTALS (044)	1610	-	707	2109	2816	1.75
Lower Flap	1100	-	-	632	632	-
SUBTOTALS (101)	1100	-	-	632	632	0.57
TOTAL	17411	-	12519	34637**	47206	2.71

*Materials:
- (010) - Ablator (2500° to 3000°)
- (011) - Ablator (2000° to 2500°)
- (012) - Ablator (1600° to 2000°)
- (013) - Ablator (1000° to 1600°)
- (080) - Titanium (Under 1000°)
- (044) - LI-1500 Base Shield
- (101) - Dynaflex Flap Shield

**31148 is ablator, 3539 lightweight insulation

TABLE I4-1

ORIGINATOR
K.URBACH

ITERATION NO. 4 – TPS ABLATOR (ELASTOMERIC)
(END ITEM SUMMARY SHEET (EIS)

DATE: 8/21/70

VEHICLE: DELTA BODY

TPS: ABLATOR CR: 1500 NM

DWG:

FIG: ITERATION #4

MAT'L CODE	BASELINE MATERIAL:	PANEL INSTALLATION		PANEL REMOVAL		INSPECTION (IN-PROCESS)		PACKAGING & HANDLING		STORAGE				MAINTENANCE REUSE		TOTAL	
		H_{pi}	U_{pi}	H_{pr}	U_{pr}	H_i	U_i	H_h	U_h	H_s	U_s	H_	U_	H_m	U_m	H_r	U_r
010	ABLATOR (Nose)	150	3.0	50	3.0	28	6.0	16	4.0	8	4.0			320	10.0	572	5.0
011	ABLATOR	40	4.0	16	4.0	3	6.0	3	3.0	4	3.0			10	5.0	78	4.17
012	ABLATOR	40	4.0	16	4.0	3	6.0	3	3.0	4	3.0			10	5.0	78	4.17
013	ABLATOR	40	4.0	16	4.0	3	6.0	3	3.0	4	3.0			10	5.0	78	4.17
080	TITANIUM	18	1.5	6	1.5	1	1.5	1	1.0	1	1.0			24	5.0	51	3.127
044	LI-1500 (Base)	40	5.0	8	7.0	15	5.0	1	5.0	3	4.0			23	5.0	90	6.033
TOTAL	WT AVE.	332	—	112	—	53	—	27	—	24	—		—	397	—	945	
	ARITH AVE.		3.5[illegible]		3.633		5.08		3.16		3.00				9.030		4.803

TABLE I4-2

ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC)

PRODUCTION PANEL MODEL

	010 Ablator	011 Ablator	012 Ablator	013 Ablator	080 Titanium	044 LI-1500	101 Insul
Erosion Shield	320	20,366	4,521	5,941	3,120	2,109	Incl. in Ablat
Sub-Panel	(537)[1]	(4,719)[1]	(1,109)[1]	(1,603)[1]	8,675[1]	519)	(707)[1]
Clips					(724)	188)	(632)[2]
(Not in Total#) Insulation	(Included in Erosion Shield)				(798)		798
Total #	320	20,366	4,521	5,941	12,519	2,109	798
$ / #	-	-	-	-	$29.44	$6.90	-
	0	0	0	0	$368,559	$14,552	0 (1100)[2]
Area(Ft²)	70	5,431	1,277	1,845	6,078[1]	1,610	6,078
$ / Ft²	$ 17.45	$ 17.45	$ 17.45	$ 17.45	-	$2.00	$1.20
TOTAL $	$ 1,222	$ 94,771	$ 22,284	$32,195	0	$ 3,220	$7,294
TOTAL $	$1,222	$94,771	$22,284	$32,195	$368,559	$17,772	$7,294
(With Insul.)	-	-	-	-	$7,294	-	($7,294)
TOTAL $	$1,222	$94,711	$22,284	$32,195	$375,853	$17,772	-

TOTAL: $544,097

1. Includes Subpanel and Clips
2. Flap Shield Insul Omitted

TABLE I4-3

ORIGINATOR
Urbach

ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC)
MAINTENANCE FACTORS

DATE: 9/28/70

VEHICLE: DELTA BODY TPS: ABLATOR CR: 1500 nm DWG: Figure 13 FIG: Iteration #4		TEMP EXPOSURE		COMBINED TEMP/LOAD		COMBINED TEMP/PRESS.		COMBINED TEMP/PRESS./ LOAD		HANDLING		ENVIRONMENT		COMPOSITE MAINTENANCE FREQUENCY		MAINTEN-ANCE RATE (FLIGHT/PANEL)	
MAT'L CODE	BASELINE MATERIAL:	F_T	U ±	F_{TL}	U ±	F_{TP}	U ±	F_{TPL}	U ±	F_H	U ±	F_E	U ±	F_F	U ±	F_r	MAX. / MIN.
010	ABLATOR (Nose)													1	0	1	1 / 1
011	ABLATOR (Fin)													1	0	1	1 / 1
011	(Body)																
012	ABLATOR (Fin)													1	0	1	1 / 1
012	(Body)																
013	ABLATOR (Fin)													1	0	1	1 / 1
013	(Body)																
080	TITANIUM, CORR. (Fin)	.0175	.005	.0327	.007	.0376	.008	.0142	.005	.0198	.006	.0247	.009	.0258	.009	38.8	59.524 / 28.736
080	(Body)																
044	LI-1500 (Base)	.0167	.003	.0373	.010	.0249	.010	.0097	.004	.0313	.010	.0324	.011	.0279	.011	35.8	59.172 / 25.707
101	DYNAFLEX (Lower Flap)																
030	COLUMBIUM (Lower Flap Sh)	.0133	.002	.0377	.020	.0485	.011	.0242	.020	.0204	.003	.0289	.008	.0311	.020	32.2	90.090 / 19.569
070	RENE 41 (Upper Flap Sh.)	.0357	.012	.0281	.006	.0304	.009	.0170	.006	.0179	.002	.0291	.006	.0272	.012	36.8	65.789 / 25.510
TOTAL	WT AVE.																
	ARITH AVE.																

TABLE I4-4

K. URBACH
9/21/70

ITERATION NO. 4 – ABLATOR (ELASTOMERIC)
(OPERATION EXPENDITURES – HOURS)

VEHICLE: DELTA BODY
TPS ABLATOR CP1500 MM
DWG: Fig. 13
FIG: ITERATION #4

MAINT CODE		TPS SUBSYSTEM Area (ft²)	Panel Area (ft²)	Subsyst. Panels (N)	MAINTENANCE RATE F_r	MAX / MIN	PANELS MAINTAINED P_r	MAX / MIN	MODEL IV MAINTENANCE REUSE H_r	MAX / MIN			TOTAL H_T	$F_r=K$ MAX / MIN	$H_r=K$ MAX / MIN	WORST CASE MAX / MIN
010	ABLATOR (Nose)	70	70	1	1	1 / 1	1	1 / 1	572	4061 / 80.6			572		572 / 572	
011	ABLATOR	5431	14	388	1	1 / 1	388	388 / 388	78	310 / 14.0			25,608		25,608 / 25,608	
012	ABLATOR	1277	14	92	1	1 / 1	92	92 / 92	78	310 / 14.0			6,348		6,848 / 6,348	
013	ABLATOR	1845	14	132	1	1 / 1	132	132 / 132	78	310.0 / 14.0			9,108		9,108 / 9,108	
080	TITANIUM	6078	14	434	38.8	54.52 / 28.74	11.19	15.10 / 7.29	51	91.8 / 28.3			570.47		270.1 / 371.9	
044	LI-1500 (Base)	1610	14	115	35.8	59.17 / 25.71	3.21	4.47 / 1.94	90	460 / 18.0			289.10		402.6 / 174.9	
		16,311		1162	1.85	1.87 / 1.84	627.4	632.57 / 622.23	945	5532.8 / 168.9			42,495.57	–	42,808.7 / 42,182.8	

ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC)

(OPERATION EXPENDITURES - MATERIAL)

K. URBACH

[illegible]: DELTA BODY
TPS ABLATOR CR1500 MM
DWG: Fig 13
[illegible]: ITERATION #4

MAT'L CODE		TPS SUBSYSTEM Area (ft²)	Panel Area (ft²)	Subsyst. Panels (N)	MAINTENANCE RATE F_r	MAX / MIN	PANELS MAINTAINED P_r	MAX / MIN	MODEL: IV MAINTENANCE REUSE M_r #	MAX / MIN			TOTAL M_T #	$F_r = K$ MAX / MIN	$M_r F_r$ MAX / MIN	WORST CASE MAX / MIN
010	ABLATOR (Nose)	70	70	1	1	1 / 1	1	1 / 1	1222	1955 / 766			293		293.28 / 293.28	
011	ABLATOR	5431	14	388	1	1 / 1	388	388 / 388	94,771	151,624 / 59,232			22,745		22,745.04 / 22,745.04	
012	ABLATOR	1277	14	92	1	1 / 1	92	92 / 92	22,284	35,654 / 13,928			5,348		5,348.16 / 5,348.16	
013	ABLATOR	1845	14	132	1	1 / 1	132	132 / 132	32,195	51,512 / 20,122			7,727		7,726.80 / 7,726.80	
080	TITANIUM	6078	14	434	38.8	57.52 / 28.74	1119	15.10 / 7.29	325,353	569,780 / 250,569			2,325		3,138.65 / 1,615.54	
044	LI-1500 (Base)	1610	14	115	35.8	57.17 / 25.71	3.21	4.47 / 1.94	17,772	21,326 / 14,810			119		165.90 / 72.09	
		16,311		1162	1.85	1.87 / 1.84	627.4	[illegible] / [illegible]	544,097	[illegible] / [illegible]			38,557		39,417.[illegible] / 37,700.9[illegible]	

TABLE I4-6

ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC)

VEHICLE LEVEL OPERATIONS

CODE NO.	MATERIAL	RECURRING LABOR HOURS			RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION			
			In-Process	Base		
010	Ablator (Nose)	544	28	2	293	
011	Ablator (Fin) (Body)	24,444	1,164	69	22,745	
012	Ablator (Fin) (Body)	6,072	276	16	5,348	
013	Ablator (Fin) (Body)	8,712	396	21	7,727	
080	Titanium (Fin) (Body)	559	11	12	2,325	
044	LI-1500 (Base)	241	48	8	119	
	TOTAL	40,572 Hrs	1,923	128*	$38,557	
		Total 42,495 hours				

*Prorated by End Itema Area

TABLE I4-7

ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC)

VEHICLE LEVEL OPERATIONS

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	18,057	$38,557	
PANEL INSTALLATION	15,101		
PANEL REMOVAL	5,094		
INSPECTION			
PRE-FLIGHT	64		
IN-PROCESS	1,923		
POST-FLIGHT	64		
PACKAGING AND HANDLING	1,228		
STORAGE	1,092		
TOTAL	42,623 Hrs.	$38,557	

TABLE I4-8

ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

CODE NO.	MATERIAL	RECURRING LABOR HOURS		RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION In-Process + Base		
010	Ablator (Nose)	408,000	22,500	219,750	32,000
011	Ablator (Fin) (Body)	18,333,000	924,750	17,058,750	942,000
012	Ablator (Fin) (Body)	4,554,000	219,000	4,011,000	212,000
013	Ablator (Fin) (Body)	6,534,000	312,750	5,795,250	284,000
080	Titanium (Fin) (Body)	419,250	17,250	1,743,750	174,000
044	LI-1500 (Base)	180,750	42,000	89,250	106,000
	TOTAL	30,429,000 Hrs	1,538,250 Hrs	$28,917,750	$1,750,000 *
		Total - 31,967,250 Hrs			

*Prorated End Item Area

TABLE 14-9

ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	13,542,955	$28,917,750	
PANEL INSTALLATION	11,325,590		
PANEL REMOVAL	3,820,681		$ 1,750,000
INSPECTION			
PRE-FLIGHT	48,000		
IN-PROCESS	1,442,250		
POST-FLIGHT	48,000		
PACKAGING AND HANDLING	921,057		
STORAGE	818,717		
TOTAL	31,967,250 hrs	$28,917,750	$1,750,000

TABLE I4-10

SYSTEM COSTS BY PHASE AND TPS SUBSYSTEM
(ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC))

SUBSYSTEM	RECURRING		NON-RECURRING	TOTAL
	OPERATIONS	PRODUCTION	DDT&E	
010 ABLATOR	$ 5,882,125	$ $ 323,769	$ 999,008	$ 7,204,902
011 ABLATOR	272,381,598	7,988,080	18,111,012	298,480,690
012 ABLATOR	67,231,532	1,954,891	4,425,332	73,611,755
013 ABLATOR	96,495,180	2,560,047	6,084,824	105,140,051
080 TITANIUM	7,911,178	12,697,362	16,457,858	37,066,398
044 LI-1500	3,012,235	2,900,141	6,561,358	12,473,734
TOTAL	$452,913,848	$ 28,424,290	$52,639,392	$533,977,530
LOGISTICS				732,100,000
ABLATOR	-	731,700,000	-	
OTHER		400,000		
TOTAL	$452,913,848	$760,524,290	$52,639,392	$1,266,077,530

TABLE I4-11

SYSTEM COST OF OPERATIONS BY PHASE AND OPERATIONAL TASK

(ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC))

OPERATIONAL TASK	HOURS	RECURRING		NON-RECURRING	TOTAL
		LABOR	MATERIAL	EQUIPMENT	
MAINTENANCE	13,542,955	$176,193,845	$37,019,925	$ -	$213,213,770
PANEL INSTALLATION	11,325,590	147,345,926	-	-	147,345,926
PANEL REMOVAL	3,820,681	49,707,060	-	-	49,707,060
INSPECTION:					
PRE-FLIGHT	48,000	624,480	-	582,482	1,206,962
IN-PROCESS	1,442,250	18,763,673	-	1,075,351	19,839,024
POST FLIGHT	48,000	624,480	-	582,428	1,206,962
PACKAGING & HANDLING	921,057	11,982,951	-	-	11,982,951
STORAGE	818,717	10,651,503	-	-	10,651,508
TOTAL	31,967,250	$415,893,923	$37,019,925	$2,240,315	$455,154,163

TABLE I4-12

SYSTEM COSTS BY PHASE AND FUNCTION

(ITERATION NO. 4 - TPS ABLATOR (ELASTOMERIC))

FUNCTION	RECURRING		NON-RECURRING	TOTAL
	OPERATION	PRODUCTION	DDT&E	
MANUFACTURING	$ -	$ 13,211,293	$ 14,279,759	$ 27,491,052
OPERATIONS	432,901,215		-	432,901,215
ENGINEERING:				
STRESS	-	1,269,078	4,052,660	-
WEIGHTS	-	746,289	2,285,310	-
LOADS & DYNAMICS	-	577,031	2,015,116	-
THERMODYNAMICS	-	2,053,369	6,223,541	-
DESIGN	-	857,309	1,650,286	-
MATERIALS	-	4,878,754	16,412,612	-
TOTAL ENGINEERING	-	$10,381,830	$33,639,525	$44,021,355
QUALITY ASSURANCE:				
MANUFACTURING	-	4,831,167	2,479,793	-
OPERATIONS	20,012,633	-	2,240,315	-
TOTAL Q.A.	$20,012,633	$4,831,167	$47,720,108	$29,563,908
TOTAL	$452,913,848	$ 28,424,290	$52,639,392	533,977,530
LOGISTICS	-	-	-	732,100,000
MANUFACTURING	-	535,000,000	-	
QUALITY ASSURANCE		197,100,000		
TOTAL	$452,913,848	$760,524,290	$52,693,392	$1,266,077,530

TABLE I4-13

SYSTEM COST UNCERTAINTY BY PHASE

(ITERATION NO. 4 - ABLATIVE TPS)

COST-UNCERTAINTY FACTORS & COST RANGE	PROGRAM PHASES			TOTAL
	DDT & E	PRODUCTION	OPERATIONS	
HIGH UNCERTAINTY FACTOR	3.42	2.57	3.59	3.50
	1	1	1	1
LOW UNCERTAINTY FACTOR	2.87	1.89	3.10	2.98
HIGHEST TPS COST	$180 M	1950.0 M	$1,617 M	$4,425.0 M
NOMINAL TPS COST	52.6M	760.5 M	453 M	1,266.1 M
LOWEST TPS COST	18 M	403.0 M	146 M	424.0 M

NOTES:
- UNCERTAINTY FACTORS ARE SUMMATION VALUES REFLECTING ALL COST-ELEMENT UNCERTAINTY ESTIMATES
- THE HIGH & LOW FACTORS ARE MULTIPLIERS TO BE USED WITH NOMINAL COSTS TO OBTAIN ESTIMATED HIGH & LOW COST LIMITS
- THESE DATA REFLECT A TYPICAL TPS COST ESTIMATE FOR A DELTA BODY ORBITER, 1500 NM CROSS RANGE

TABLE I4-14

ITERATION NO. 5

Iteration No. 5 is a non-metallic TPS system with six (6) TPS subsystem materials selected through computer analysis. Fail Safe LI-1500 (Material Code 110) is used as the primary subsystem for investigation and sizing purposes.

TPS Sizing For Baseline Vehicle

Each TPS material subsystem is structurally depicted and sized in Table I5-1. TPS covers 17,411 ft^2 of the vehicle surface and weighs 53,215 lbs. for an average unit weight of 3.06 PSF.

Material and panel geometry are a function of the temperature regimes listed at the bottom of the table. While surface geometry and location on the vehicle are listed parameters, they are not at this time carried as factors in the total system cost analysis.

The data contained in this table is used for calculating the number of panels (N) of a given material type. In this evaluation 14 ft^2 panels (approximately 45" x 45") are used. Further use of the data is made in the Production Panel Model where area and weight are the principle cost generating factors.

End Item Summary (EIS)

The End Item Summary Sheet (EIS) is the basic cost estimating document on which all original data regarding operations is recorded. Operations personnel have been selected six(6) operation tasks for which a given material subsystem, End Item, can be expected to produce a cost impact. These are presented in Table I5-2 as:

- Panel Installation
- Panel Removal
- In Process Inspection
- Packaging and Handling
- Storage
- Maintenance

Various methods and techniques were considered for each of these tasks and hourly weights assigned commensurate with the degree of effort required. The nominal hourly estimates are based on performing similar type operational tasks on a known baseline material which in this case is titantium. The uncertainty assigned to each End Item/Operation Task element indicates the degree to which selected methods and techniques are well enough understood to be accomplished in fact in the time indicated. All values listed in Table I5-2 are for a single panel.

The tantalum nose cone requires the greatest expenditure of time and has the largest uncertainty, followed by LI-1500 on the base shield and then Fail Safe TPS subsystems. Titanium exhibits the lowest cost and uncertainty.

For the Operation tasks, cost and uncertainty are highest in the maintenance area where repairs are made on removed panels. Panel installation follows next in terms of high cost although the uncertainty is not as large as that for the remaining tasks. Inspection carries the largest uncertainty.

End Item totals and Operation task totals are used in the Operational Expenditures calculation where they are modified by the Maintenance Factors to produce a vehicle refurbishment labor cost.

Production Panel Model

Panel structural design varies with material type, temperature regime, location on the primary structure and design approach taken on the vehicle structure.

In Table I5-3, the weight and area values obtained from Table I5-1 are represented in a format where those costs which are a function of weight can be separated from those that are a function or area. Cost per pound and per square foot are provided by Procurement Material estimators.

Summary results indicate that a complete TPS system will require a material expenditure of $669,092. Titanium has the highest cost per pound and its total cost is greater than that for the combined total of the other subsystems. The nose cone has a high cost per pound but its weight contribution is small relative to all other TPS subsystems.

Production panel costs are used in <u>Operations Expenditure</u> calculations where they are modified according to <u>Maintenance Factors</u> to produce a vehicle refurbishment material cost.

<u>Maintenance Factors</u>

The combined effect of all mission hazards encountered by a TPS system while flying a selected mission profile will determine the nature and extent of operational refurbishment. Inspection, maintenance, and logistic TPS activities (and costs) are essentially a direct function of the operations that must be undertaken as a result of the hazards experienced.

In Table I5-4 a matrix of TPS Maintenance Frequencies provides values that indicate the degree to which a selected TPS subsystem will respond to a given hazard. Integrating the spectrum of hazards over the mission profile provides a maintenance rate (F_r). Maintenance rates are interpreted as "the expected number of flights a TPS subsystem will experience before some maintenance action is required". Both frequency and uncertainty are iteratively developed measures derived from existing documentation and best engineering judgments.

The lowest maintenance rate ($F_r = 10.7$) and highest uncertainty ($\pm$ .033) occur on the tantalum nose cone due primarily to the large temperature/load frequency.

The end item maintenance rates are used in the Operation Expenditures calculation where they are used to determine the numbers of panels replaced per TPS subsystem and from this the vehicle labor hours and materials.

Operation Expenditures

Operation Expenditure calculations are made to determine the vehicle labor and material cost subject to the data just described in the previous step and operation premises (Appendix C).

In Tables I5-5 and I5-6, the results show that thirty-nine (39) panels out of 1162 total panels can be expected to require refurbishment in this case, necessitating removal and replacement. A labor expenditure of 2,429 hours and a material committment of $5,573 will result.

It should be noted that, while the tantalum nose cone had the lowest maintenance rate (F_r = 10.7) of the six (6) TPS subsystems, its contribution to total labor is the lowest of the six subsystems. Its size and single panel feature produce this outcome. On the bottom of the vehicle (110) FS-1500 produces the largest labor cost followed by titanium. Material costs for titanium exceed those for (110) FS-1500 largely due to difference in dollars per panel.

The primary cost driver for labor is (110) FS-1500, with titanium second, and LI-1500 third. For material, the primary cost driver is titanium, the (110) FS-1500 and tantalum.

Cost uncertainty differences between subsystems are not large enough to produce any change in the total labor or material costs of end items. This in spite of the high labor uncertainty for tantalum and LI-1500.

Vehicle Level Operations

Vehicle costs are summarized by end item in Table I5-7 and operation task in Table I5-8. Maintenance, Inspection, Material and Equipment costs are displayed as recurring or non-recurring for those costs that were determined from the Operation Expenditure analysis, as well as, those prorated costs which are not estimated at the end item level. Base Inspection fall into this latter category and is prorated to the subsystem level on an end item area basis.

The consolidation of all recurring and non-recurring end item and operation task costs on one summary sheet is in preparation for the application of mission life cycle requirements in determination of System Level Operations cost.

System Level Operations

System level operation costs are summarized by End Item in Table I5-9 and by Opertion Task in Table I5-10. Table values are obtained by multipying the vehicle level operations by the number of missions flown over the life of the program by a given fleet of vehicles. In this evaluation, there are eight vehicles in the fleet. This group will fly 75 missions a year for 10 years, which will require 750 refurbishments over the life of the program.

The total expenditures for labor, material and equipment are:

Labor	–	1,917,750 hours
Material	–	$4,179,750 (In support of Maintenance operations)
Equipment	–	$1,750,000

Equipment is an Inspection requirement. It is a system level cost and applies across the whole vehicle fleet for the life of the program. For cost comparison purposes its cost is prorated to the subsystem on the basis of end item area.

System Cost by Phase and TPS Subsystem

TPS subsystem expenditures are provided in Table I5-11. End Item costs are greatest for (110) FS-1500 with titanium second. Logistic cost amounts to 147.8 million dollars or 52% of the total system cost. The relative rank in percent of total cost is as follows.

Rank	Material Code	Material	Percent	Uncertainty Mat'l	Uncertainty Labor
1	110	FS-1500	36.3	1.6	5.00
2	080	Titanium	27.1	1.1	3.13
3	112	FS-1500	10.6	1.6	4.67
4	044	LI-1500	9.2	1.2	6.03
5	020	Tantalum	8.8	1.1	6.83
6	111	FS-1500	8.0	1.6	5.00

Logistic expenditures are prorated by the initial production cost.

System Cost of Operations by Phase and Operational Task

System costs for Operations are shown in Table I5-12 by Operation Task. Maintenance costs rank highest in total cost followed by Panel Installation and Inspection. Their relative rank in percent of total cost is as follows:

Rank	Operational Task	Percent	Uncertainty Mat'l	Uncertainty Labor
1	Maintenance	58.0	H 1.42 / L 1/1.73	8.99
2	Panel Installation	19.1	-	3.19
3	Inspection	14.1	-	5.08
4	Panel Removal	6.1	-	3.28
5	Packaging and Handling	1.4	-	4.17
6	Storage	1.3	-	3.50

Refurbishment operations amount to $14,606,978 or 45% of the total cost.

System Cost by Phase and Function

Total system cost for Iteration No. 5 is $282,899,765. In Table I5-13, this cost is broken down into its six (6) functional areas and two (2) summary cost groups for the three (3) program phases.

Refurbishment cost for non-metallic TPS system described in this Iteration, composed of six TPS subsystems and requiring 750 refurbishments over the 10 year life of the program, amount to $30,300,761, approximately 10.7% of the total TPS system cost. This compares with the other program phases as follows:

Group	Phase	Percent	Uncertainty High	Uncertainty Low
Recurring	Operation	10.7	4.84	1/3.36
	Production	64.7	2.50	1/1.47
Non-recurring	DDT&E	24.6	2.98	1/3.32

The contribution by each of the nine (9) functional groups is summarized as follows:

Function	Percent	
Operation	9.9	
Manufacturing	52.9	
Quality Assurance	16.5	(1.7 of which is for Operations)
Engineering	20.7	

Cost estimates for the functions other than Operations were derived in a manner similar to that just described. Due to its volume, the supporting data is not provided.

System Cost Uncertainty by Phase

Nominal costs to perform the DDT&E, Production, and Operation phases reflect the depth of informational detail avaiable to all functional groups. The costs shown in Table 15-14 are based on a mix of subjective judgment, "similar to" knowledge, and definitive information. The extent to which definition is lacking will appear in the magnitude of the uncertainty factor.

The importance of this information is twofold: (1) It provides perspective which allows the establishment of priorities for further development activities that will effectively lead to uncertainty reduction and definitive costing, and (2) the data can be directly related to a function, activity, or end item, permitting critical appraisal of design and system tradeoffs and maintenance of program objectives.

Conditions shown in Table I5-15, indicate that the Fail Safe TPS system can cost 3.26 times nominal or 924 million dollars. Technological uncertainty can result in a 1/2.5 reduction in the nominal cost to 113.1 million dollars for a non-metallic TPS system.

Operations exhibits the widest range of uncertainty exceeding that for the system. Operations can cost 4.84 times nominal or 146.1 million dollars, while a 1/3.36 reduction due to technological uncertainty would result in a cost of 9.0 million dollars.

TPS SIZING DATA FOR BASELINE VEHICLE
(ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE LI-1500))

TPS Element Location and Type*	Area (ft^2)	Insulation Thickness (in.)	Sub-Panel (lb)	Insulation (lb)	Total (lb)	PSF
Nose Cone – Ta (with fail-safe system)	70	-	537	690	1227	17.53
SUBTOTALS (020)	70	-	537	690	1227	17.53
Fin – 2000° - 2500°	855	2.60	742	3728	4470	
Body – 2000° - 2500°	4576	2.60	3977	19951	23928	
SUBTOTALS (110)	5431	-	4719	23679	28398	5.23
Fin – 1600° - 2000°	248	2.50	215	1054	1269	
Body – 1600° - 2000°	1029	2.50	894	4373	5267	
SUBTOTALS (111)	1277	-	1109	5427	6536	5.12
Fin – 1000° - 1600°	665	2.25	578	2653	3231	
Body – 1000° - 1600°	1180	2.25	1025	4708	5733	
SUBTOTALS (112)	1845	-	1603	7361	8964	4.86
Fin – Corrugated Ti	912	0.25	577	120	697	
Body – Corrugated Ti	5166	0.25	3267	678	3945	
SUBTOTALS (080)	6078	-	3844	798	4642	0.76
Body – Base Heat Shield	1610	-	707	2109	2816	
SUBTOTALS (044)	1610	-	707	2109	2816	1.75
Lower Flap	1100	-	-	632	632	
SUBTOTALS (101)	1100	-	-	632	632	0.57
TOTAL	17411	-	12519	40696	53215	3.06

*Materials:
(020) - Tantalum (2500° to 3000°)
(110) - LI-1500/LI-1500-Polyethylene (2000° to 2500°)
(111) - LI-1500/LI-1500-Polyethylene (1600° to 2000°)
(112) - LI-1500/LI-1500-Polyethylene (1000° to 1600°)
(080) - Titanium (Under 1000°)
(044) - LI-1500 Base Shield
(101) - Dynaflex Flap Shield

TABLE I5-1

ATOR
bach

8/21/70

E: Delta Body

ail Safe CR: 1500 nm

teration #5

ITERATION NO. 5 – TPS NON-METALLIC (FAIL SAFE LI-1500)
(END ITEM SUMMARY SHEET (EIS)

	PANEL INSTALLATION		PANEL REMOVAL		INSPECTION (IN-PROCESS)		PACKAGING & HANDLING		STORAGE				MAINTENANCE REUSE		TOTAL	
	H_{pi}	U_{pi}	H_{pr}	U_{pr}	H_i	U_i	H_h	U_h	H_s	U_s	$H\_$	$U\_$	H_m	U_m	H_r	U_r
BASELINE MATERIAL:																
Tantalum (Nose)	150	1.40	50	2.0	24	6.0	16	4.0	8	4.0			300	10.0	548	6.825
FS-1500	34	5.0	12	5.0	2	6.0	2	5.0	3	4.0			10	5.0	63	5.0
FS-1500	34	5.0	10	5.0	2	6.0	2	5.0	3	4.0			10	5.0	61	5.0
FS-1500	31	4.0	10	4.0	2	6.0	2	5.0	3	4.0			10	5.0	58	4.666
LI-1500 (Base)	40	7.0	8	7.0	15	5.0	1	5.0	3	4.0			23	5.0	90	6.033
Titanium	18	1.5	6	1.5	1	1.5	1	1.0	1	1.0			24	5.0	51	3.127
L WT AVE.	307	—	96	—	46	—	24	—	21	—		—	377	—	871	
ARITH AVE.		3.195		3.281		5.682		4.166		3.500				8.978		6.123

TABLE I5-2

ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE LI-1500)

PRODUCTION PANEL MODEL

	Tantalum	110 FS-1500	111 FS-1500	112 FS-1500	080 Titanium	044 LI-1500	181 Insul
Erosion Shield	412	23,679	5,427	7,361	3,120	2,109	
Sub-Panel	(125)	(4,719)[1]	(1,109)[1]	(1,603)[1]	8,263	(707)[1]	(632)[2]
Clips					724		1,488
Not in) Insulation					(798)		
Total #) Total #	412	23,679	5,427	7,361	12,007	2,109	-
$ / #	$50.00	$7.40	$7.40	$7.40	$29.44	$6.90	
	$20,600	$175,225	$40,160	$54,471	$353,486	$14,552	
Area (FT^2)	70	5,431	1,277	1,845	6,078	1,610	6,148
$ / Ft2	-	-	-	-	-	$2.00	$1.20
	0	0	0	0	0	$3,220	$7,378
TOTAL $	$20,600	$175,225	$40,160	$54,471	$353,486	$17,772	$7,378
(With Insulation)	$ 3,421	-	-	-	$ 3,957	-	($7,378)
TOTAL $	$24,021	$175,225	$40,160	$54,471	$357,443	$17,772	-

TOTAL: $669,092

1 Includes Subpanel and Clips
2 Flap Shield Insul. Omitted

TABLE I5-3

GINATOR

IRBACH

ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE LI-1500)

MAINTENANCE FACTORS

E: 9/28/70

ICLE: DELTA BODY

: Fail Safe CR: 1500 nm

: Figure 14

: Iteration #5

'L / E	BASELINE MATERIAL:	TEMP EXPOSURE F_T	TEMP EXPOSURE U ±	COMBINED TEMP/LOAD F_{TL}	COMBINED TEMP/LOAD U ±	COMBINED TEMP/PRESS. F_{TP}	COMBINED TEMP/PRESS. U ±	COMBINED TEMP/PRESS./LOAD F_{TPL}	COMBINED TEMP/PRESS./LOAD U ±	HANDLING F_H	HANDLING U ±	ENVIRONMENT F_E	ENVIRONMENT U ±	COMPOSITE MAINTENANCE FREQUENCY F_F	COMPOSITE MAINTENANCE FREQUENCY U ±	MAINTENANCE RATE (FLIGHT/FAIL) F_r	MAINTENANCE RATE MAX. / MIN.
20	TANTALUM (Nose)	.0224	.012	.1041	.033	.0565	.020	.1510	.033	.0530	.003	.1093	.033	.0932	.033	10.7	16.611 / 7.924
10	FS-1500 (Fin)	.0182	.003	.0789	.020	.0349	.010	.0117	.004	.0363	.010	.0389	.011	.0442	.020	22.6	41.322 / 15.576
10	FS-1500 (Body)																
11	FS-1550 (Fin)	.0167	.003	.0679	.020	.0299	.010	.0097	.004	.0313	.010	.0334	.011	.0364	.020	27.5	60.976 / 17.730
11	FS-1500 (Body)																
12	FS-1500 (Fin)	.0152	.006	.0569	.033	.0249	.015	.0079	.004	.0263	.015	.0279	.015	.0306	.020	32.7	94.34 / 19.763
12	FS-1500 (Body)																
44	LI-1500 (Base)	.0167	.003	.0373	.010	.0249	.010	.0097	.004	.0313	.010	.0324	.011	.0279	.011	35.8	59.172 / 25.707
80	TITANIUM, CORR. (Fin)	.0175	.005	.0327	.007	.0376	.008	.0142	.005	.0198	.006	.0247	.009	.0258	.009	38.8	59.524 / 28.736
80	TITANIUM, CORR. (Body)																
01	DYNAFLEX (Lower Flap)																
030	COLUMBIUM (Lower Flap Sh)	.0133	.002	.0377	.020	.0485	.011	.0242	.020	.0204	.003	.0289	.008	.0311	.020	32.2	80.090 / 19.569
070	RENE' 41 (Upper Flap Sh)	.0357	.012	.0281	.006	.0304	.009	.0170	.006	.0179	.002	.0291	.006	.0272	.012	36.8	65.789 / 25.510
TOTAL	WT AVE.																
	ARITH AVE.																

TABLE I5-4

ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE LI-1500)

(OPERATION EXPENDITURES - HOURS)

. Urbach

ate: 9/21/70

EHICLE: DELTA BODY TPS FAIL SAFE CR: 1500 NM DWG: FIG 14 FIG: ITERATION # 5		TPS SUBSYSTEM Area (ft²)	Panel Area (ft²)	Subsyst. Panels (N)	MAINTENANCE RATE F_r	MAX / MIN	PANELS MAINTAINED P_r	MAX / MIN	MODEL: IX MAINTENANCE REUSE H_r	MAX / MIN			TOTAL H_T	$F_r=K$ MAX / MIN	$H_r=K$ MAX / MIN	WORST CASE MAX / MIN
AVL ...																
020	Tantalum (Nose)	70	70	1	10.7	16.61 / 7.92	.093	.13 / .06	548	3726 / 80.58			51.18		69.2 / 33.0	
110	FS-1500	5431	14	388	22.6	41.32 / 15.58	17.16	24.90 / 9.39	63	315 / 12.6			1081.1		591.6 / 316.0	
111	FS-1500	1277	14	92	27.5	60.98 / 17.73	3.34	5.18 / 1.50	61	305 / 12.2			203.8		91.5 / 387.4	
112	FS-1500	1845	14	132	32.7	94.17 / 19.76	4.03	6.68 / 1.40	58	249 / 13.5			233.8		81.2 / 402.6	
044	LI-1500 (Base)	1610	14	115	35.8	59.17 / 25.71	3.21	4.47 / 1.94	90	450 / 18.0			289.10		174.9 / 770.1	
080	Titanium	6078	14	434	38.8	59.52 / 28.74	11.19	15.10 / 7.29	51	91.8 / 28.3			570.47		371.9	
		16,311		1162	29.8	54.0 / 20.6	39.02	56.46 / 21.58	871.0	5136.8 / 165.2			242945		3514.0 / 1344.1	

K. Urbach

Date: 9/21/70

ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE LI-1500)
(OPERATION EXPENDITURES - MATERIAL)

VEHICLE: DELTA BODY		TPS SUBSYSTEM			MAINTENANCE RATE		PANELS MAINTAINED		MODEL: IV MAINTENANCE REUSE		TOTAL			
TPS: FAIL SAFE CR: 1500NM; DWG: FIG 14; FIG: ITERATION #5		Area (ft^2)	Panel Area (ft^2)	Subsyst. Panels (N)	F_r	Max / Min	P_r	Max / Min	M_r $	Max / Min	M_T $	F_r=K Max / Min	M_r=K Max / Min	Worst Case Max / Min
MAT'L CODE														
020	Tantalum (Nose)	70	70	1	10.7	16.61 / 7.92	.093	.13 / .06	24,021	26,423 / 21,837	538.79		727.91 / 347.08	
110	FS-1500	5431	14	388	22.6	41.32 / 15.58	17.16	24.90 / 9.39	175,275	280,360 / 109,516	1860.79		2699.22 / 1017.76	
111	FS-1500	1277	14	92	32.7	60.98 / 17.73	3.34	5.18 / 1.50	40,160	64,256 / 25,100	350.48		543.62 / 158.05	
112	FS-1500	1845	14	132	35.8	94.17 / 19.76	4.03	6.68 / 1.40	54,471	87,154 / 34,044	399.78		661.59 / 138.82	
044	LI-1500 (Base)	1610	14	115	38.8	59.17 / 25.71	3.21	4.47 / 1.94	17,772	21,326 / 14,810	119.14		165.90 / 72.09	
080	Titanium	6078	14	434		59.52 / 28.74	11.19	15.10 / 7.29	357,443	409,768 / 338,651	2304.23		3110.78 / 1502.08	
		16,311		1162	29.8	54.0 / 20.6	39.02	56.46 / 21.58	669,092	889,287 / 543,958	5573.20		7909.02 / 3235.88	

TABLE 15-6

ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE LI-1500)

VEHICLE LEVEL OPERATIONS

CODE NO.	MATERIAL	RECURRING LABOR HOURS			RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION			
			In-Process	Base		
020	Tantalum (Nose)	49	2	3	539	
110	FS-1500 (Fin) (Body)	1,047	34	69	1,861	
111	FS-1500 (Fin) (Body)	197	7	16	350	
112	FS-1500 (Fin) (Body)	226	8	22	400	
044	LI-1500 (Base)	241	48	7	119	
080	Titanium (Fin) (Body)	559	11	11	2,304	
	TOTAL	2,319	110	128 *	$5,573	
		Total 2,429 hours				

*Prorated by End Item Area

TABLE I5-7

ITERATION NO. 5 - TPS NON-METALLIC (FAIL-SAFE LI-1500)

VEHICLE LEVEL OPERATIONS

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	1,060	$5,573	
PANEL INSTALLATION	863		
PANEL REMOVAL	270		
INSPECTION			
PRE-FLIGHT	64		
IN-PROCESS	110		
POST-FLIGHT	64		
PACKAGING AND HANDLING	67		
STORAGE	59		
TOTAL	2,557 Hrs	$5,573	

TABLE I5-8

ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE LI-1500)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENTS)

CODE NO.	MATERIAL	RECURRING LABOR HOURS MAINTENANCE	RECURRING LABOR HOURS INSPECTION In-Process + Base	RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
020	Tantalum (Nose)	36,750	3,750	404,250	40,800
110	FS-1500 (Fin) (Body)	785,250	77,250	1,395,750	945,300
111	FS-1500 (Fin) (Body)	147,750	17,250	262,500	217,400
112	FS-1500 (Fin) (Body)	169,500	22,500	300,000	298,400
044	LI-1500 (Base)	180,750	16,500	89,250	93,700
080	Titanium (Fin) (Body)	419,250	41,250	1,728,000	154,400
	TOTAL	1,739,250 Hrs	178,500 Hrs	$4,179,750	$1,750,000 *
		Total 1,917,750 Hrs			

*Prorated by End Item Area

ITERATION NO. 5 - TPS NON-METALLIC (FAIL-SAFE LI-1500)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	795,000	$ 4,179,750	
PANEL INSTALLATION	647,250		
PANEL REMOVAL	202,500		$ 1,750,000
INSPECTION			
PRE-FLIGHT	48,000		
IN-PROCESS	82,500		
POST-FLIGHT	48,000		
PACKAGING AND HANDLING	50,250		
STORAGE	44,250		
TOTAL	1,917,750 Hrs	$4,179,750	$1,750,000

TABLE I5-10

SYSTEM COSTS BY PHASE AND TPS SUBSYSTEM
(ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE))

SUBSYSTEM	RECURRING		NON-RECURRING	TOTAL
	OPERATIONS	PRODUCTION	DDT&E	
020 TANTALUM	$ 1,044,419	$ 2,544,987	$ 8,223,458	$ 11,812,864
110 FS-1500	13,007,936	11,278,219	24,817,052	49,103,207
111 FS-1500	2,482,697	2,633,876	5,737,346	10,853,919
112 FS-1500	2,881,974	3,356,600	8,049,456	14,288,630
080 TITANIUM	7,881,258	12,504,925	16,217,257	36,603,440
044 LI-1500	3,002,477	2,900,141	6,535,687	12,438,305
TOTAL	$30,300,761	$35,218,748	$69,580,256	$135,099,765
LOGISTICS		147,800,000		147,800,000
TOTAL	$30,300,761	$183,018,748	$69,580,256	$282,899,765

TABLE I5-11

SYSTEM COST OF OPERATIONS BY PHASE AND OPERATIONAL TASK

(ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE))

OPERATIONAL TASK	HOURS	RECURRING		NON-RECURRING	TOTAL
		LABOR	MATERIAL	EQUIPMENT	
MAINTENANCE	795,000	$ 10,342,950	$ 5,350,833	$ -	$ 15,693,783
PANEL INSTALLATION	647,250	8,420,723	-	-	8,420,723
PANEL REMOVAL	202,500	2,634,525	-	-	2,634,525
INSPECTION					
PRE-FLIGHT	48,000	624,480	-	582,482	1,206,962
IN-PROCESS	82,500	1,073,324	-	1,075,351	2,148,675
POST-FLIGHT	48,000	624,480	-	582,482	1,206,962
PACKAGING & HANDLING	50,250	653,753	-	-	653,753
STORAGE	44,250	575,693	-	-	575,693
TOTAL	1,917,750	$24,949,928	$ 5,350,833	$2,240,315	$32,541,076

TABLE I5-12

SYSTEM COSTS BY PHASE AND FUNCTION

(ITERATION NO. 5 - TPS NON-METALLIC (FAIL SAFE))

FUNCTION	RECURRING OPERATION	RECURRING PRODUCTION	NON-RECURRING DDT&E	TOTAL
MANUFACTURING	$ -	$ 17,320,875	$ 18,654,713	$ 35,975,588
OPERATIONS	27,978,476	-	-	27,978,476
ENGINEERING:				
STRESS	-	1,375,147	2,945,613	—
WEIGHTS	-	742,840	3,269,784	—
LOADS & DYNAMICS	-	577,032	2,015,115	—
THERMODYNAMICS	-	1,588,316	5,092,841	—
DESIGN		909,776	1,744,587	—
MATERIALS		7,585,306	30,793,436	
TOTAL ENGINEERING	-	$12,778,417	$45,861,376	$58,639,793
QUALITY ASSURANCE				
MANUFACTURING	—	5,119,456	2,823,852	—
OPERATIONS	2,322,285	-	2,240,315	—
TOTAL Q.A.	$2,322,285	$5,119,456	$5,064,167	$12,505,908
TOTAL	$30,300,761	$35,218,748	$69,580,256	$135,099,765
LOGISTICS				147,800,000
MANUFACTURING	-	113,500,000	-	
QUALITY ASSURANCE		34,300,000		
TOTAL	$30,300,761	$183,018,748	$69,580,256	$282,899,765

TABLE I5-13

SYSTEM COST UNCERTAINTY BY PHASE

(ITERATION NO. 5 - NON-METALLIC TPS)

COST-UNCERTAINTY FACTORS & COST RANGE	PROGRAM PHASES			TOTAL
	DDT & E	PRODUCTION	OPERATIONS	
HIGH UNCERTAINTY FACTOR	2.98	2.50	4.84	3.26
	1	1	1	1
LOW UNCERTAINTY FACTOR	3.32	1.47	3.36	2.5
HIGHEST TPS COST	$207 M	457.5 M	$146.1 M	$924.0 M
NOMINAL TPS COST	69.6 M	183.0 M	30.3 M	282.9 M
LOWEST TPS COST	21 M	124.5 M	9.0 M	113.1 M

NOTES:
- UNCERTAINTY FACTORS ARE SUMMATION VALUES REFLECTING ALL COST-ELEMENT UNCERTAINTY ESTIMATES
- THE HIGH & LOW FACTORS ARE MULTIPLIERS TO BE USED WITH NOMINAL COSTS TO OBTAIN ESTIMATED HIGH & LOW COST LIMITS
- THESE DATA REFLECT A TYPICAL TPS COST ESTIMATE FOR A DELTA BODY ORBITER, 1500 NM CROSS RANGE

TABLE I5-14

ITERATION NO. 6

Iteration No. 6 is a metallic TPS system with six (6) TPS subsystem materials selected through computer analysis. TDNiCr (Material Code 050) is used as the primary subsystem for investigation and sizing purposes.

TPS Sizing For Baseline Vehicle

Each TPS material subsystem is structurally depicted and sized in Table I6-1. TPS covers 17,411 ft^2 of the vehicle surface and weighs 41,735 lbs. for an average unit weight of 2.40 PSF.

Material and panel geometry are a function of the temperature regimes listed at the bottom of the table. While surface geometry and location on the vehicle are listed parameters, they are not at this time carried as factors in the total system cost analysis.

The data contained in this table is used for calculating the number of panels (N) of a given material type. In this evaluation 14 ft^2 panels (approximately 45" x 45") are used. Further use of the data is made in the Production Panel Model where area and weight are the principle cost generating factors.

End Item Summary (EIS)

The End Item Summary Sheet (EIS) is the basic cost estimating document on which all original data regarding operations is recorded. Operations personnel have been selected six(6) operation tasks for which a given material subsystem, End Item, can be expected to produce a cost impact. These are presented in Table I6-2 as:

- Panel Installation
- Panel Removal
- In Process Inspection
- Packaging and Handling
- Storage
- Maintenance

Various methods and techniques were considered for each of these tasks and hourly weights assigned commensurate with the degree of effort required. The nominal hourly estimates are based on performing similar type operational tasks on a known baseline material which in this case is titantium. The uncertainty assigned to each End Item/Operation Task element indicates the degree to which selected methods and techniques are well enough understood to be in fact accomplished in the time indicated. All values listed in Table I6-2 are for a single panel.

The tantalum nose cone requires the greatest expenditure of time and has the largest uncertainty, followed by LI-1500 on the base shield and then TDNiCr which is applied to the bottom surface of the vehicle.

For the Operation tasks, cost and uncertainty are highest in the maintenance area where repairs are made on removed panels. Panel installation follows next in terms of high cost although the uncertainty is **not adversely** large.

End Item totals and Operation task totals are used in the <u>Operational Expenditures</u> calculation where they are modified by the <u>Maintenance Factors</u> to produce a vehicle refurbishment labor cost.

<u>Production Panel Model</u>

Panel structural design varies with material type, temperature regime, location on the primary structure and design approach taken on the vehicle structure.

In Table I6-3, the weight and area values obtained from Table I6-1 are represented in a format where those costs which are a function of weight can be separated from those that are a function or area. Cost per pound and per square foot are provided by Procurement Material estimators.

Summary results indicate that a complete TPS system will require a material expenditure of $998,309. TDNiCr has the highest cost per pound but its total cost is less than that for titantium, because of the must greater weight of titantium. The nose cone has a high cost per pound, but its weight contribution is small relative to all other TPS subsystems.

Production panel costs are used in Operations Expenditure calculations where they are modified according to Maintenance Factors to produce a vehicle refurbishment material cost.

Maintenance Factors

The combined effect of all mission hazards encountered by a TPS system while flying a selected mission profile will determine the nature and extent of operational refurbishment. Inspection, maintenance, and logistic TPS activities (and costs) are essentially a direct function of the of the operations that must be undertaken as a result of the hazards experienced.

In Table I6-4 a matrix of TPS Maintenance Frequencies provides values that indicate the degree to which a selected TPS subsystem will respond to a given hazard. Integrating the spectrum of hazards over the mission profile provides a maintenance rate (F_r). Maintenance rates are interpreted as "the expected number of flights a TPS subsystem will experience before some maintenance action is required". Both frequency and uncertainty are iteratively developed measures derived from existing documentation and best engineering judgments.

The lowest maintenance rate ($F_r = 10.7$) and highest uncertainty ($\pm .033$) occur on the tantalum nose cone due primarily to the large frequency for temperature/load, temperature/pressure/load and environment.

The end item maintenance rates are used in the Operation Expenditures calculation where they are used to determine the numbers of panels replaced per TPS subsystem and from this the vehicle labor hours and materials.

Operation Expenditures

Operation Expenditure calculations are made to determine the vehicle labor and material cost subject to the data just described in the previous step and operation premises, (Appendix C).

In Table I6-5 and I6-6, the results show that thirty-three (33) panels out of 1163 total panels can be expected to require refurbishment, in this case, necessitating removal and replacement. A labor expenditure of 2,290 hours and a material committment of $7,311 will results.

It should be noted that while the tantalum nose cone had the lowest maintenance rate (F_r = 10.7) of the six (6) TPS subsystems, it contribution to total labor cost is the lowest for the six subsystems. Its size and single panel feature produce this outcome.

The primary cost driver for both labor and material is TDNiCr with titanium second. The lower maintenance rate for TDNiCr and higher labor and material differential costs produce this result.

Material cost uncertainty differences between subsystems are not large enough to produce significant changes in the total material costs of end items.

Vehicle Level Operations

Vehicle costs are summarized by end item in Table I6-7 and operation tasks in Table I6-8. Maintenance, Inspection, Material and Equipment costs are displayed as recurring or non-recurring for those costs that were determined from the Operation Expenditure analysis, as well as, those prorated costs which are not estimated at the end item level. Base Inspection fall into this latter category and is prorated to the subsystem level on an end item area basis.

The consolidation of all recurring and non-recurring end item and operation task costs on one summary sheet is in preparation for the application of mission life cycle requirements in determination of System Level Operations cost.

System Level Operations

System level operation costs are summarized by End Item in Table I6-9 and by Opertion Task in Table I6-10. Table values are obtained by multipying the vehicle level operations by the number of missions flown over the life of the program by a given fleet of vehicles. In this evaluation, there are 8 vehicles in the fleet. This group will fly 75 missions a year for 10 years, which will require 750 refurbishments over the life of the program.

The total expenditures for labor, material and equipment are:

Labor - 1,814,250 hours
Material - $5,484,000 (In support of Maintenance operations)
Equipment - $1,750,000

Equipment is an Inspection requirement. It is a system level cost and applies across the whole vehicle fleet for the life of the program. For cost comparison purposes its cost is prorated to the subsystem on the basis of end item area.

System Cost by Phase and TPS Subsystem

TPS subsystem expenditures are provided in Table I6-11. End item costs are greatest for TDNiCr with titanium second. While the production costs for both are comparible, there is a 4.4 million dollar differential between TDNiCr and titantium in Operations, and a 5.1 million dollar differential in DDT&E. The relatively lower production cost for LI-1500 is due to its lower material cost. Tantalum has a low cost because of its small material weight contribution. Logistic cost amounts to 142.9 million dollars or 44% of the total system cost. The relative rank in percent of total cost is as follows:

				Uncertainty	
Rank	Material Code	Material	Percent	Mat'l	Labor
1	050	T D Ni Cr	32.8	1.9	4.93
2	080	Titanium	25.8	1.1	3.13
3	060	Haynes	13.8	1.2	4.03
4	070	Rene' 41	11.7	1.1	3.47
5	044	LI-1500	8.2	1.2	6.03
6	020	Tantalum	7.7	1.1	6.83

Logistic expenditures are prorated by the initial production cost.

System Cost of Operation by Phase and Operational Task

System costs for Operations are shown in Table I6-12 by Operation Task. Maintenance costs rank highest in total cost followed by Panel Installation and Inspection. Their relative rank in percent of total cost is as follows:

			Uncertainty	
Rank	Operational Task	Percent	Mat'l	Labor
1	Maintenance	55.9	(H 1.46 (L 1/1.88	8.39
2	Panel Installation	20.3	-	3.29
3	Inspection	14.4	-	5.34
4	Panel Removal	6.2	-	3.06
5	Packaging and Handling	1.7	-	3.69
6	Storage	1.5	-	3.38

Refurbishment operations amount to $12,301,281 or 38% of the total cost.

System Cost by Phase and Function

Total system cost for Iteration No.6 is $294,639,324. In Table 16-13, this cost is broken down into its six (6) functional areas and two (2) summary cost groups for the three (3) program phases.

Refurbishment costs for the metallic TPS system described in this Iteration, composed of six TPS subsystems and requiring 750 refurbishments over the 10 year life of the program, amount to $30,623,900, approximately 10.4% of the total TPS system cost. This compares with the other program phases as follows:

Group	Phase	Percent	Uncertainty High	Uncertainty Low
Recurring	Operation	10.4	4.87	1/4.00
	Production	62.2	2.43	1/1.89
Non-recurring	DDT&E	27.4	3.73	1/2.88

The contribution by each of the nine (9) functional groups is summarized as follows:

Function	Percent	
Operation	9.5	
Manufacturing	52.7	
Quality Assurance	14.4	(1.6% of which is for Operations)
Engineering	23.4	

Cost estimates for the functions other than Operations were derived in a manner similar to that just described. Due to its volume, the supporting data is not provided.

System Cost Uncertainty by Phase

Nominal costs to perform the DDT&E, Production, and Operation phases reflect the depth of informational detail avaiable to all functional groups. The costs shown in Table I6-14 are based on a mix of subjective judgment, "similar to" knowledge, and definitive information. The extent to which definition is lacking will appear in the magnitude of the uncertainty factor.

The importance of this information is twofold: (1) It provides perspective which allows the establishment of priorities for further development activities that will effectively lead to uncertainty reduction and definitive costing, and (2) the data can be directly related to a function, activity, or end item, permitting critical appraisal of design and system tradeoffs and maintenance of program objectives.

Conditions shown in Table I6-14, indicate that the metallic TPS system can cost 3.62 times nominal or 1068.0 million dollars. Technological uncertainty can result in a 1/2.67 reduction in the nominal cost to 110.0 million dollars for a metallic TPS system.

Operations exhibits the widest range of uncertainty exceeding that for the system. Operations can cost 4.87 times nominal or 148.9 million dollars, while a 1/4.00 reduction due to technological uncertainty would result in a cost of 7.7 million dollars.

TPS SIZING DATA FOR BASELINE VEHICLE
(ITERATION NO. 6 – TPS METALLIC (TDNiCr))

TPS Element Location and Type*	Area (ft2)	Insulation Thickness (in.)	Outer Panel (lb)	Clips	Sub-Panel (lb)	Insulation (lb)	Total (lb)	PSF
Body – Nose Cone – Ta	70	0.25	412	30	95	452	989	
SUBTOTAL (020)	70	–	412	30	95	452	989	14.10
Body – Smooth – TD Ni Cr	1195	3.3	1434	508	1028	2070	5040	
Body – Corrugated – TD Ni Cr	3381	3.3	1633	1657	2903	5858	12051	
SUBTOTAL (050)	4576	–	3067	2165	3931	7928	17091	3.73
Fin – Leading Edge – Haynes	855	2.7	2468	206	734	1212	4620	
Fin – Smooth – Haynes	248	2.3	342	57	214	299	912	
Body – Smooth – Haynes	1029	2.8	1419	251	877	1513	4060	
Body – Corrugated – Haynes	–	–	–	–	–	–	–	
SUBTOTAL (060)	2132	–	4229	514	1825	3024	9592	4.50
Fin – Smooth – Rene	665	2.3	826	141	570	803	2340	
Body – Smooth – Rene	1180	1.5	1466	224	1014	929	3633	
Body – Corrugated – Rene	–	–	–	–	–	–	–	
SUBTOTAL (070)	1845	–	2292	365	1584	1732	5973	3.23
Fin – Corrugated – Ti	912	0.25	468	109	–	120	697	
Body – Corrugated – Ti	5166	0.25	2652	615	–	678	3945	
SUBTOTAL (080)	6078	–	3120	724	–	798	4642	0.76
Body – Base Heat Shield	1610	–	–	188	519	2109	2816	
SUBTOTAL (044)	1610	–	–	188	519	2109	2816	1.75
Lower Flap	1100	–	–	–	–	632	632	
SUBTOTAL (101)	1100	–	–	–	–	632	632	0.57
TOTAL	17411	–	13120	3986	7954	16675	41735	2.40

*Materials:
- (020) – Tantalum (2500° to 3000°)
- (050) – TD Ni Cr (2000° to 2200°)
- (044) – LI-1500 Base Shield
- (060) – Haynes 188 (1600° to 2000°)
- (070) – Rene 41 (1000° to 1600°)
- (080) – Titanium (Under 1000°)
- (101) – Dynaflex Flap Shield

TABLE I6-1

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E: DELTA BODY

TDNiCr CR: 1500 NM

ITERATION NO. 6 - TPS METALLIC (TDNiCr)
(END ITEM SUMMARY SHEET (EIS)

ITERATION #6	PANEL INSTALLATION		PANEL REMOVAL		INSPECTION (IN-PROCESS)		PACKAGING & HANDLING		STORAGE				MAINTENANCE REUSE		TOTAL	
BASELINE MATERIAL:	H_{pi}	U_{pi}	H_{pr}	U_{pr}	H_i	U_i	H_h	U_h	H_s	U_s	H_-	U_-	H_m	U_m	H_T	U_T
TANTALUM (Nose)	150	2.5	50	2.5	24	6.0	16	4.0	8	4.0			300	10.0	548	6.825
TDNiCr - (Smooth)	24	5.0	8	5.0	5	5.0	3	4.0	3	4.0			40	5.0	83	4.928
TDNiCR - (Corrugated)	24	4.0	8	4.0	5	6.0	3	4.0	3	4.0			40	5.0	83	4.928
HAYNES (L. Edge)	18	3.0	6	3.0	1	4.0	1	2.0	2	2.0			32	5.0	60	4.033
HAYNES (Smooth)	18	3.0	6	3.0	1	4.0	1	2.0	2	2.0			32	5.0	60	4.033
RENE 41	18	1.5	6	1.5	1	1.5	1	1.0	1.5	1.0			36	5.0	63.5	3.465
TITANIUM	18	1.5	6	1.5	1	1.5	1	1.0	1	1.0			24	2.0	51	3.127
LI-1500 (Base)	40	5.0	8	5.0	15	5.0	1	5.0	3	4.0			23	5.0	90	6.033
WT AVERAGE	310		98		53		27		23.5				527		1038.5	
ARITH AVERAGE		3.295		3.059		5.340		3.696		3.378				8.397		5.934

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TABLE I6-2

ITERATION NO. 6 - TPS METALLIC (TDNiCr)

PRODUCTION PANEL MODEL

	Tantalum 020	TDNiCr C50	Haynes 060	Rene 41 070	Titanium 080	LI-1500 044	Insul 101
Erosion Shield	412	3,067	4,229	2,292	3,120	2,109	-
Sub-Panel	(95)	(3,931)	(1,825)	(1,584)	-	(519)	-
Clips	(30)	(2,165)	(514)	(365)	(724)	(188)	-
Not in Total#) Insulation	(452)	(7,928)	(3,024)	(1,732)	(798)	-	(632)[1]
TOTAL #	412	3,067	4,229	2,292	15,060[2]	2,109	14,934
$ / #	$50.00	$127.00	$20.00	$10.00	$29.44	$6.90	-
	$20,600	$389,509	$84,580	$22,920	$443.366	$14,552	-
Area (Ft^2)	70	4,576	2,132	1,845	6,078	1,610	16,302
$ / #	-			-	-	$2.00	$1.20
TOTAL $	0	0	0	0	0	$3,220	$19,562
TOTAL $	$20,600	$389,509	$84,580	$22,920	$443,366	$17,772	$19,562
(With Insul)	635	11,130	4,245	2,432	1,120	-	($19,562)
TOTAL $	$21,235	$400,639	$88,825	$25,352	$444.486	$17,772	-
TOTAL: $998,309							

1. Flap Shield Insul Omitted.
2. Includes Subpanel and Clips.

TABLE I6-3

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(ITERATION NO. 6 - TPS METALLIC (TDNiCr)

MAINTENANCE FACTORS

E: DELTA BODY DNiCr CR: 1500 nm IGURE 15 teration #6	TEMP EXPOSURE		COMBINED TEMP/LOAD		COMBINED TEMP/PRESS.		COMBINED TEMP/PRESS./ LOAD		HANDLING		ENVIRONMENT		COMPOSITE MAINTENANCE FREQUENCY		MAINTENANCE RATE (FLIGHT/PANEL)	
	F_T	U ±	F_{TL}	U ±	F_{TP}	U ±	F_{TPL}	U ±	F_H	U ±	F_E	U ±	F_F	U ±	F_r	MAX. MIN.
BASELINE MATERIAL:																
TANTALUM (Nose)	.0224	.012	.1041	.033	.0565	.020	.1510	.033	.0530	.033	.1093	.033	.0932	.033	107	15.611 7.924
TDNiCr (Smooth)	.0445	.009	.0381	.007	.0414	.020	.0200	.006	.0247	.004	.0286	.004	.0341	.020	29.3	70.922 18.484
TDNiCr (Corrugated)																
Haynes (Leading Edge)	.0199	.003	.0316	.007	.0359	.011	.0142	.005	.0185	.003	.0185	.003	.0244	.011	41.0	74.627 28.249
Haynes (Smooth)																
RENE' 41	.0357	.012	.0281	.006	.0304	.009	.0170	.006	.0179	.002	.0291	.006	.0272	.012	36.8	65.789 25.510
TITANIUM	.0175	.005	.0327	.007	.0376	.008	.0142	.005	.0198	.006	.0247	.009	.0258	.009	38.8	71.524 28.736
LI-1500	.0167	.003	.0373	.010	.0299	.010	.0097	.004	.0313	.010	.0324	.011	.0279	.011	35.8	59.172 25.707
DYNAFLEX (Flap Shield)																
COLUMBIUM(Lower Flap Sh)	.0133	.002	.0377	.020	.0185	.011	.0242	.020	.0204	.003	.0289	.008	.0311	.020	32.2	90.090 19.569
RENE' 41(Upper Flap Sh)	.0357	.012	.0281	.006	.0304	.009	.0170	.006	.0179	.002	.0291	.006	.0272	.012	36.8	65.789 25.510
TAL WT AVE.																
ARITH AVE.																

TABLE I6-4

ITERATION NO. 6 – TPS METALLIC (TDNiCr)
(OPERATION EXPENDITURES – HOURS)

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	VEHICLE: DELTA BODY / TPS TDNiCr CR:1500 NM / Fig. 15 / ITERATION #6	TPS SUBSYSTEM Area (ft²)	Panel Area (ft²)	Subsyst Panels (N)	Maintenance Rate F_r	Max / Min	Panels Maintained P_r	Max / Min	Model: IV Maintenance Reuse H_r	Max / Min			H_T	TOTAL $F_r = K$ Max / Min	$H_r = K$ Max / Min	Worst Case Max / Min
L																
0	TANTALUM (Nose)	70	70	1	10.7	16.61 / 7.92	.093	.13 / .06	548	3726 / 80.58			51.18		69.2 / 33.0	
50	TDNiCr (Smooth)	1195	14	85	29.3	70.92 / 18.48	11.16	17.69 / 4.61	83	382 / 18.04			926.31		1468.7 / 382.7	
50	TDNiCr (Corrugated)	3381	14	242												
50	HAYNES (L. Edge)	855	14	62	41.0	74.63 / 28.25	3.76	5.45 / 2.06	60	240 / 15.0			225.36		327.1 / 123.8	
50	HAYNES (Smooth)	1277	14	92												
70	RENE 41	1845	14	132	36.8	65.79 / 25.51	3.59	5.17 / 2.01	635	222 / 18.14			227.77		328.6 / 127.4	
30	TITANIUM	6078	14	434	38.8	59.52 / 28.74	11.19	15.10 / 7.29	51	91.8 / 28.33			570.47		770.1 / 371.9	
44	LI-1500 (Base)	1610	14	115	35.8	59.17 / 25.71	3.21	4.47 / 1.94	90	450 / 18			289.10		402.6 / 174.9	
		16,311		1163	35.2	64.8 / 24.2	33.00	48.01 / 17.97	955.5	5351.8 / 193.1			2290.19		3366.3 / 1213.7	

TABLE I6-9

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ITERATION NO. 6 – TPS METALLIC (TDNiCr)

(OPERATION EXPENDITURES – MATERIAL

[illegible]: DELTA BODY

[illegible] TDNiCr CP1500 NM

[illegible]: Fig. 15

[illegible]: ITERATION #6

	Item	TPS Subsystem Area (ft^2)	TPS Subsystem Panel Area (ft^2)	TPS Subsystem Panels (N)	Maintenance Rate F_r	Maintenance Rate Max / Min	Panels Maintained P_r	Panels Maintained Max / Min	Model: IV Maintenance Reuse M_r $	Model: IV Maintenance Reuse Max / Min	M_T $	[illegible] $F_r = K$ Max / Min	[illegible] $M_r = K$ Max / Min	[illegible] Worst Case Max / Min
0	TANTALUM (Nose)	70	70	1	10.7	16.61 / 7.92	.093	.13 / .06	21,235	23,359 / 19,305	476.29		643.48 / 306.82	
0	TDNiCr (Smooth)	1195	14	85	29.3	70.42 / 18.48	11.16	17.69 / 4.61	400,639	761,214 / 210,863	3281.68		5203.10 / 1355.80	
0	TDNiCr (Corrugated)	3381	14	242										
0	HAYNES (L. Edge)	855	14	62	41.0	74.63 / 28.25	3.76	5.45 / 2.06	88,825	102,149 / 77,239	519.95		754.61 / 285.64	
0	HAYNES (Smooth)	1277	14	92										
70	RENE 41	1845	14	132	36.8	65.79 / 25.51	3.59	5.[illegible] / 2.01	25,352	37,85[illegible] / [illegible]047	165.33		238.57 / 92.18	
30	TITANIUM	6078	14	434	38.8	57.52 / 25.74	11.19	15.10 / 7.29	444,480	448,735 / 404,078	2749.39		3711.78 / 1742.28	
44	LI-1500 (Base)	1610	14	115	36.8	59.17 / 25.71	3.21	4.47 / 1.94	17,772	21,326 / 14,810	119.14		165.90 / 12.09	
		16,311		1163	35.2	64.8 / 24.2	33.0	45.01 / 17.97	998,304	1,424,870 / 749,342	7311.78		10,717.46 / 3,705.11	

TABLE 16-6

ITERATION NO. 6 - TPS METALLIC (TDNiCr)

VEHICLE LEVEL OPERATIONS

CODE NO.	MATERIAL	RECURRING LABOR HOURS			RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION In-Process	INSPECTION Base		
020	Tantalum (Nose)	49	2	3	476	
050	TDNiCr (Smooth) (Corrugated)	871	56	53	3,282	
060	Haynes (L. Edge) (Smooth)	222	4	30	520	
070	René 41	224	4	19	165	
080	Titanium	559	11	14	2,750	
044	LI-1500	241	48	9	119	
	TOTAL	2,166	125	128 *	$7,312	
		Total 2,291 hours				

*Prorated by End Item Area

TABLE I6-7

ITERATION NO. 6 - TPS METALLIC (TDNiCr)

VEHICLE LEVEL OPERATIONS

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	1,158.3	$ 7,311.78	
PANEL INSTALLAION	681.4		
PANEL REMOVAL	215.4		
INSPECTION			
PRE-FLIGHT	64.0		
IN-PROCESS	125.0		
POST-FLIGHT	64.0		
PACKAGING AND HANDLING	59.3		
STORAGE	51.6		
TOTAL	2,419.0 Hrs.	$7,311.78	

TABLE I6-8

ITERATION NO. 6 - TPS METALLIC (TDNiCr)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

CODE NO.	MATERIAL	RECURRING LABOR HOURS		RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
		MAINTENANCE	INSPECTION In-Process + Base		
020	Tantalum (nose)	36,750	3,750	357,000	42,107
050	TDNiCr (Smooth) (Corrugated)	653,250	81,750	1,461.500	727,667
060	Haynes (L. Edge) (Smooth)	166,500	25,500	390,000	408,388
070	Rene' 41	168,000	17,250	123,750	254,306
080	Titanium	419,250	42,750	2,062,500	197,638
044	LI-1500	180,750	18,750	89,250	119,894
	TOTAL	1,624,500 Hrs	189,750 Hrs	$5,484,000	$1,750,000 *
		TOTAL - 1,814,250 Hrs			

*Prorated by End Item Area

TABLE I6-9

ITERATION NO. 6 - TPS METALLIC (TDNiCr)

SYSTEM LEVEL OPERATIONS
(750 REFURBISHMENT)

OPERATION TASKS	LABOR HOURS RECURRING	MATERIAL $ RECURRING	EQUIPMENT $ NON-RECURRING
MAINTENANCE	868,725	$ 5,484,000	
PANEL INSTALLATION	511,050		
PANEL REMOVAL	161,550		
INSPECTION			$ 1,750,000
PRE-FLIGHT	48,000		
IN-PROCESS	93,750		
POST-FLIGHT	48,000		
PACKAGING AND HANDLING	44,475		
STORAGE	38,700		
TOTAL	1,814,250 hrs.	$5,484,000	$1,750,000

TABLE I6-10

SYSTEM COSTS BY PHASE AND TPS SUBSYSTEM
(ITERATION NO. 6 - TPS METALLIC (TDNiCr))

SUBSYSTEM	RECURRING		NON-RECURRING	TOTAL
	OPERATIONS	PRODUCTION	DDT&E	
020 TANTALUM	$ 983,930	$ 2,512,110	$ 8,200,500	$ 11,696,540
050 TDNiCR	12,713,511	12,286,275	24,674,352	49,674,138
060 HAYNES	2,997,190	5,028,404	12,898,101	20,923,695
070 RENE' 41	2,568,526	4,128,225	11,002,899	17,699,650
080 TITANIUM	8,338,751	13,349,493	17,549,194	39,237,438
044 LI-1500	3,021,992	2,890,204	6,595,867	12,508,063
TOTAL	$30,623,900	$40,194,711	$80,920,913	$151,739,524
LOGISTICS	-	142,900,000	-	142,900,000
TOTAL	$30,623,900	$183,094,711	$80,920,913	$294,639,324

TABLE I6-11

SYSTEM COST OF OPERATIONS BY PHASE AND OPERATIONAL TASK

(ITERATION NO. 6 - TPS METALLIC (TDNiCr))

OPERATIONAL TASK	HOURS	RECURRING		NON-RECURRING	TOTAL
		LABOR	MATERIAL	EQUIPMENT	
MAINTENANCE	868,725	$ 11,302,112	$ 7,020,507	$ -	$ 18,322,619
PANEL INSTALLATION	511,050	6,648,760	-	-	6,648,760
PANEL REMOVAL	161,550	2,101,766	-	-	2,101,766
INSPECTION					
PRE-FLIGHT	48,000	624,480	-	582,482	1,206,962
IN-PROCESS	93,750	1,219,688	-	1,075,351	2,295,039
POST-FLIGHT	48,000	624,480	-	482,482	1,206,962
PACKAGING & HANDLING	44,475	578,620	-	-	578,620
STORAGE	38,700	503,487	-	-	503,487
TOTAL	1,814,250	$23,603,393	$7,020,507	$2,240,315	$32,864,215

TABLE I6-12

SYSTEM COSTS BY PHASE AND FUNCTION

(ITERATION NO. 6 - TPS METALLIC (TDNiCr))

FUNCTION	RECURRING OPERATION	RECURRING PRODUCTION	NON-RECURRING DDT&E	TOTAL
MANUFACTURING	$ -	$ 20,662,562	$ 21,040,300	$ 41,702,862
OPERATIONS	28,155,252	-	-	28,155,262
ENGINEERING:				
STRESS	-	2,025,623	4,004,383	-
WEIGHTS	-	754,624	3,323,051	-
LOADS & DYNAMICS	-	586,201	2,046,266	-
THERMO DYNAMICS	-	1,128,186	4,035,365	-
DESIGN	-	1,481,561	3,262,849	-
MATERIALS	-	8,329,940	87,232,737	-
TOTAL ENGINEERING	-	$14,306,135	$53,904,651	$ 68,210,786
QUALITY ASSURANCE:				
MANUFACTURING	-	5,226,014	3,735,647	-
OPERATIONS	2,468,648	-	2,240,315	
TOTAL Q.A.	$2,468,648	$5,226,014	$5,975,962	$ 13,670,624
TOTAL	$30,623,900	$40,194,711	$80,920,913	$151,739,524
LOGISTICS				
MANUFACTURING	-	114,000,000	-	142,900,000
QUALITY ASSURANCE	-	28,900,000	-	
TOTAL	$30,623,900	$183,094,711	$80,920,913	$294,639,524

TABLE I6-13

SYSTEM COST UNCERTAINTY BY PHASE
(ITERATION NO. 6 – TPS METALLIC)

COST-UNCERTAINTY FACTORS & COST RANGE	PROGRAM PHASES			TOTAL
	DDT & E	PRODUCTION	OPERATIONS	
HIGH UNCERTAINTY FACTOR	3.73 / 1	2.43 / 1	4.87 / 1	3.62 / 1
LOW UNCERTAINTY FACTOR	1 / 2.88	1 / 1.89	1 / 4.00	1 / 2.67
HIGHEST TPS COST	$301 M	445.0 M	$148.9 M	$1,068 M
NOMINAL TPS COST	80.9 M	183.1 M	30.6 M	294.6 M
LOWEST TPS COST	28 M	96.9 M	7.7 M	110.0 M

NOTES:
- UNCERTAINTY FACTORS ARE SUMMATION VALUES REFLECTING ALL COST-ELEMENT UNCERTAINTY ESTIMATES
- THE HIGH & LOW FACTORS ARE MULTIPLIERS TO BE USED WITH NOMINAL COSTS TO OBTAIN ESTIMATED HIGH & LOW COST LIMITS
- THESE DATA REFLECT A TYPICAL TPS COST ESTIMATE FOR A DELTA BODY ORBITER, 1500 NM CROSS RANGE

TABLE 16-14

APPENDIX C

OPERATION PREMISES

1.1 Introduction

Operations for the Thermal Protection System (TPS) of the Space Shuttle Orbiter Vehicle are primarily considered to encompass activities associated with maintaining the TPS at acceptable performance levels over the ten-year "operational" life defined for the system. A successful development phase is assumed to have preceded the operational phase and has resulted in TPS designed for easy removal and replacement and fully qualified for the application. Labor estimates are based on time-line analysis of the concepts, without considering vehicle turn-around constraints or lost time due to schedule cycles or irregularities. Thus actual manpower requirements will be considerably higher because of high peak loads that make for low manpower utilization factors.

The operations analyses have, of necessity, been based on preliminary concept definitions and sketches, and should be reviewed and updated when detail definitive designs become available, perhaps in a year or two. Uncertainty factors have been assigned to each parameter in the anlysis to reflect probable bounds based upon past experiences, state-of-the-art and confidence in the available data and techniques. For areas of significant cost the desirability of reducing the uncertainty is apparent; experimental fabrication, operation simulation and environmental test of specific TPS material and structure are necessary to reduce the uncertainties.

Operational premises that relate to TPS have been derived from previous studies and NASA documents, as well as the RCS, and are listed herein. Most have been incorporated in the operational cost models; the few that were not able to be applied at the present time are identified for reconsideration in future iterations. Various Operations Maintenance Models are described and one option "Reuse", has been selected for the detailed cost analyses. The cost analyses procedures and forms used to develop operating costs are described with commentary on the rationale.

1.2 Operational Premises

The following operational premises have been formulated for the TPS RCS or derived from previous studies, reports and NASA documents. The more significant references are listed at the end of this appendix. There are, of course, many different vehicle and operating concepts represented, and mission models range from 10/yr to 150/year from one to three operational sites. Turn-around requirements for the vehicle mostly are listed as 2 weeks (10 working days) as a desired goal, without any limitation on cost of facilities and manpower for either development or operations for achieving this rapid refurbishment and launch capability. The one common denominator in the references is the recognition of the need for "routine airlines-type operations" during the operational phase. The applicability or need for some of these premises is very much subject to the particular systems model and accounting methods employed. However, if the individual premises are applied or modified on a consistant basis for the operational models analyzed, the comparitive results will be valid. In fact, modification of premises to determine sensitivity may be desirable if the ranking of competitive systems is obscured by uncertainties or closeness in numerical results.

1. Development has been completed, including development flight testing, and operations are on a routine basis, with the system operational span being ten years.
2. Operations will be conducted at two launch sites.
3. TPS Maintenance Operations will be accomplished with base type personnel, so that operations costs will be calculated at "remote" rates which bear lower overhead than "factory" rates.
4. Engineering Liaison will be provided by launch base personnel. Labor hours will be charged against Operations as a "level of effort".
5. Sustaining Engineering will be a "level of effort" activity at the vehicle level, essentially independent of the TPS.

6. Material costs and Logistics Spares costs will be established through the Maintenance Model and the Maintenance Rate Model.

7. Labor estimates will be made on Maintenance Operations functions normally performed, using "time-line analysis" techniques. Tasks which might normally be expected to occur within each function will be listed and used as a basis for substantiating the functional cost estimate. Operating constraints, particularly the turn-around time allocated to TPS, non-interference from other subsystem turn-around activities, availability of adequate "on-board checkout" data and ground computer historical records, effectiveness of inspection techniques, etc. should be considered in establishing facility and man-loading requirements. (Note: Operational constraints were not applied to the initial estimates for Iterations 2 thru 6 because of insufficient data and time.)

8. Labor hours to remove, replace, package, handle and store TPS will be charged against Operations, as will material costs.

9. TPS panels provided as logistics spares for use in the vehicle refurbishment will be charged against Production rather than Operations. (This must be applied or not applied*on a uniform basis to all systems.)

10. Preflight, in-process and postflight TPS inspection services will be charged to Operations. Base inspection activities that are not "TPS-peculiar" will be treated as "level of effort" applicable at the vehicle level.

11. Launch and Flight Operations costs are not chargeable to the TPS. The labor/materials/equipment/facilities for these operations or functions are essentially independent of the TPS.

12. TPS removal and repair costs ascribable to another subsystem shall be charged to that subsystem. For example, the removal of a TPS panel or panels to permit servicing of an antenna should be considered part of the cost of maintaining the avionics and not charged to TPS. (If

*Not applied in this Study.

the maintenance requirements of other subsystems involved appreciable TPS removal and replacement adequate facilities, manpower and scheduled turn-around time must be allocated.)

13. Special TPS tools and test equipment, including the maintenance and replacement thereof, is a prorated charge against TPS operations.

14. Ground Support Equipment, including maintenance and spares, is common to the entire vehicle and therefore is not charged against TPS operations.

15. Ground Test/Operations Checkout equipment for TPS will be comparable to that used by Production. The development of such equipment will be charged as development support to Production.

16. Only Ground Test/Operations Checkout that is performed as part of the maintenance operations will be included in TPS operations labor estimates. (Specifically, vehicle systems test and inspection are not TPS operations costs.)

17. Facilities and equipment for ground cooling the vehicle at the landing field are not chargeable against the TPS. (The main function of ground cooling is to protect primary structure and the vehicle contents from overheating as a result of heat soak-back.)

18. An operational system model of 750 flights in the ten-year span shall be used for the TPS RCS cost analyses. (The so-called alpha model has ten flights in the year preceding IOC and 435 in the nine years following IOC: much of the analysis work had already been accomplished before the alpha model won wide-spread acceptance.)

1.3 Estimating Techniques for TPS Operations

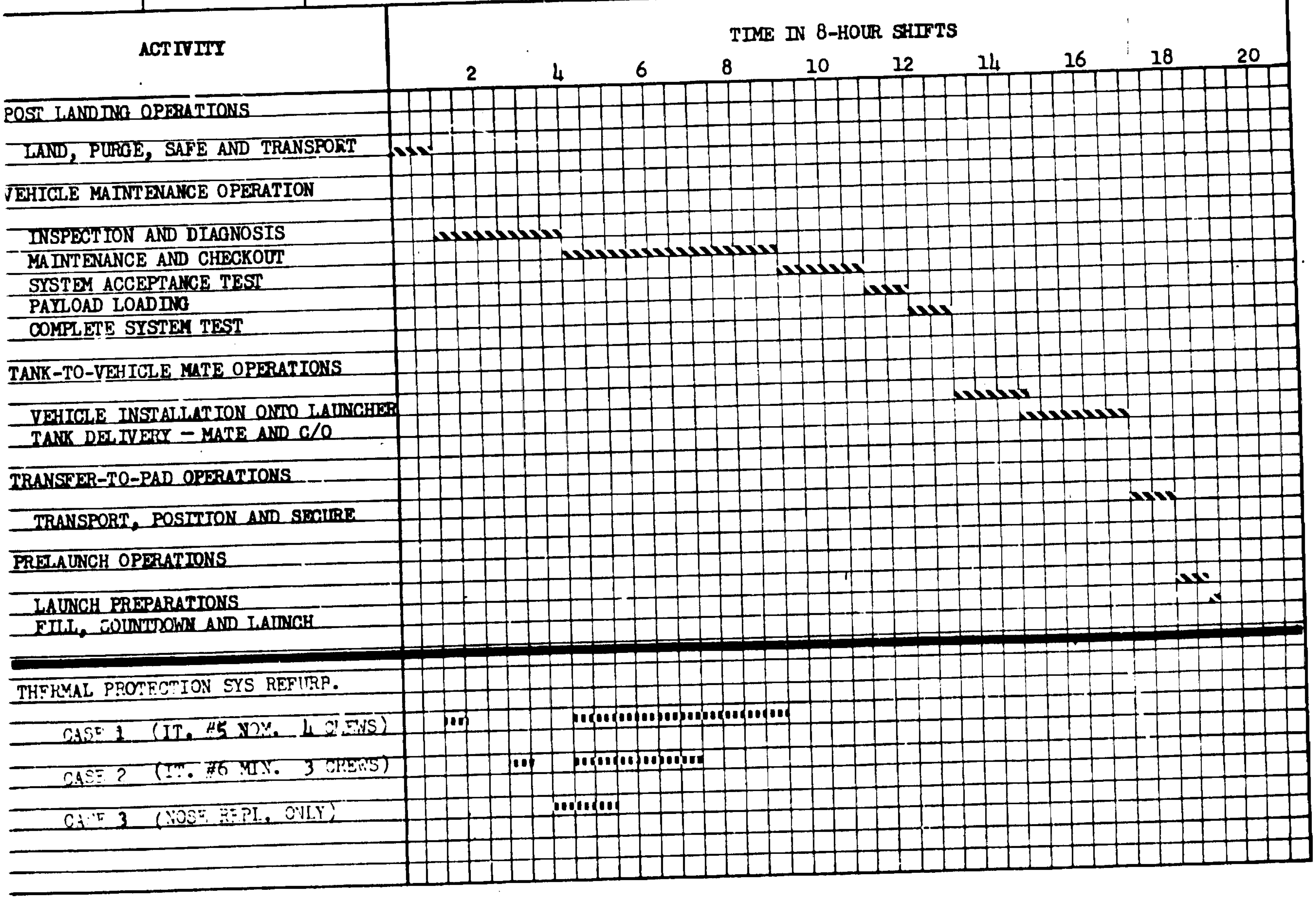
Routine operations with a TPS designed and qualified for use on the reusable Space Shuttle Orbiter, and a development flight test program that has eliminated most of the "bugs" and established or verified the maintenance techniques is the basis for an operational time-line analysis.

Experience with maintenance of Agena and Polaris space vehicles, military and commerical aircraft; launch base, ground support, and factory equipment; and facilities has been integrated into the RCS estimates at the major task level, and has been applied, in conjunction with state-of-the-art evaluations of materials and fabrication techniques, to arrive at uncertainty factors. These factors are strongly influenced by the specific application; for example, the extensive use of titanium in high performance aircraft has increased the confidence level of fabrication estimates, but the application in higher temperature regimes than aircraft normally experience has raised some questions of the validity of extrapolation, leading to a higher uncertainty factor than might at first glance be expected.

Years of experience tell us that operations manning must be on a level of effort basis that considers constraints beyond the purview of the TPS subsystem alone. For example, Figure C-1 shows a typical turn-around time allocation for a Space Shuttle. A fairly recent estimate, it is based on 19 work shifts because studies of the functions that must be accomplished indicated that trying to achieve a 10-shift turn-around seems overly optimistic. These activities obviously can be accomplished in 19 days of one-shift operation or two weeks of 5-day/2-shift operation between orbiter touch-down and launch readiness. Note that all inspection and diagnosis must be done in the 2-1/2 shifts preceding the maintenance or refurbishment span of only 5 shifts. Furthermore, this time is not exclusively for TPS, but must be shared with all other subsystems on a non-interference basis. Allowance must be made for the order in which some work is done, such as removing a panel to permit avionics repairs, and installing the panel after the avionics maintenance has been completed. Since most subsystems for

SCHEDULE PLAN

MODEL	PLAN	TITLE	PREPARED BY:	DATE
		TYPICAL TURN-AROUND ESTIMATE FOR SPACE SHUTTLE ORBITER AND TPS	RRR/KU	10/5/70
ISSUE NO.	REFERENCE		APPROVED BY:	DATE



Shuttle are still in the conceptual development phase, and since mission models are very tentative, it is not considered practical to apply constraints to the maintenance/refurbishment labor estimates at this time. Task estimates are therefore made on an "actual task requirement" basis.

Converting from "actual task requirement" time spans to manhours is done by multipying by the crew size. A nominal crew makeup of one crew chief, four technicians and one QA technician was arrived at based on actual launch base and aircraft repair experience, factoring in a 14 square foot panel, the vehicle size, typical hangar working conditions and the assumption that "delicate" surface coatings may exist. If small panels (and hence, more of them) are employed, the crew might be reduced by two technicians; on the other hand, larger panels, difficult mating or fastening operations, awkward work positions, etc., could conceivably require augmenting the nominal crew. Only by experience, on the mockup or on a vehicle, using the selected size panels, either real or simulated materials, and particular fastening system, will the crew size be verified. For the estimates, therefore, crew size has been held constant.

Completely independent of the time-line analysis, but employing the same experience factors and concept drawings of candidate TPS panels, estimates were made for six major work categories constituting the TPS refurbishment cycle. Figure C-2 illustrates the form used. Labor hours and uncertainty factors are estimated for each material system and for each of the categories. Weighted average uncertainty factors may then be calculated for each TPS Iteration, permitting an evaluation of the relative confidence in the operations estimates on a comparitive basis.

Maintenance Labor calculations are tabulated using the form shown in Figure C-3. The estimated failure rates, F_r, are obtained from the Materials Analysis of failure modes. The statistical average number of panels to be replaced per flight, P_r, is obtained by dividing the number of panels in each TPS subsystem by the failure rate. Uncertainties have been assigned to F_r, so maximum and minimum P_r are also calculated. The labor hours and uncertainty factors are obtained from Figure C-2 , and max/min H_r values calculated.

ATOR

E:

END ITEM SUMMARY SHEET - OPERATIONS

	PANEL INSTALLATION		PANEL REMOVAL		INSPECTION (IN-PROCESS)		PACKAGING & HANDLING		STORAGE				MAINTENANCE REUSE		TOTAL	
	H _	U _	H _	U _	H _	U _	H _	U _	H _	U _	H _	U _	H _	U _	H_	U_
BASELINE MATERIAL: ______																
AL WT AVE.																
ARITH AVE.																

FIGURE C-2

OPERATION EXPENDITURE - HOURS

...CLE: S .CR: NM G: r:	TPS SUBSYSTEM Area (ft^2)	Panel Area (ft^2)	Subsyst. Panels (N)	MAINTENANCE RATE F_r	MAX / MIN	PANELS MAINTAINED P_r	MAX / MIN	MODEL: IX MAINTENANCE REUSE H_r (hrs)	MAX / MIN		Insp	Maint	H_T (hrs)	TOTAL $F_r=K$ MAX / MIN	$H_r=K$ MAX / MIN	WORST CASE MAX / MIN

FIGURE C-3

From this data Maintenance and Inspection hours per nominal refurbishment cycle are derived for each TPS subsystem. Calculations are also made assuming F_r has no uncertainty, H_r has no uncertainty, and for worst case combination of F_r and H_r uncertainties.

The form shown in Figure C-4 is used to calculate estimated Maintenance Material costs for each refurbishment cycle for each TPS subsystem. F_r and P_r are the same as for Figure C-3, while Material cost per panel, M_r, is obtained from the Manufacturing Analysis, as is the scrap rate, d. The Repair/Refurbish index, a, and the Replace index, b, are obtained from the applicable Maintenance Model. The material cost per refurbishment cycle for each subsystem, M_t is then the sum of the R/R cost, x, and the Replace cost, y.

- $x = (a \times d \times M_r/F_r)$
- $y = (b \times M_r/F_r)$
- $M_t = x + y$

Calculations are made for F_r held constant (no uncertainty), for M_r held constant, and for the worst case combination of failure rate and material cost uncertainties. Figure C-5 shows that format used for compiling an Operations Summary on a subsystem basis; the same form is used at the Vehicle Level and at the System Level. The latter is obtained by multipying the recurring vehicle level hours and dollars by the total number of operational refurbishments (nominally the same as total flights). Labor data come from Figure C-3. and Material data from Figure C-4. The non-recurring equipment item has been limited, for this exercise, to the development and procurement of two sets of maintenance base inspection equipment. Figure C-6 is the Operations Summary format used on a functional basis. The functional labor estimate totals from Figure C-2 (excluding inspection) are used to prorate the total hours and dollars from Figures C-3 and C-4 , and Base Inspection (pre-flight and post-flight) is taken as 128 hour total. The System Level Summary is on the same basis as described for Figure C-5 above.

OPERATION EXPENDITURES - MATERIAL

:LE: CR: NM	TPS SUBSYSTEM			MAINTENANCE RATE		PANELS MAINTAINED		MODEL: IV MAINTENANCE REUSE					TOTAL			
:	Area (ft²)	Panel Area (ft²)	Subsyst. Panels (N)	F_r	MAX / MIN	P_r	MAX / MIN	M_T ($)	MAX / MIN	Scrap Rate	x	y	M_T ($)	F_r=K MAX / MIN	H_r=K MAX / MIN	WORST CASE MAX / MIN

FIGURE C-4

(VEHICLE)
(SYSTEM) LEVEL OPERATIONS - SUBSYSTEM

ITERATION NO.____

MATERIAL SUB-SYSTEM	RECURRING LABOR HOURS			RECURRING MATERIAL $	NON-RECURRING EQUIPMENT $
	MAINTENANCE	INSPECTION			
		In-Process	Base		
TOTALS					
	TOTAL				

FIGURE C-5

(VEHICLE)
(SYSTEM) LEVEL OPERATIONS - OPERATION TASKS

ITERATION NO.____

	RECURRING		NON-RECURRING
OPERATION TASKS	LABOR HOURS	MATERIAL $	EQUIPMENT $
MAINTENANCE			
PANEL INSTALLATION			
PANEL REMOVAL			
INSPECTION			
PRE-FLIGHT			
IN-PROCESS			
POST-FLIGHT			
PACKAGING AND HANDLING			
STORAGE			
TOTALS			

FIGURE C-6

1.4 Maintenance Model Analyses

Maintenance or refurbishment of the TPS during turn-around could conceivably be accomplished by complete replacement with new panels, by removing, repairing and then replacing the old panels, by making repairs in place on the vehicle without removal, or by some combination of all three basic options. Not all are practical for specific systems and/or locations on the vehicle. A Maintenance Model is therefore necessary to obtain valid cost comparison data on the operations involved. Each TPS Iteration will have a separate Maintenance Model. Data on Flights to Replacement (F_r) is obtained from the corresponding Maintenance Rate Model. The Repair/Refurbish index (a) and the Replace index (b) are derived from estimates of the distribution of the Maintenance Options among the TPS subsystems.

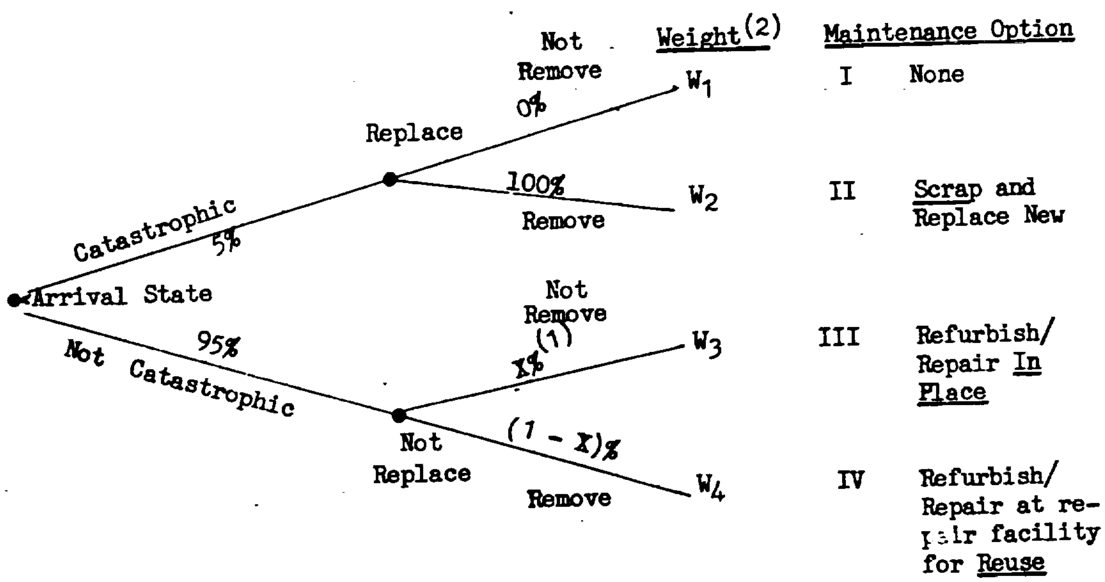
1.4.1 Definitions:

Repair	Local maintenance performed to restore a panel to serviceable condition.
Interchangeable Item	One that has the ability of being exchanged for the other item (a) without selection for fit or performance, and (b) without alteration of the items themselves or of adjoining items, except for adjustment.
Replaceable Item	One which is interchangeable with another item, but which differs physically in that the installation may require operations such as drilling, cutting, filing, shimming, etc., in addition to the normal application and methods of attachment.

1.4.2 Maintenance Rate Model. The Maintenance Rate (or Frequency, F_r) is the aggregate of the effects of all hazards during ascent, orbital, re-entry, landing, ground and launch operations. This is a gross rate, subject to modification by the application of Reliability and Safety criteria/limitations, so that the net rate (probably only obtainable after considerable development testing of the total system) could be either lower or higher. It should be noted that the application of this statistical rate concept does not correlate to individual flights, but should represent a good average for a number of flights. Figure C-7 shows the format used to calculate the Composite Maintenance Frequency, which is the RMS of the individual factors estimated in the six categories shown:

- Temperature Exposure
- Combined Temperature/Load
- Combined Temperature/Pressure
- Combined Temperature/Pressure/Load
- Handling
- Environment

1.4.3 Maintenance Options. The maintenance options are derived from the following logic diagram:



(1) Where x% is a function of the TPS subsystem's degradation mode.
(2) Where $W_1 + W_2 + W_3 + W_4 = 100$ for each TPS subsystem.

ORIGINATOR ____________

MAINTENANCE FACTORS

DATE:

VEHICLE: ____________

TPS: ____________

LNG: ____________

FIG:

MAT'L CODE	BASELINE MATERIAL: ______	TEMP EXPOSURE		COMBINED TEMP/LOAD		COMBINED TEMP/PRESS.		COMBINED TEMP/PRESS./LOAD		HANDLING		ENVIRONMENT		COMPOSITE MAINTENANCE FREQUENCY		MAINTENANCE RATE (FLIGHT/PANEL)	
		$F_{\underline{T}}$	U ±	$F_{\underline{TL}}$	U ±	$F_{\underline{TP}}$	U ±	$F_{\underline{TPL}}$	U ±	$F_{\underline{H}}$	U ±	$F_{\underline{E}}$	U ±	$F_{\underline{\ \ }}$	U ±	$^{I}/_{F}$	MAX. / MIN.
TOTAL	WT AVE.																
	ARITH AVE.																

FIGURE C-7

Maintenance Option events are defined as follows:

OPTION I — None

OPTION II — Scrap and Replace New

1. Inspect (scrap)
2. Remove and scrap
3. Transport new panel from storage and unpack
4. Inspect new panel
5. Install new panel
6. Inspect installed panel

OPTION III — Refurbish/Repair In Place

1. Inspect (Refurbish/Repair In Place)
2. Perform maintenance
3. Inspect maintenance

OPTION IV — Refurbish/Repair at repair facility for Reuse

1. Inspect (remove for maintenance)
2. Remove and package
3. Transport to repair facility and unpack
4. Perform maintenance
5. Inspect maintenance
6. Package and transport to vehicle
7. Install panel
8. Inspect installation

In the event of turn-around constraints, Option IV could be modified to a "First In - First-Out" approach where the repaired panel would go into storage after repair. Events would be defined as follows:

OPTION IV A

1. Inspect (remove for maintenance
2. Remove and package
3. Transport to repair facility and unpack
4. Perform maintenance:
   a. Inspect maintenance
   b. Package and place in storage

5. Transport previously maintained panel from storage and unpack
6. Inspect panel
7. Install panel
8. Inspect installed panel

1.4.4 Maintenance Models. The relative applicability of the Repair/Refurbish and the Replace indices for the Maintenance Cptions has been estimated for each TPS iteration, and the resulting Maintenance Model used in estimating operating costs. The values given in the matrix (body of the Model) a . percentages of time each option can be expected to occur when the maintenance index is either Repair/Refurbish or Replace. These values are considered engineering judgments based on TPS concept drawings and descriptions, material, and associated uncertainties, mission model and a large measure of assimilated aircraft type maintenance experience.

Maintenance Model I has been formulated from the original estimates. For purposes of mathematical convenience, since the values are estimates, Model IA is derived from Model I by rounding or smoothing the matrix values. This is done for each iteration, Figures C-8 to C-12.

ITERATION NO. 2

MAINTENANCE MODEL I

TPS SUBSYSTEM	FLIGHTS TO REPLACEMENT	REPAIR/REFURBISH III In Place %	REPAIR/REFURBISH IV Reuse %	REPLACE II Scrap %
020 TANTALUM	10.7	0	100	100
030 COLUMBIUM	32.2	0	100	100
060 HAYNES 188	41.0	95	5	100
070 RENE' 41	36.8	97	3	100
080 TITANIUM	38.3	98	2	100
044 LI-1500	35.8	50	50	100
		a = 0.95		b = 0.05

ITERATION NO. 2

MAINTENANCE MODEL IA

TPS SUBSYSTEM	OPTIONS III IN PLACE %	OPTIONS IV REUSE %	OPTIONS II SCRAP %
020 TANTALUM	0	100	100
030 COLUMBIUM	0	100	100
060 HAYNES 188	100	0	100
070 RENE' 41	100	0	100
080 TITANIUM	100	0	100
044 LI-1500	50	50	100
	a = 0.95		b = 0.05

FIGURE C-8

ITERATION NO. 3

MAINTENANCE MODEL I

TPS SUBSYSTEM	FLIGHTS TO REPLACEMENT	REPAIR/REFURBISH III In Place %	REPAIR/REFURBISH IV Reuse %	REPLACE II Scrap %
020 TANTALUM	10.7	0	100	100
041 LI-1500 (2000-2500)	22.6	50	50	100
042 LI-1500 (1600-2000)	27.5	50	50	100
043 LI-1500 (1000-1600)	32.7	50	50	100
080 TITANIUM	38.3	98	2	100
044 LI-1500 (Base)	35.8	50	50	100
		a = 0.95		b = 0.05

ITERATION NO. 3

MAINTENANCE MODEL IA

TPS SUBSYSTEM	OPTIONS III IN PLACE %	OPTIONS IV REUSE %	OPTIONS II SCRAP %
020 TANTLUM	0	100	100
041 LI-1500	50	50	100
042 LI-1500	50	50	100
043 LI-1500	50	50	100
080 TITANIUM	100	0	100
044 LI-1500 (Base)	50	50	100
	a = 0.95		b = 0.05

FIGURE C-9

ITERATION NO. 4

MAINTENANCE MODEL I

TPS SUBSYSTEM		FLIGHTS TO REPLACEMENT	REPAIR/REFURBISH		REPLACE
			III In Place %	IV Reuse %	II Scrap %
010	ABALTOR	1	0	100	100
011	ABLATOR	1	0	100	100
012	ABLATOR	1	0	100	100
013	ABLATOR	1	0	100	100
080	TITANIUM	38.8	98	2	100
044	LI-1500	35 2	50	50	100
			a = .95		b = .05

ITERATION NO. 4

MAINTENANCE MODEL IA

TPS SUBSYSTEM		OPTIONS		
		III IN PLACE %	IV REUSE %	II SCRAP %
010	ABLATOR	0	100	100
011	ABLATOR	0	100	100
012	ABLATOR	0	100	100
013	ABLATOR	0	100	100
080	TITANIUM	100	0	100
044	LI-1500	50	40	100
		a = 0.95		b = .05

FIGURE C-10

ITERATION NO. 5

MAINTENANCE MODEL I

TPS SUBSYSTEM		FLIGHTS TO REPLACEMENT	REPAIR/REFURBISH III In Place %	REPAIR/REFURBISH IV Reuse %	REPLACE II Scrap
020	TANTALUM	10.7	0	100	100
110	FS-1500	22.6	50	50	100
111	FS-1500	27.5	50	50	100
112	FS-1500	32.7	50	50	100
080	TITANIUM	38.8	98	2	100
044	LI-1500 (Base)	35.8	50	50	100
			a = 0.95		b = 0.05

ITERATION NO. 5

MAINTENANCE MODEL IA

TPS SUBSYSTEM		OPTIONS III IN PLACE %	OPTIONS IV REUSE %	OPTIONS II SCRAP %
020	TANTALUM	50	50	100
110	FS-1500	50	50	100
111	FS-1500	50	50	100
112	FS-150	50	50	100
080	TITANIUM	100	0	100
044	LI-1500 (Base)	50	50	100
		a = 0.95		b = 0.05

FIGURE C-11

ITERATION NO. 6

MAINTENANCE MODEL I

TPS SUBSYSTEM		FLIGHTS TO REPLACEMENT	REPAIR/REFURBISH		REPLACE
			III In Place %	IV Reuse %	II Scrap %
020	TANTALUM	10.7	0	100	100
050	TDNiCr	29.3	10	90	100
060	HAYNES	41.0	95	5	100
070	RENE' 41	36.8	97	3	100
080	TITANIUM	38.8	98	2	100
044	LI-1500 (Base)	35.8	50	50	100
			a = 0.95		b = 0.05

ITERATION NO. 6

MAINTENANCE MODEL IA

TPS SUBSYSTEM		OPTIONS		
		III IN PLACE %	IV REUSE %	II SCRAP %
020	TANTALUM	0	100	100
050	TDNiCr	0	100	100
060	HAYNES	100	0	100
070	RENE' 41	100	0	100
080	TITANIUM	100	0	100
044	LI-1500 (Base)	50	50	100
		a = 0.95		b = 0.05

FIGURE C-12

1.4.5 Fastening Methods. The Operations Premises and Maintenance Models are based on successful development and application of the reusable TPS panel concepts. This implies a fastener system or method for each type of material that does not degrade in use, that is reparable or replaceable during the refurbishment cycle, if necessary, without having to disassemble major portions of the vehicle, and which is operatable under field conditions in reasonable times and without damaging adjacent systems. Figure C-13 is a tabulation of Evaluation Results based on preliminary concept drawings for different fastening methods.

EVALUATION RESULTS OF TPS FASTENING METHODS

Fastening Method	Drawing	Time to Refurbish/Flight		Comments
1. Long Shank Screw (plain, sleeve, spring) (preferred, but may be prone to abrade skin dimple)	LO-2011 LO-2021 LO-2029 LO-2039 LO-2013 LO-2019	1 man, 1 panel 2 men, 1 panel 2 men, all panels 16 men, all panels	3.0 Hrs 1.5 Hrs 96 Hrs 12 Hrs	(a) These estimates are for delta body 400 NM C.R. (b) 1500 NM C.R. increase refurbishment time by 8% (c) 64 panels (400 NM), 69 panels (1500 NM) are replaced each flight*
2. Recess Screw with Plug (poor but better than 3 below)	LO- Study joint between LI-1500 and metallic heat shield panels	(Total Orbiter) 1 man, 1 panel 2 men, 1 panel 2 men, all panels 16 men, all panels	 5.0 Hrs. 2.5 Hrs. 125 Hrs. 16 Hrs.	(a) The added task of drilling out plugs and probable increased difficulty in retrieving recess screw accounts for increased refurbishment time in excess of the configuration with long shank screws.
3. Internal fastening from Orbiter Interior (very poor from standpoint of accessibility)	First Look Nose Cap Joint - No print number	(Nose Shield Only) 2 men, 1 segment 2 men, Nose Cap	 5.0 Hrs. 30.0 Hrs.	(a) Replacement time for Nose Cap fastened with long shank screws is 9 hours. (b) The difficulty of getting to Nose Cap from interior and getting to all screws is increased 30%.

* The estimated number of panels that will require replacement for study purpose is based on approximation of exposure cycles that we could expect without cyclic testing. The TPS surface area considered was obtained from a Metallic Heat Shield Area Weights Report dated 2-18-70, on the TPS for delta body orbiter. The total number of panels was estimated at 1380.

FIGURE C-13

REFERENCES

1. Statement of Work, Space Shuttle System Program Definition, (Phase B), Enclosure No. 4 to RFP No. 10-8423, dated February 1970, NASA/HQ.

2. Data Requirement Description No. ME003M, 16 January 1970; "Program Costs and Schedule Estimations".

3. Space Shuttle Program, Boeing/Lockheed Proposal D2001, March 1970.

4. Preliminary Technical Requirements for Space Shuttle Orbiter Cost Estimation, Lockheed Engineering Memorandum No. L-1-M4, dated 25 April 1970.

5. Orbiter Thermal Protection System Design Analysis, LMSC-A972005, dated 1 April 1970.

6. NASA NHB 9501.2, Procedures for Reporting Cost Information from Contractors, March 1967

Appendix D

Operational Analysis

A detailed operational analysis was performed using time line techniques, to define the operational task more explicitly than they were in the total system economic evaluation. As it turns out, vehicle design is not sufficiently advanced for the cost/uncertainty approach to be applied with any degree of credibility. It is too early for operations people to project what amounts to operation "point designs". In the iterative process of design evaluation, a point in time will be reached when this approach can be easily and effectively applied because the ground work which it thrives on would be prepared.

However, several features of the approach did produce some interesting and worthwhile results. Table D-1 is a representative time line for the removal of a single panel with time weights (hours). The total elapsed time to perform all time line operational tasks is 18 hours.

Total economic operational tasks defined for the system economic evaluation are compared with the time line operational tasks developed for the time line analysis. This was done to see if the times derived from the time line approach would closely approximated those estimated in the economic evaluation.

Operational and Quality Assurance relationship is also established for purposes of costs division. An additional category is concerned with the nature of the operational task activity. Can cost estimates be made based on actual time to accomplish the task or is the task of such a nature that only level-of-effort estimation is possible? As might be expected the only place where time can be directly controlled, based on the task analysis, is from step 4.1 to 4.12.

TABLE D-1
TIME LINE-ELAPSED TASK HOURS

	Refurb. Oper Level 3 2 1	Total Economic Operational Tasks	Time Line Operational Task	OPS/QA Relationship	Nature of Operational Task Activity
I. Post Flight Inspection	4 hrs				
1.1	1	Inspection	Rev Flt Records	Post Flt Inspect	Level of Effort
1.2	2		MDT		
1.3	1		Locate Panels		
II. Schedule	2 hrs				
2.1	1.5	OPS	Assign Crews	Operations	
2.2	1	Storage	Requisition Matrls		
III. Preparation	2 hrs				
3.1	2	Pkg&Hdl	Transport Materials	Operations	
3.2	1	OPS	Transport Crews		
3.3	.75	Storage	Prepare Wrk Stands		
IV. Conduct Refurbishment	6 hrs				
4.1	.5	OPS (Remove)	Locate Panel & Plugs	Operations & Process Inspection	Actual
4.2	.5		Remove Plug		
4.3	.25		Remove Closure (if applicable)		
4.4	.5		Detach & Remove Panel		
4.5	.5	(Inspect)	Insp Panel Insul & Fittings		
4.6	.5		Insp Adjacent Panels		
4.7	.75		Clean & Inspect, Replace Fittings (as nec)		
4.8	.25		Unpack and Inspect New Panel		
4.9	.75	OPS (Replace)	Pos. Panel & Chk Fit		
4.10	.5		Attach Panel		
4.11	.5		Inst Plug & Closure (if applicable)		
4.12	.5	Inspect	Clean & Inspect		
V. Final Operations	4 hrs				
5.1	1	Inspec.	Inspect compl R/R	Operations & Preflight Inspection	Level of Effort
5.2	1	Pkg&Hdl	Pkg & ret panels		
5.3	1		Ret Materials		
5.4	1.5	Storage	Rem Wrk Stands		
5.5	1		Fill Reports		
5.6	.5	OPS	Release Crews		

TOTAL 18 hrs

This result would indicate that, of the time available to perform the refurbishment function, only 6.0 hours out of the 18 hours total can be controlled through effective use of manpower skill, good procedures and TPS panel operational design efficiency, others are of necessity level of effort activities. This represents approximately 33% of the total time available and within this period of time all refurbishment must be accomplished. The refurbishment operation period then is considerably less than what the original total of eighteen (18) hours would at first indicate. Herein lies the fundamental problem of operations, the utilization of skilled manpower. In effect they will be working 33% of the time available while the other 67% of the refurbishment period they sit around. System level tradeoffs must be conducted to solve this problem of manpower optimization. However, within the period that crews are gainfully employed something can be done to improve efficiency either through methods improvements or TPS panel design performance improvements. It is in this area that the Langley mockup will be effective.

Table D-2 illustrate the uncertainty values assigned to the operational tasks. Uncertainties are provided for three (3) TPS subsystems. Because of the interchangeability feature of all panels the nominal times are considered to be the same. Uncertainties resulting from the effect of material system, did result in changes for selected task uncertainty values.

TABLE D-2
TIME LINE WEIGHTS AND UNCERTAINTIES

Step	Nom	U		
I	4	8		
II	2	2		
III	2	2		
IV	(See Below)			
	Metallic		Ablative Non-Metallic	
Step	Nom	U	Nom	U
4.1	.5	2	.5	2
4.2	.5	2	.5	3
4.3	.25	4	.25	3
4.4a	.4	2	.4	2
b	.1	5	.1	5
4.5	.5	1.5	.5	1.5
4.6	.5	1.5	.5	1.5
4.7	.75	8	.75	8
4.8	.25	1	.25	1
4.9	.75	5	.75	3
4.10	.5	4	.5	3
4.11a	.25	4	.25	3
b	.25	2	.25	3
4.12	.5	2	.5	2
Nominal Total	6.00		6.00	
High Uncer.		3.19		2.94
Low Uncer.		1/2.34		1/2.30
V	4	2		

The uncertainties from Step IV show that the time to remove a metallic system is more uncertain than that for a non-metallic or ablative TPS system as shown in Table D-3.

TABLE D-3

PANEL REMOVAL TIME FOR TPS SYSTEMS

	Metallic	Non-Metallic Ablators
High Uncertainty	3.19	2.94
Low Uncertainty	1/2.34	1/2.30
High Cost	19.14 hours	17.64 hours
Nominal Cost	6 hours	6 hours
Low Cost	2.56 hours	2.61 hours

A study was performed using the data in Table D-2 to observe the effect of removing a large number of panels in close proximity to one another or widely dispersed from each other. Study results are shown in Figure D-1. The table shows that the average time to remove panels will level off soon after 10 to 15 panels are removed. The average rate per panel then stays constant at 4.4 hours. When uncertainty is applied to this result the outcome ranges from 14 to 1.88 hours for a metallic system and from 13 to 1.92 hours for an ablator or non-metallic system. The Langely mockup would be effective in establishing the correctness of the data in Figure D-1. The outcome would be of considerably interest, since this estimate is quite large for such a fundamental operational task. Quite possibility better procedures and techniques of accomplishment must be found.

A priority list of operation tasks is shown in Table D-4. Each operational event is ranked in descending order of nominal cost magnitude subject to the condition of highest uncertainty.

(INTERCHANGEABLE PANEL DESIGN CONCEPT)

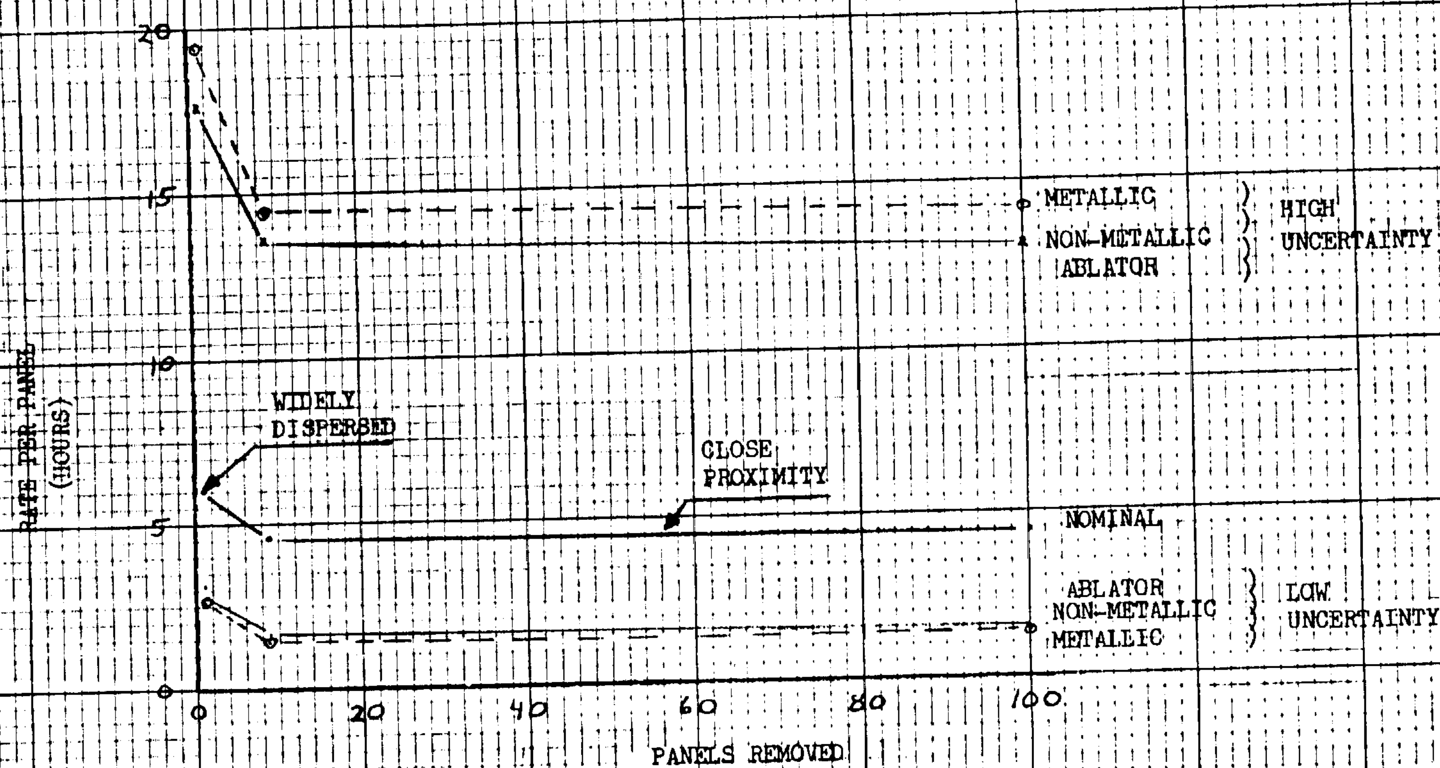


FIGURE D-1 — TIME EXPECTED TO REMOVE A PANEL

TABLE D-4

PRIORITY LIST OF OPERATIONAL TASKS

Priority	Time Line Event	Nom	Uncertainty H	Uncertainty L	Event Description
1.0	Step IV	6	3.19	1/2.34	Conduct Refurbishment
1.1	4.7	.75	8	1/8	Clean and Inspect
1.2	4.9	.75	5	1/5	Position Panel & Check Fit
1.3	4.10	.5	4	1/4	Attach Panel
1.4	4.46	.1	5	1/5	Remove Panel
1.5	4.12	.5	2	1/2	Clean & Inspect
	4.2	.5	2	1/2	Remove Plugs
	4.1	.5	2	1/2	Locate Panel & Plugs
1.6	4.3	.25	4	1/4	Remove Closure
	4.11a	.25	4	1/4	Install Plugs
1.7	4.4a	.4	2	1/2	Detach Panel
1.8	4.11b	.25	2	1/2	Install Closure
1.9	4.8	.25	1	1	Unpack & Inspect New
2.0	Step I	4	8	1/8	Post Flight Inspection
3.0	Step V	4	2	1/2	Final Operations
4.0	Step II	2	2	1/2	Scheduling
	Step III	2	2	1/2	Preparation

Priorities will assist in selecting the composition of test activities that can be most effectively performed on the Langeley mockup. It does appear that only activities which occur in Step IV can be handled on the mockup. The test plan presented in Task IV will reflect this information.

APPENDIX E

TPS PANEL DESIGN, PERFORMANCE, AND COST

The Phase II Test Plan will be a continuing activity closely coordinated with each development phase of the Space Shuttle program. As a first step in initiating this plan, a test program is to be initiated where representative Shuttle operational tasks are performed using representative TPS panel structure. The objective of Step 1 is to demonstrate the feasibility of paneling concepts, resolve time uncertainties associated with installing and removing panels and observe operational difficulties that might not be otherwise observable except through the use of the mockup. Results of Step 1 will be used to improve procedures in the steps that follow and in securing operationally efficient TPS designs. Therefore, it is important that the panels selected for testing be as close to current design concepts as possible.

Representative TPS panel designs covering non-metallic, metallic, and ablator material systems are contained in below-listed LMSC drawings which are provided in this appendix. The concepts shown are preliminary designs which satisfy several baseline vehicle applications, possess physical features and handling characteristics suitable for application and evaluation on the mockup, and are adequate for costing purposes.

List of LMSC Drawings:

TP-1011	Panel Assembly, Rigidized Insulation
TP-1012	Panel Assembly, Metallic Substrate
TP-1013	TPS Test Assembly, Mockup
TP-1015	Panel Assembly, Mockup
TP-1016	Metallic Heat Shield Test Panel
TP-1017	Ablative Panel Mockup, Details and Assembly

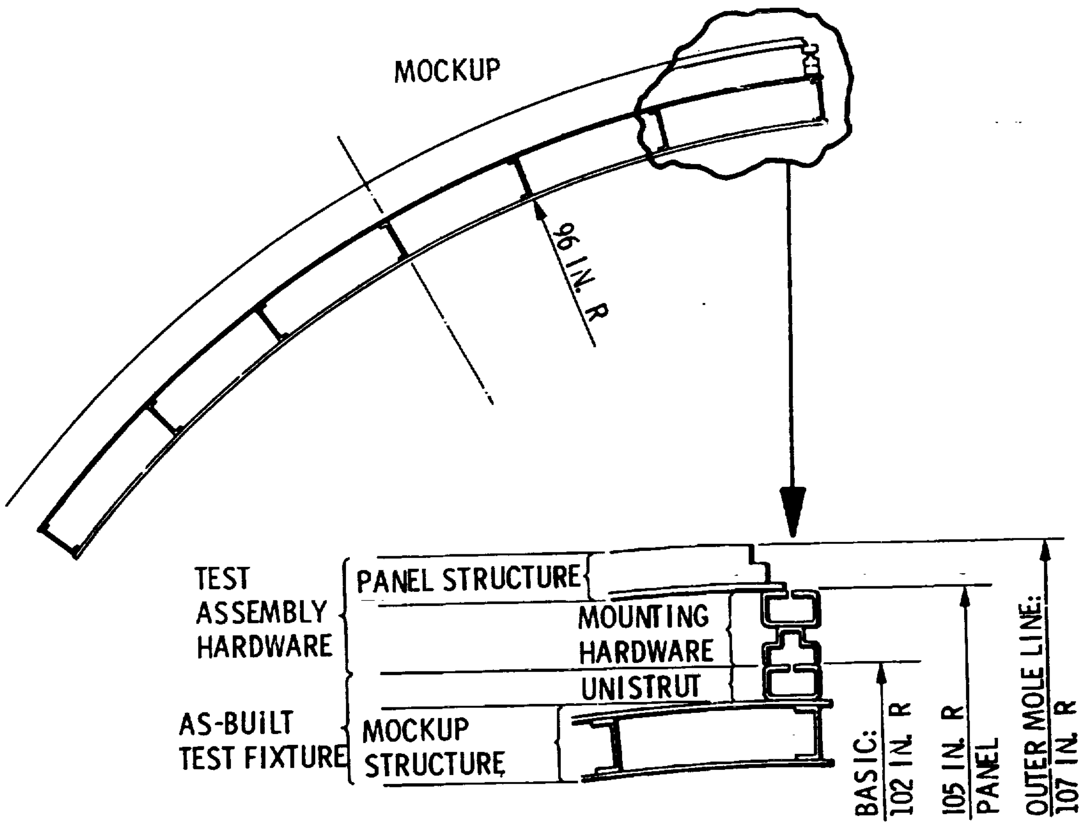
TP-1018	Metallic and LI-1500 TPS Test Assembly
TP-1019	Ablative TPS Test Assembly
TP-1020	Closure Assemblies, Non-metallic Mockup
TP-1021	Panel Assembly, Non-metallic
LO-2097B	Corrugated Heat Shield Panels

Test hardware portrayed by these drawings is based upon NASA/Langley drawings LE-922927 through LE-922931, inclusive, all dated 19 June 1970, and the set of "as built" drawings LE-522927 through LE-522931, inclusive, submitted by NASA/Langley on 23 December 1970 and received by LMSC on 4 January 1971. Key interface dimensions between LMSC test assembly hardware and the "as built" test fixture are shown in Figure E-1. The basic mockup radial dimension to which all LMSC drawings are referenced is 102 inches which corresponds to the outer radial surface of the Unistruts. All panels are nominally 2 inches thick and simply curved (105 inches). The 107 inch outer surface dimension was established to insure a smooth mole line and to accommodate transitions where two TPS material systems interface. Particular attention has been given to arrangements of primary structure to which the heat shield must be attached and to the methods of attachment as well as closure.

The concept presented in layout drawing TP-1011 is an actual design application for the MSC-DC3 Orbital Vehicle. TPS panels are shown mounted on the vehicle base which is a position that can be easily simulated on the mockup. All remaining drawings cover a spectrum of real and simulated TPS systems and structural components, and these are described in Table E-1. Test assembly drawings TP-1013, TP-1018, and TP-1019 include panel/subpanel options, "bill of material" requirements and mockup mounting hardware. Associated indentured drawings provide panel, closure, attachment and primary structure details.

Test Panel Selection

LMSC and Langley representatives have selected options for each TPS material system which appear to best satisfy the objectives of Phase II, Step 1. Heat shield material and fabrication methods will be evaluated for low cost under the condition that physical characteristics such as size and weight, and handling characteristics do not seriously jeopardize TPS design objectives or credibility of the resulting operations data. Where it is is possible, simulated materials will be provided if the advantages thus derived



- Reference: LE-522930, Test Fixture, Space Shuttle Vehicle Radiation Shield Housing

FIGURE E-1 KEY MOCKUP REFERENCE DIMENSIONS

TABLE E-1 - TPS SYSTEMS

DRAWING NO.	TITLE	MATERIAL			
		Panel		Subpanel	
		Real	Simulated	Real	Simulated
1) TP 1013	TPS Test Assembly	(Provides LI-1500 Closure and Test Fixture Details)			
2) TP 1012	Panel Assembly, Metallic Substrate	LI-1500	-	Be, Ti	Al
3) TP 1018	Metallic and LI-1500 TPS Test Assy	(Provides Test Fixture Details)			
4) TP 1015	Panel Assembly, Mockup	LI-1500	Foam	-	Wood
5) TP 1016	Metallic Heat Shield Test Panel	Cb, TDNiCr	Steel, Al	-	Wood
6) TP 1020	Closure Assemblies, Non-Metallic Group	(Provides LI-1500 Foam Closure and Plug Details)			
7) TP 1021	Panel Assembly, Non-Metallic	LI-1500	Foam	-	Steel
8) TP 1019	Ablative Test Assembly	(Provides Panel and Panel Assy, and Test Fixture Details)			
9) TP 1017	Ablative Panel Mockup, Details	Elastomeric	-	(Fiberglass backface)	

from the anticipated cost saving can be satisfactorily demonstrated. However, when it is apparent that technical consideration and cost are not mutually compatible, then technical justification will be the controlling factor in TPS system selection and not cost.

Non-Metallic System

Firm cost quotes for material and labor will be provided on nine (9) (24" x 24" x 2") panel structures and twenty-four (24) closures using material and layup configurations shown in Table E-2.

TABLE E-2 - NON-METALLIC PANEL OPTIONS

OPTION	LAYUP CONFIGURATION (**)	MATERIAL		
		HEAT SHIELD	SUBPANEL	CLOSURES
1	A	Foam	Wood	Foam
2	A	Foam	Steel	Foam
(*)3	B	LI-1500X Foam	Wood	LI-150CX Foam
4	B	LI-1500X Foam	Steel	LI-1500X Foam
5	A	LI-1500X	Wood	LI-1500X
6	A	LI-1500X	Steel	LI-1500X
7	A	LI-1500X	Titanium	LI-1500X

(*)LI-1500X has all the physical and handling qualities of LI-1500 but will not meet established temperature requirements.

(**)Layup configuration pertains to paneling concept and the distribution of panel materials on the mockup. There are two configurations under evaluation.

Configuration A - Panel Concept - Open panel with closures
All nine (9) panels are either Foam or LI-1500X

Configuration B - Panel Concept - Open panel with closures
This configuration is a mix of Foam and LI-1500X

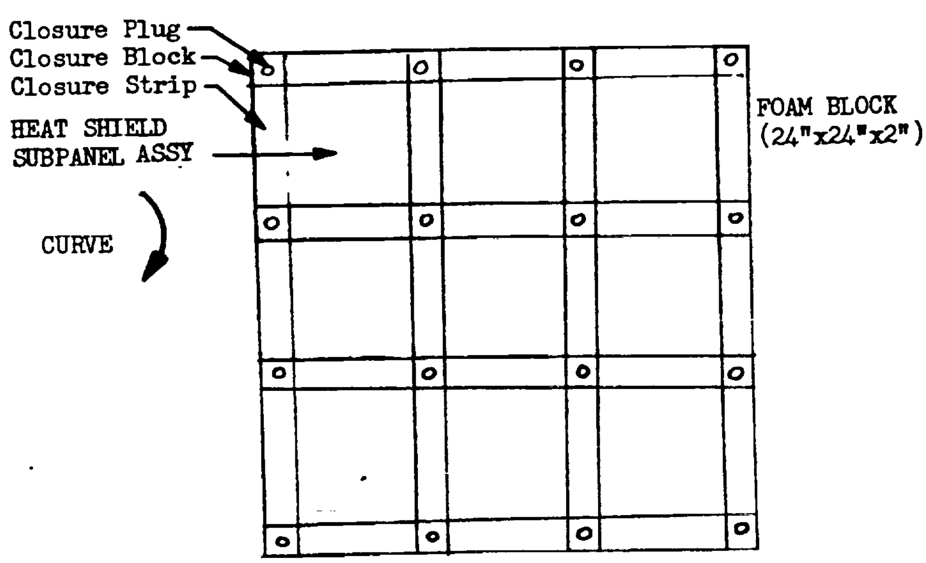
In Tables E-3 through E-9, the design drawings, material quantities, and layup configuration for the selected options are provided for purposes of estimating fabrication and material costs.

TABLE E-3

NON-METALLIC TEST PANEL

OPTION #1 - CONFIGURATION A

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	DETAIL DRAWINGS	ASSY DRAWING
9	Heat Shield	-	Foam	TP 1015-501-1	TP-1018-503
9	Sub Panel	-	Wood	TP 1015-501-301-3	
24	Closure Strip	-	Foam < Straight / Curved	TP 1020-501-1 TP 1020-505-11	
16	Closure Block	-	Foam	TP 1020-509-23	
16	Closure Plug	-	Foam	TP 1020 -17	



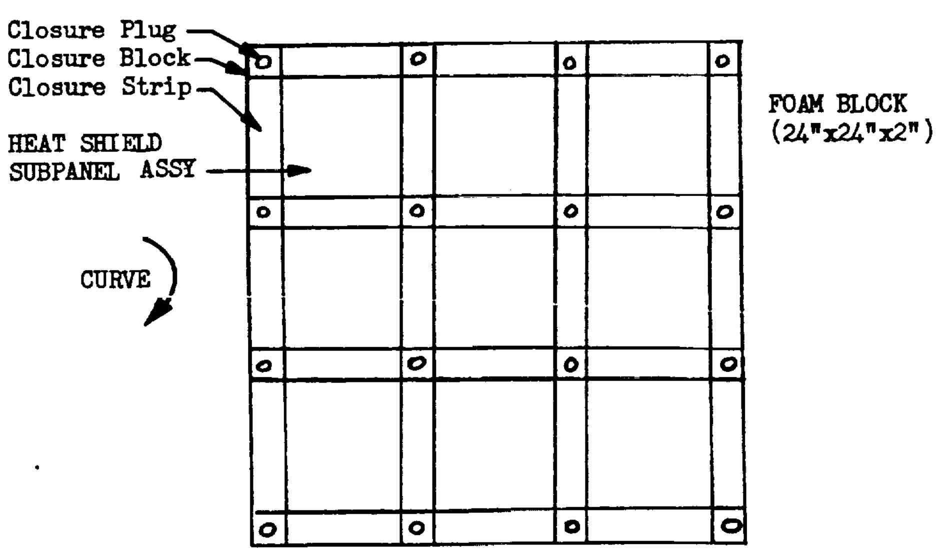
LAYUP CONFIGURATION A

TABLE E-4

NON-METALLIC TEST PANEL

OPTION #2 - CONFIGURATION A

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	DETAIL DRAWINGS	ASSY DRAWING
9	Heat Shield	-	Foam	TP 1021-501-7	TP-1018-507
9	Sub Panel	-	Steel	TP 1021-501-301-1	
24	Closure Strip	-	Foam < Straight / Curved	TP 1020-501-1 TP 1020-505-11	
16	Closure Block	-	Foam	TP 1020-509-23	
16	Closure Plug	-	Foam	TP 1020 -17	



LAYUP CONFIGURATION A

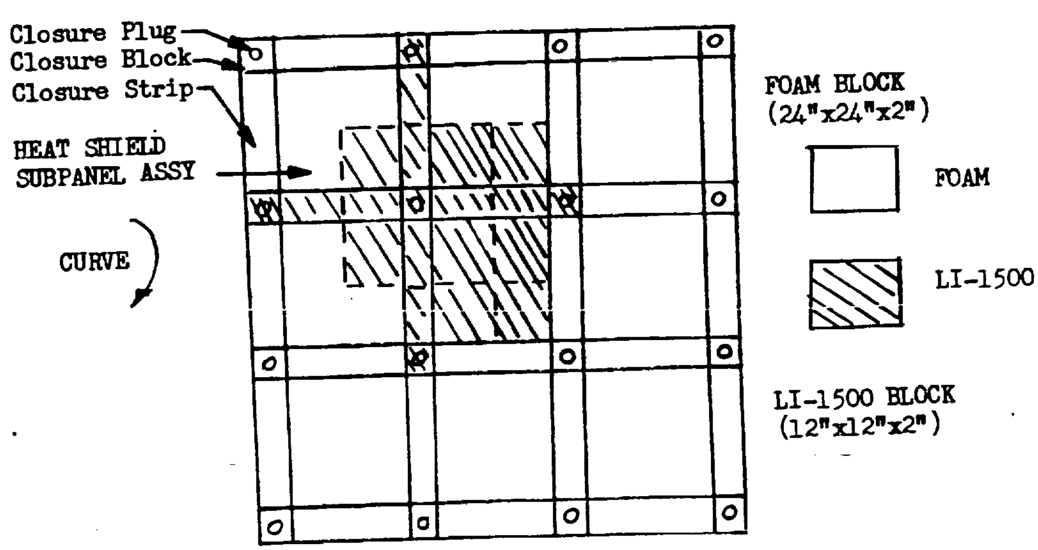
TABLE E-5

NON-METALLIC TEST PANEL

OPTION #3 - CONFIGURATION B

QUANTITY FOAM	QUANTITY LI-1500	STRUCTURE ITEM		STRUCTURE MATERIAL	DETAIL DRAWINGS		ASSY DRAWING
5	-	Heat Shield	-	Foam	TP 1015-501-1	(24"x24"x2")	TP-1018-515
-	4		-	LI-1500	TP 1015-503-11	(12"x12"x2")	
1	1		-	LI-1500/Foam	-505(-1,-11)	*	
1	1		-	LI-1500/Foam	-507(-1,-11)	*	
1	2		-	LI-1500/Foam	-509(-1,-11)	*	
9		Subpanel	-	Wood	TP 1015-301-3		
20		Closure Strip	-	Foam < Straight / Curved	TP 1020-501-1 / TP 1020-505-11		
	8		-	LI-1500 < Straight / Curved	-503-9 / -507-13		
11	5	Closure Blocks	- / -	Foam / LI-1500	-509-23 / -511-21		
11	5	Closure Plugs	- / -	Foam / LI-1500	-509-17 / -511-25		

* Foam will be made in panel size and then cut to allow mounting of LI-1500 Blocks



LAYUP CONFIGURATION B

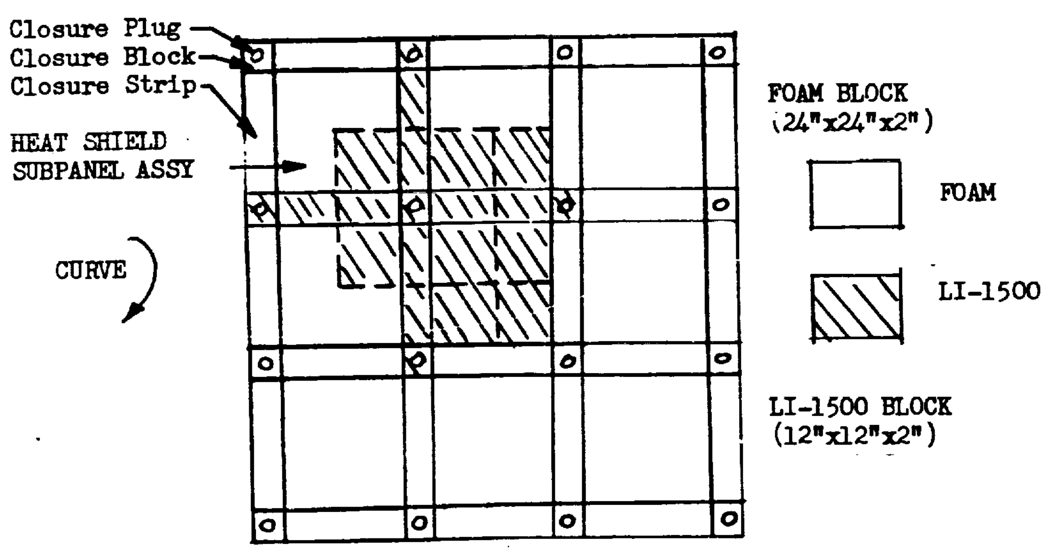
TABLE E-6

NON-METALLIC TEST PANEL

OPTION #4 - CONFIGURATION B

QUANTITY FOAM	QUANTITY LI-1500	STRUCTURE ITEM	STRUCTURE MATERIAL	DETAIL DRAWINGS	ASSY DRAWING
5	-	Heat Shield	Foam	TP 1021-501-7 (24"x24"x2")	TP-1018-415
-	4		LI-1500	-503-9 (12"x12"x2")	
1	1		LI-1500/Foam	-505 (-9,-11) *	
1	1		LI-1500/Foam	-507 (-9,-11) *	
1	2		LI-1500/Foam	-509 (-9,-11) *	
9		Subpanel	Steel	TP 1015-301-3	
20		Closure Strip	Foam Straight / Curved	TP 1021-501-1 / -505-11	
	8		LI-1500 Straight / Curved	-503-9 / -507-13	
11	5	Closure Blocks	Foam / LI-1500	-509-23 / -511-21	
11	5	Closure Plugs	Foam / LI-1500	-509-17 / -511-25	

* Foam will be made in panel sizes and then cut to allow mounting of LI-1500 Blocks



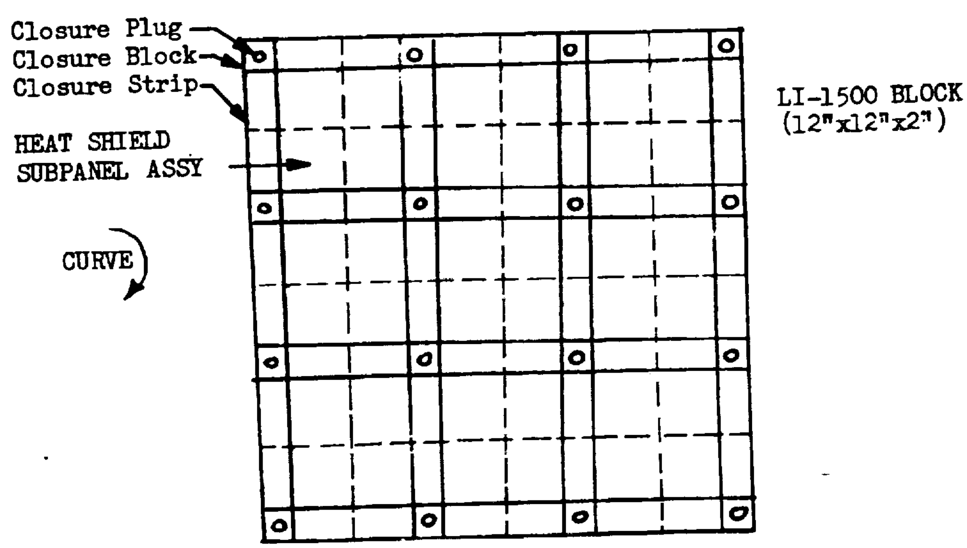
LAYUP CONFIGURATION B

TABLE E-7

NON-METALLIC TEST PANEL

OPTION #5 - CONFIGURATION A

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	DETAIL DRAWINGS	ASSY DRAWING
36	Heat Shield	-	LI-1500	TP 1015-503-11	TP-1018-509
9	Subpanel	-	Wood	-301-3	
48	Closure Strip	-	LI-1500 Straight / Curved	TP 1020-503-9 / -507-13	
16	Closure Block	-	LI-1500	TP 1020-511-21	
16	Closure Plug	-	LI-1500	TP 1020-511-25	



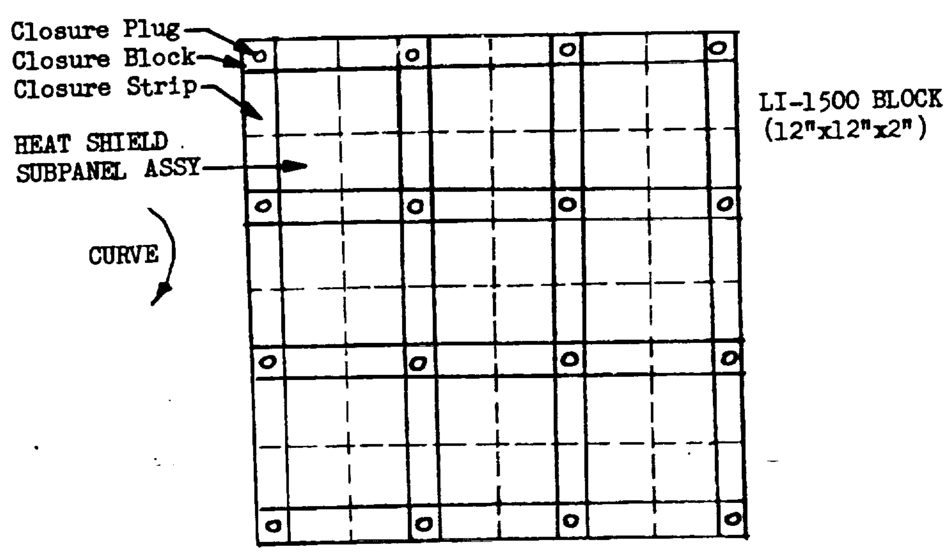
LAYUP CONFIGURATION A

TABLE E-8

NON-METALLIC TEST PANEL

OPTION #6 - CONFIGURATION A

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	DETAIL DRAWINGS	ASSY DRAWING
36	Heat Shield	-	LI-1500	TP-1021-503-9	TP-1018-511
9	Subpanel	-	Steel	-301-1	
48	Closure Strip	-	LI-1500 Straight / Curved	TP 1020-503-9 / -507-13	
16	Closure Block	-	LI-1500	TP 1020-511-21	
16	Closure Plug	-	LI-1500	TP 1020-511-25	



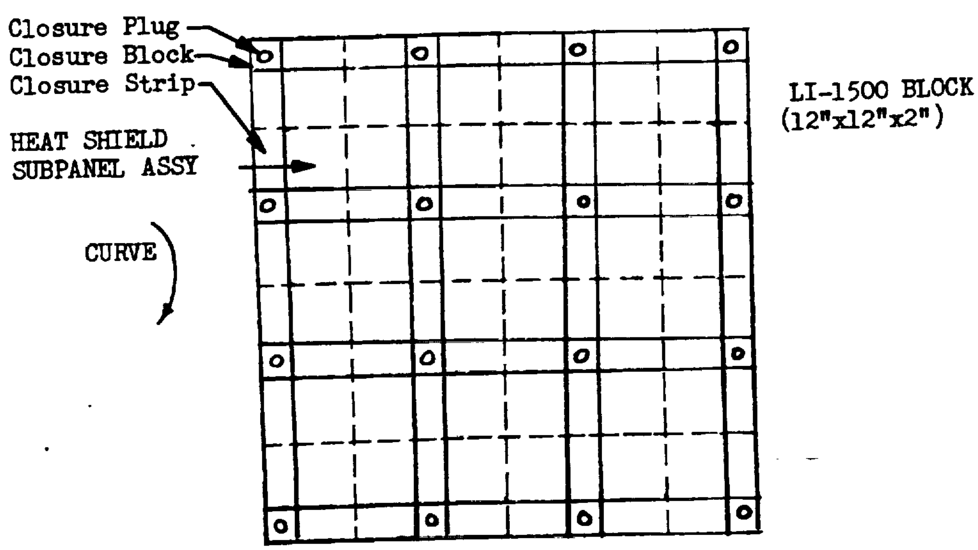
LAYUP CONFIGURATION A

TABLE E-9

NON-METALLIC TEST PANEL

OPTION #7 - CONFIGURATION A

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL		DETAIL DRAWINGS	ASSY DRAWING
36	Heat Shield	-	LI-1500		TP 1012-501 (-33,-35,-37) -305-23	TP-1013-505
9	Subpanel	-	Titanium			
48	Closure Strip	-	LI-1500	Straight Curved	TP 1013-10 - 9	
16	Closure Block	-	LI-1500		-6	
16	Closure Plug	-	LI-1500	Parallel Taper	-8 -7	



LAYUP CONFIGURATION A

Metallic TPS System

Firm cost quotes for material and labor will be provided on nine(9) (24" x 24" x 2") panel structures and twelve (12) closures using materials and layup configurations shown in Table E-10.

TABLE E-10 - METALLIC PANEL OPTIONS

OPTION	LAYUP (*) CONFIGURATION	MATERIAL			
		HEAT SHIELD	STAND-OFF	SUBPANEL	CLOSURES
1	C	Steel	Steel	Wood	Steel
2	C	Al	Al	Al	Al
3	C	TDNiCr	TDNiCr	Ti	TDNiCr
4	C	Cb	Cb	Ti	Cb

(*) Layup configuration pertains to the paneling concept and the distribution of panel material on the mockup.

Configuration C - Panel Concept - Partial Shingle with closures
All nine (9) panels are the same TPS material system

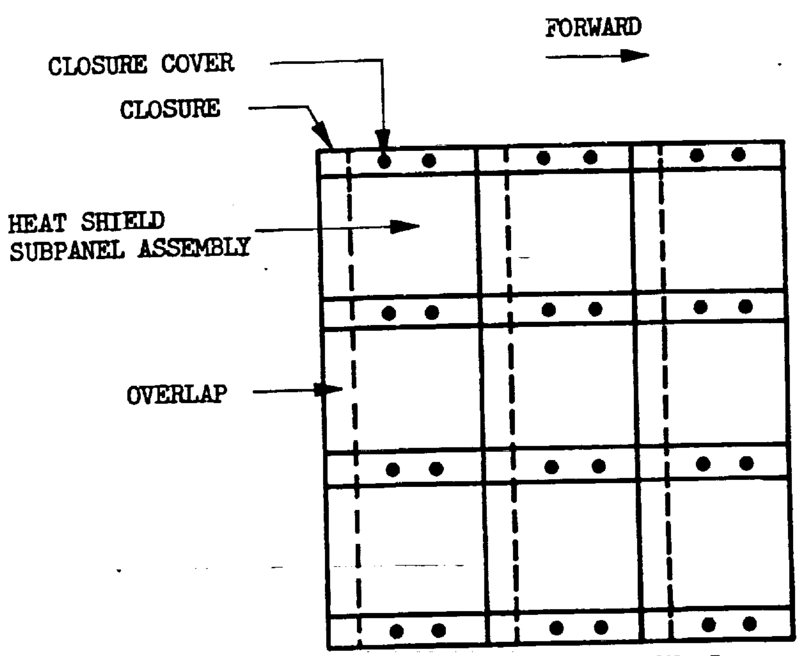
Insulation will be simulated between standoffs. All simulated heat shields will be enameled to simulate coating. Option 3 and 4 will use actual coating materials.

In Tables E-11 through E-14, the design drawings, material quantities, and layup configuration for the selected options are provided for purposes of estimating fabrication and material costs.

TABLE E-11 - METALLIC TEST PANEL

OPTION #1 - CONFIGURATION C

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	CONCEPTUAL DRAWING
9	Heat Shield	-	Steel (corrugated)	LO-2097-A
180	Stand-off	-	Steel	
36	Insulation	-	Dynaflex	
9	Subpanel	-	Wood	
12	Closure Strip	-	Steel	
12	Insulation	-	Dynaflex	
24	Closure Covers	-	Steel	
12	Overlap Insulation		Dynaflex	

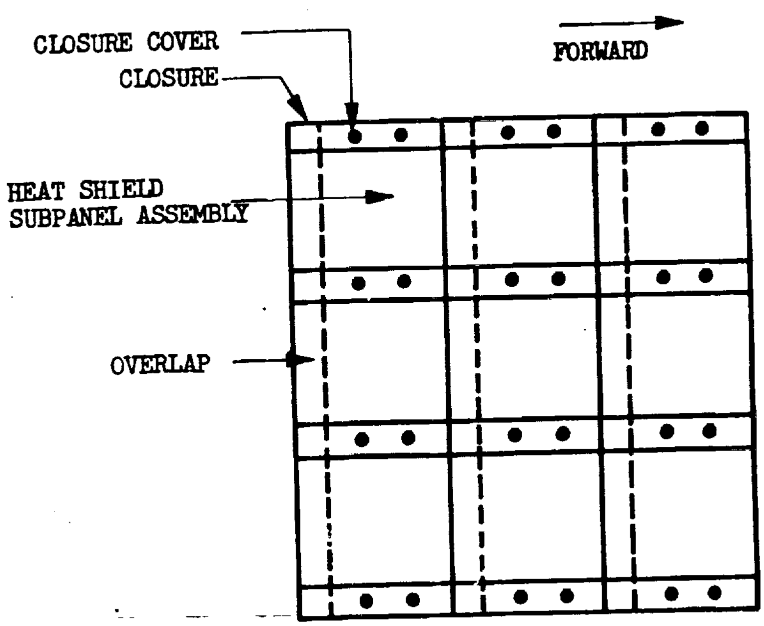


LAYUP CONFIGURATION C

TABLE E-12 - METALLIC TEST PANEL

OPTION #2 - CONFIGURATION C

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	CONCEPTUAL DRAWING
9	Heat Shield	-	Al (corrugated)	LO-2097-A
180	Stand-off	-	Al	
4	Insulation	-	Dynaflex	
9	Subpanel	-	Al	
12	Closure Strip	-	Al	
36	Insulation	-	Dynaflex	
24	Closure Covers	-	Al	
12	Overlap Insulation	-	Dynaflex	

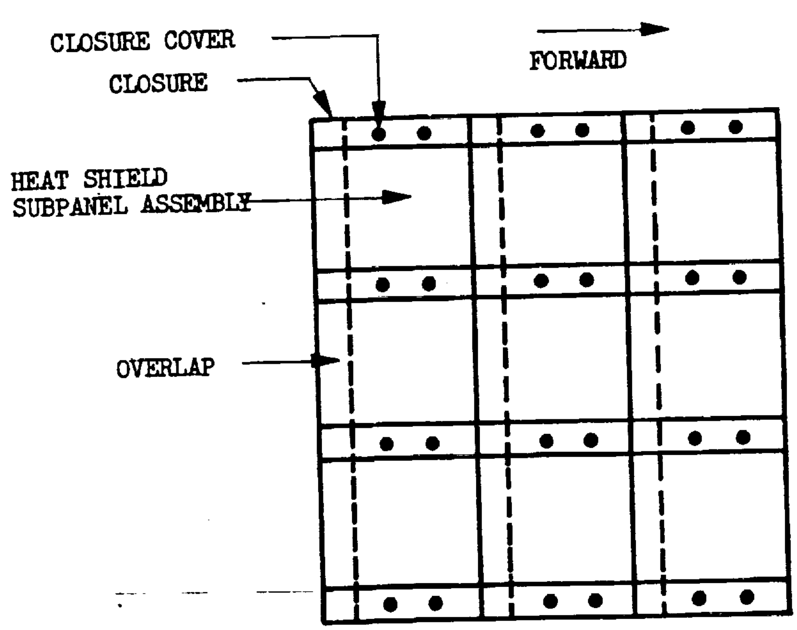


LAYUP CONFIGURATION C

TABLE -13 - METALLIC TEST PANEL

OPTION #3 - CONFIGURATION C

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	DRAWINGS
9	Heat Shield	-	TDNiCr (corrugated)	LO-2097-A
36	Stiffener	-	TDNiCr	
45	Stand-off	-	TDNiCr	
	Insulation	-	Dynaflex	
9	Subpanel	-	Ti	
12	Closure Strip	-	TDNiCr	
12	Insulation	-	Dynaflex	
24	Closure Covers	-	TDNiCr	
	Overlap Insulation	-	Dynaflex	

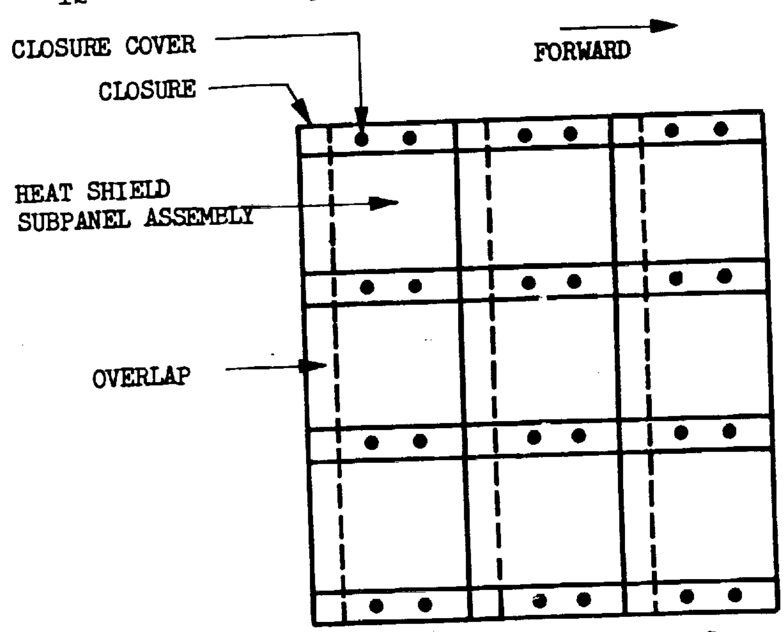


LAYUP CONFIGURATION C

TABLE E-14 - METALLIC TEST PANEL

OPTION #4 - CONFIGURATION C

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	CONCEPTUAL DRAWING
9	Heat Shield	-	Cb (corrugated	
36	Stiffner	-	Cb	
45	Stand-off	-	Cb	
36	Insulation	-	Dynaflex	
9	Subpanel	-	Ti	LO-2097-A
12	Closure Strip	-	Cb	
12	Insulation	-	Dynaflex	
24	Closure Covers	-	Cb	
12	Overlap Insulation	-	Dynaflex	



LAYUP CONFIGURATION C

Ablative TPS System

Mockup drawings for an Ablative TPS system will be provided for a candidate system provided by Langley. There will be one (1) mockup option as shown in Table E-15

TABLE E-15 - ABLATIVE PANEL OPTION

OPTION	LAYUP (*) CONFIGURATION	MATERIAL		
		HEAT SHIELD	SUBPANEL	CLOSURE
1	D	Phenolic Honeycomb with fiber glass back-face sheet	None (Assumes use of primary structure)	Butt Joint (RTV-560 Joint Compound)

(*)Layup configuration pertains to the paneling concept and the distribution of panel materials on the mockup.

Configuration D - Panel Concept - Open Panel with butt joint
All nine (9) panels are the same TPS material system

The Materials Laboratory at Langley will provide six (6) (4' x 6' x 2") and three (3) (2' x 6' x 2") phenolic honeycomb elastomeric ablative panels simply curved (105 inch radius) and bonded to a glass sheet. Attachment holes will be spaced on 12.5" centers with a 2" edge clearance for affected holes. Inter-facing panels will use butt joints with RTV-560 as the sealer.

Ablative panels will not use subpanels as do the metallic and non-metallic systems. Panels will be attached to the primary structure with mounting bolts which attach to captive nuts welded to the back side of the primary structure. Plugs will be used to fill the holes after attachment. An aluminum sheet will be used on the mockup to represent the primary structure and for handling the captive nuts.

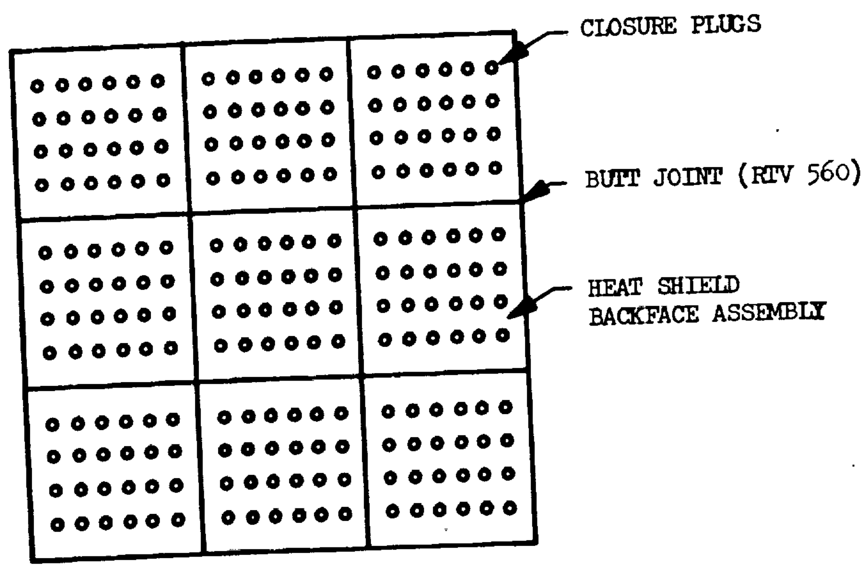
Sufficient ablative material will be made available by Langley to cover extras, breakage and spares. Firm cost quotes for material and labor will not be required for the ablator system.

In Table E-16, the design drawings, material quantities and layup configuration for the selected option are provided for purposes of estimating material requirements.

TABLE E-16 - ABLATIVE TEST PANEL

OPTION #1 - CONFIGURATION D

QUANTITY	STRUCTURE ITEM		STRUCTURE MATERIAL	DRAWINGS
9	Heat Shield Backface	- -	Phenolic Honeycomb Fiberglass	TP-1017(-5,-7)
-	Subpanel	-	(Skin of Primary Structure)	
180	Closure Plugs	-	Phenolic Honeycomb	TP-1017-9



LAYUP CONFIGURATION D

Panel Physical and Handling Characteristics

When substituting alternative materials for real TPS motival components, it is essential that both physical properties and handling features of a real system be properly represented in the simulated versions. Counterparts must be analogous in terms of weight, structural configuration, size and dimensions, and durability.

Panel weights for real and simulated TPS systems are provided in Table E-17 for the four (4) metallic, seven (7) non-metallic, and other candidate panel options of interest. Flight-worthy design concepts are designated as "real" system. "Simulated" panels are at least as rigid as their corresponding real counterparts and present comparable "feel" and handling features, however, they cannot withstand large direct loads.

Real and simulated alternatives are compared in Figure E-2. The variation in weight of real material systems is designated by the crosshatched bands. Metallic TPS has two (2) bands because the outerpanel gage of a smooth panel must be greater for comparable strength than that for same-strength corrugated panel, hence, the panel will weigh more. Also, the density of columbium (Cb) is greater than that of TD NiCr . The signal band for the non-metallic system results from the density difference between titanium (Ti) and beryllium (Be).

Simulated materials can be fabricated to weight the same as real systems. With the addition of filler material, both the steel and aluminum metallic systems can be fabricated to weigh the same as either TDNiCr or Cb. Simulation of both real non-metallic systems can be accomplished with a balsa wood outer panel and wood subpanel along with some added weight. Any outer panel material and wood subpanel can be used to represent the LI-1500/Ti system. A steel subpanel is heavier than either real system except when combined with balsa wood; then it can be used to simulate the LI-1500/Ti system.

The structural configuration, size, and dimensions of simulated panels are comparable to real systems. They will "feel" the same and present the same handling features. The variation in gage thickness of metallic outer panels

TABLE E-17 - HEAT SHIELD WEIGHT SUMMARY

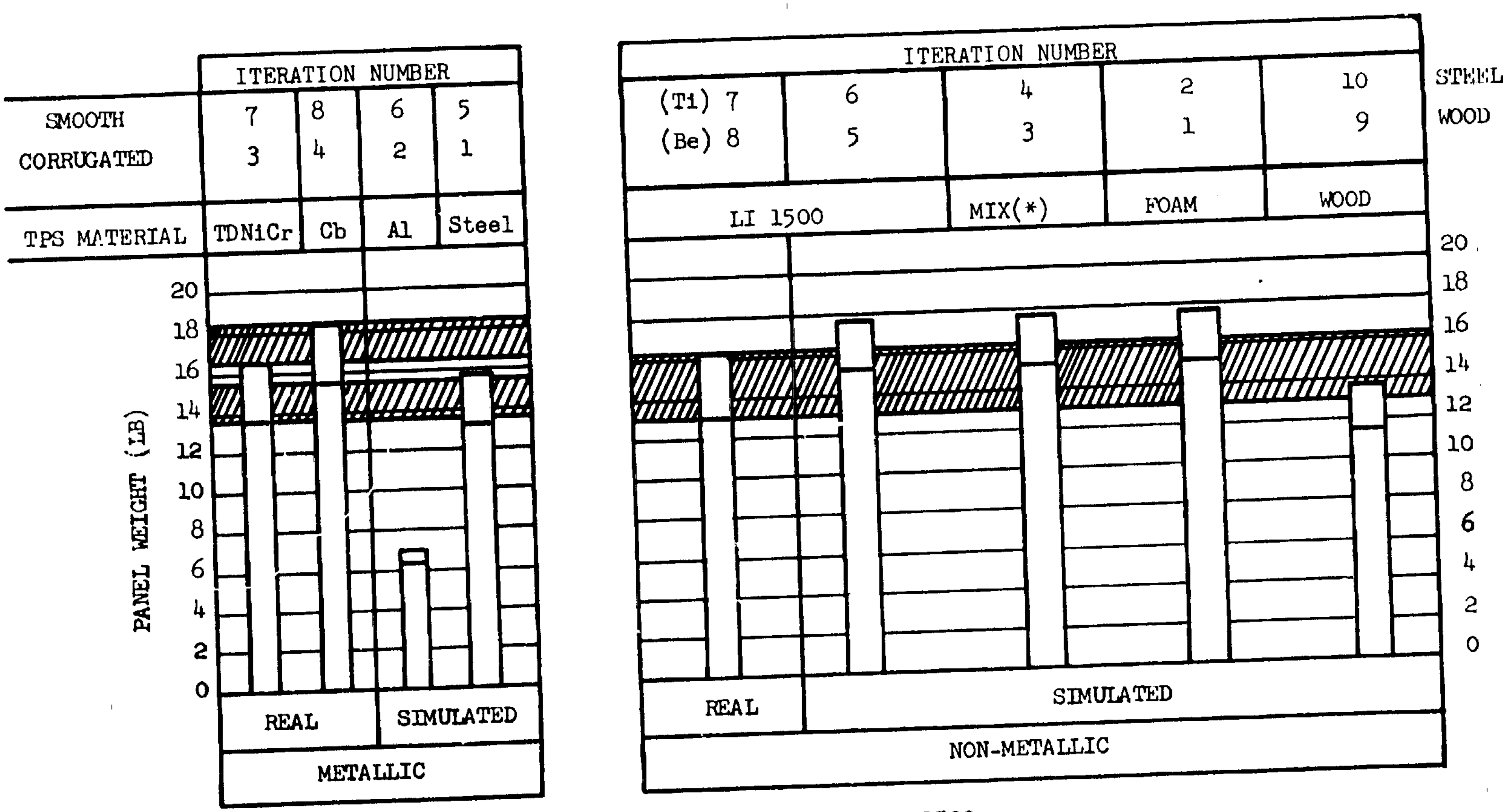
DESIGN CONDITION

Substrate Temp: $600^{\circ}F$
Span Length: 25 in

Crushing Press: +2.5 psi
Bursting Press: -1.6 psi

		MATERIAL STRESS ANALYSIS	OUTER PANEL GAGE IN.	SMOOTH CORRUG	OUTER PANEL UNIT WT LB/FT^2	CLIPS HT IN.	CLIPS UNIT WT LB/FT^2	SURPANEL MAT'L	SURPANEL UNIT WT LB/FT^2	INSUL UNIT WT LB/FT^2	ADHES UNIT WT LB/FT^2	Σ UNIT WT LB	25"x25 PANEL LB	OPTION
METALLIC	REAL	TDNiCr	.010	C	.51	2.5"	.45	Ti	.89	1.312		3.162	13.74	A-3
			.020	S	1.14	2.5"	.44	Ti	.89	1.312		3.782	16.41	7
		Cb	.015	C	.924	2.5"	.48	Ti	.89	1.312		3.606	15.65	A-4
			.020	S	1.519	2.5"	.49	Ti	.89	1.312		4.211	18.28	B
	SIMULATED	Al	.012	C	.179	2.5"	.69	Al	.58	Filler Required		1.449	6.28	A-2
			.020	S	.288	2.5"	.69	Al	.58			1.558	6.75	6
		Steel	.012	C	.52	2.2"	.97	Wood	1.62	Filler Required		3.11	13.51	A-1
				S				Wood					15.83	5
NON-METALLIC	REAL	LI-1500	2		2.50			Be	.40		.15	3.05	13.24	8
			2		2.50			Ti	1.07		.15	3.72	16.15	B-7
	SIMULATED	LI-1500	2		2.50			Steel	1.44		.15	4.09	17.78	B-6
			2		2.50			Wood	.96		.15	3.61	15.68	B-5
		MIX (*)	2		2.50			Steel	1.44		.15	4.09	17.78	B-4
			2		2.50			Wood	.96		.15	3.61	15.68	B-3
		FOAM	2		2.50			Steel	1.44		.15	4.09	17.78	B-2
			2		2.50			Wood	.96		.15	3.61	15.68	B-1
		BALSA WOOD	2		1.50			Steel	1.44		.15	3.09	13.43	10
			2		1.50			Wood	.96		.15	2.61	11.33	9

(*) Mix includes a panel combination of foam and LI-1500



(*) MIX INCLUDES A PANEL COMBINATION OF FOAM AND LI-1500

FIGURE E-2 REAL AND SIMULATED TPS WEIGHT COMPARISONS and subpanels using metallic materials, will not be operationally significant for the operational tasks envisioned on the mockup. However, when a wood subpanel is considered, the greater thickness may affect the feel and handling qualities that are under consideration.

Panel durability should be excellent for the metallic and non-metallic options where the steel subpanel is used. These materials should hold up well under operational testing during Phase II and to some degree will be useful in gaging operational wear and tear on the real system they represent. Wood subpanels can be expected to require more care during testing to prevent undue wear and will be of little value in measuring operational wear experienced during refurbishment.

The metallic and non-metallic options which appear to best represent real TPS systems are summarized below:

TPS System	Outer Panel/Subpanel
Metallic	(1) Al/Al
	(2) Steel/Wood
Non-Metallic	(1) Balsa Wood/Steel
	(2) LI-1500X/Steel
	(3) Foam/Steel

From a physical and handling standpoint, the balsa wood/steel system is capable of simulating either real TPS system. If it were conjectured that the real system weights are only representative of downstream point designs, which they are, than the other non-metallic material options with wood subpanels can be considered representative. When this and durability of the wood subpanel are considered together, it appears that the most representative non-metallic TPS systems should use steel subpanels. The indicated weight differential will not be a serious factor in design performance determination or degrade credibility of operational test measurements.

Cost Analysis

While technical performance is to be the primary panel selection criterion, cost is still a major consideration. When comparable performance is evident, the lowest cost system will be recommended for the Phase II test program.

A heat shield cost summary is provided in Table E-18. The data were developed by material and manufacturing cost estimators and priced by LMSC price estimators. The prices are those necessary to provide nine (9) material system panels, closures, test assembly hardware, and spares. All expenditures based on the most current negotiated labor and overhead rates.

Manufacturing cost is the primary cost driver followed by material and engineering expenditures. In general, when considering comparable metallic and non-metallic systems, the metallic candidate costs less than the non-metallic. Further, simulated systems are considerably less expensive than real systems. These latter features are evidenced in Figure E-3 where the list of options are graphically displayed.

The least expensive non-metallic system is a foam heat shield and wood subpanel combination, costing $45,873 dollars. With a steel subpanel the system would cost $2,018 more. An LI-1500 system will cost approximately $43,000 more than a foam system, amounting to $87,598 and $91,144 dollars with a wood or steel subpanel respectively. The mix configuration will cost approximately $13,000 dollars more than the foam system. For purposes of comparison the real metallic systems are approximately twice as expensive as the simulated system. With the real non-metallic system, savings realized in utilizing wood or steel subpanels amounts to approximately $19,000 dollars. A mix of foam and LI-1500 panels will result in a savings of $50,000 dollars and for foam alone, approximately $60,000. The fabrication cost differential between LI-1500 and foam accounts for this large cost savings.

These results indicate that simulated systems should be selected in preference to real systems. Depending on the cost relationship between options, the following options are recommended:

TABLE E-18 - HEAT SHIELD COST SUMMARY

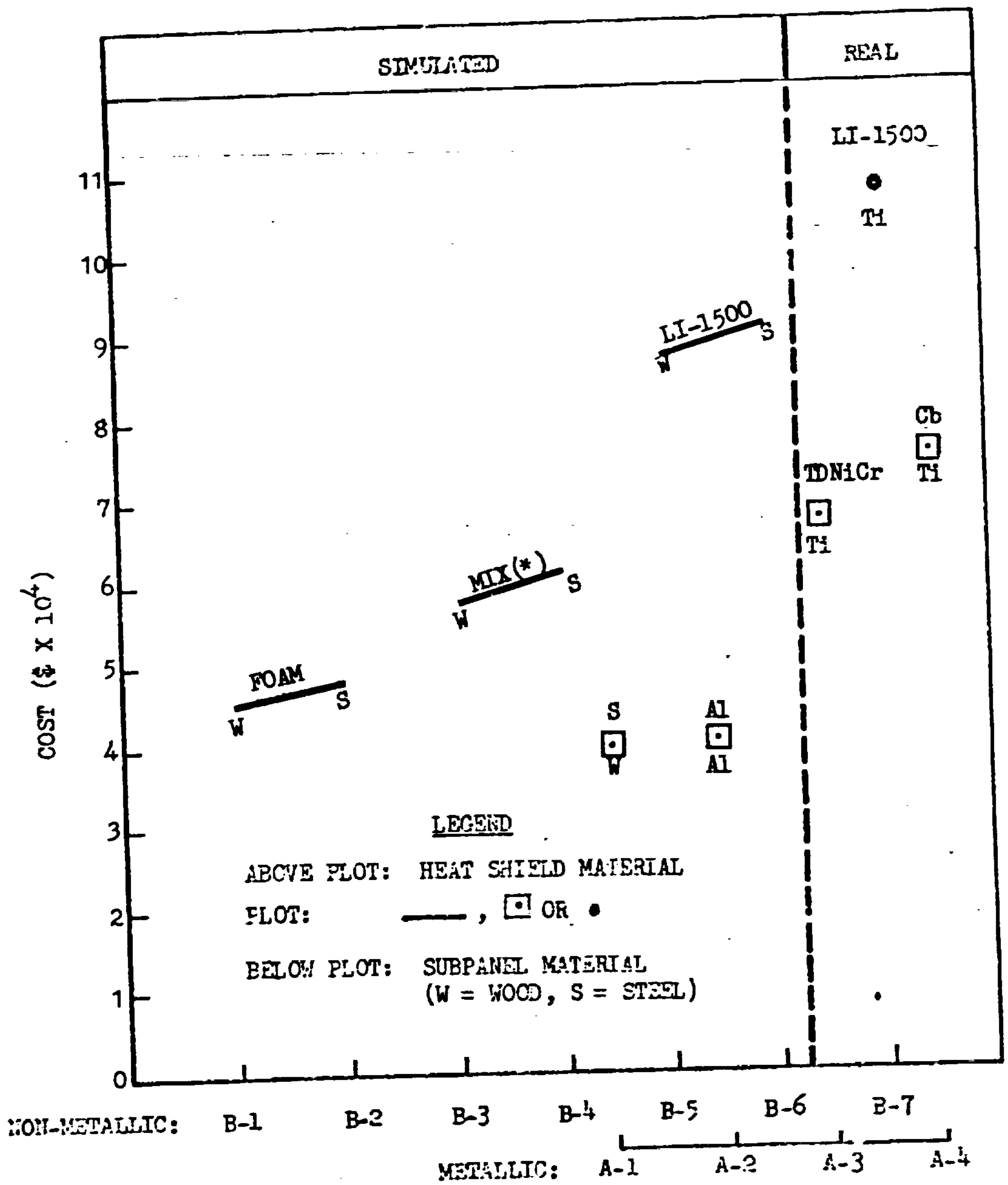
DESIGN CONDITION

Substrate Temp: 600°F
Span Length: 25 in

Crushing Press: +2.5 psi
Bursting Press: -1.6 psi

		HEAT SHIELD MATERIAL	SUB-PANEL	OPTION	LAYOUT CONFIG	TPS COST SUMMARY ($) ENGR	MFG	MAT'L	OTHER	G&A	(*) TOTAL
METALLIC (Corrugated)	REAL	Cb	Ti	A-4	C	6,756	28,610	31,877	3,039	4,509	74,791
		TDNiCr	Ti	A-3	C	7,906	33,355	16,806	3,545	5,260	66,872
	SIMU-LATED	Al	Al	A-2	C	6,214	26,426	321	2,808	4,161	39,930
		Steel	Wood	A-1	C	6,121	25,959	331	2,758	4,090	39,259
NON-METALLIC	REAL	LI-1500	Ti	B-7	A	14,925	63,542	14,351	6,751	10,004	109,573
	SIMULATED	LI-1500	Steel	B-6	A	12,850	54,569	9,332	5,798	8,595	91,144
		LI-1500	Wood	B-5	A	12,308	52,272	9,232	5,553	8,233	87,598
		Mix	Steel	B-4	B	9,188	33,971	2,736	4,140	6,140	61,175
		Mix	Wood	B-3	B	8,633	36,660	2,846	3,895	5,775	57,809
		Foam	Steel	B-2	A	7,377	31,210	1,068	3,317	4,919	47,891
		Foam	Wood	B-1	A	7,037	29,934	968	3,180	4,718	45,873

(*) Excludes Fee



*MIX INCLUDES A PANEL COMBINATION OF FOAM AND LI-1500

FIGURE E-3 METALLIC/NON-METALLIC OPTION COST COMPARISON

TPS System	Components
Metallic	(1) Steel/Wood
	(2) Al/Al
Non-Metallic	(1) Foam/Wood
	(2) Foam/Steel
	(3) Mix/Wood
	(4) Mix/Steel

Recommended Panels for Test

Low cost TPS structural materials and fabrication methods have been identified for a number of metallic and non-metallic TPS system options. It has been determined for simulated systems that such physical characteristics as size, structure, and weight, and handling features are not significantly different from those exhibited by real panels. What variations do exist will not seriously jeopardize TPS design objectives or credibility of the resulting operations data. Consequently, it is recommended that simulated TPS systems be selected for the Phase II test program.

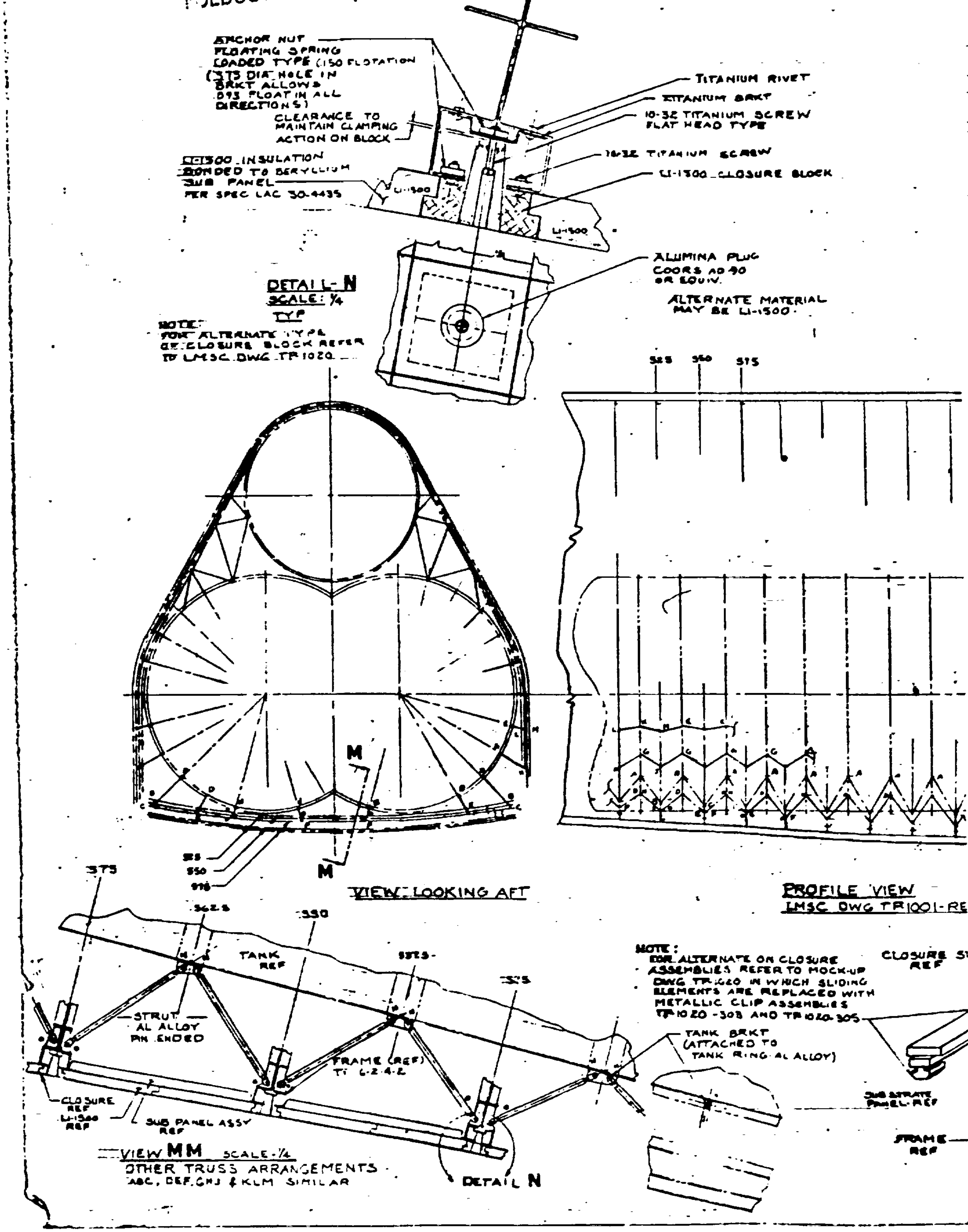
Another factor which merits consideration in the final selection process is the general status of the space shuttle design effort and its likely effect on the information obtained from the Phase II test program. Adequate space shuttle baseline design criteria do not exist as yet. The low level of design maturity is evidenced in the layout drawings and sketches in the literature and the particular lack of point design effort in the TPS subsystem area. Because of this situation, it is both practical and expedient to use materials which reduce the ultimate cost of the Phase II test program.

Simulated TPS systems which are considered to be the best technical representation of metallic and non-metallic systems and are relatively inexpensive to fabricate can be identified as follows:

TPS System	Component
Metallic	Al/Al
Non-metallic	Foam/Steel

Neither system is the least expensive but the desirability of using metallic subpanels resulted in their selection. Wood subpanels were discarded because they were not considered sufficiently desirable. The balsa wood candidates were eliminated because blocks of the size required for the test panels were not available and the cost to fabricate laminated counterparts could not be justified in lieu of foam cost.

FOLDOUT FRAME 1



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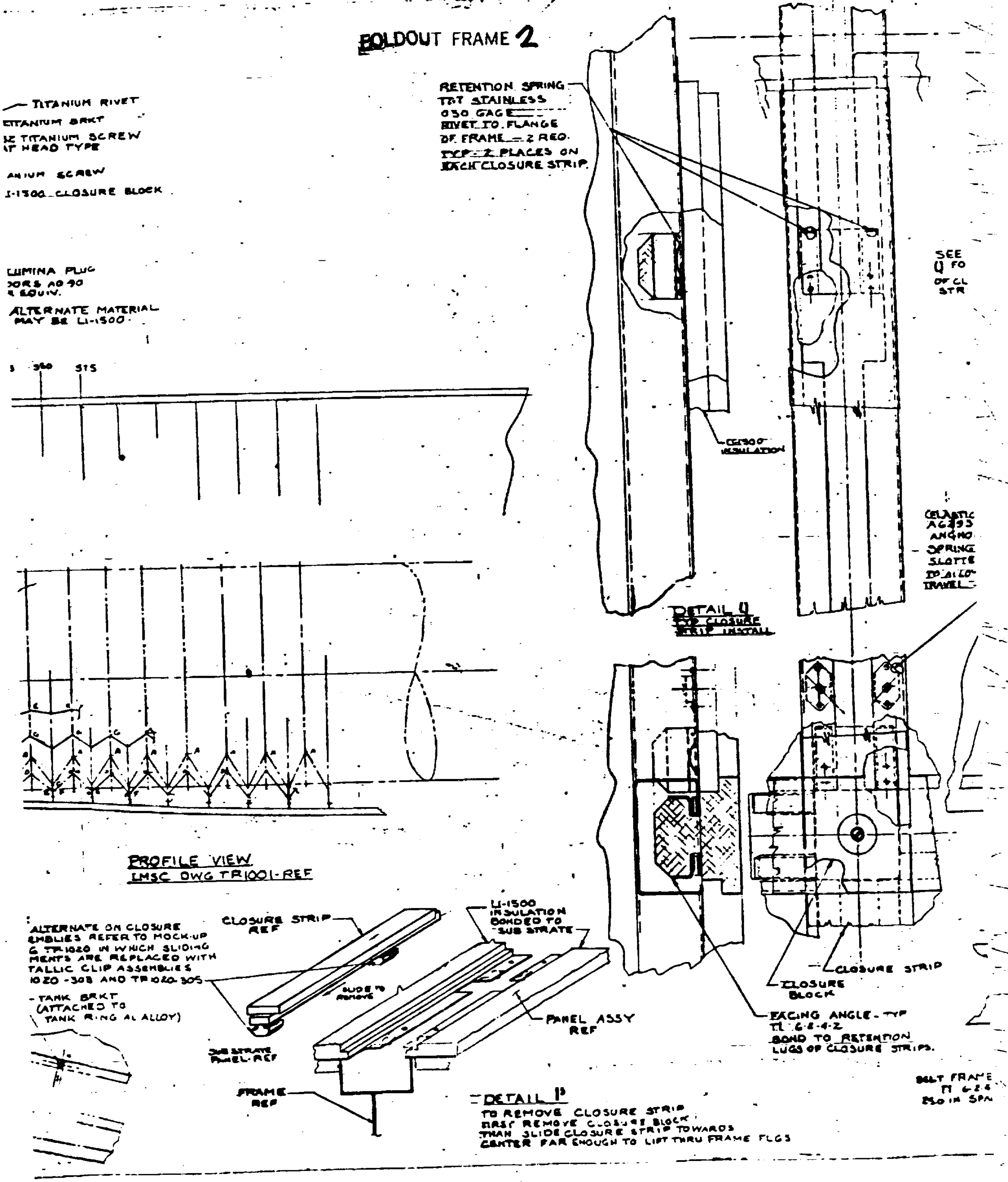

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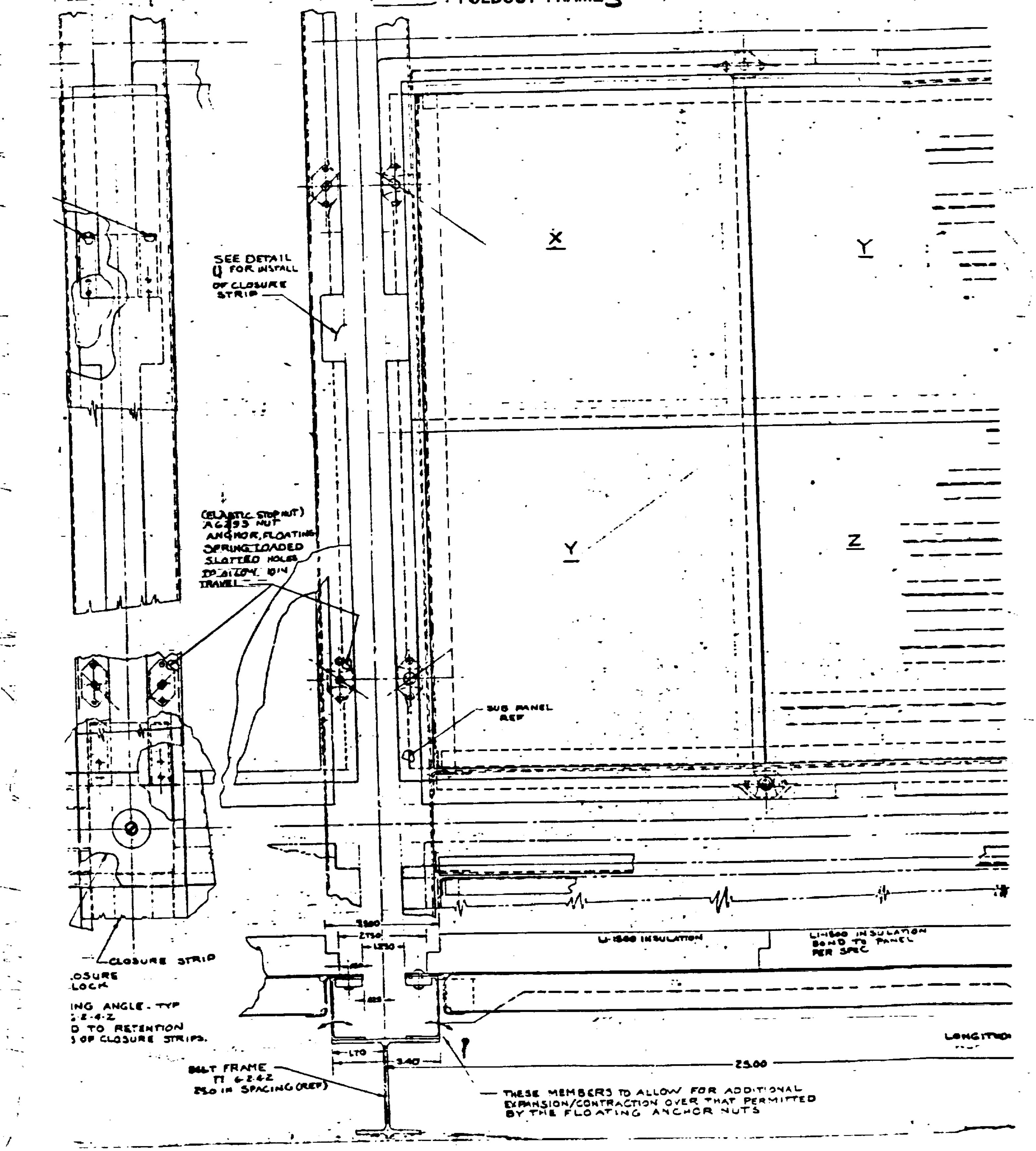

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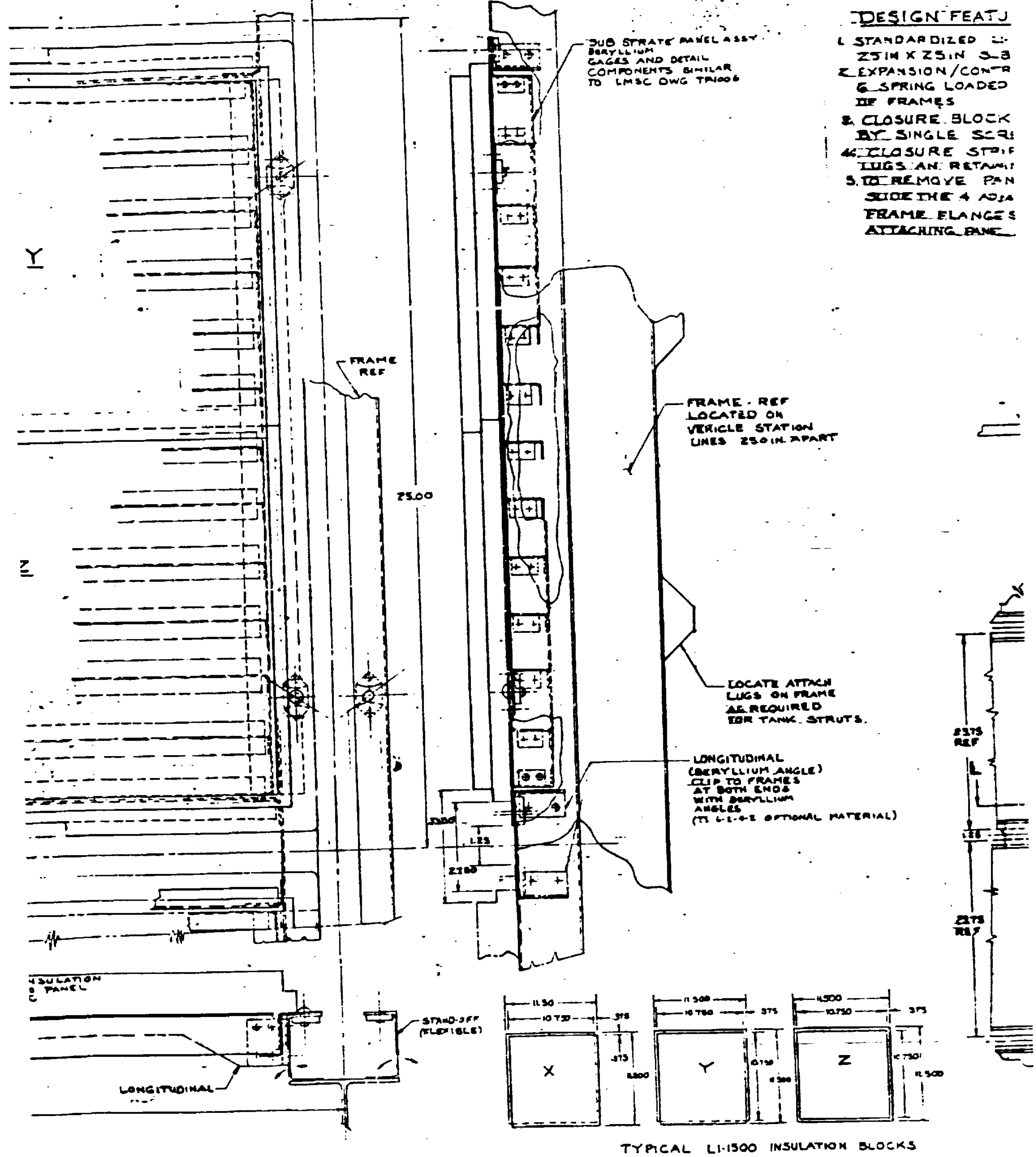
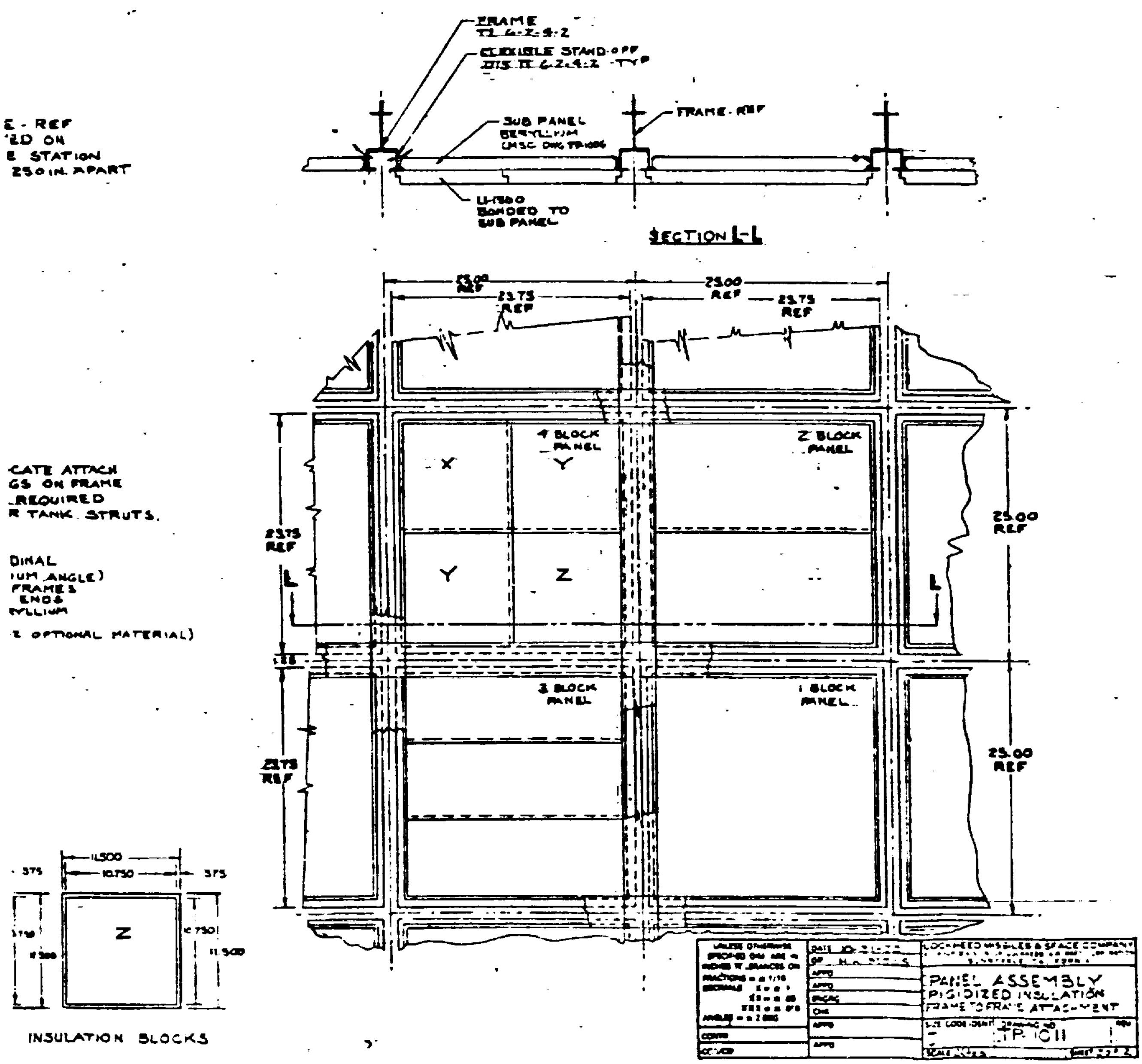


FOLDOUT FRAME 5

DESIGN FEATURES CONCEPT NO.2 (RECTANGULAR BLOCKS)

1. STANDARDIZED LI-1500 BLOCKS MOUNTED ON A STANDARDIZED 25IN X 25IN SUBSTRATE PANEL.
2. EXPANSION/CONTRACTION CONTROLLED BY MOUNTING WITH 6 SPRING LOADED, FLOATING ANCHOR NUTS MOUNTED TO FLANGES OF FRAMES
3. CLOSURE BLOCKS HELD IN PLACE BY CONICAL PLUG RETAINED BY SINGLE SCREW.
4. CLOSURE STRIPS HELD IN PLACE BY METAL FACED INTEGRAL LUGS AND RETAINING SPRINGS.
5. TO REMOVE PANEL REMOVE THE 4 ADJACENT CLOSURE BLOCKS, SLIDE THE 4 ADJACENT STRIPS TO DISENGAGE THROUGH SLOTS IN FRAME FLANGES TO EXPOSE THE 6 REMOVABLE SCREWS ATTACHING PANEL ASSY TO FRAMES AND LONGITUDINALS OF STRUCTURE.



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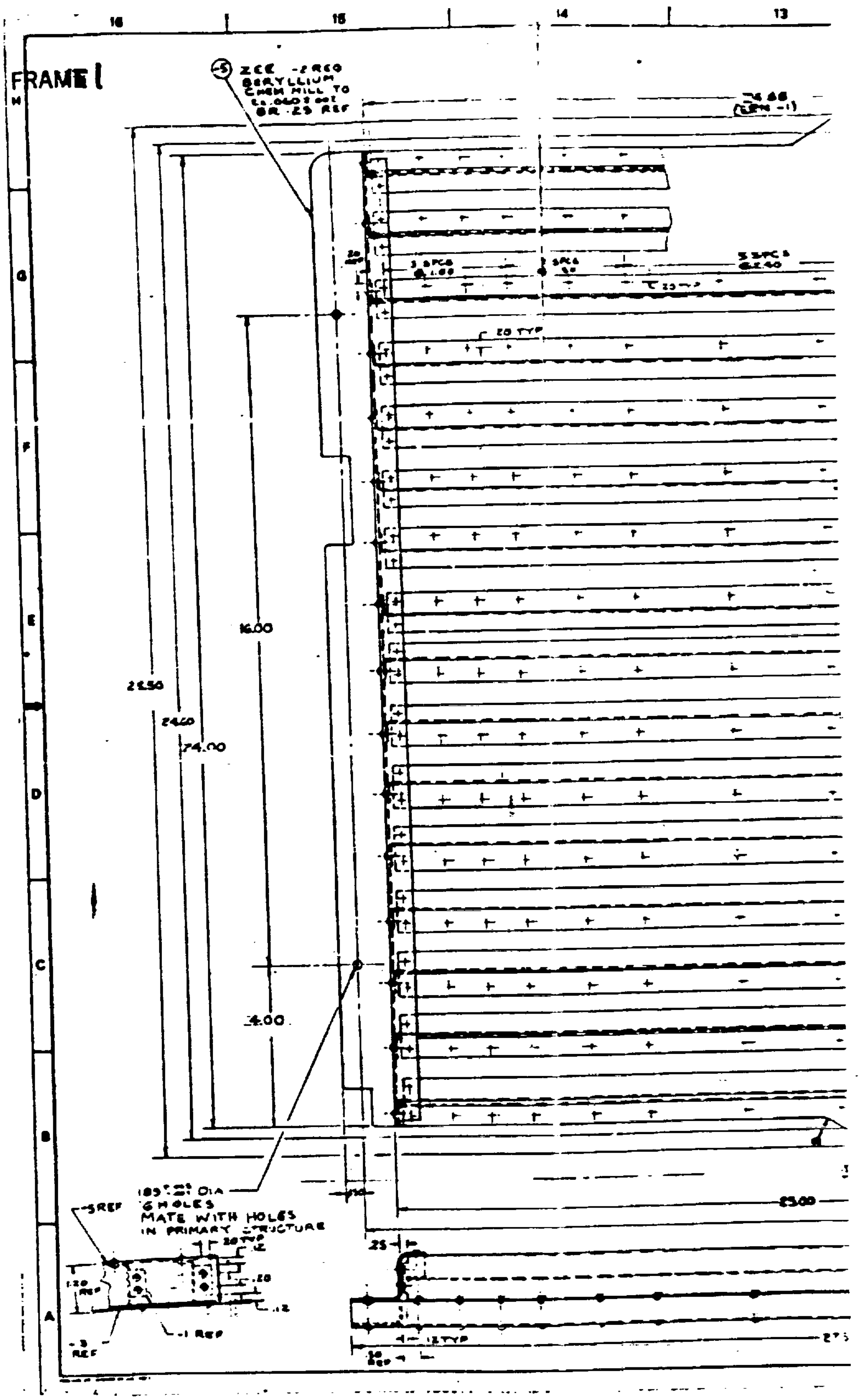

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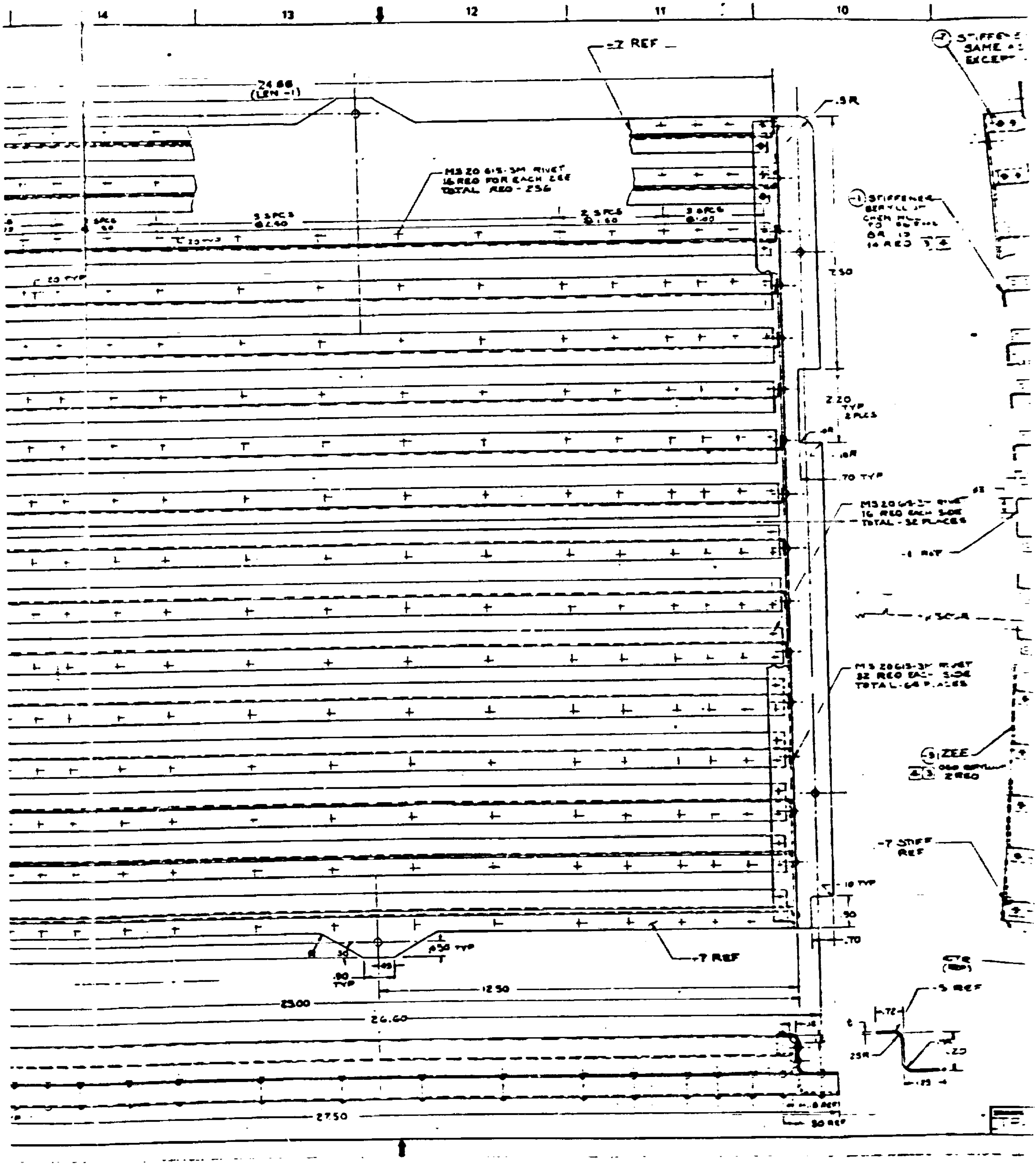
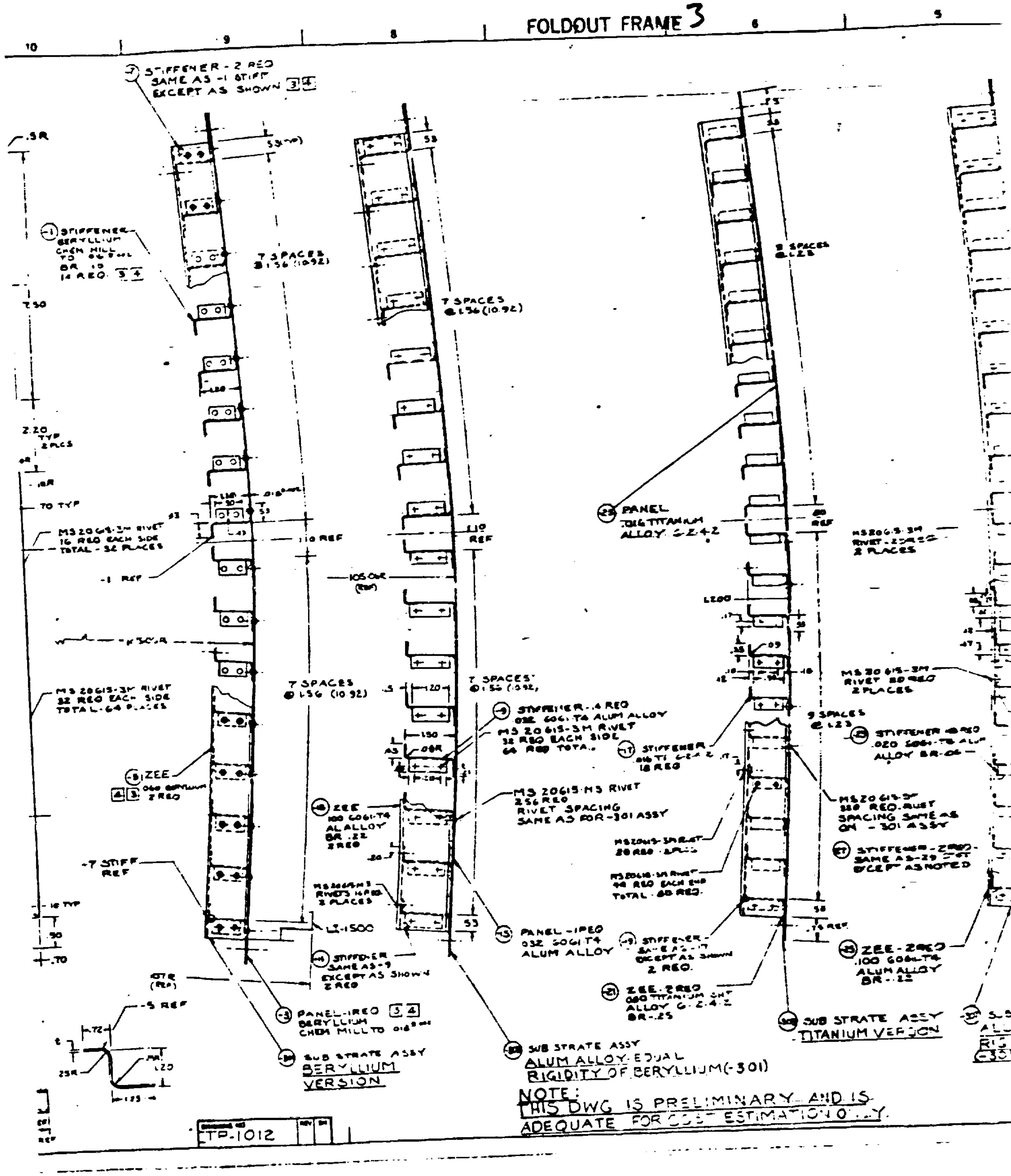
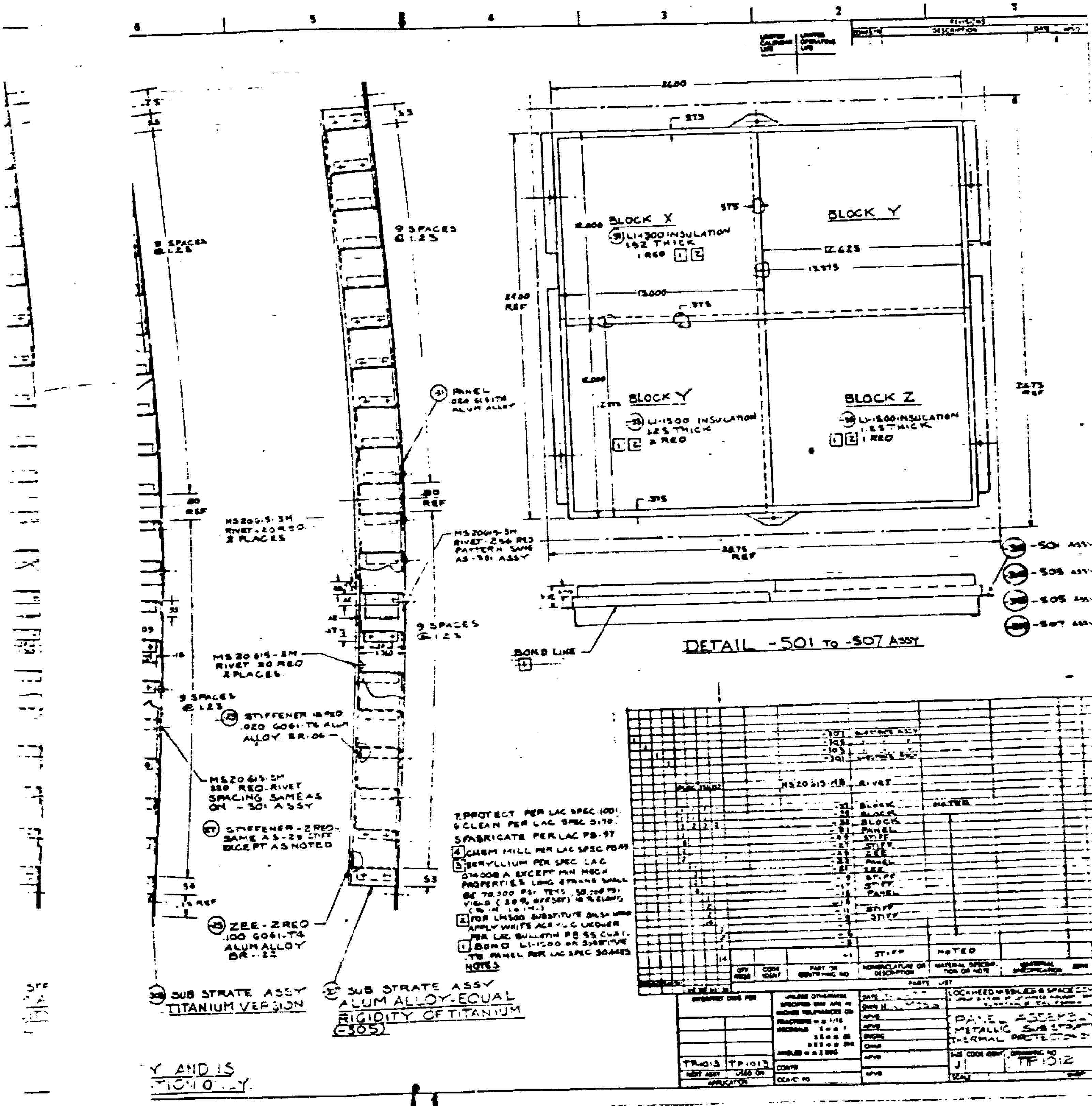




FOLDOUT FRAME 3
STIFFENER - 2 REQ SAME AS -1 STIFF EXCEPT AS SHOWN
STIFFENER BERYLLIUM CHEM MILL
7 SPACES
7 SPACES @ 1.56 (10.92)
PANEL .016 TITANIUM ALLOY 6-2-4-2
MS20615-3M RIVET 16 REQ EACH SIDE TOTAL - 32 PLACES
-1 REF
.10 REF
.70 TYP
7 SPACES @ 1.56 (10.92)
MS 20615-3M RIVET 32 REQ EACH SIDE TOTAL - 64 PLACES
ZEE
STIFFENER - 4 REQ .032 6061-T6 ALUM ALLOY
MS 20615-3M RIVET 32 REQ EACH SIDE 64 REQ TOTAL
MS 20615-M3 RIVET 256 REQ RIVET SPACING SAME AS FOR -301 ASSY
ZEE .100 6061-T6 AL ALLOY BR .22 2 REQ
STIFFENER 18 REQ
9 SPACES @ 1.23
-7 STIFF REF
PANEL - 1 REQ .032 6061-T4 ALUM ALLOY
STIFFENER SAME AS -9 EXCEPT AS SHOWN 2 REQ
PANEL - 1 REQ BERYLLIUM CHEM MILL TO .018
SUB STRATE ASSY BERYLLIUM VERSION
SUB STRATE ASSY ALUM ALLOY EQUAL RIGIDITY OF BERYLLIUM (-301)
ZEE - 2 REQ .100 6061-T6 ALUM ALLOY BR - .22
ZEE - 2 REQ TITANIUM ALLOY 6-2-4-2 BR - .25
SUB STRATE ASSY TITANIUM VERSION
-5 REF
NOTE: THIS DWG IS PRELIMINARY AND IS ADEQUATE FOR COST ESTIMATION ONLY.
TP-1012

FOLDOUT FRAME 4



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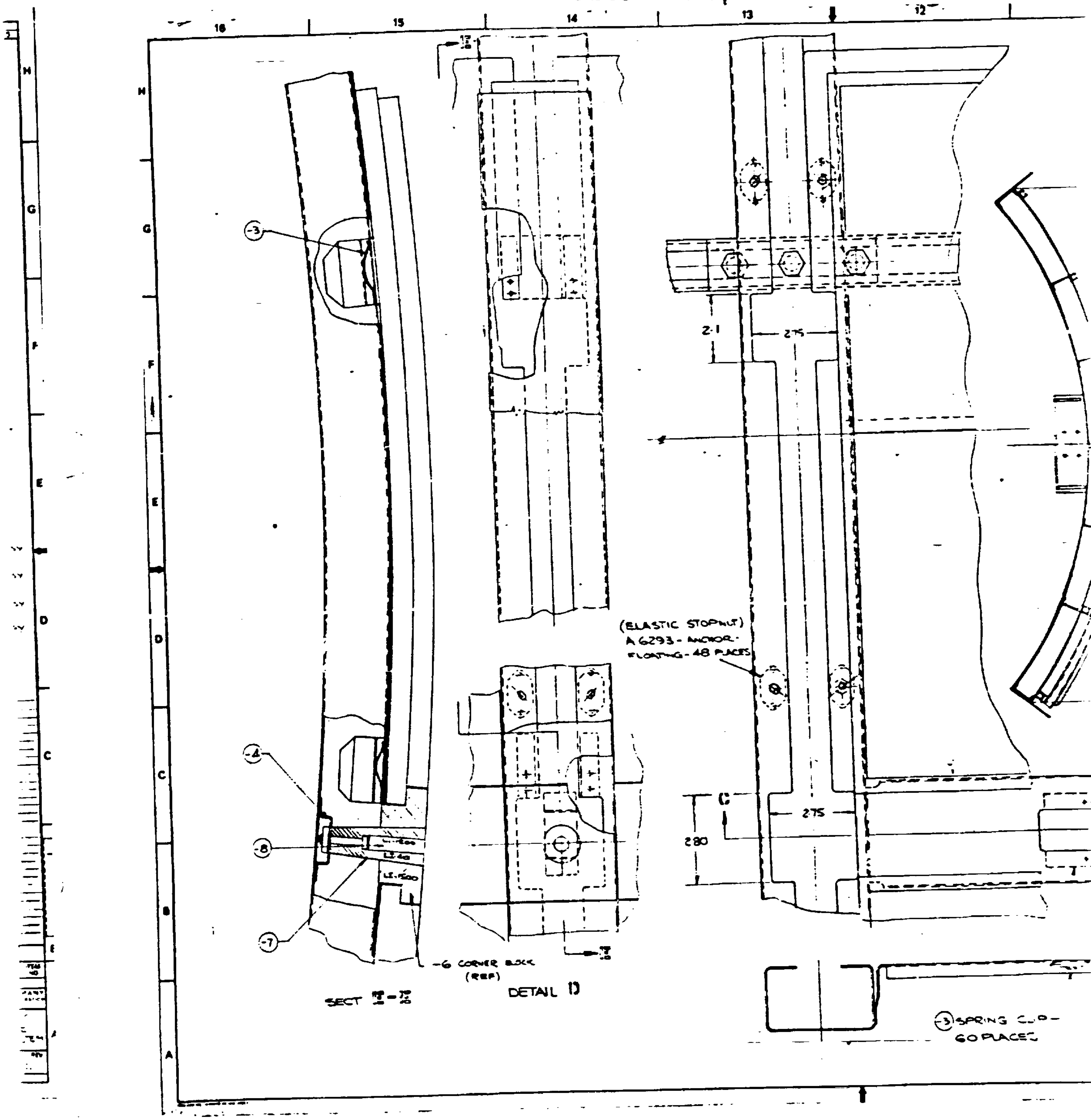

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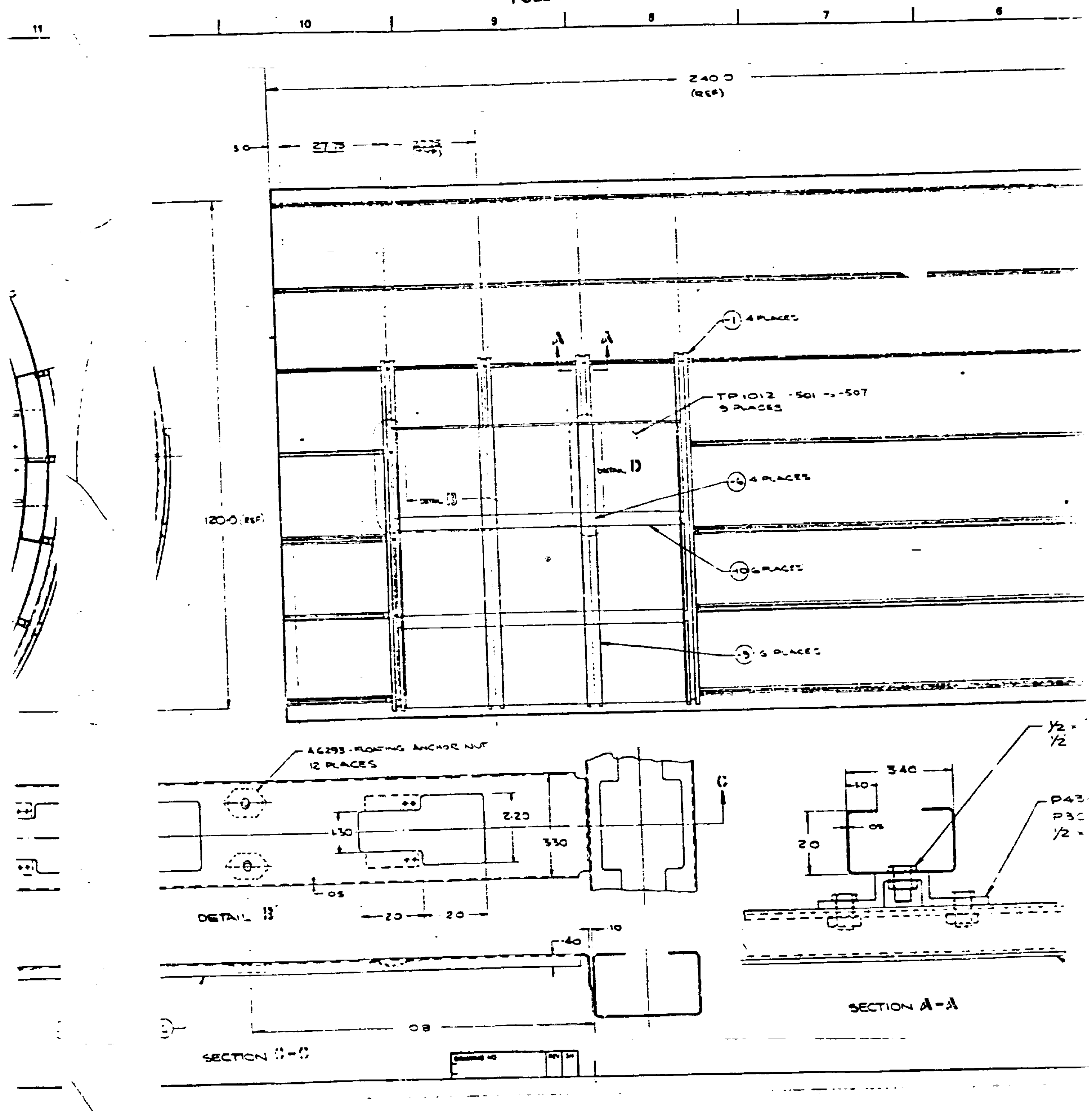

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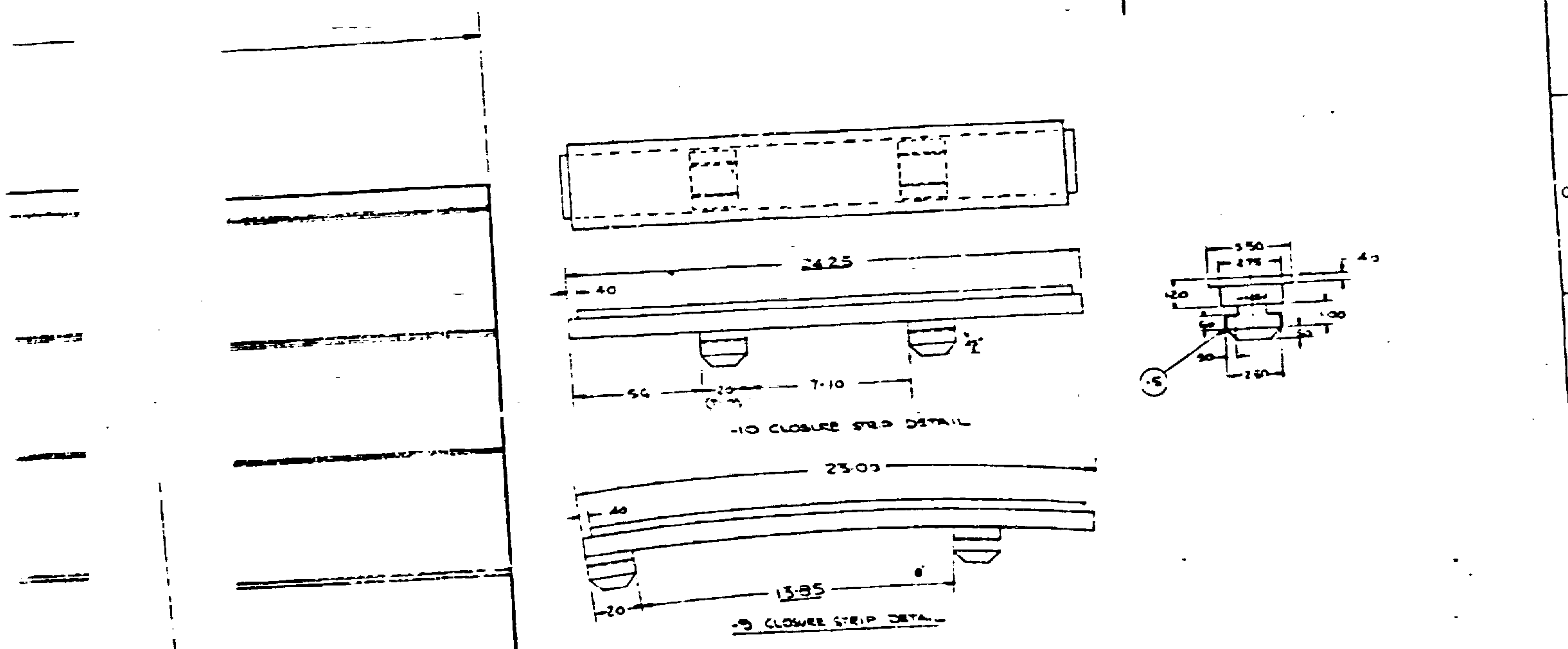

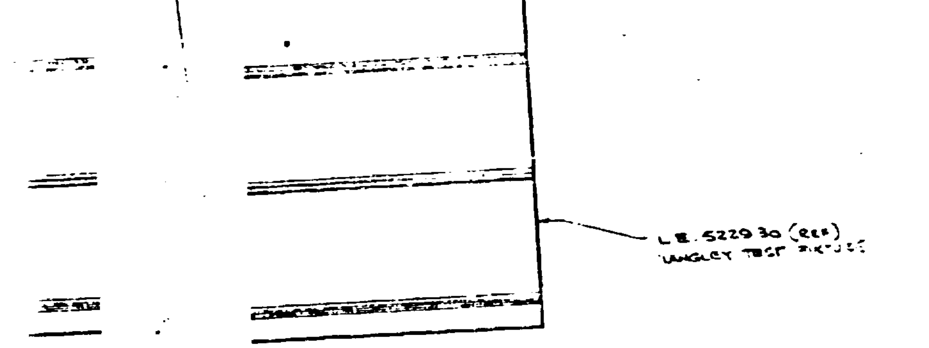

-½ x ⅝ HEX HEAD CAP SCREW
½ HEX NUT

-P4385 FITTING
P3010 NUT
½ x 13/16 HEX HEAD CAP SCREW

LANGLEY TEST FIXTURE

PRELIMINARY

NOTE:- THIS DWG IS PRELIMINARY AND IS ADEQUATE FOR COST ESTIMATION ONLY.

-507-502-505-5C				-301						
9						TP1012-507	PANEL			
	9					TP1012-503	PANEL			
		9				TP1012-501	PANEL			
1	1	1	1			-301	PANEL MOUNTING ASSY			
				60		A6293	FLOATING ANCHOR NUT	ELASTIC STOP NUT		
				20		½	HEX NUT	UNISTRUT		
				60		½ x ⅝	CAP SCREW	UNISTRUT		
				40		P3010	NUT	UNISTRUT		
				20		P4385	FITTING	UNISTRUT		
	9					TP1012-505	PANEL			
				6		-10	CLOSURE STRIP (FLAT)	4 x 4 x 25	LI-1500	
				6		-9	CLOSURE STRIP (CURVED)	4 x 4 x 24	LI-1500	
				4		-8	PLUG (PANEL)	1 x 1 x 3	LI-1500	
				4		-7	PLUG (ROOT)	1.5 x .5 x 3	LI-40	
				4		-6	CORNER BLOCK	1.5 x 4 x 4	LI-1500	
				48		-5	RUBBING STRIP	.5 x 2.5 x .02	2024-T4 ALUM	
				4		-4	BRACKET	1 x 3 x .05	2024-T4 ALUM	
				60		-3	SPRING CLIP	.5 x 2 x .02	SPRING STEEL	
				6		-2	LONGITUDINAL	5 x 32 x .05	2024-T4 ALUM	
				4		-1	FRAME	10 x 9[illegible] x .05	2024-T4 ALUM	
				QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS = ± 1/16 DECIMALS .X = ± .1, .XX = ± .03, .XXX = ± .010 ANGLES = ± 2 DEG

LOCKHEED MISSILES & SPACE COMPANY

TPS TEST ASSY

NASA LANGLEY

DATE | DRAWN | APVD | APVD | ENGRG | CHKD | APVD

NEXT ASSY | USED ON | APPLICATION

SIZE J | CODE IDENT | DRAWING NO

SCALE | SHEET

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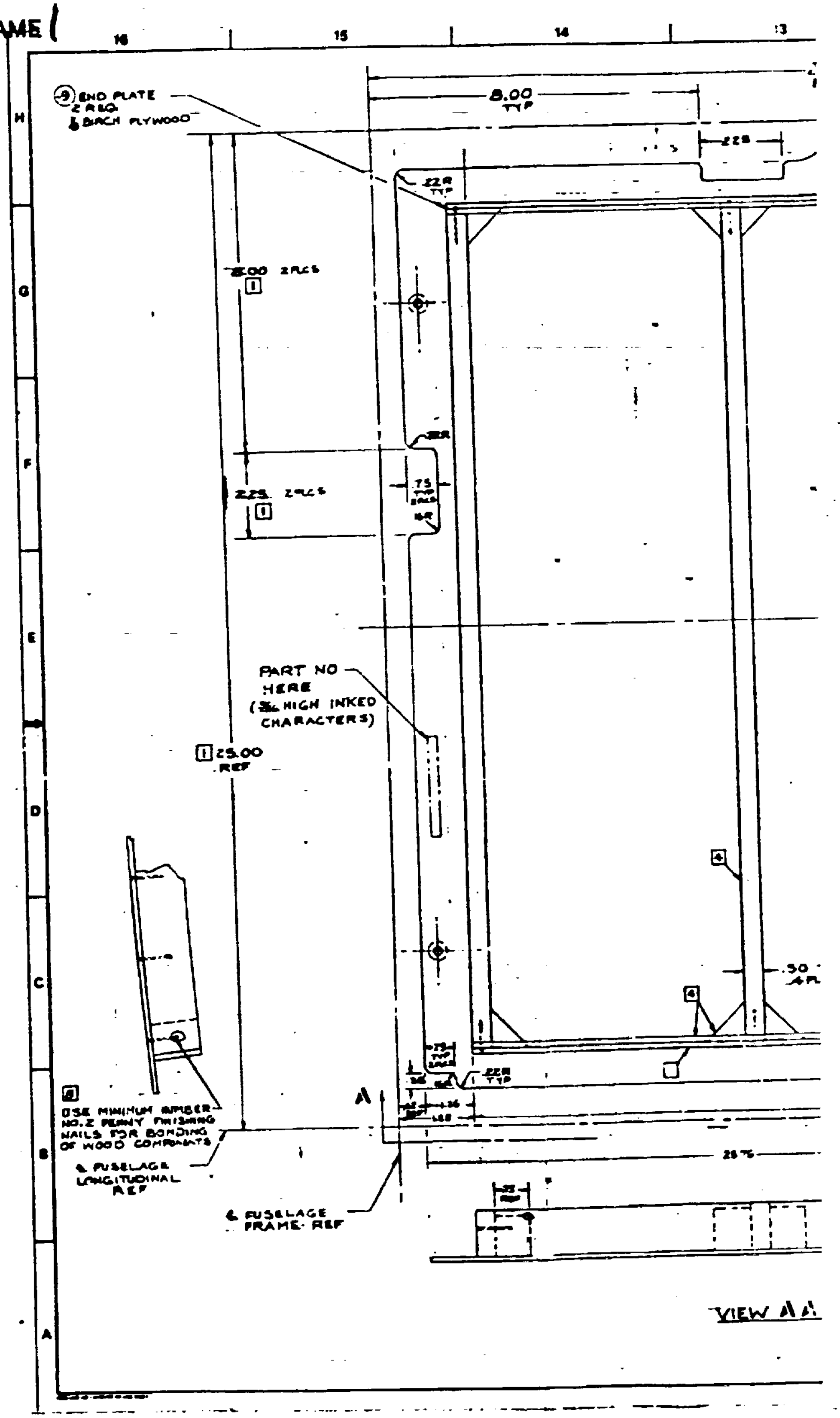

26

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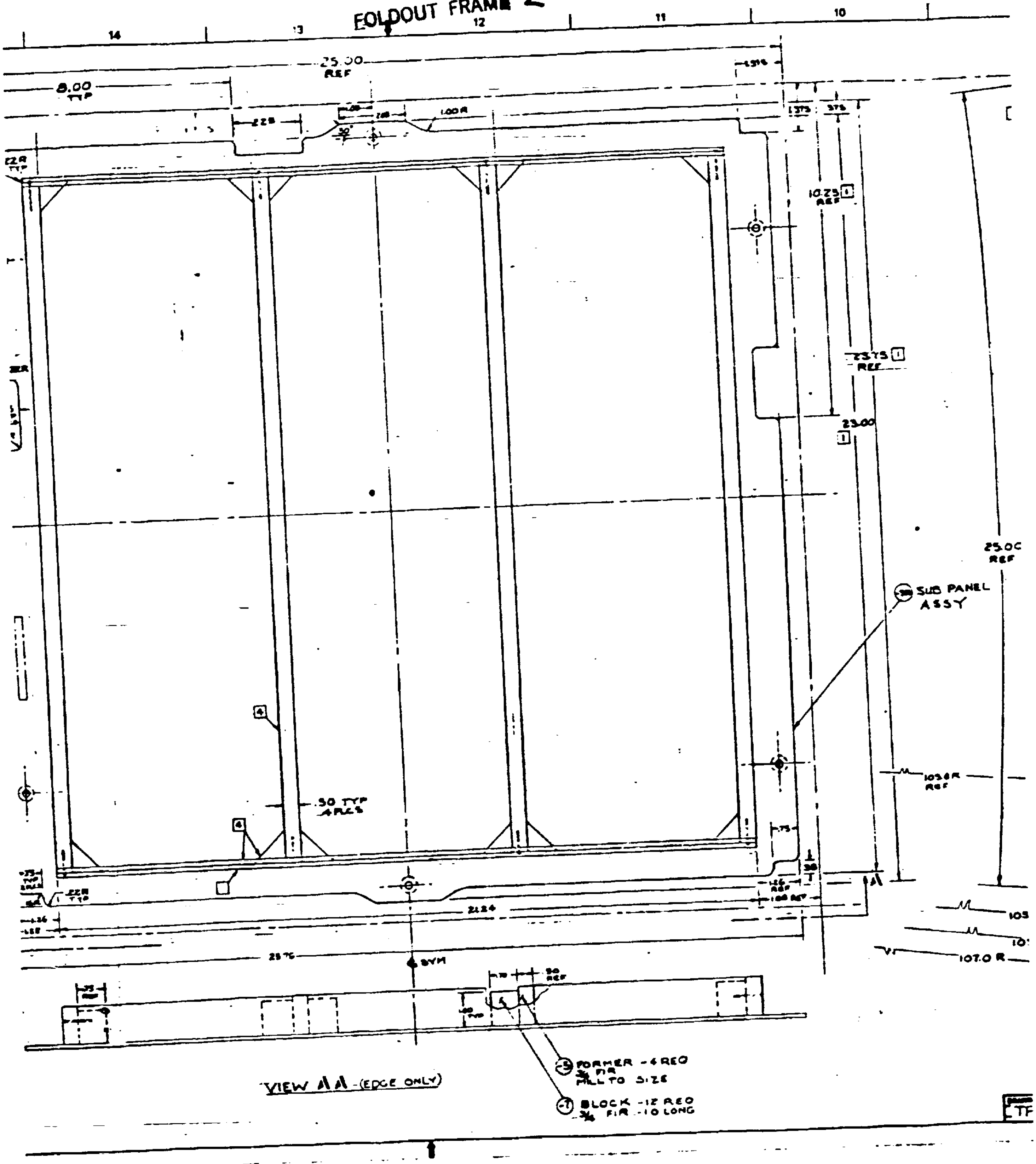

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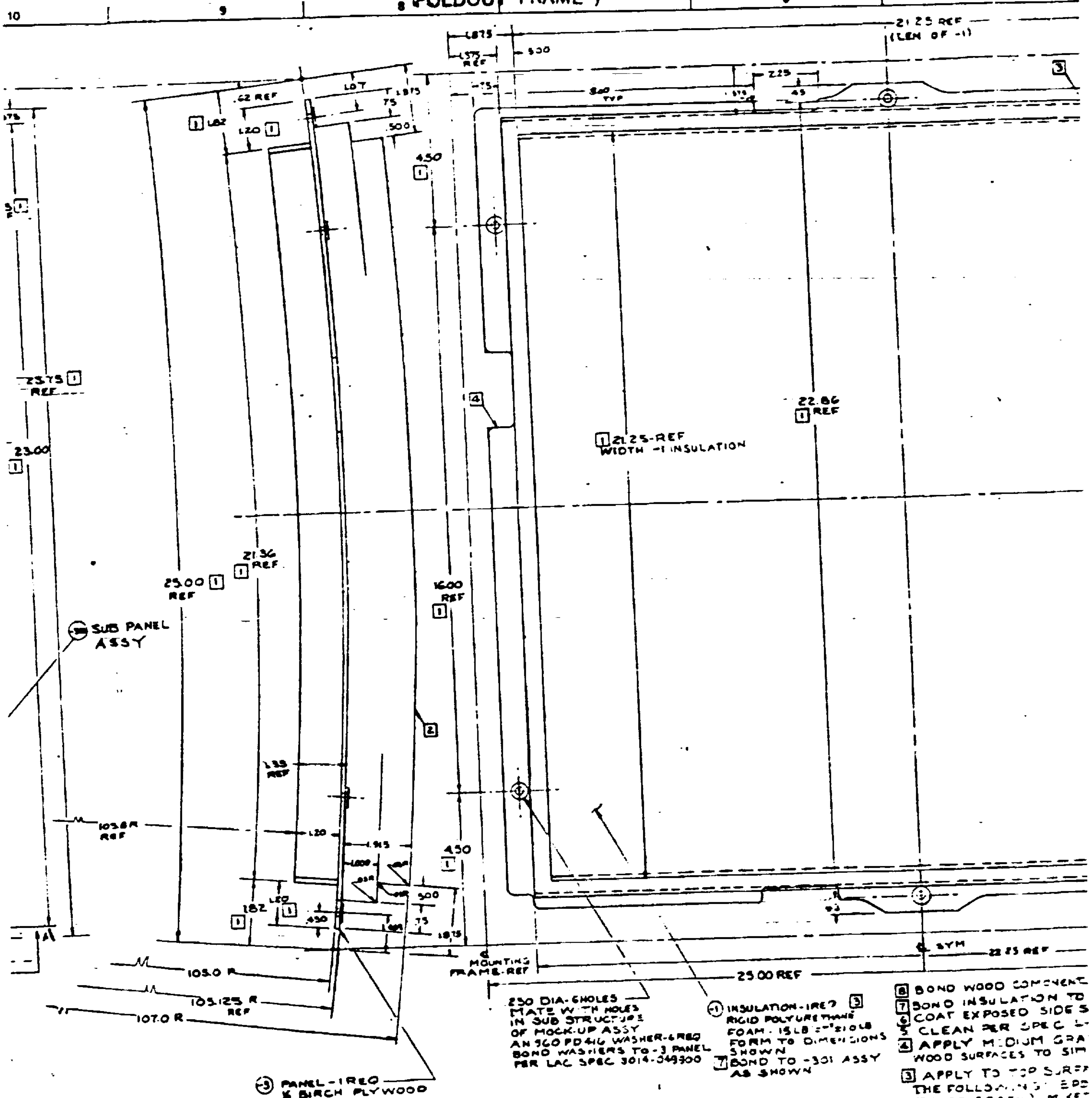
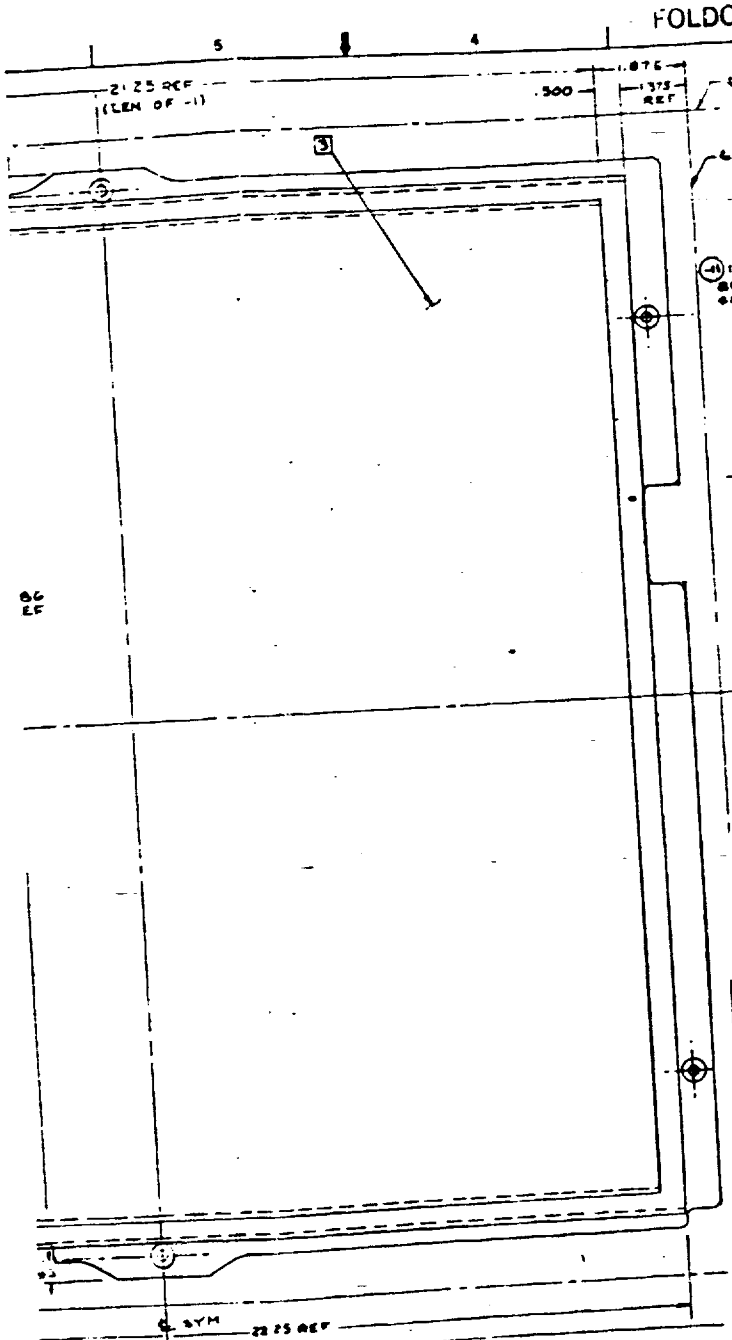


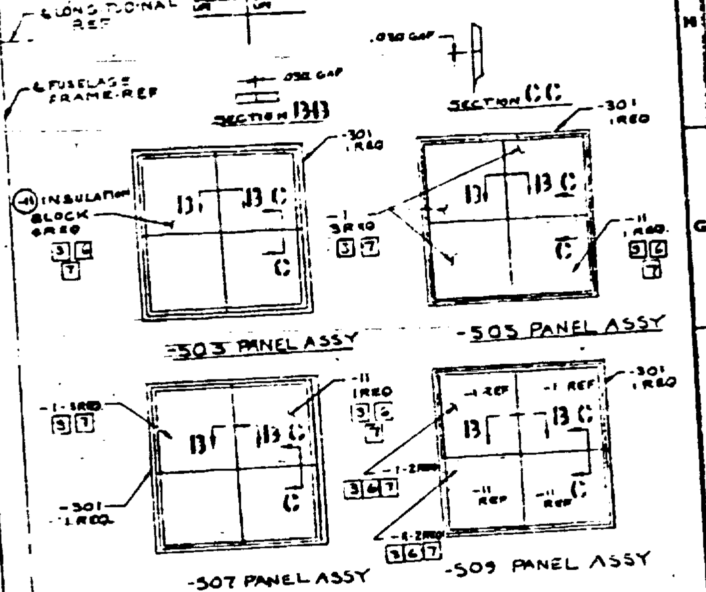
-501 PANEL ASSY

8 BOND WOOD COMPONENT
7 BOND INSULATION TO
6 COAT EXPOSED SIDE S
5 CLEAN PER SPEC
4 APPLY MEDIUM GRA WOOD SURFACES TO SIM
3 APPLY TO TOP SURF THE FOLLOWING EPO (COLOR GREEN) MIXED OF GLASS BEADS FIL COATED SURFACE
2 PROTECT PER LAC SPE
1 DIMENSION IN PLANE
NOTE

TP-1015

FOLDOUT FRAME 4





ABOVE PANEL ASSEMBLIES (-503, -505, -507, -509) SAME AS -501 PANEL ASSEMBLY EXCEPT FOR VARIATION IN INSULATION INSTALLATION AS SHOWN. ALL INSULATION IS SAME THICKNESS AS THAT SHOWN ON -501 ASSY.

-509	-507	-505	-503	-301	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO
							-301	SUB PANEL ASSY				
1	1	1	1	1								
								WASHER	AN 960 PD416		A	7
					6			PAINT	GRAY ENAMEL		C	12
					AS REQ							
								FILLER	GLASS BEADS			
					AS REQ			ADHESIVE	BOND	304435	A	6
					AS REQ			EPOXY FLOOR COATING-GREEN				
					AS REQ							
								NO. 2 EPOXY FINISHING NAILS				15
					AS REQ							
							-11	INSULATION	BLOCK LI-1500			
2	1	1	4									5
					2	8	-9	END PLATE	BIRCH PLYWOOD		A	
					12	8	-7	BLOCK	FIR		A	
					4	7	-5	FORMER	FIR		A	
					1	8	-3	PANEL	BIRCH PLYWOOD		A	9
2	3	3		1			-1	INSULATION	20 RIGID FOAM POLYURETHANE		A	

PARTS LIST

DATE	2-7-70
DWN	H. K. MOSS
APVD	
APVD	
ENGRG	
CHKD	
APVD	

LOCKHEED MISSILES & SPACE COMPANY, SUNNYVALE, CALIFORNIA

PANEL ASSEMBLY, NON METALLIC SYSTEM, FRAME TO FRAME ATTACH

SIZE J | DRAWING NO TP-1015

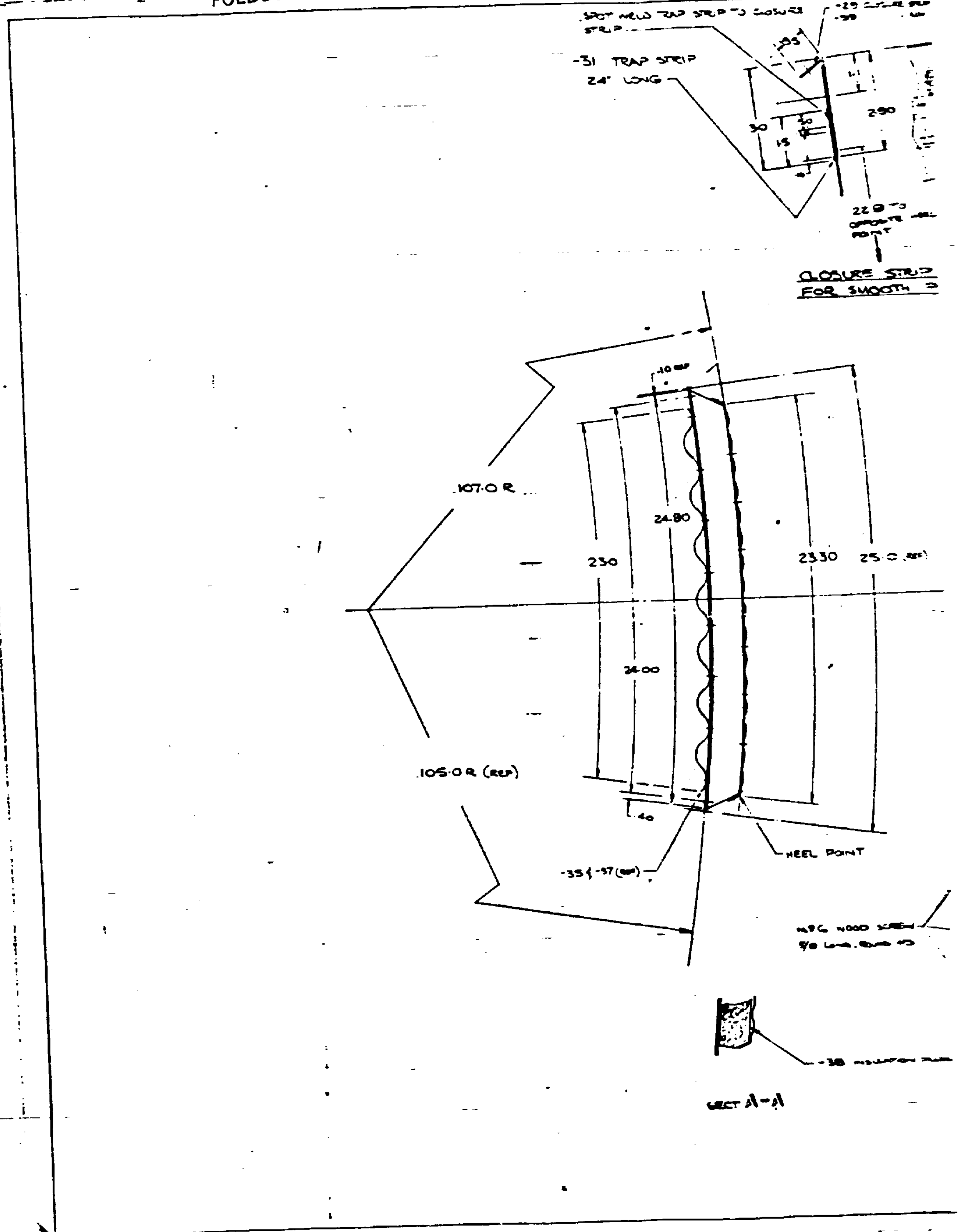
TP-1015

NEXT ASSY: TR1015 | APPLICATION

8 BOND WOOD COMPONENTS PER SPEC LAC 3014-104.
7 BOND INSULATION TO SUB-PANEL PER LAC SPEC 304435 WITH SILICONE.
6 COAT EXPOSED SIDE SURFACES OF LI-1500 WITH SILICONE.
5 CLEAN PER SPEC LAC 0170.
4 APPLY MEDIUM GRAY ENAMEL TO ALL EXPOSED WOOD SURFACES TO SIMULATE METALLIC SUB PANEL.
3 APPLY TO TOP SURFACE ONLY OF INSULATION THE FOLLOWING: EPOXY FLOOR COVERING (COLOR GREEN) MIXED WITH APPROPRIATE AMOUNT OF GLASS BEADS FILLER TO SIMULATE CERAMIC COATED SURFACE. DO NOT APPLY TO SIDE SURFACES.
2 PROTECT PER LAC SPEC 1001
1 DIMENSION IN PLANE OF PLATE AT 1050 IN RADIUS.

NOTE

FOLDOUT FRAME 1



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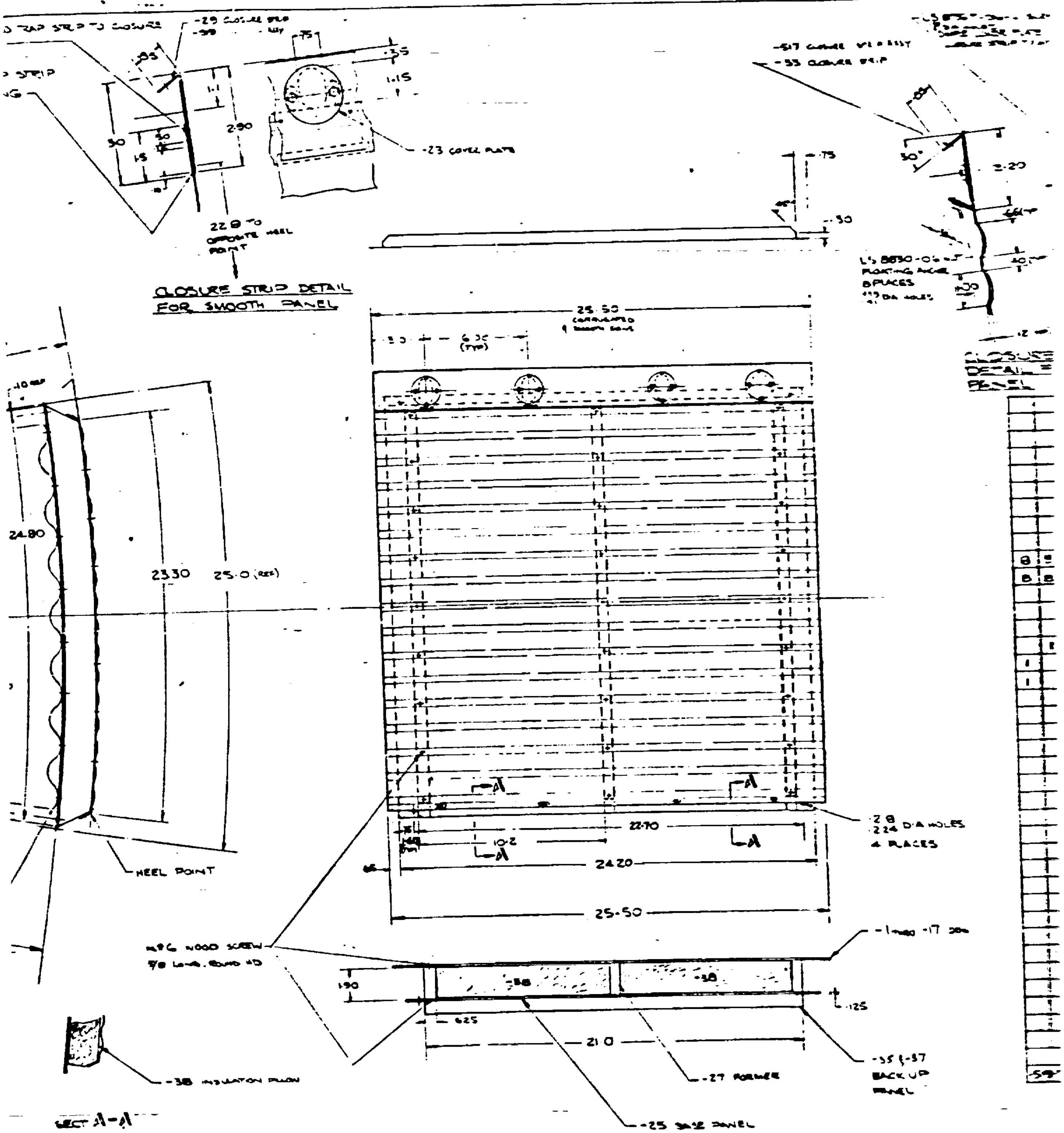
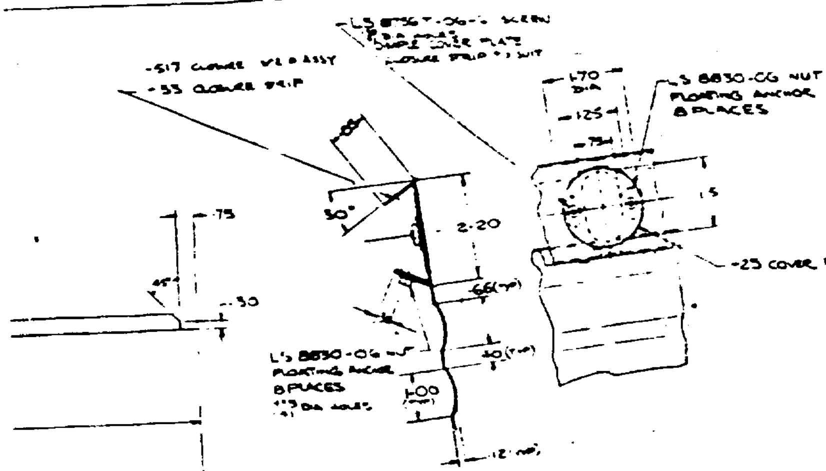
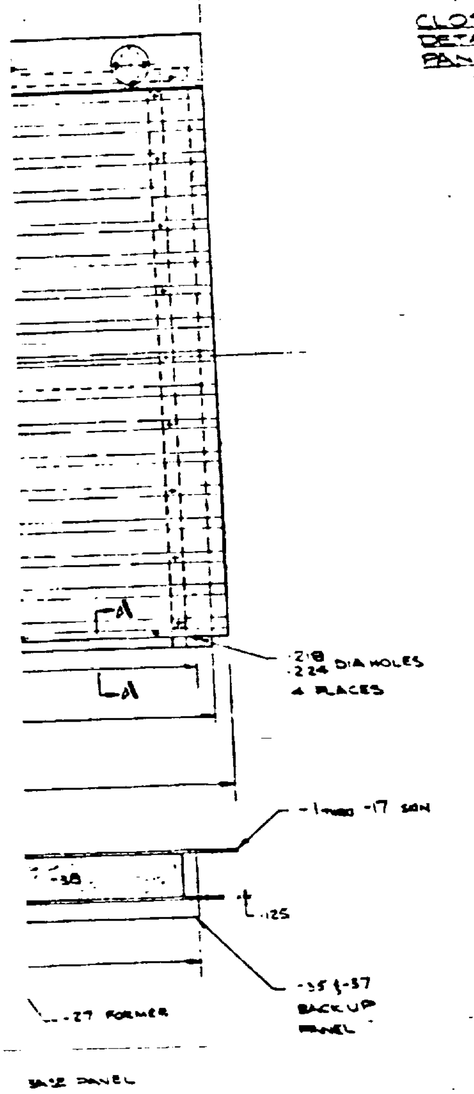


FOLDOUT FRAME 3



CLOSURE STRIP DETAIL FOR CORRUGATED PANEL



-519	-517	-515	-513	-511	-509	-507	-505	-503	-501	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR SIZE	MATERIAL SPECIFICATION
		51	51	51	51	51	51	51	51	COMMERCIAL	WOOD SCREW		
8	8	4	4	[illegible]	4	8	8	8	8	LS 8830-06	NUT		
8	8									LS 8756T-06	SCREW		
		2	2	2	2	2	2	2	2	-38	INSULATION PILLOW	[illegible]	
		1	1		1	1	1		1	-37	BACK UP PILLOW	24×24×.203	
				1				1		-35	-	24×14×.203	
	1									-33	CLOSURE STRIP	30×3×.02	SAME AS SKIN
1										-31	TEAR STRIP	30×2×.02	-
1										-29	CLOSURE STRIP	30×5×.02	-
		3	3	3	3	3	3	3	3	-27	FORMER	30×3×.625	FIR
		1	1	1	1	1	1	1	1	-25	BASE PANEL	30×30×.125	BIRCH PLYWOOD
		4	4	4	4	4	4	4	4	-23	COVER PLATE	2×2×.02	SAME AS SKIN
		1	1	1	1					-519	CLOSURE STRIP (SMOOTH PANEL ASSY)		
						1	1	1	1	-517	CLOSURE STRIP (CORRUGATED PANEL ASSY)		
		1								-17	SKIN (SMOOTH)	30×30×.05	CB 752
			1							-15	SKIN (SMOOTH)	.010	TD NICKEL
				1						-13	SKIN (SMOOTH)	0.2 ALUM	6061-T6
					1					-11	SKIN (SMOOTH)	.012 STEEL	
						1				-7	SKIN (CORRUGATED)	.015	C8752
							1			-5	SKIN (CORRUGATED)	.010	TD NICKEL
								1		-3	SKIN (CORRUGATED)	0.2 ALUM	6061-T6
									1	-1	SKIN (CORRUGATED)	30×30×.012 STEEL	
										-515	PANEL ASSY		
										-513	PANEL ASSY		
										-511	PANEL ASSY		
										-509	PANEL ASSY		
										-507	PANEL ASSY		
										-505	PANEL ASSY		
										-503	PANEL ASSY		
										-501	PANEL ASSY		

QTY REQD | CODE IDENT | PART OR IDENTIFYING NO | NOMENCLATURE OR DESCRIPTION | MATERIAL DESCRIPTION OR SIZE | MATERIAL SPECIFICATION | ZONE | ITEM NO

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIM ARE IN INCHES TOLERANCES ON FRACTIONS ± 1/16 DECIMALS ANGLES ± 1 DEG

DATE | DR | APPD | APPD | ENGRG | CHK | APPD | APPD

CONTR | CCA CP | NEXT ASSY | USED ON | APPLICATION

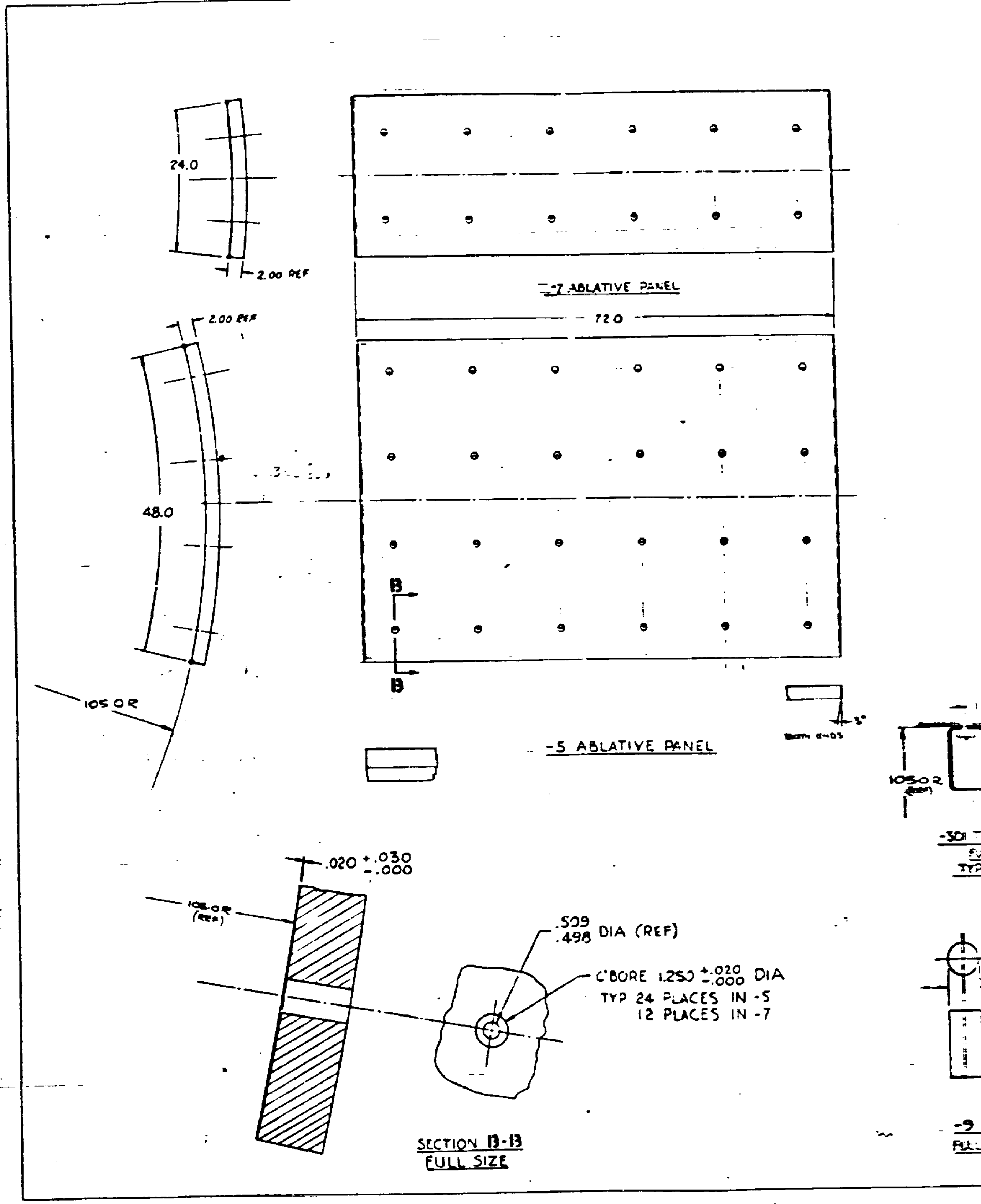
LOCKHEED MISSILES & SPACE COMPANY

METALLIC HEAT SHIELD TEST PANEL FOR NASA LANGLEY MOCK UP

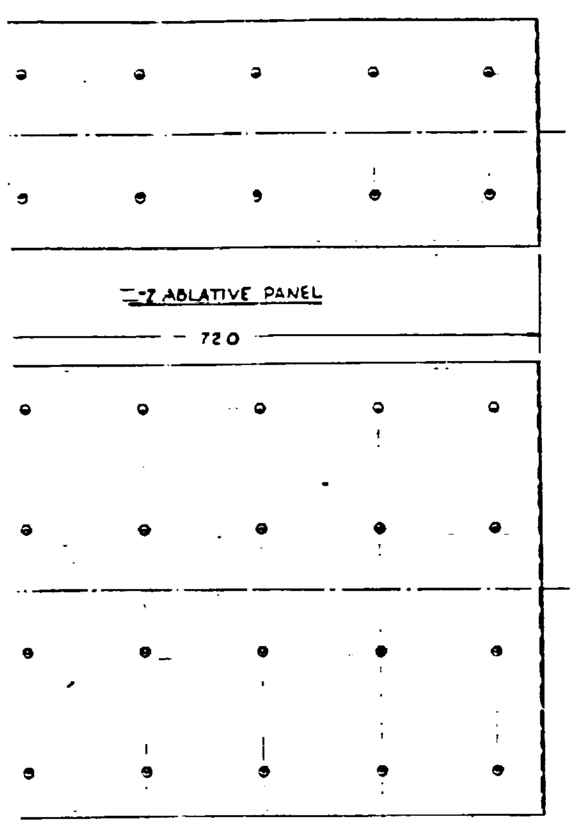
SIZE | CODE IDENT | DRAWING NO | SCALE | SHEET

FOLDOUT FRAME

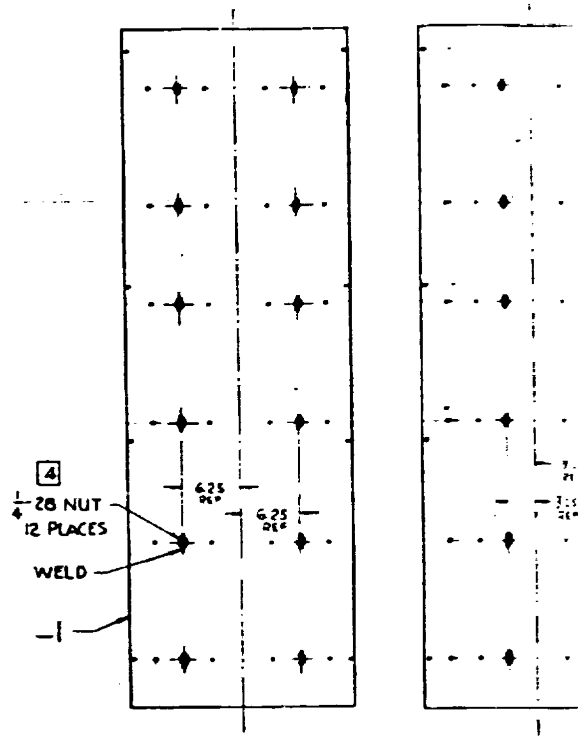
FOLDOUT



FOLDOUT FRAME 2

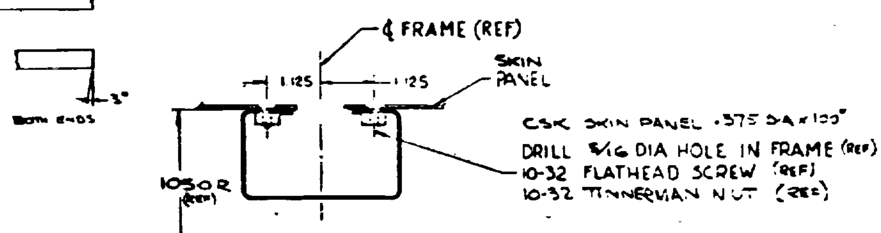


-5 ABLATIVE PANEL



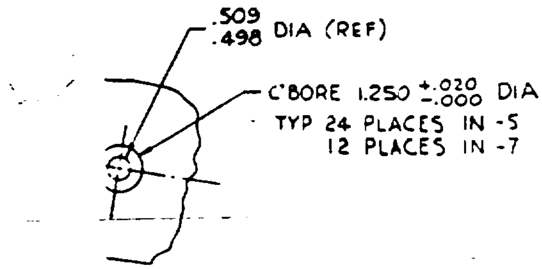
-307 PANEL ASS'Y

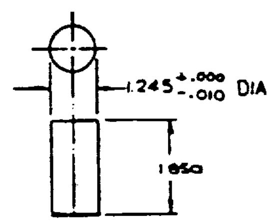
-305 PANEL
-306 PANEL



-301 THRU -307 PANEL INSTALL (REF)
FULL SIZE
TYPICAL 108 PLACES

+ INDIC...
FAST...
SYMME...
VERT...
FAR...





-9 PLUG
FULL SIZE

13-13
ZE

6 LOCATE PANELS ON MOCKUP ...
ABOVE PARTS LIST

5 MAKE FROM PHENOLIC ...
ABLATIVE MATERIAL TO BE F...
LANGLEY RESEARCH CENTER...
COATED WITH TITANIUM OX...

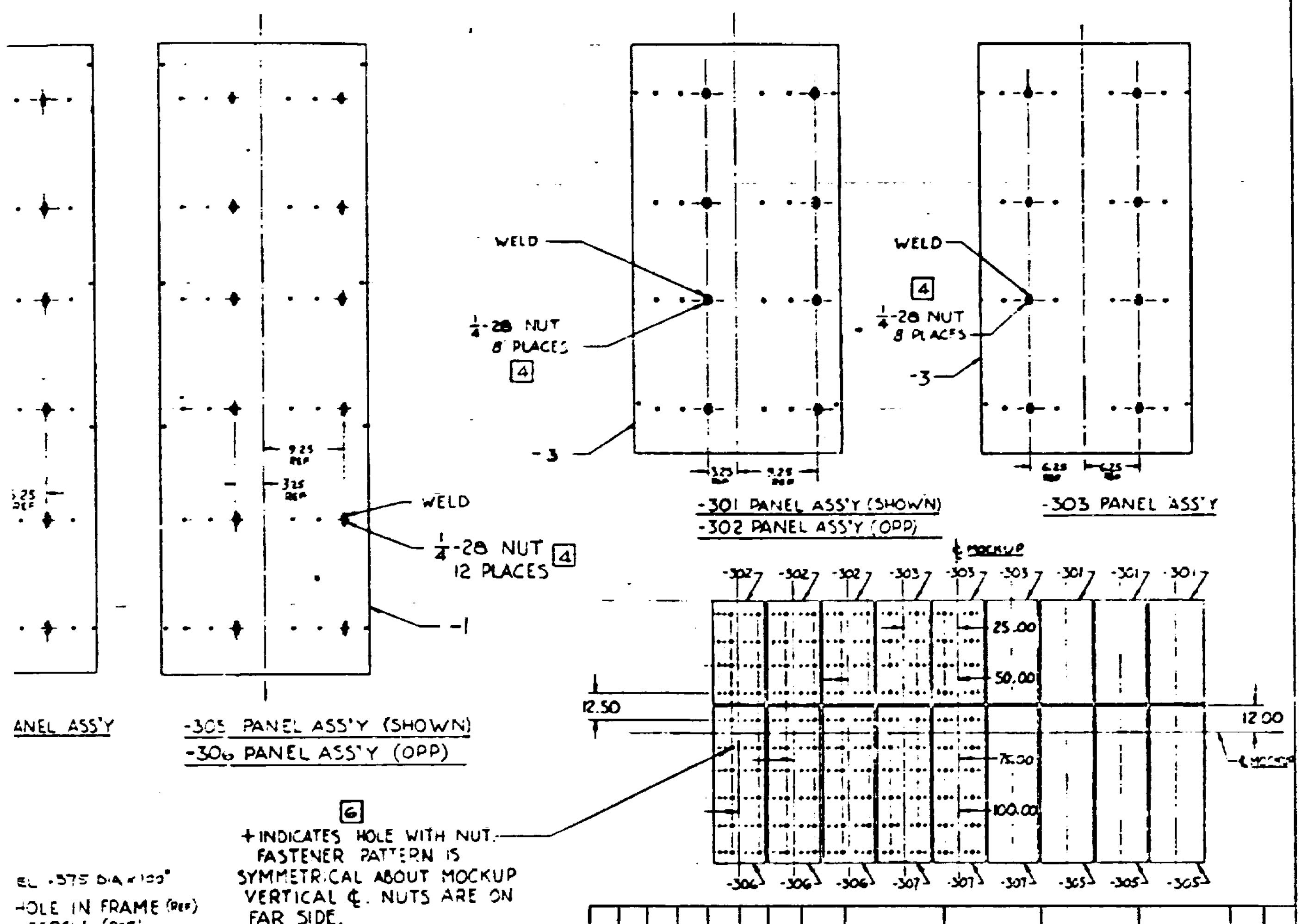
4 PITCH DIA OF NUT TO BE CON...
HOLE WITHIN .005 DIA

3 ALL HOLE LOCATIONS ARE BA...
INSIDE SURFACE OF -5 &...
SHOWN IN EDGE VIEW.

2 ALL HOLE LOCATIONS ARE B...
OUTSIDE SURFACE OF -5 &...
IN EDGE VIEW.

NOTES: 1 AT ASSEMBLY WITH FRAME...
CSK -7 & -5 PANELS FOR...

FOLDOUT FRAME 3



EL .375 DIA × 100°
HOLE IN FRAME (REF)
SCREW (REF)
IN NUT (REF)

6. LOCATE PANELS ON MOCKUP AS SHOWN ABOVE PARTS LIST

5. MAKE FROM PHENOLIC HONEYCOMB ELASTOMERIC ABLATIVE MATERIAL TO BE FURNISHED BY LANGLEY RESEARCH CENTER. MATERIAL WILL BE FURNISHED COATED WITH TITANIUM OXIDE PAINT.

4. PITCH DIA OF NUT TO BE CONCENTRIC WITH 9/32 DIA HOLE WITHIN .005 DIA.

3. ALL HOLE LOCATIONS ARE BASIC & MEASURED ON INSIDE SURFACE OF -5 & -7 PANELS, AS SHOWN IN EDGE VIEW.

2. ALL HOLE LOCATIONS ARE BASIC & MEASURED ON OUTSIDE SURFACE OF -1 & -3 PANELS, AS SHOWN IN EDGE VIEW.

1. AT ASSEMBLY WITH FRAMES DRILL THRU FRAMES & CSK -1 & -3 PANELS FOR 10-32 × 100° FLATHEAD SCREW.

	-307	-306	-305	-303	-302	-301 QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION	MATERIAL SPECIFICATION	ZONE	ITEM NO.
180								-9	PLUG	2.00 × 1.50 DIA PHENOLIC HONEYCOMB	5		
3								-7	ABLATIVE PANEL	2.00 × 24 × 72 PHENOLIC HONEYCOMB	5		
6								-5	ABLATIVE PANEL	2.50 × 48 × 72 PHENOLIC HONEYCOMB	5		
3								-307	PANEL ASS'Y				
3								-306					
3								-305					
3								-303					
3								-302					
3								-301	PANEL ASS'Y				
	12	12	12	8	8	8			1/4-28 SQUARE NUT	[illegible] STEEL	COMM		
				1	1	1		-3	SKIN PANEL	.064 × 24 × 63 [illegible]			
	1	1	1					-1	SKIN PANEL	.064 × 24 × 72 [illegible] STEEL SHEET			

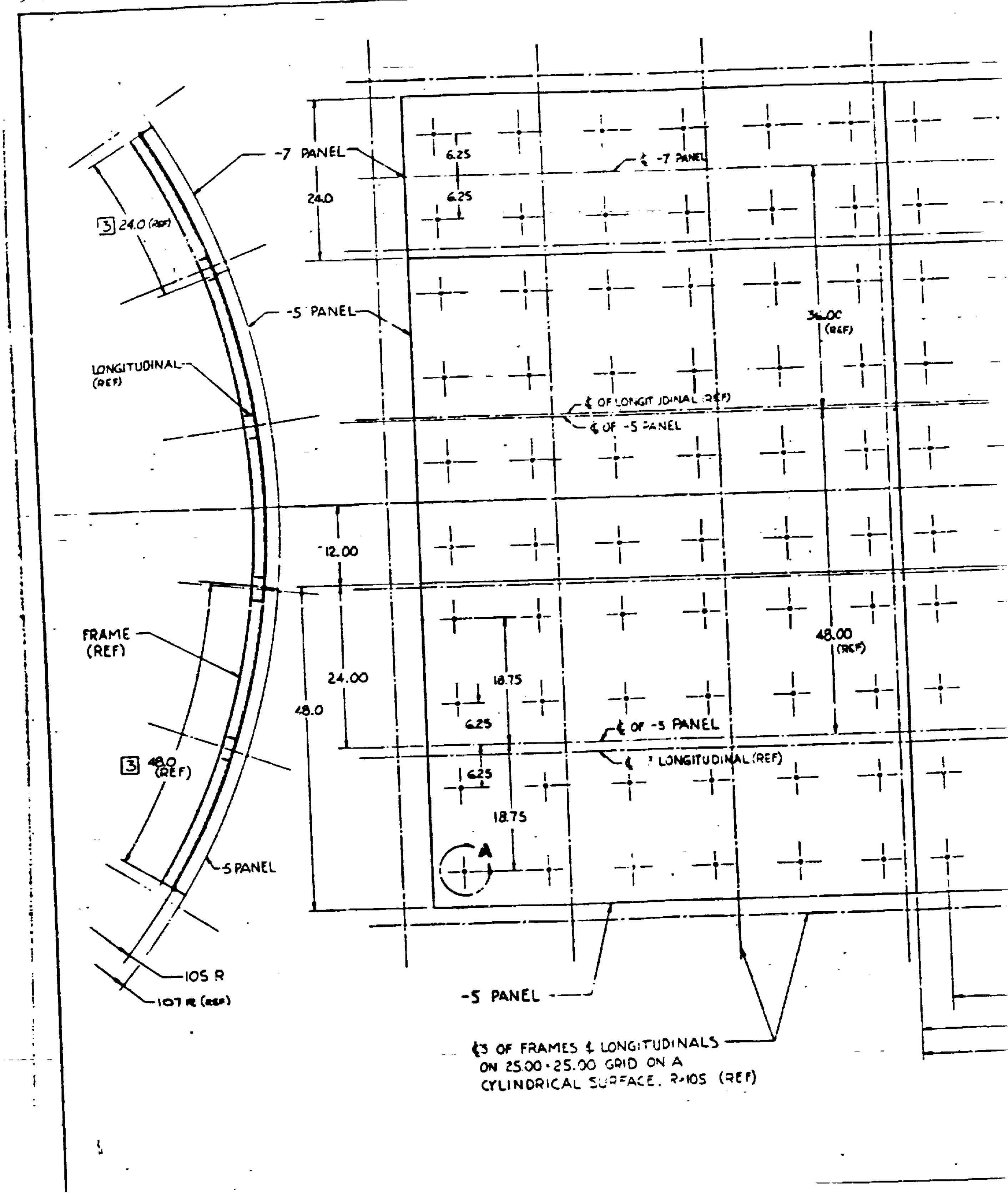
PARTS LIST

UNLESS OTHERWISE SPECIFIED DIM ARE IN INCHES TOLERANCES ON FRACTIONS ± 1/16 DECIMALS .X ± .1 .XX ± .03 .XXX ± .010 ANGLES ± 2°

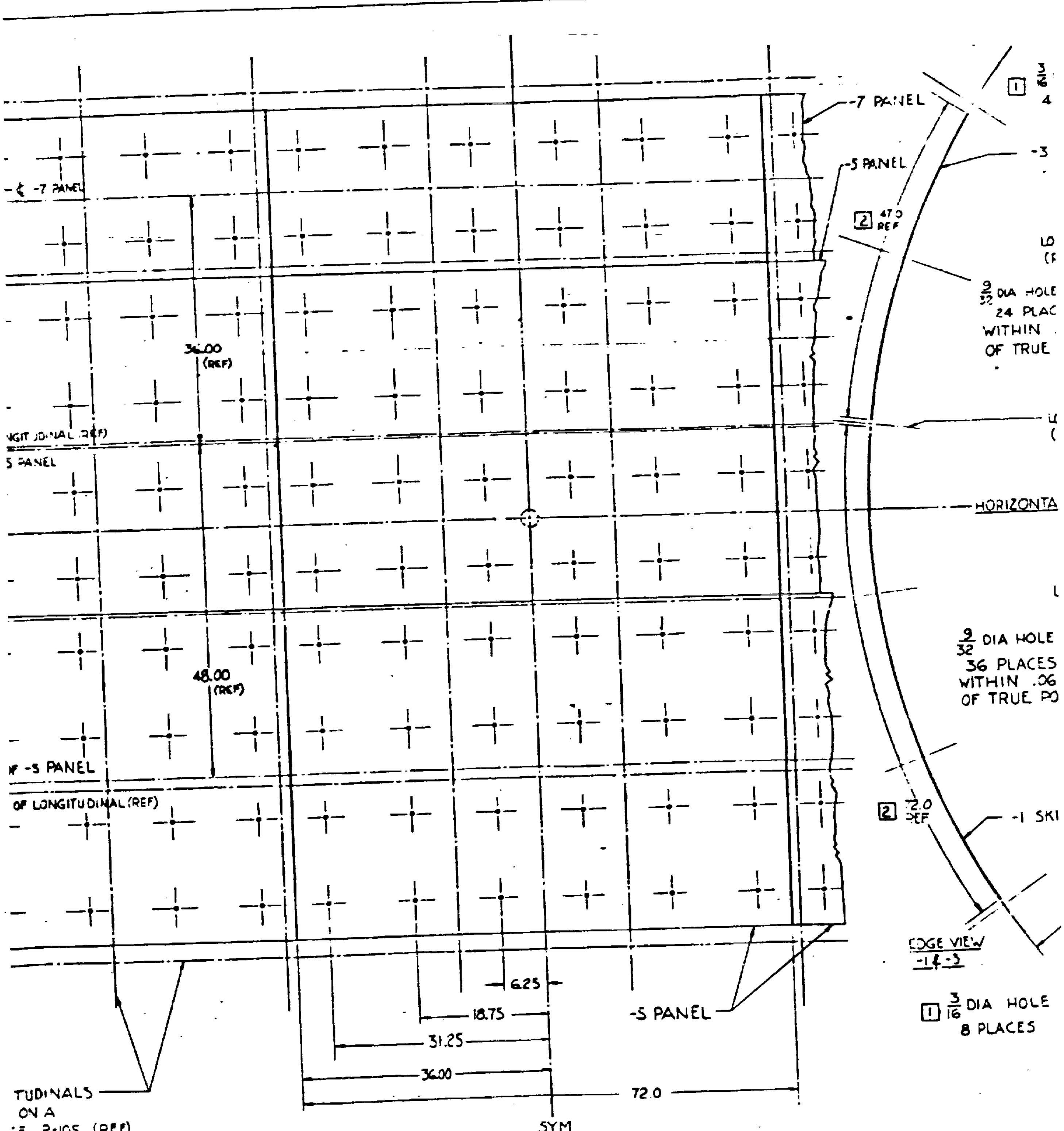
LOCKHEED MISSILES & SPACE COMPANY

ABLATIVE PANEL MOCKUP — DETAILS & ASSEMBLY

FOLDOUT FRAME 1

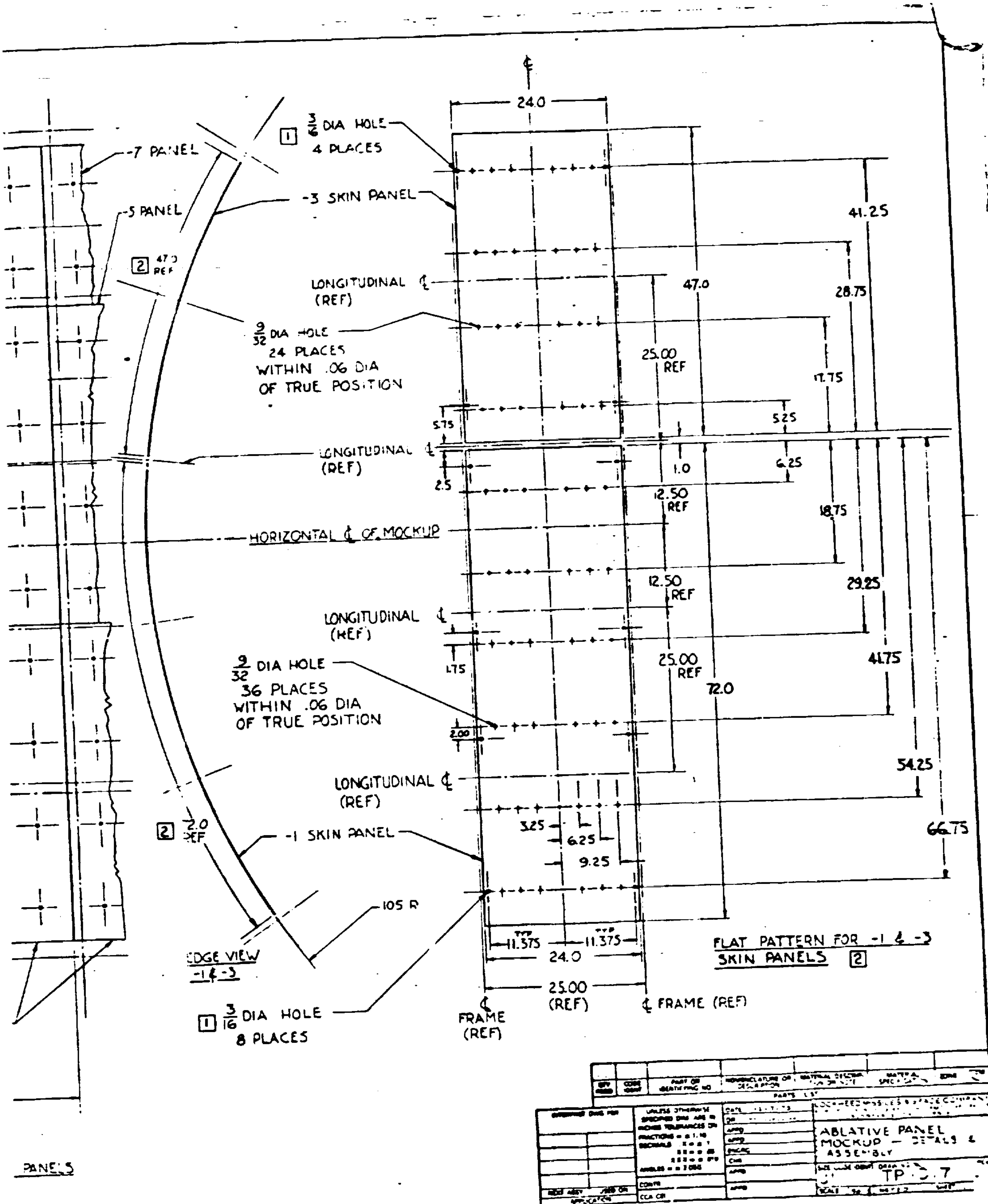


FOLDOUT FRAME 2



3 INSIDE SURFACE OF -5 & -7 ABLATIVE PANELS DEVELOPED INTO A PLANE

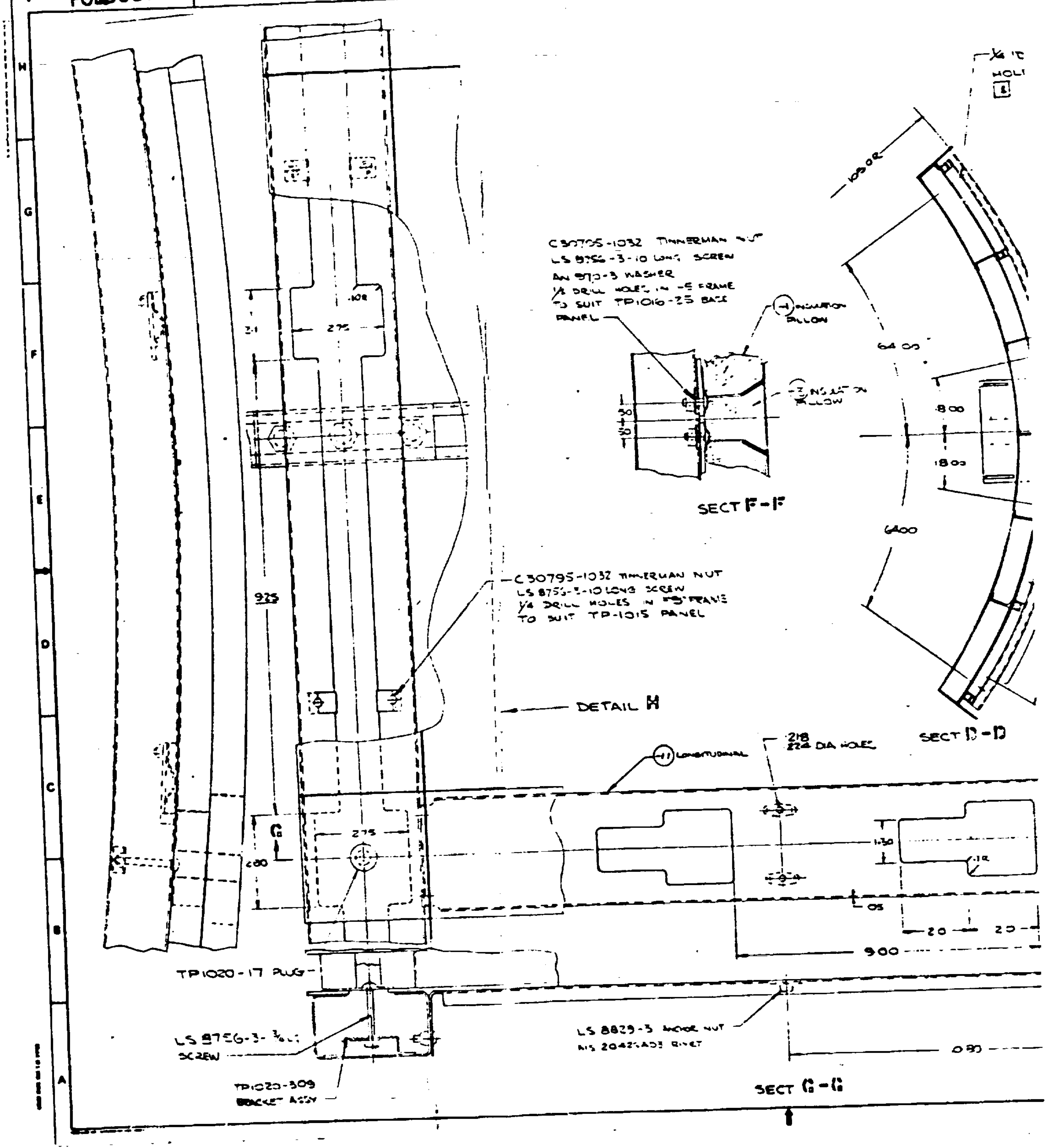
FOLDOUT FRAME 3



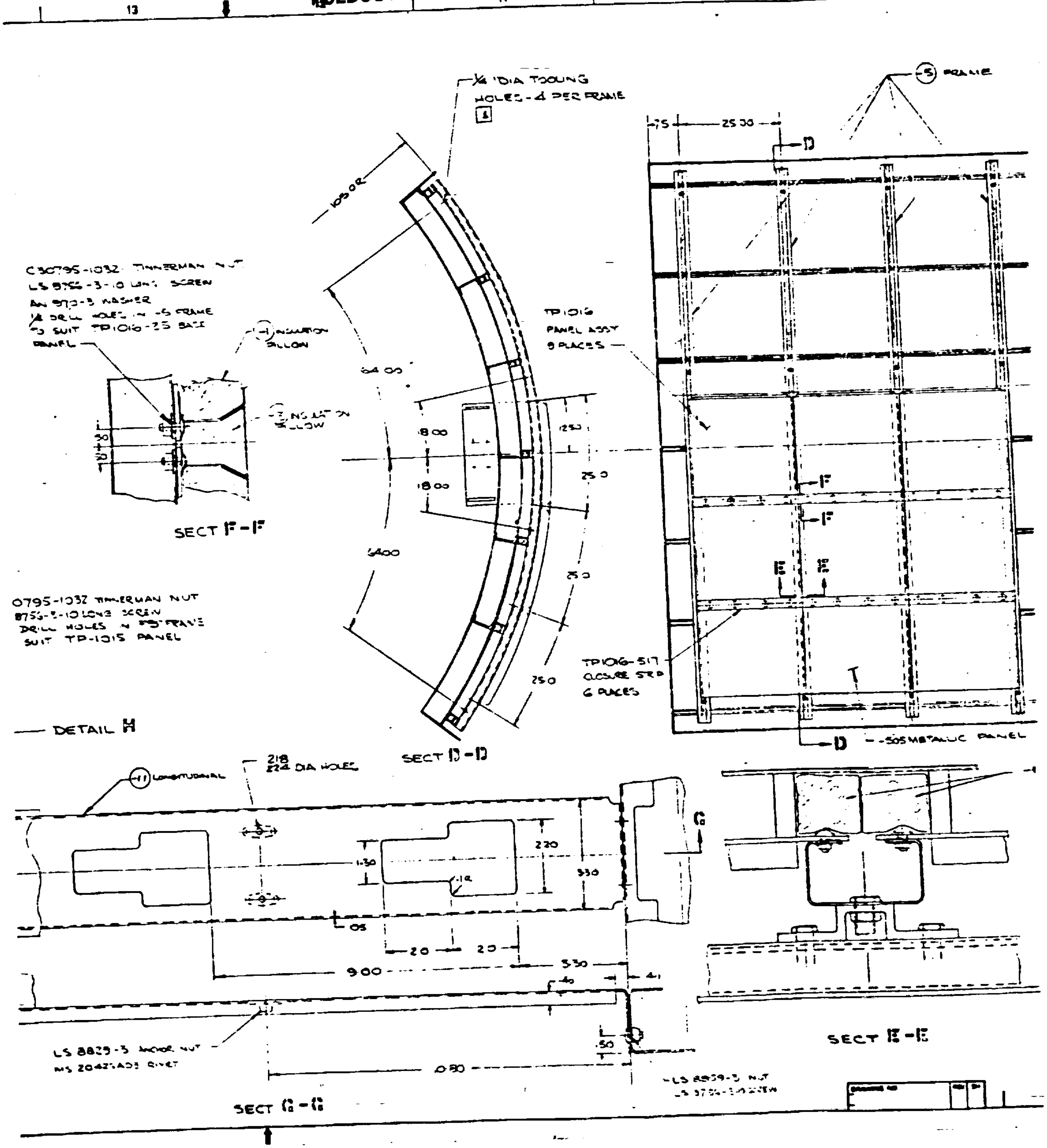
PANELS

FOLDOUT FRAME 1

FOLDOUT FRAME 2



FOLDOUT FRAME 2



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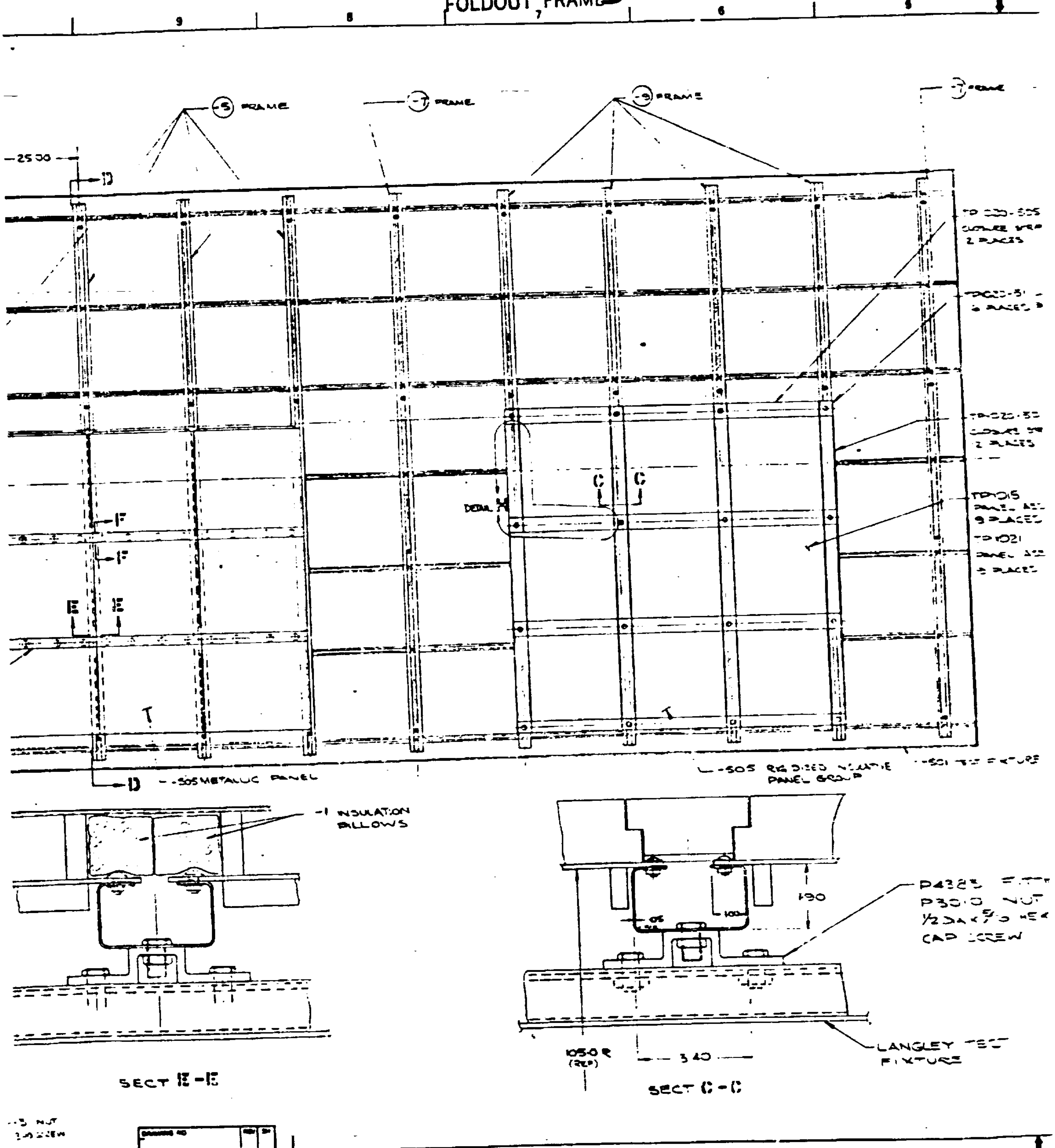

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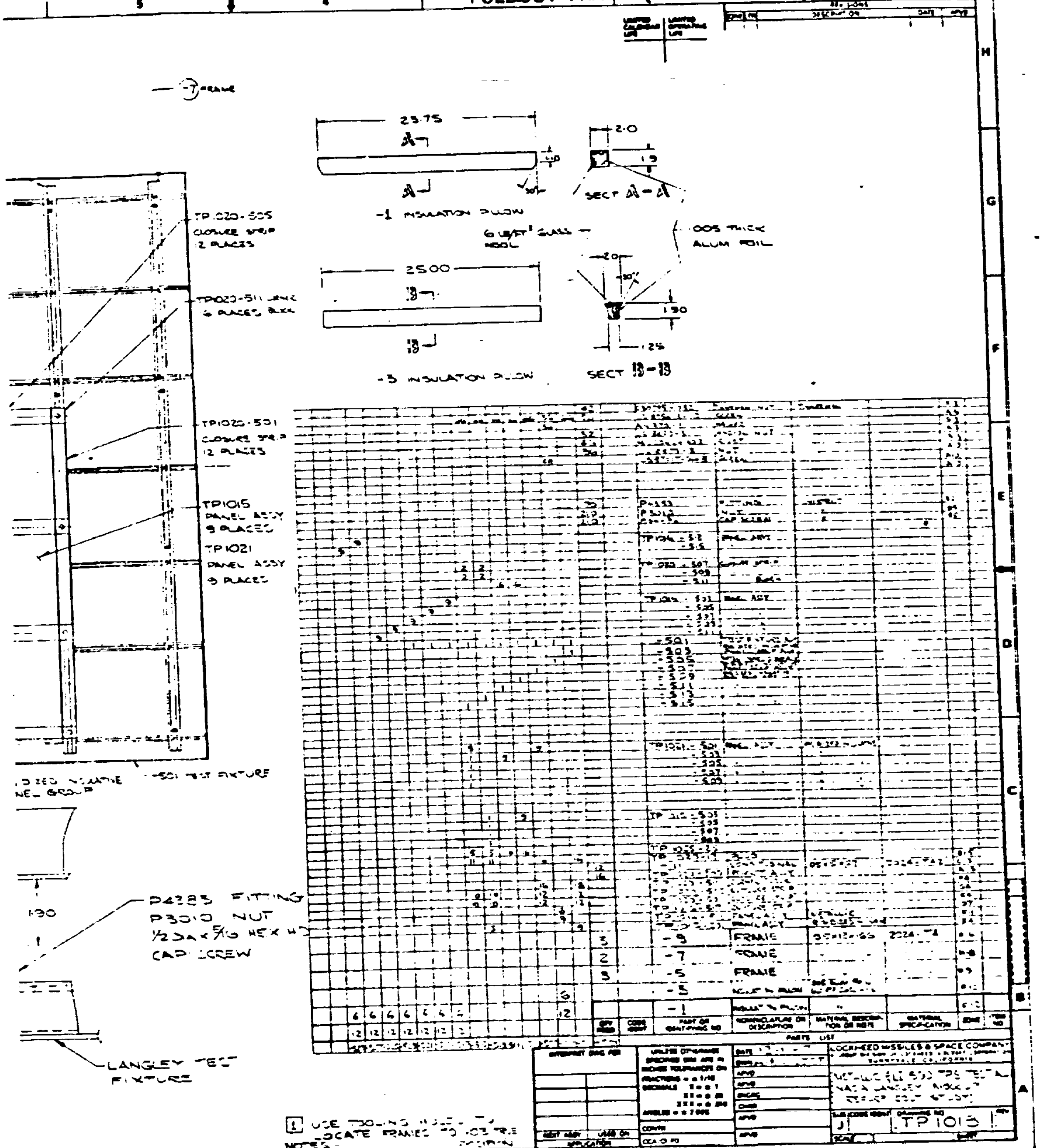

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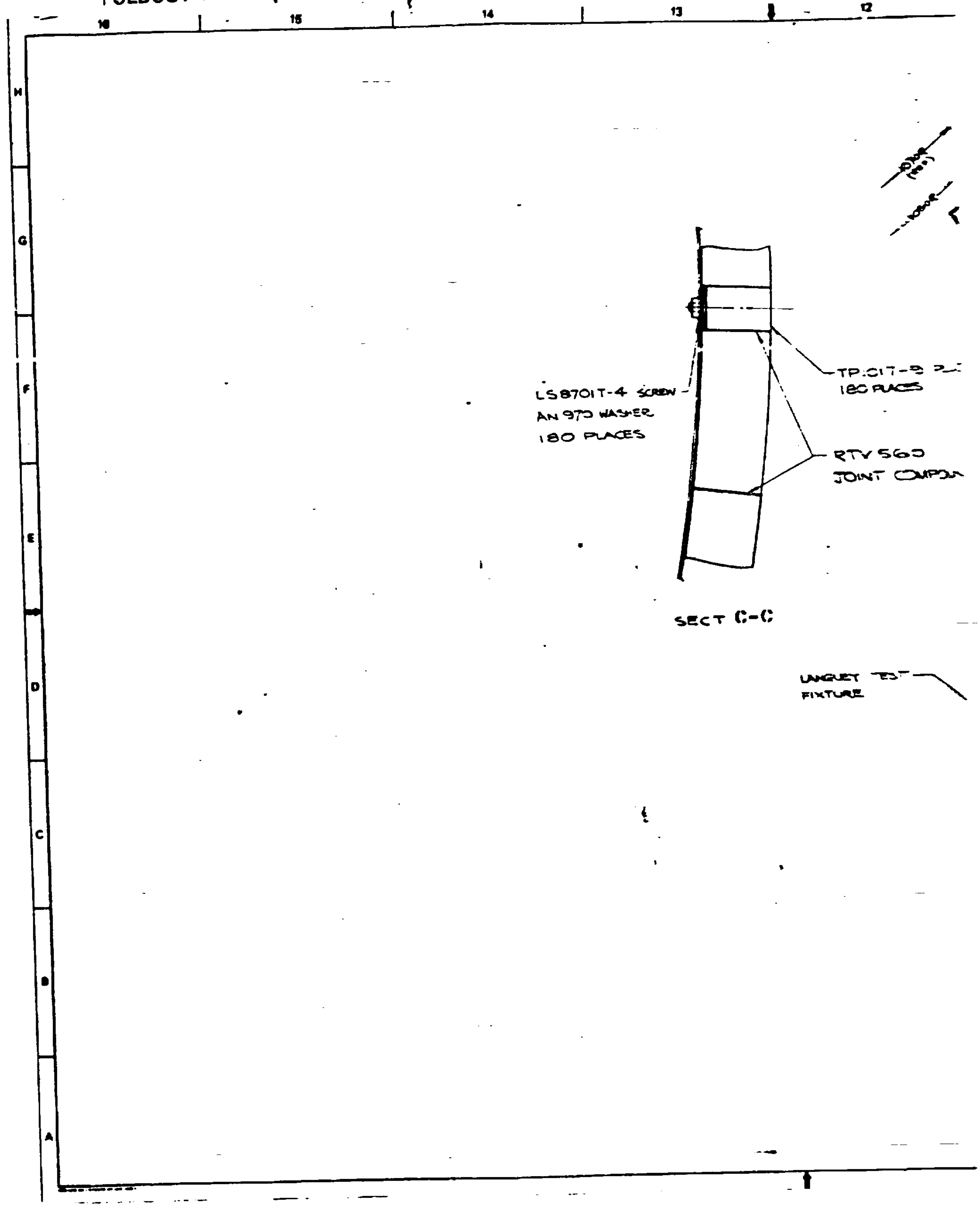

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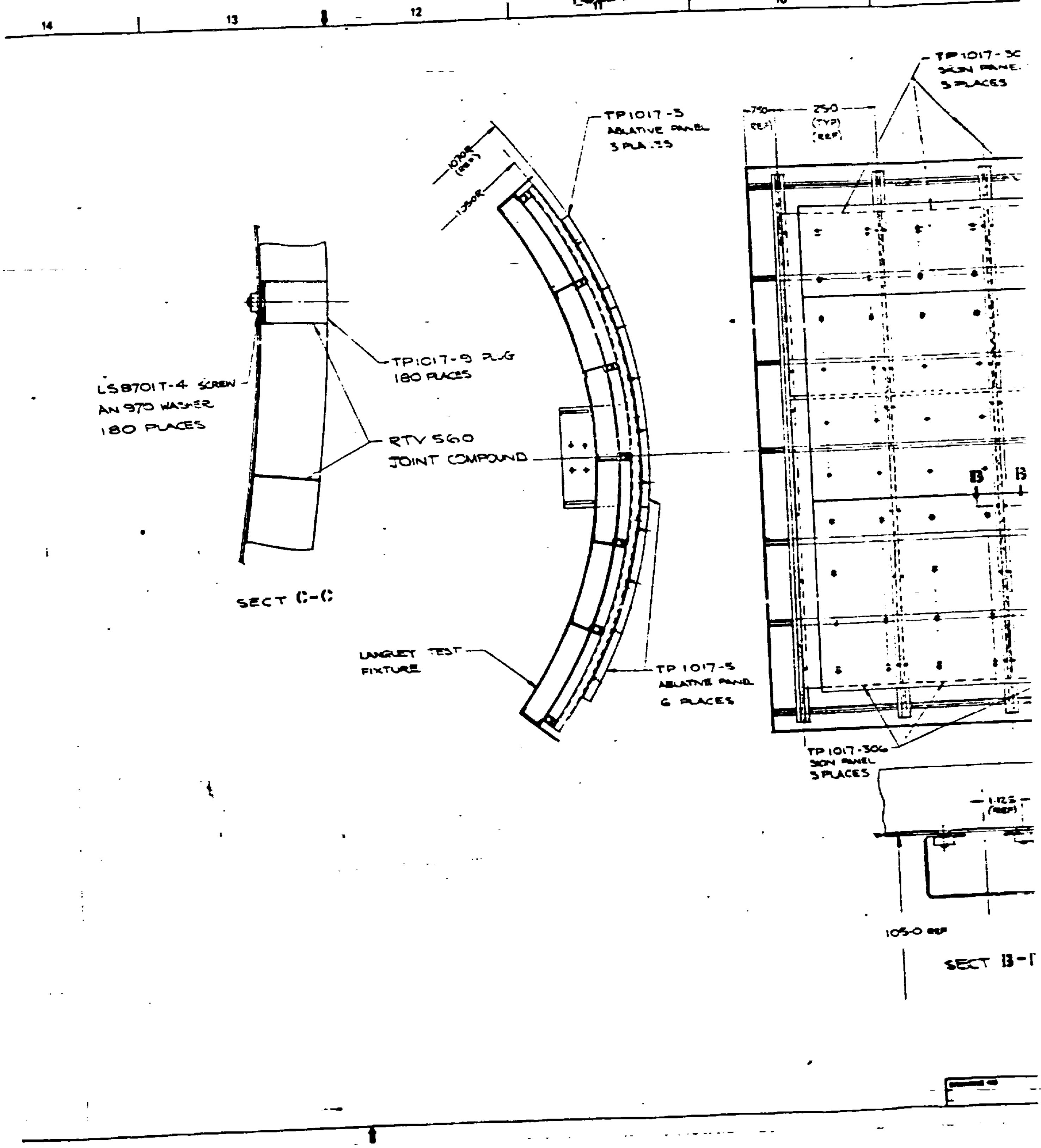
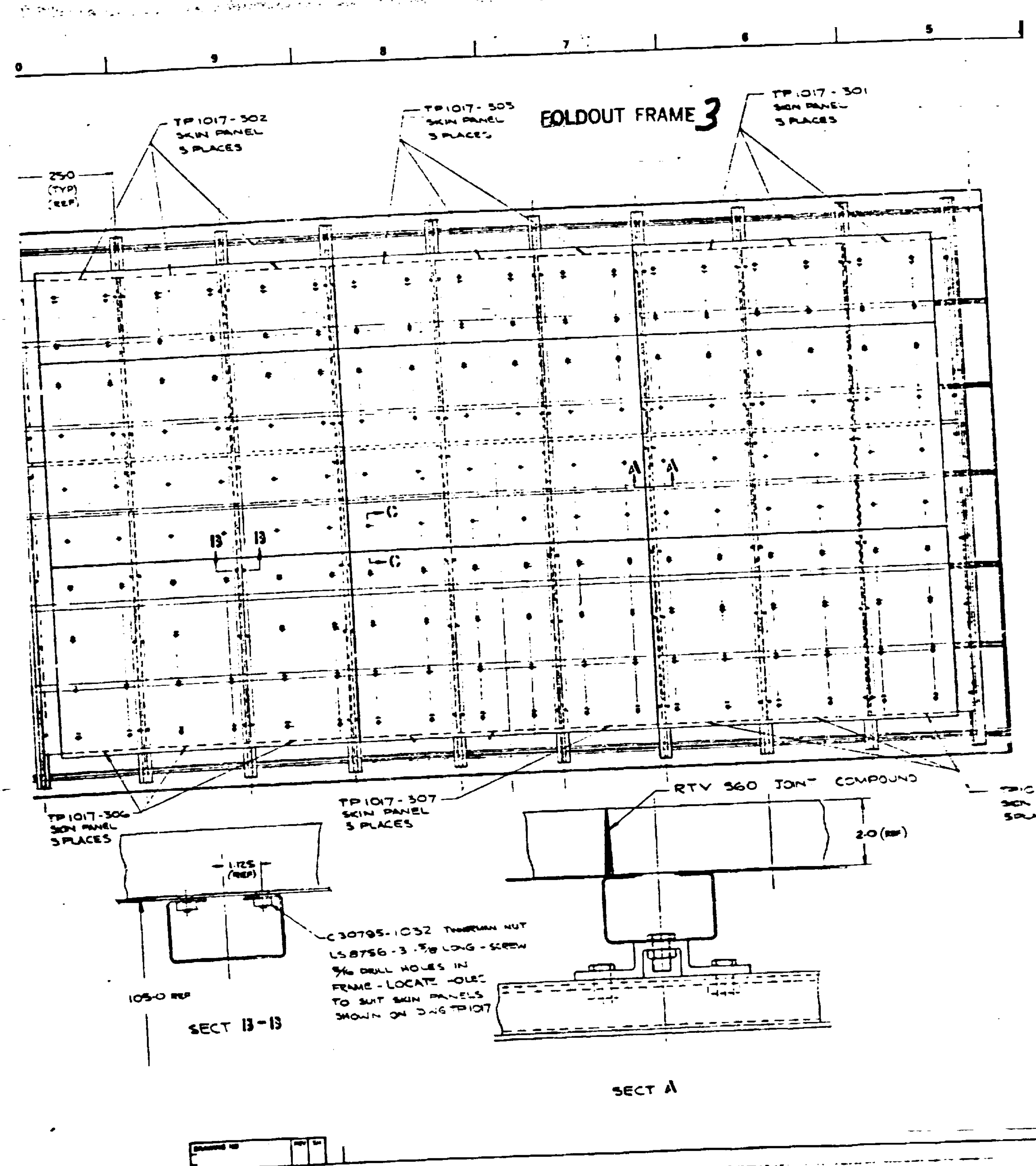
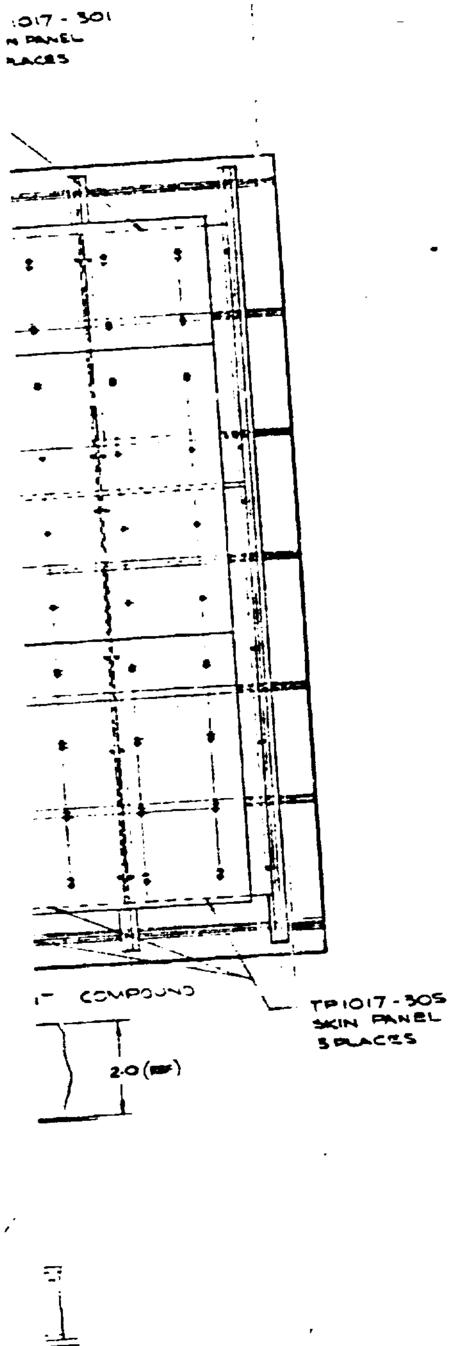


FOLDOUT FRAME 3



FOLDOUT FRAME 4



QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO
180		AN 970-4	WASHER			P14	
180		LS 87017-4	SCREW			P14	
108		LS 8756-3-7	SCREW			B8	
108		C 30796-1032	TINNERMAN			B8	
180		TP1017-9	PLUG				
3		TP1017-7	ABLATIVE PANEL				
6		TP1017-5	ABLATIVE PANEL				
3		TP1017-307	PANEL ASSY				
3		TP1017-306					
3		TP1017-305					
1		TP1017-303					
1		TP1017-302					
1		TP1017-301	PANEL ASSY				

PARTS LIST

LOCKHEED MISSILES & SPACE COMPANY
SUNNYVALE, CALIFORNIA

ABLATIVE TPS TEST ASSY
NASA LANGLEY MOCKUP
REFURB COST STUDY

UNLESS OTHERWISE SPECIFIED DIMS ARE IN INCHES TOLERANCES ON FRACTIONS = ± 1/16 DECIMALS X = ± .1, .XX = ± .03, .XXX = ± .010 ANGLES = ± 1 DEG

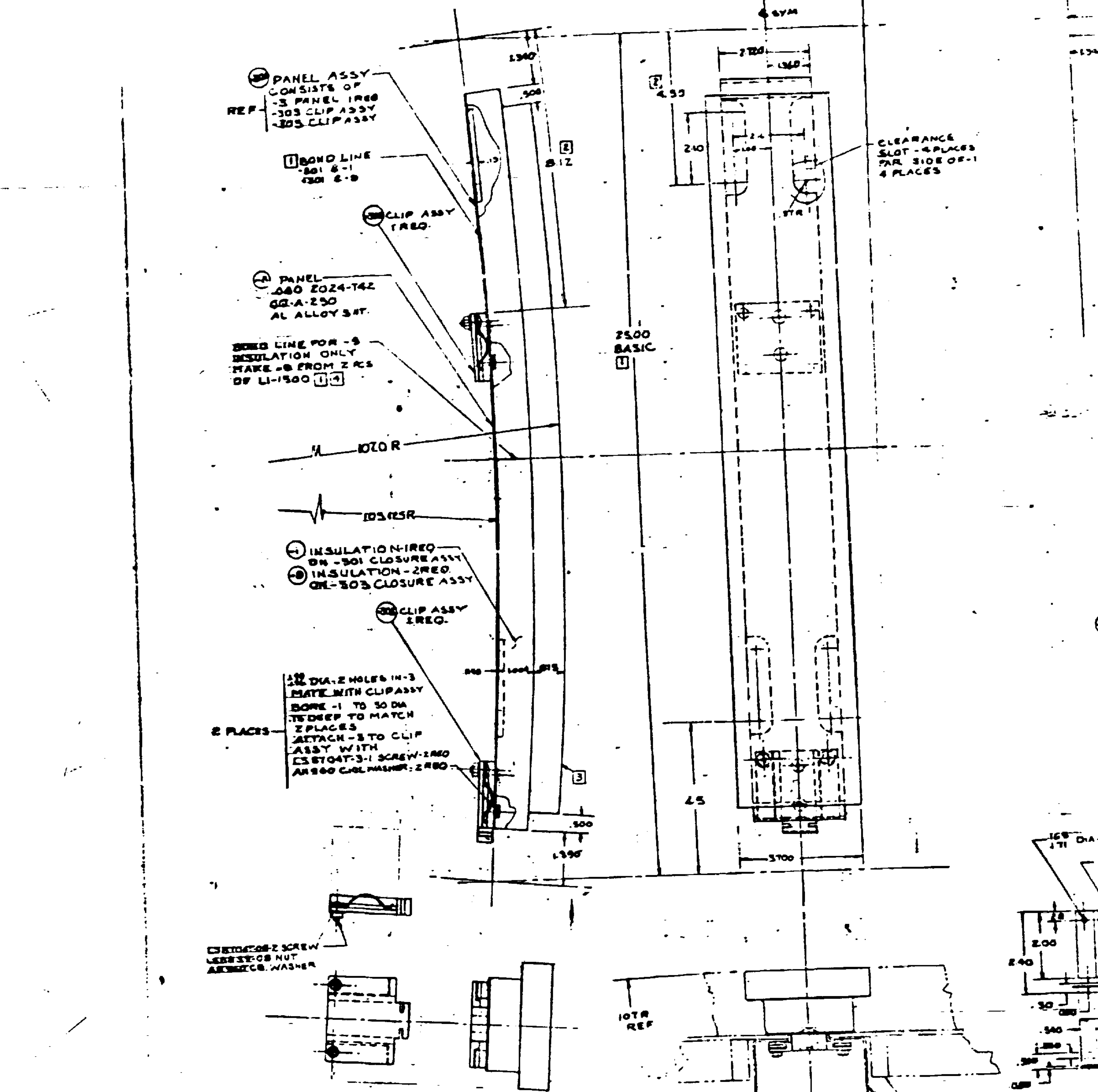
DATE | DRN | APVD | APVD | ENGRG | CHKR | APVD | APVD

SIZE J | CODE IDENT | DRAWING NO TP1019

SCALE | SHEET

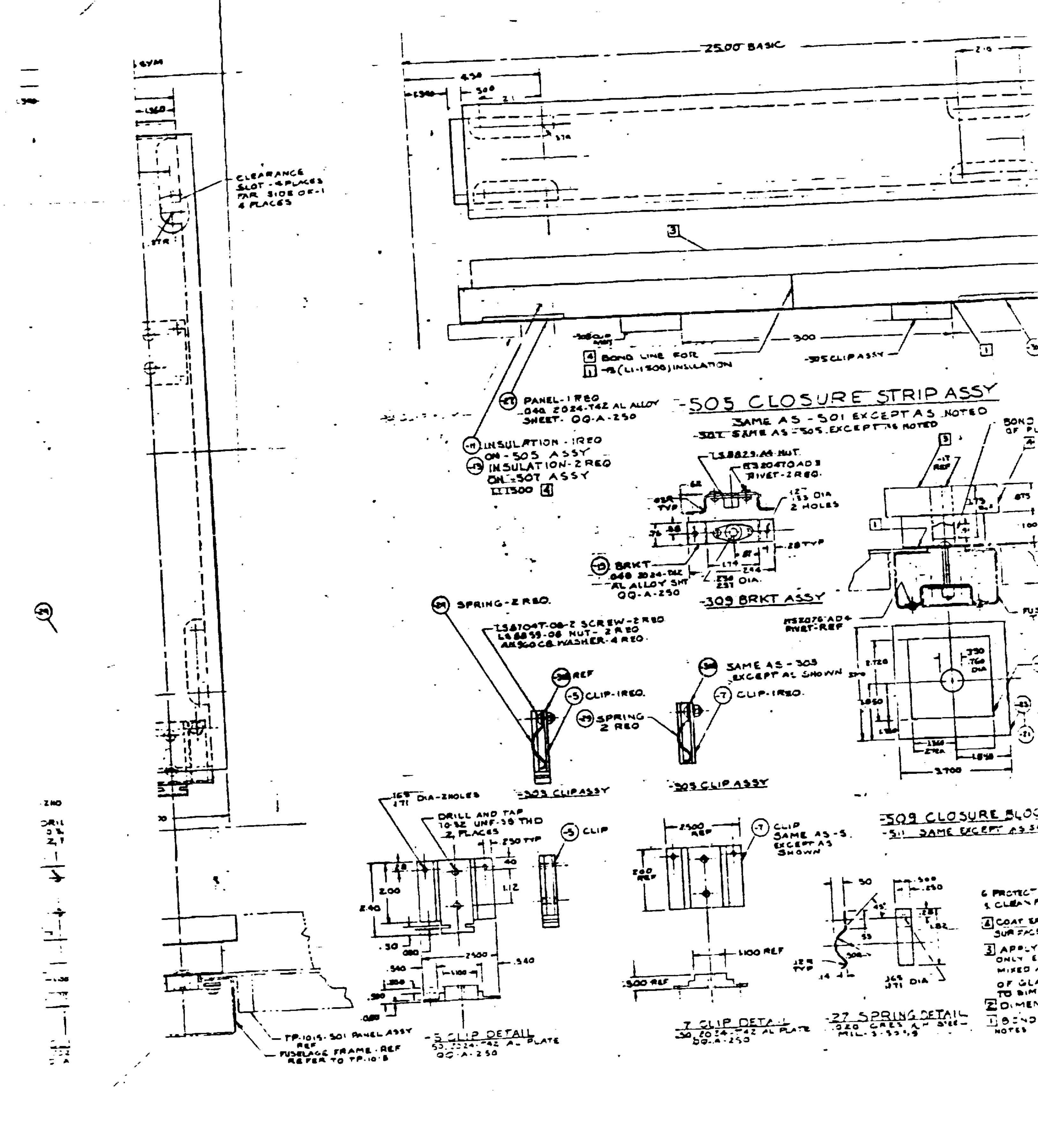
NEXT ASSY | USED ON | APPLICATION | CONTR | CCA/O. FD

FOLDOUT FRAME

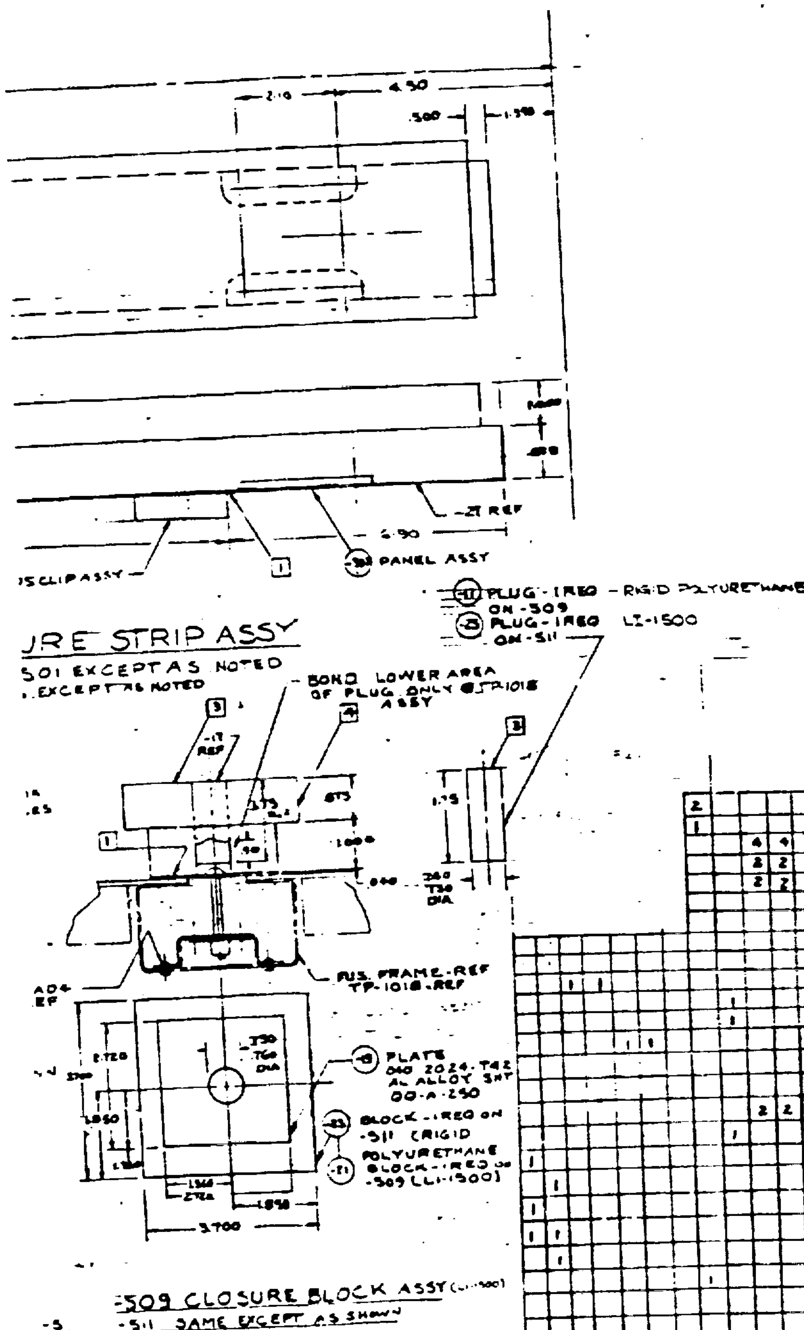


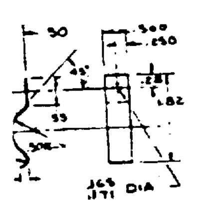
501 CLOSURE ASSY
-503 SAME EXCEPT AS NOTED

FOLDOUT FRAME 2



FOLDOUT FRAME 3





7 SPRING DETAIL
.020 CRES 1/4 H STEEL
MIL-S-5059

6 PROTECT PER LAC SPEC 1001
5 CLEAN PER LAC SPEC 0170
4 COAT EXPOSED SIDE SURFACE WITH SILICONE
3 APPLY TOP SURFACE ONLY EPOXY FLOOR COVERING MIXED WITH APPROPRIATE AMOUNT OF GLASS BEAD (MICRO SIZE) FILLER TO SIMULATE CERAMIC COATING
2 DIMENSIONS IN PLANE OF SHEET @ 105 R.
1 BOND PER LAC 30-4435
NOTES

PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION
RIVET	MS20470AD3		
NUT	LS8829A4		
WASHER	AN960C8		
NUT	LS8887-08		
SCREW	LS8709T-08-1		
-310	BLOCK ASSY		
-308	BRKT ASSY		
-307	PANEL ASSY		
-305	CLIP ASSY		
-303	CLIP ASSY		
-306	PANEL ASSY		
-29	SPRING	[illegible]	MIL-S-5059
-27	PANEL	.040 x 40 x 340	2024-T42 QQ-A-250
-25	PLUG	1.0 DIA x 2.0	LI-1500
-23	BLOCK	4.0 x 4.0 x 2.0	POLYURETHANE FOAM-RIGID
-21	BLOCK	4.0 x 4.0 x 2.0	LI-1500
-19	PLATE	3.0 x 3.0 x .040	2024-T42 QQ-A-250
-17	PLUG	1.0 DIA x 2.0	POLYURETHANE FOAM-RIGID
-15	BRKT	.080 x 1.0 x 3.0	2024-T42 QQ-A-250
-13	INSULATION	20 x 40 x 2.0	LI-1500
-11	INSULATION	20 x 40 x 2.0	RIGID FOAM POLYURETHANE
-9	INSULATION	20 x 40 x 1.2	LI-1500
-7	CLIP	[illegible]	2024-T42 QQ-A-250
-5	CLIP	[illegible] x 3.0 x 1.0	2024-T42 QQ-A-250
-3	PANEL	.040 x 40 x 56.0	2024-T42 QQ-A-250
-1	INSULATION	20 x 40 x 2.0	RIGID FOAM POLYURETHANE

PARTS LIST

LOCKHEED MISSILES & SPACE COMPANY

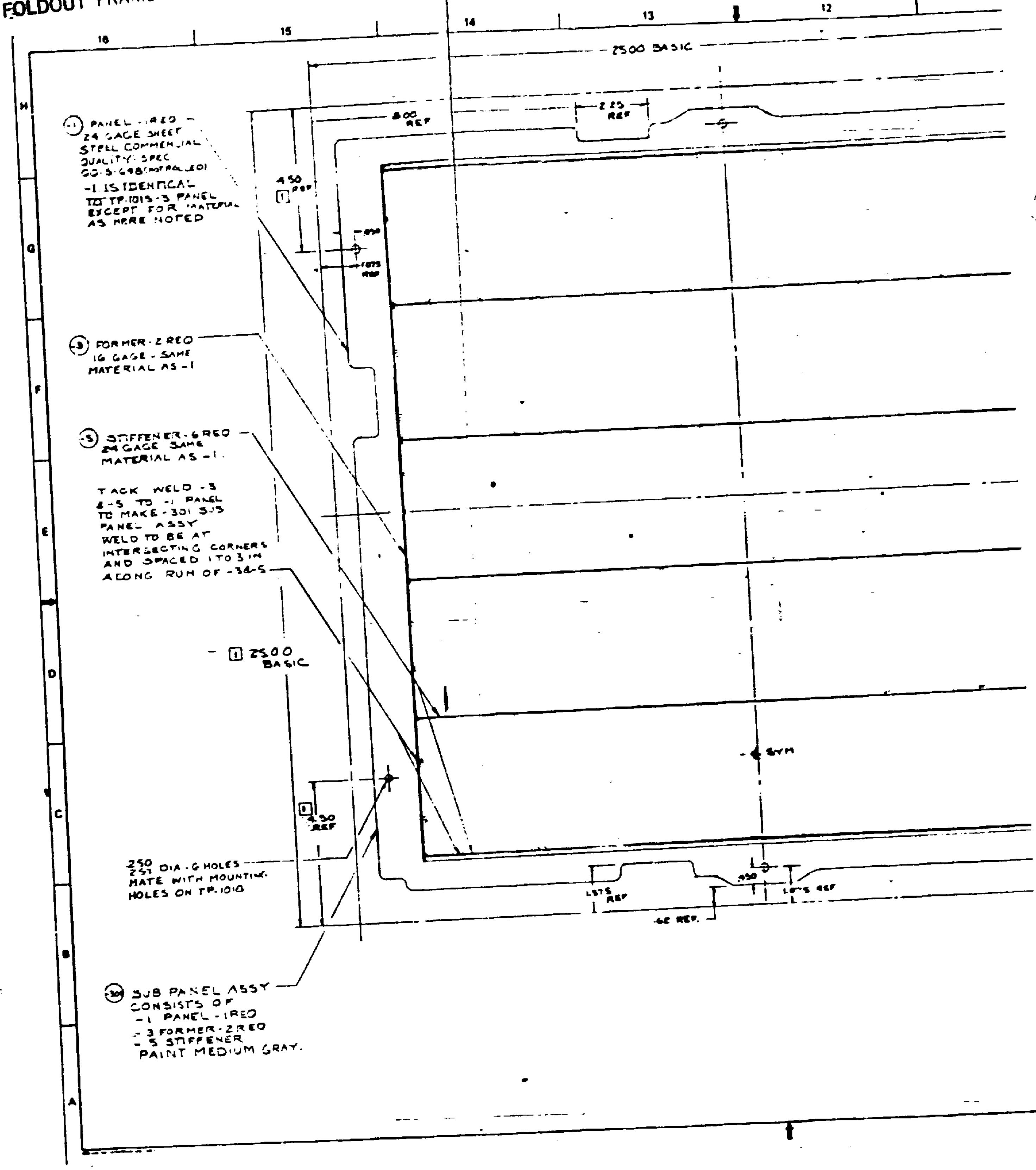
CLOSURES ASSEMBLIES NON METALLIC MOCK UP FRAME TO FRAME ATTACH

TP 1020

TP 1015

FOLDOUT FRAME

FOLDOUT FRAME



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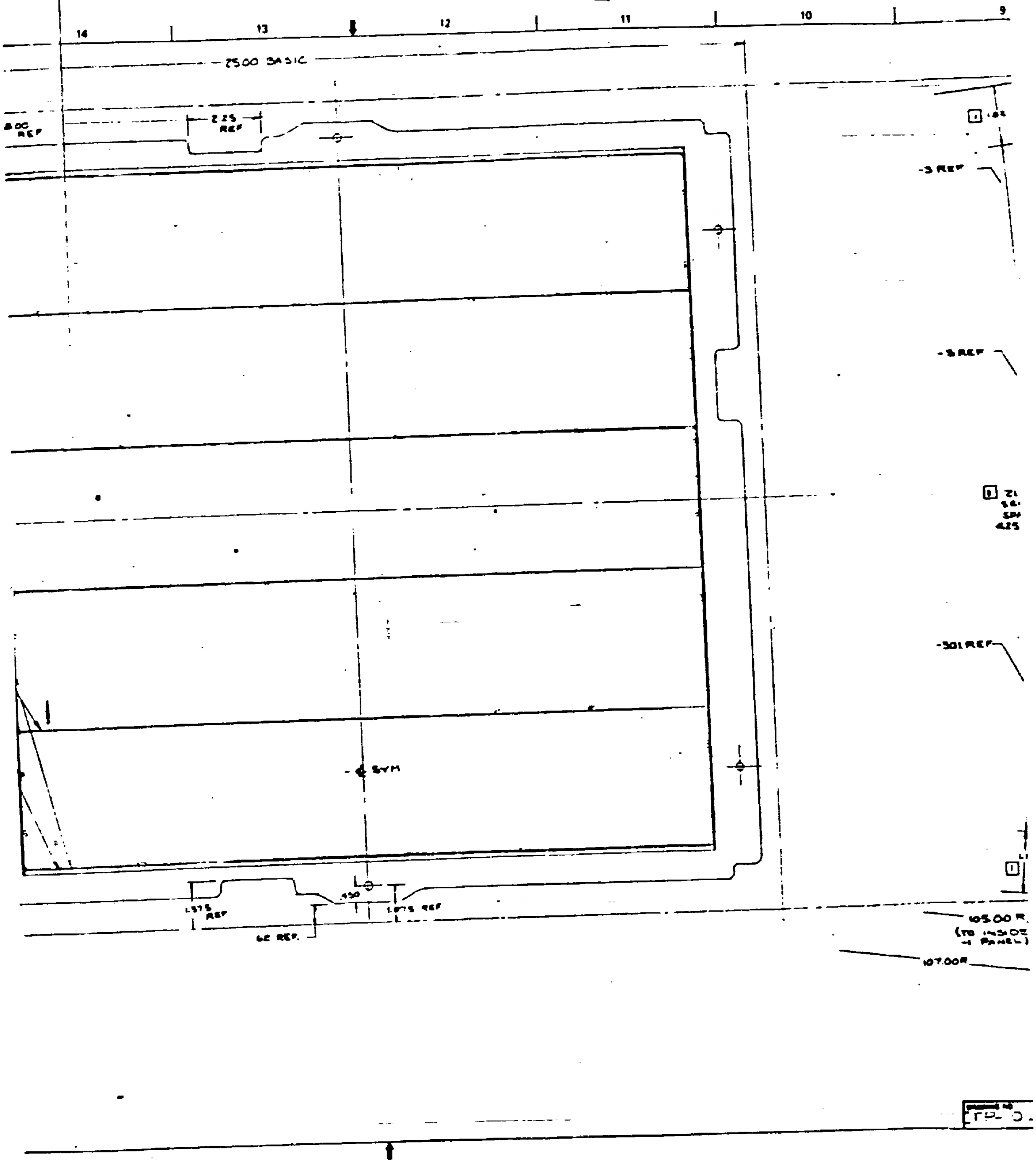

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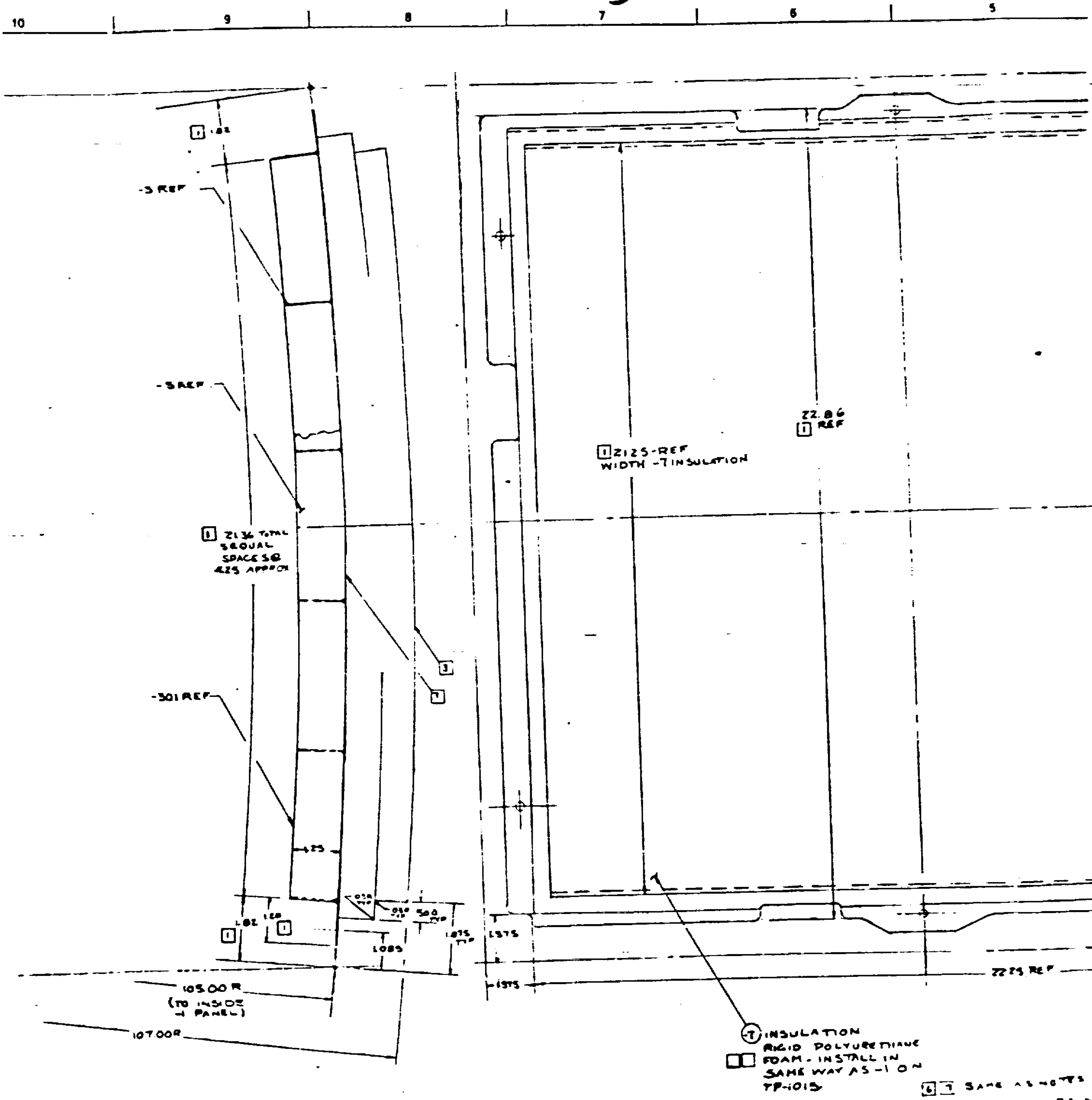
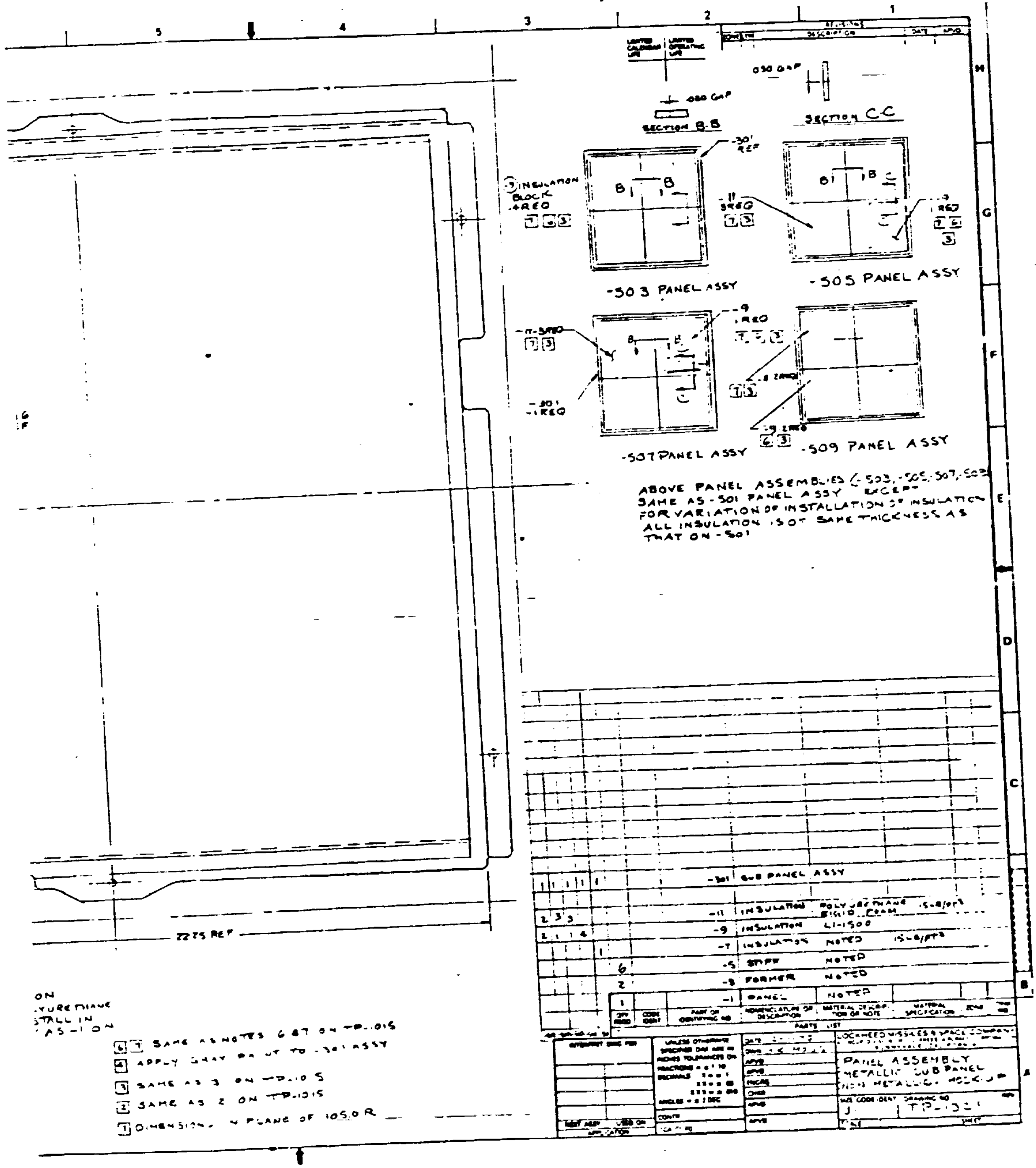


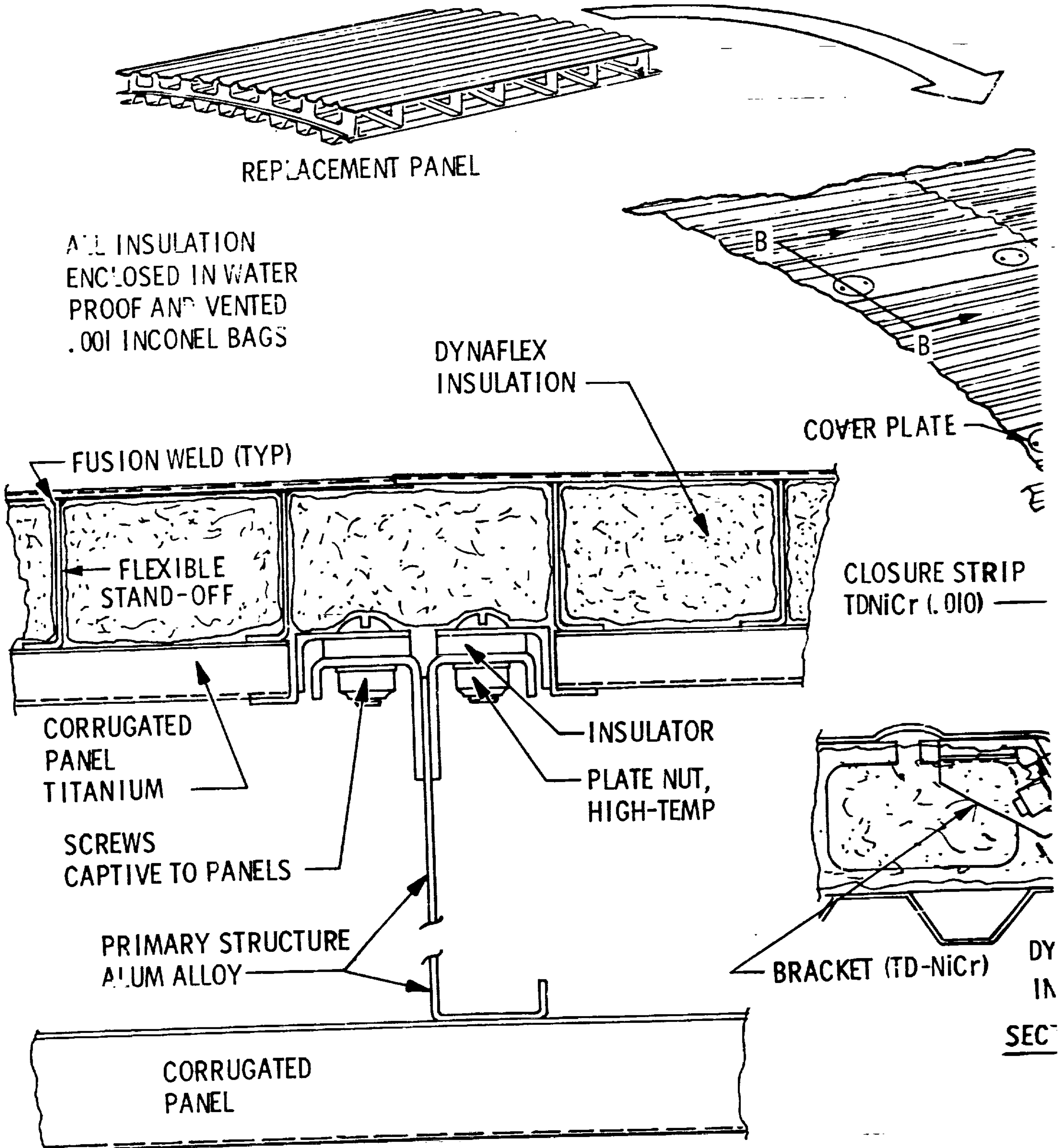
-501 PANEL ASSY

TP- D

FOLDOUT FRAME 4



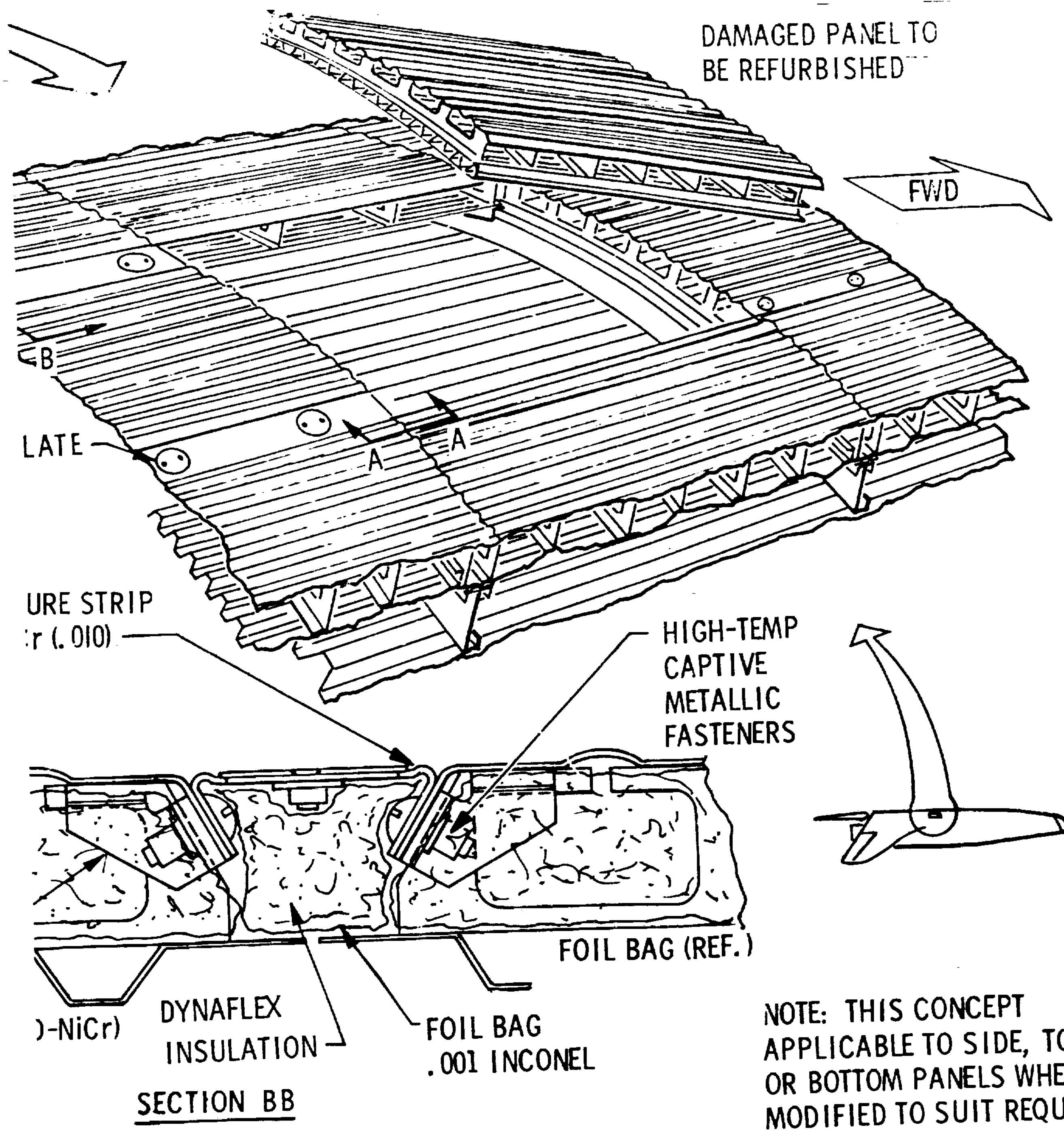
FOLDOUT FRAME 1



SECTION AA

CONCEPT

FOLDOUT FRAME 2



NOTE: THIS CONCEPT APPLICABLE TO SIDE, TOP, OR BOTTOM PANELS WHEN MODIFIED TO SUIT REQUIRED NEED

LO-2097B

CORRUGATED HEAT SHIELD PANELS

CONCEPTUAL ONLY