NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-716

Thermoelectric Outer Planets Spacecraft (TOPS) Electronic Packaging and Cabling Development Summary Report

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December 15, 1974

PREFACE

The work described in this report was performed by the Applied Mechanics Division of the Jet Propulsion Laboratory.

ACKNOWLEDGMENT

The successful accomplishment of the TOPS packaging and cabling development tasks required the contributions and support of many individuals. The authors are particularly indebted to the following: S. J. Raimey, for his invaluable help with the detailed design and drawings; R. A. McCreary, for configuration development; R. Bamford, for constructive comments on structural design; C. R. King and A. L. Prisk, for connector and cabling developments; J. T. Rice and A. G. Fitak, for microcircuit package development; C. F. Krinke and M. S. Bickler, for development of hybrid microelectronic devices; and M. S. Bickler and G. M. Thompson, for preparation and testing of samples used in the joining technique and Module developments. The authors also wish to thank J. O. Lonborg for his many contributions to the preparation and editing of this report.

FOREWORD

The Thermoelectric Outer Planets Spacecraft (TOPS) project was an Advanced Systems Technology (AST) activity having as its objective the development of the mission, spacecraft, and subsystem technology required for advanced outer planets missions. It was not intended to develop a flight spacecraft, but rather, to identify and solve the key problems attendant with such missions, wherein the spacecraft is required to operate for as much as 10 years, at ranges as great as 30 AU from the sun, and during and after exposure to both natural and artificial radiation environments. This report describes the electronic packaging and cabling activities that were performed in support of the TOPS project, beginning in July 1969 and extending through the conclusion of the project, in December 1971.

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ABSTRACT

This document details electronic packaging and cabling activities performed in support of the Thermoelectric Outer Planets Spacecraft (TOPS) Advanced Systems Technology (AST) project. It describes new Electronic Compartment, Electronic Assembly, and Module concepts, and a new high-density, planar interconnection technique called Discrete Multilayer (DML). Development and qualification of high-density cabling techniques, using small-gage wire and microminiature connectors, are also reported.

THERMOELECTRIC OUTER PLANETS SPACECRAFT (TOPS)
ELECTRONIC PACKAGING AND CABLING DEVELOPMENT
SUMMARY REPORT

I. INTRODUCTION

The Thermoelectric Outer Planets Spacecraft (TOPS) project, which was concluded in December 1971, was an Advanced System Technology activity. Its broad objective was to develop and demonstrate the capability for performing advanced outer planets missions, such as the proposed Grand Tour. Project accomplishments included the establishment of mission requirements, the conceptual design of a spacecraft capable of satisfying those mission requirements, and the development of the new subsystem technology required to implement this spacecraft.

This report summarizes the electronic packaging and cabling activities that were performed under the TOPS project. These can be grouped in three categories: (1) establishment of packaging and cabling goals and concepts in support of system and spacecraft configuration development; (2) design of the Electronic Compartment and its subelements, and development of the new technology required for these; and (3) project support activities.

The packaging and cabling goal, based on past experience and on the unique requirements of TOPS, was to develop a new packaging and cabling system concept which would:

(1) Provide higher packaging and interconnection density.

(2) Provide the capability for performing electrical and mechanical system level operations in parallel.

(3) Minimize flight weight by making more extensive use of removable handling and assembly tooling, rather than building in these features.

(4) Conform to established JPL packaging principles, such as: use of connectors at all levels where field assembly or test is required, standardization of assembly and subassembly envelopes, inspectability of parts and joints, etc.

In this work, English Technical System units were used for primary measurements and calculations. Conversion to International System (SI) units was done for reporting purposes only.

II. PACKAGING AND CABLING SYSTEM CONCEPT

Historically, JPL/NASA planetary spacecraft have been built around a basic bus such as that shown in Fig. 1. Modularly packaged electronic equipment is mounted in standardized chassis, which are attached to the primary structure to form an open-cored polygon (an octagon on the most recent Mariners). Two levels of cabling are used: case harnesses for intraconnection within electronic assemblies and ring harnesses for interconnection between electronic assemblies. The interior of the polygon houses other spacecraft equipment (e.g., propellant tankage), but is still relatively open, for good radiative heat transfer within the bus. The open interior also allows access for plug-in of system level connectors. Other equipment (e.g., solar panels and antennas) is mounted on the outside of the bus. There is a fairly high degree of integration, both of the electronic equipment within itself and of this with other spacecraft equipment.

As the TOPS project progressed, several things became apparent: that the trend toward a decreasing ratio of electronic equipment to total spacecraft weight would continue; that the equivalent parts count would increase by an order of magnitude over that of current Mariners; that subsystem interconnections would increase (perhaps double); and that the increased complexity and functional capability of the spacecraft would impose additional demands on system test and assembly operations. Thus, it was evident that the Electronic Compartment should be highly integrated, should employ high-density packaging techniques, and should be separable from the remainder of the spacecraft to facilitate parallel electrical and mechanical operations.

The TOPS packaging concept, as it finally evolved, is a significant departure from previous practice. The major portion of the spacecraft electronics--that which performs housekeeping functions (e.g., communications, computing,

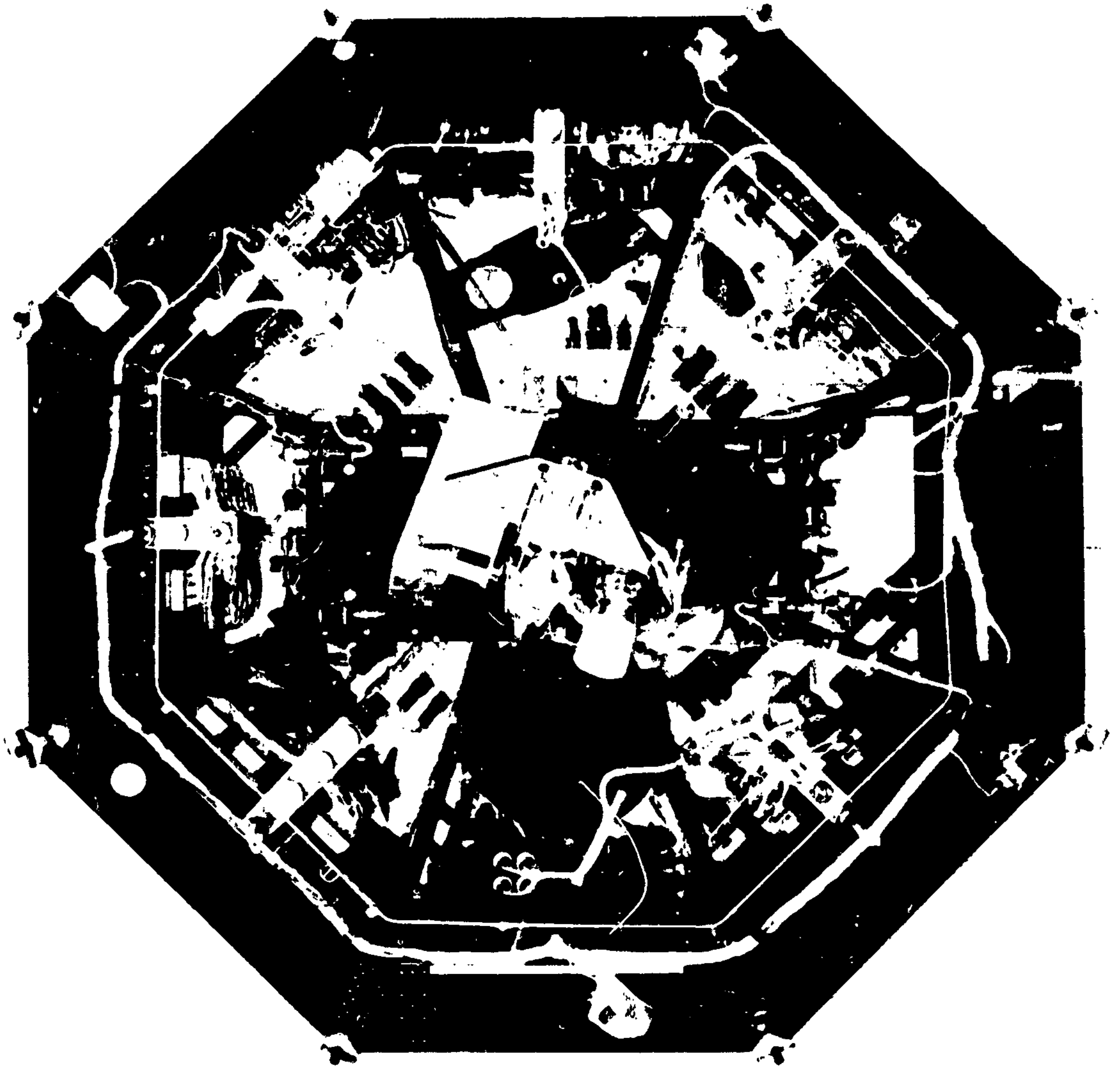


Fig. 1. Octagonal Spacecraft Bus with Electronic Assemblies and Harnesses

control, power conditioning and switching, etc.)--is contained in a rectangular Electronic Comparment (EC), as shown in Fig. 2. Electronic Assemblies (EAs) plug into the EC from two opposite faces, requiring blind insertion. While some of the EAs would be packaged otherwise, it is envisioned that many would employ the plug-in modular construction illustrated in Fig. 3. Electronic Assembly intraconnection is by means of fixed wiring on one side of the EA chassis. The Mariner ring harnesses are replaced in the TOPS packaging concept by system cabling that is located in a core passing through the center of the Compartment. Figure 4 shows spacecraft configuration 12L, which was selected as the baseline for the TOPS project. The EC is removable as a unit.

It will be observed that the packaging concept described generally meets the previously stated goals. The TOPS Electronic Compartment was envisioned as a multi-use, bolt-on engineering package; quantity fabrication would result in cost and reliability advantages. Reference 1 describes the TOPS packaging and cabling concept, and the rationale for its selection in more detail.

III. PACKAGING AND CABLING DEVELOPMENT

The following key elements were required to establish and demonstrate the feasibility of the TOPS packaging concept:

(1) Design and development of a packaging system satisfying structural, thermal, and dynamic requirements, and including: the Electronic Compartment, Electronic Assembly, and Module (Subassembly).

(2) Design and development of cabling and electrical interconnections at the system, assembly, and module levels having four times greater pin density than on Mariners.

(3) Packaging process and part development to support (1) and (2).

(4) Testing and evaluation of (1) and (2), using (3), to establish reliability and confidence levels.

(5) Application and integration of these developments into the subsystem areas.

The following subsections summarize the accomplishments in these areas. Although developments are reported in groups, it must be recognized that many of these are highly interdependent in the development of an integrated packaging

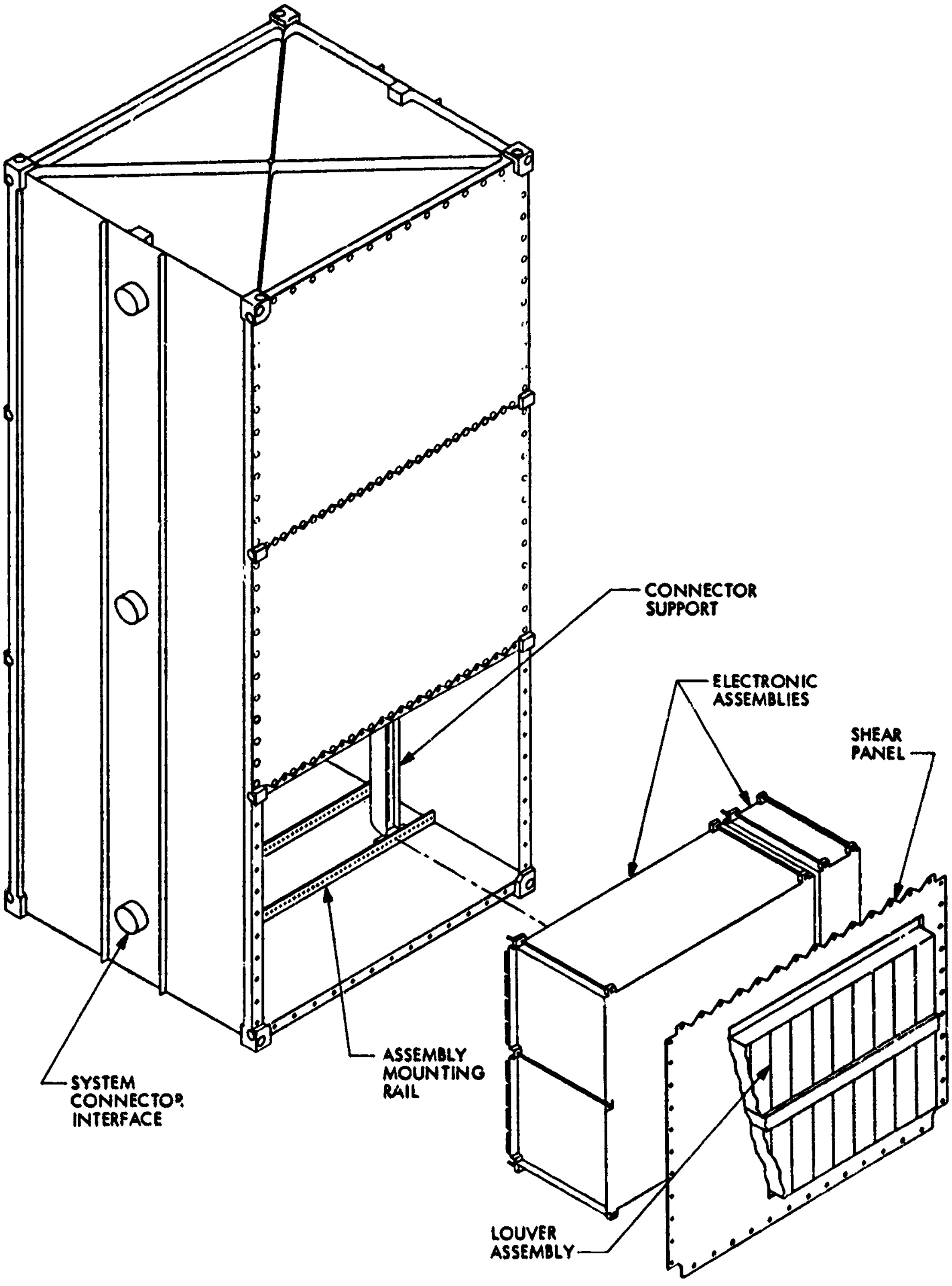


Fig. 5. TOPS Electronic Compartment

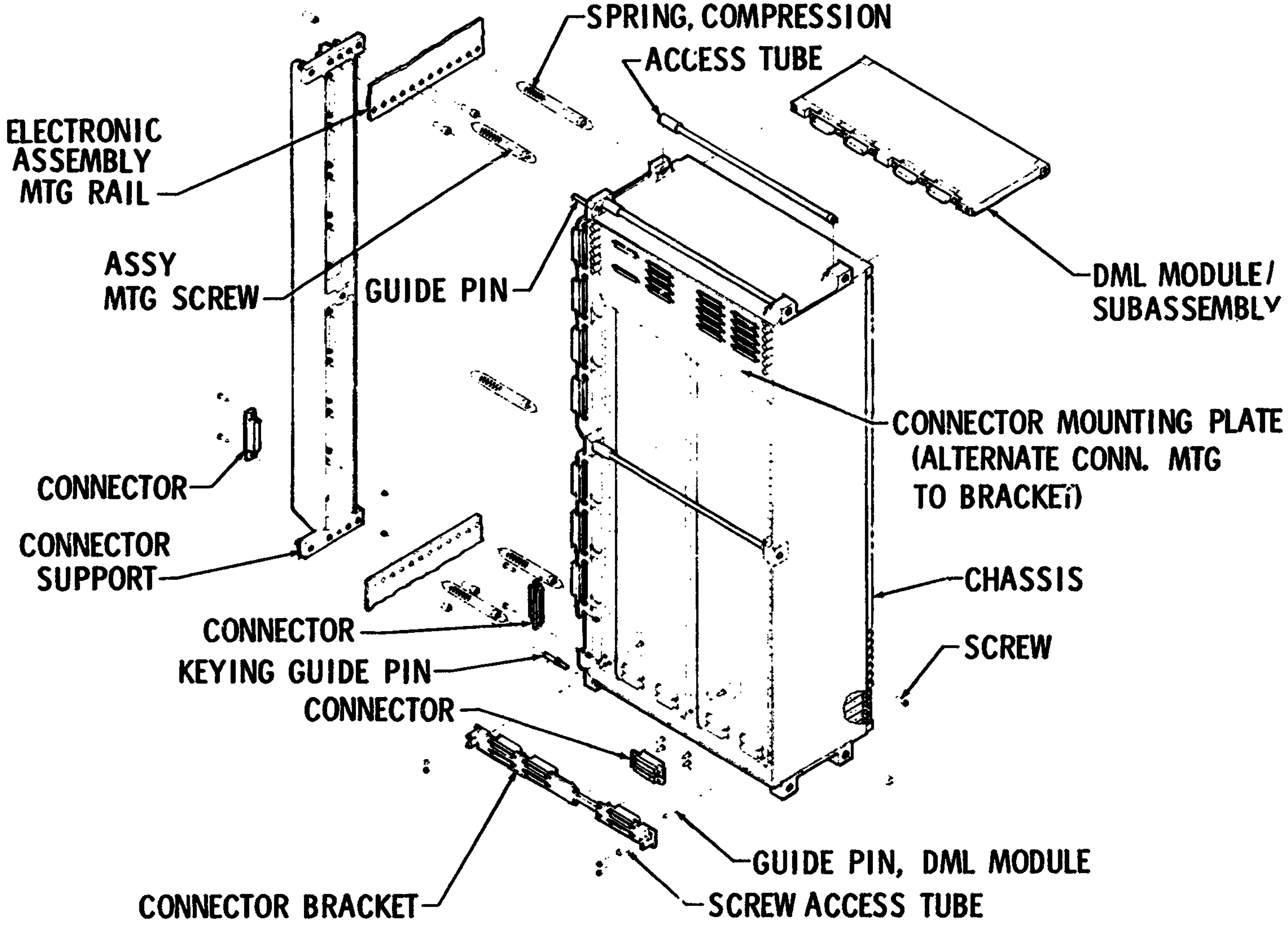


Fig. 3. TOPS Electronic Assembly, with Module and Compartment Interfaces

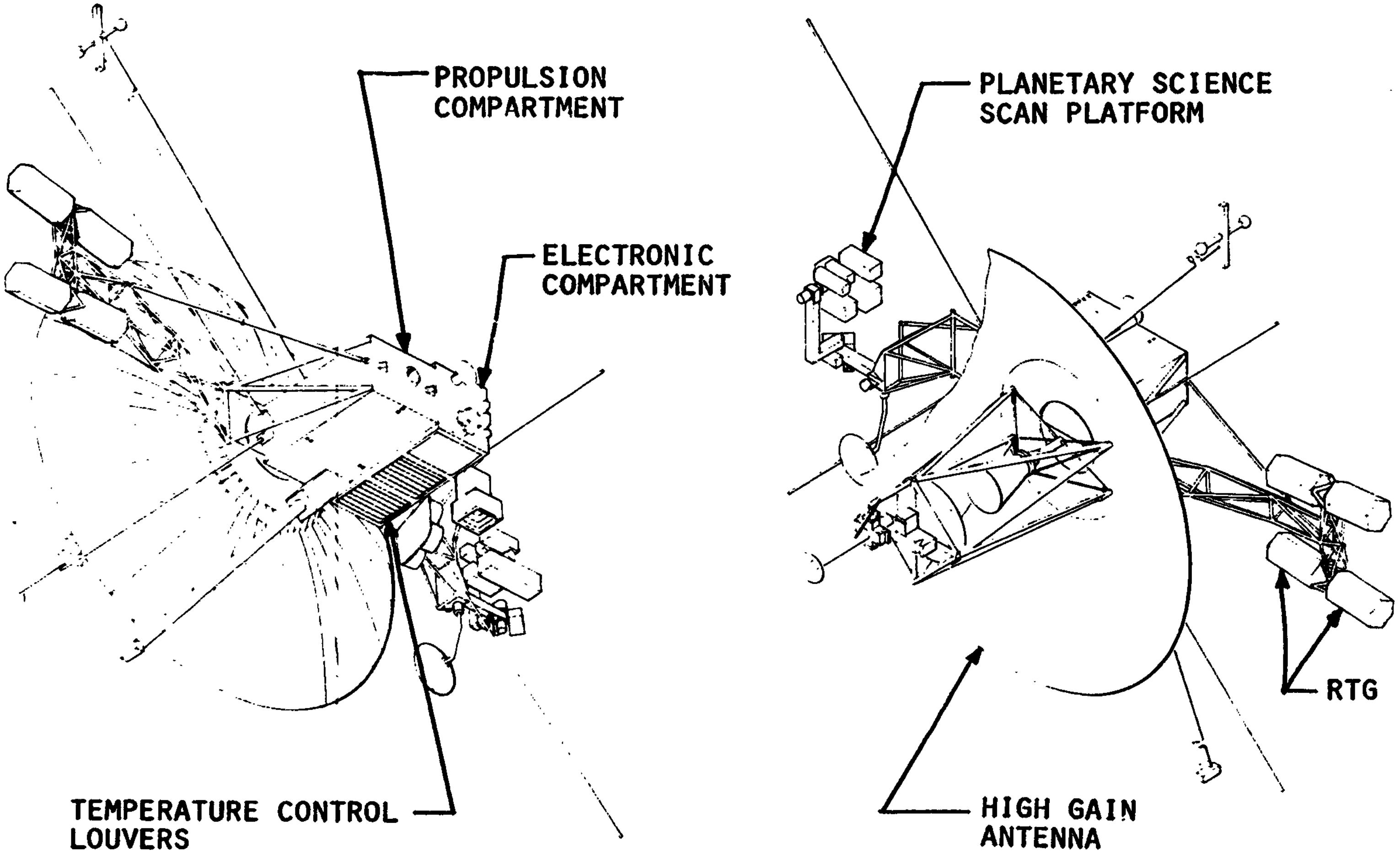


Fig. 4. TOPS Spacecraft Configuration 12L

system. Detailed technical reports are referenced, where available. TOPS packaging drawings are listed in Appendix A.

A. Electronic Compartment

Figure 2 shows the TOPS Electronic Compartment and Ref. 1 discusses the rationale for this design. The Compartment houses single-side access, plug-in Assemblies, mounted back to back.

The results of the initial volume estimates for TOPS subsystems are given in Table 1. Based on these estimates, the EC was sized at 54.6 x 47.2 x 125.7 cm (21.5 x 18.6 x 49.5 in). The Compartment volume could be adjusted by varying the 54.6 cm dimension, each centimeter of width being equivalent to 3.88×10^{-3} m^3 (237 in^3) of net packaging volume. Comparisons of TOPS weight and volume estimates with those of Mariner 69 are given in Tables 2 and 3, indicating that a significant improvement in electrical functional density has been achieved. The subsystem packaging arrangement is shown in Fig. 5.

An efficient, integrated Compartment structure was defined, providing: minimum weight penalty; minimum wire lengths for interconnection of subsystems; flexible sizing for specific missions; power sharing for thermal control; compact arrangement for ease of radiation and micrometeorite protection; a moderate thermal environment, with decoupling possible for heat conservation; and high stiffness.

The Electronic Compartment is a skin-stringer-box structure. The principle is to carry the applied loads in shear on the exterior skin surfaces, with the internal structure and complementary EA chassis providing stiffening, and distributing and carrying the internal loads. The side and end skins were machined with integral stringers; together with two intercostal frames and six shear panels, they comprise the primary structure. These primary structural elements are shown in Fig. 6 and their weight breakdown is given in Table 4. There was an effort to maintain simple and clean shapes, such that these structural elements could be made from exotic materials (e.g., beryllium), if further study showed this to have a major cost or weight advantage. The design goal was to achieve a 325 Hz fundamental resonance with a Compartment structural weight of 22.2 kg (49 lb_m), and a total Compartment weight of 192.8 kg (425 lb_m).

Table 1. Electronic Compartment Subsystem Comparisons

Subsystem	Mariner Mars 69 Volume, m^3 (in^3)	Mariner Mars 69 Weight, kg (lb)	TOPS Volume m^3 (in^3)	TOPS Weight, kg (lb)
Radio frequency	0.0220 (1,340)	25.4 (56.0)	0.0324 (1,980)	39.0 (86)
Command	0.0049 (300)	3.6 (8.0)	0.0048 (290)	3.6 (8)
Power (no battery)	0.0249 (1,520)	17.6 (38.7)	0.0269 (1,640)	22.7 (50)
Central data handling				
Central computer and sequencer	0.0098 (600)	10.9 (24.0)	0.0262 (1,600)	18.2 (40)
Central processor unit	0.0137 (835)	9.8 (21.5)	0.0111 (680)	6.4 (14)
Data storage unit	0.0182 (1,110)	16.9 (37.2)	0.0324 (1,980)	34.5 (76)
Central clock	---- -----	-- ----	0.0025 (150)	1.8 (4)
Attitude Control	0.0127 (775)	13.0 (28.7)	0.0213 (1,300)	13.2 (29)
Pyro	0.0046 (280)	3.9 (8.6)	0.0035 (216)	3.6 (8)
Approach guidance	---- -----	-- ----	0.0057 (350)	5.5 (12)
Data automation	0.0095 (580)	6.3 (13.8)	---- -----	-- --
Television	0.0085 (520)	5.3 (11.7)	0.0066 (400)	6.8 (15)
Science instrument electronics	---- ----	-- ----	0.0098 (600)	9.1 (20)
	0.1288 (7,860)	112.7 (248.2)	0.1826 (11,146)	164.3 (362)
Structure	---- -----	39.0 (85.9)	---- -----	22.2 (49)
Cabling	0.1660 (10,130)	19.0 (41.9)	0.0737 (4,500)	6.4 (14)
Total	0.2948 (17,990)	170.7 (376.0)	0.2564 (15,646)	193.0 (425)

Table 2. Weight Comparison, Mariner Mars 69 and TOPS Electronic Compartments

Item	Weight, kg (lb)			
	Mariner Mars 69		TOPS	
Electronic Assemblies	112.7	(248.2)	164.3	(362)
Structure	39.0	(85.9)	22.2	(49)
Cabling	19.0	(41.9)	6.4	(14)
Total	170.7	(376.0)	192.9	(425)

Table 3. Volume Comparison, Mariner Mars 69 and TOPS Electronic Compartments

Item	Volume, m^3 (in^3)			
	Mariner Mars 69		TOPS	
System cabling	0.0687	(4,190)	0.0737	(4,500)[a]
Subsystem cabling	0.0973	(5,940)	----	-----[b]
Packaging space				
Used	0.1288	(7,860)	0.1826	(11,146)
Additional available	0.0147	(900)	0.0140	(854)
Total	0.3110	(18,980)	0.2704	(16,500)

[a] No battery.
[b] Part of packaging volume.

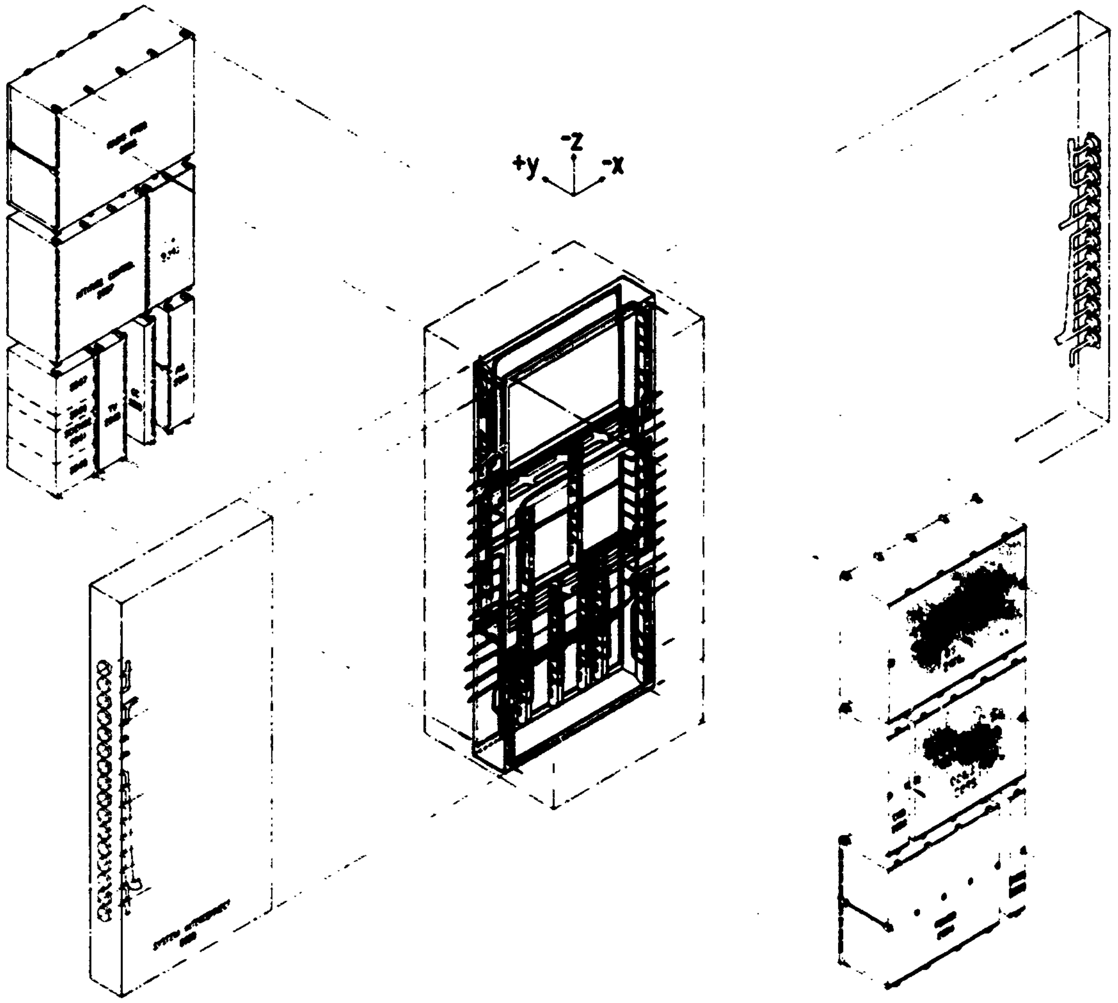
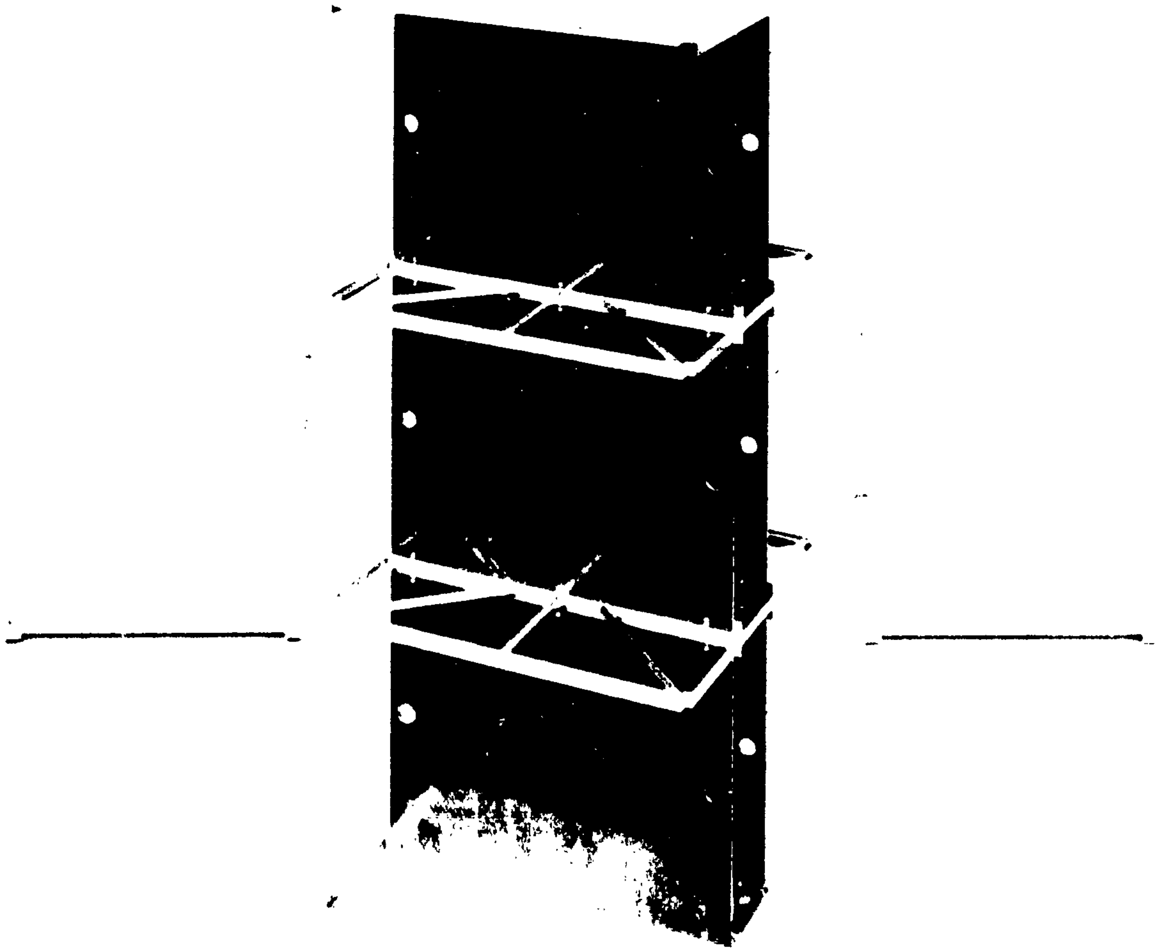


Fig. 5. TOPS Electronic Compartment Subsystem Arrangement Concept



[illegible]

Table 4. Weights of TOPS Packaging Structure Elements

Item	Quantity	Weight	
		kg	lb
End frame	2	3.70	8.16
Center frame	2	2.50	5.50
Side frame	2	7.58	16.69
Shear panel	6	5.73	12.63
Connector support	16	2.47	48.92
Total		21.98	48.42

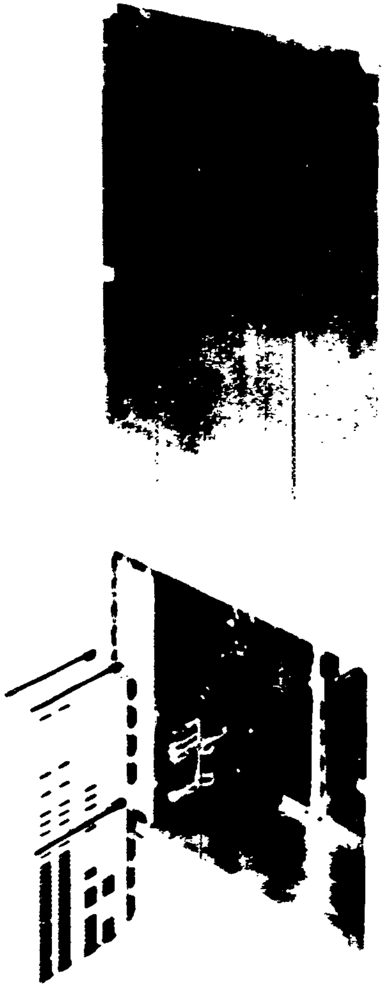
A unique design feature provides precisely located, pre-machined, close tolerance holes on 8.9 mm (0.350 in) centers in the Assembly mounting rails. These holes are used for mounting of the connector supports and EA attachment hardware. Together with the EA alignment/shear pins, they assure proper mating of the connectors and provide a shear tie across the center of the Compartment. Figure 6 shows the alignment tooling that is used in the assembly of the Compartment structure to assure proper location of these hole patterns. The use of a uniform, precisely located mounting hole grid permits flexibility in the sizing and placement of Electronic Assemblies and connector supports, without requiring any post-assembly machining of the EC. Thus, reconfiguration of the EC to meet changed system requirements can be readily accomplished.

The hole patterns for shear panel attachment are added after assembly of the basic EC frame. Threaded inserts, installed in machined bosses located at the corners of the EC, provide for attachment of the EC to the spacecraft or to handling fixtures.

A functional mock-up of the EC was fabricated. Aluminum alloy (6061-T6) was used for convenience; it also meets the contact resistance requirement of 0.1 ohm-cm^2 at the interfaces. The design weight of 22.2 kg was met. No attempt was made to optimize the weight of the mock-up, but it was designed to allow it to be updated to test model status, where weight and structural optimization could be pursued. It is estimated that the weight could be reduced to 17.3 kg, based only on structural and dynamic requirements, and without considering special requirements imposed by thermal and micrometeorite protection aspects. Figures 7 and 8 show the EC mock-up with the EA installation.

Fit-and-function tests and insertion force measurements of the single-side access installation of the EA into the EC demonstrated the feasibility of this concept and are covered in Appendix B. Insertion forces ranged from 450 to 680 N (101 to 153 lb_f) for various alignments of the connectors at the 296-contact interface. Planned completion of the EC, EA, and cabling, and the performing of static, dynamic, and thermal tests on the EC and EA were not accomplished on the TOPS project.

As previously suggested, thermal control was an important aspect of the TOPS electronic packaging system design. It was initially thought that dissipation in the electronics would be so low that heat conservation at large sun-



[illegible] TOPS Electronic Compartment Mock-up with Electronic Assembly Installation

Fig. 8. TOPS Electronic Compartment Mock-up with Electronic Assembly Installation, Showing Module

spacecraft ranges would be the dominant temperature control consideration. Thus, design efforts were directed toward satisfying this objective.

As subsystem design progressed, power dissipation estimates increased to the point where the opposite condition, requiring heat removal, assumed major importance. Uniform power loading per unit area of radiator is desirable in order to minimize require radiator area. Since the shear panels are of equal size, this implies power sharing between bays having high dissipation (e.g., radio) and those dissipating little power (e.g., science). The thermal performance of the Electronic Compartment was analyzed (Ref. 2). The analysis shows that there is significant power sharing between bays, although not as much as desired. There are known design changes which would improve this, such as modifying the Compartment center frame design to increase thermal conduction between the two sides of the bays and from the connector mounting area to the shear panels. The temperature control range of the TOPS Compartment is greater than that of previous Mariners.

A detailed model of the cabling support and routing was not built. No obstacles are envisioned; however, the use of existing technology would not result in the most efficient or cost effective system. There are many areas where new and innovative cabling techniques would be utilized and/or developed. These include: means for direct access for incoming power lines and for cabling to the RTG load resistors; direct access for squib firing lines; separate light-weight, low-loss redundant power distribution wiring; command and data bus wiring; lightweight wire and splicing systems for the microminiature connectors; and investigation of alternate OSE and subsystem direct access test connection methods.

Small-gage wire and microminiature connectors were evaluated in support of the EC design; this work is described in Section III-D. Requirements for flight connectors (microminiature rectangular and subminiature circular) and for small gage wire were developed and, except for minor aspects, were ready for implementation in project procurement documents. Radiation testing of the wire was not completed, but a test program and est samples were prepared and set up for completion on the Outer Planets Project.

B. Electronic Assembly and Electrical Interconnection System

The development of the single-side access Electronic Assembly for TOPS had several specific objectives in addition to the general goals of ten times the functional packaging density and four times the interconnection pin density of existing Mariners. These included: compatibility with existing Mariner equipment, where it would be necessary or desirable to use it; development of a packaging and interconnection system that would efficiently utilize the part developments and hybrid microelectronic packaging techniques that are available and evolving; decoupling of the parts and interconnections from the main space vehicle structural load paths, while maintaining good rigidity and thermal dissipation capability; providing subsystem-to-assembly integrity; providing the capability to accommodate "black boxes"; and achieving a 400 Hz fundamental resonance.

Although it was recognized that various types of packaging would be used for other spacecraft equipment, the primary effort of the TOPS EA development was directed toward a method for efficiently packaging digital circuitry, where extensive use of monolithic integrated circuits and hybrid microelectronic packaging techniques was anticipated. Thus, the companion Module/Subassembly development was keyed to the packaging of a Self Test and Repair (STAR) computer processor.

The Electronic Assembly shown in Figs. 9 and 10 was designed and fabricated as a test bed and demonstration vehicle for the high-density, single-side access concept. Two of the Assembly envelope dimensions, 17.8 cm (7.00 in) and 39.1 cm (15.40 in) are set by the basic sizing established for the EC. The remaining dimension is a variable, to be selected based on the functional requirements for packaging of the particular subsystem under consideration. Thus, one of the Module envelope dimensions is fixed by the basic sizing of the EC, another by the selection of the variable EA dimension, and the remaining Module envelope dimension is free to be chosen to suit its functional requirements.

The thinnest Module, 6.3 mm (0.250 in) thick, is intended for the packaging of flat pack integrated circuits, and is described in more detail in Section III-C. Thicker Modules would be used for packaging of larger components, such as power conversion and switching equipment associated with the subsystem. The following points will be noted: the Module edges are keyed into the EA for

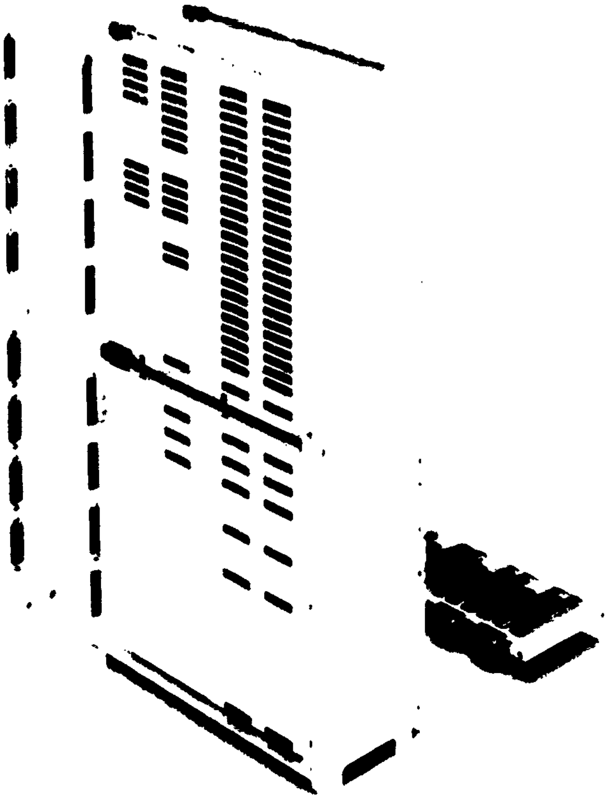


Fig. 9. TOPS Electronic Assembly (Interconnection Side) with Interface to System Connector Support

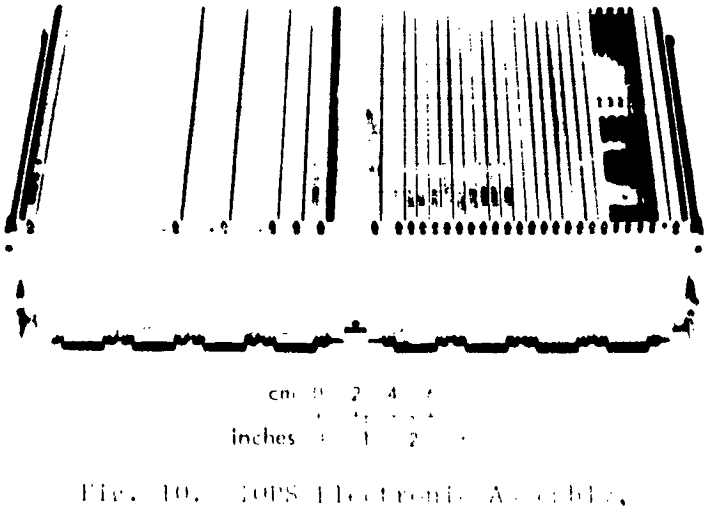
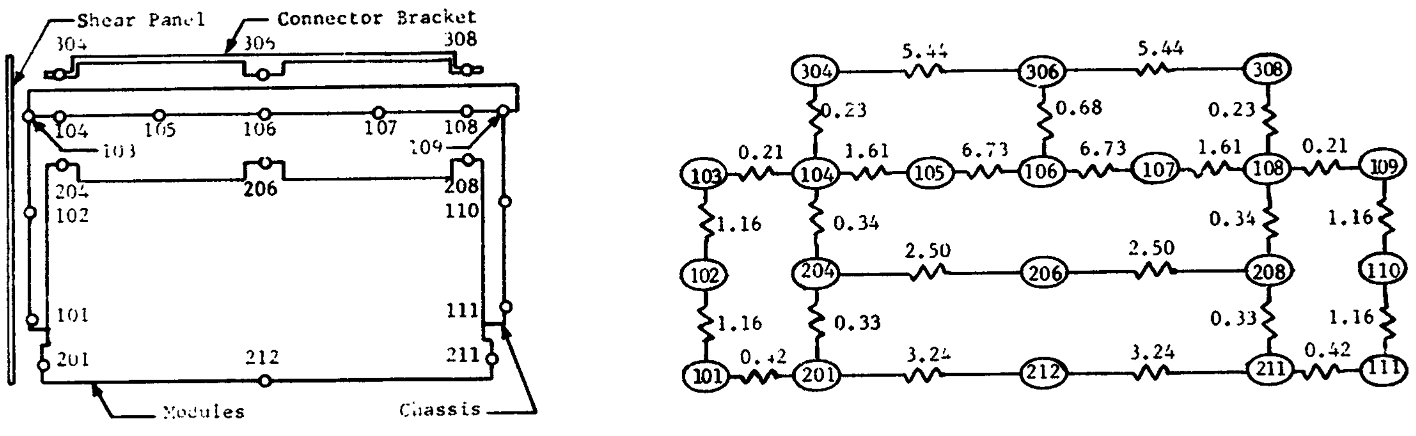


Fig. 10. TOPS Electronic Assembly, Showing Various Module Sizes

alignment; the primary attachment of the Module to the EA is by means of screws at the connector interface edge; and additional attachment is by means of screws passing through slots in the EA chassis and into the corners of the Module, at the edge farthest from the connectors. Some of the areas that required resolution to define the hardware were: functional sizing requirements; material and gage selection; requirements for keying, guiding, and fastening; connector location, tolerancing, and keying; basic increment of EA width; Module connector support and harness-to-Module fastener clearance; minimum Module spacing (6.6 mm); blind captive fastener development; and minimum requirements for shear panel attachment.

The Electronic Compartment thermal analysis (Ref. 2) indicated that there could be excessively large temperature gradients across the TOPS digital-type Electronic Assembly. To clarify this point, a more detailed thermal resistance model of the EA was generated. Figure 11 shows this revised network, along with the simplified equivalent circuit which was derived. The calculated thermal resistance of the critical path was reduced by a factor of approximately five, chiefly by inclusion of shunt heat paths which were omitted in the EC analysis. Thus, the estimated temperature gradient across the EA was revised downward to an acceptable 3° C.

As previously stated, heat conservation was initially a major design consideration. Thus, the number and size of the mechanical attachments between EAs and shear panels were kept to a minimum, consistent with structural and dynamic requirements. The EC thermal analysis resulted in calculated temperature gradients from EA to shear panel of as much as 9.4° C. These could easily be reduced to about 3° C by increasing the area of attachment to the shear panel. In addition to increasing this area, the design provides the capability to substantially increase the number of fasteners across the interconnection area. Thermal conduction could be still further increased by modifying the Module, such that the Module-to-Assembly fasteners would extend through the shear panel. Fortunately, it is unlikely that this latter modification would be required, as it would complicate system operations. In any event, the EA chassis detail design requirements would include appropriate thermal conduction to the shear panel.



(a) Physical Diagram with Node Numbering

(b) Thermal Circuit. TOPS Development EA

(c) Simplified EA Thermal Circuit

(d) Equivalent EA Resistance for TC Model Comparison

Units: °C/W

Fig. 11. Electronic Assembly Thermal Resistance Network

A fit-and-function demonstration of the installation of the EA in the EC was successfully accomplished. Measurements were made of insertion forces, chassis and connector support separation distance, and connector support deflections. This information is given in Appendix B. A typical force-deflection curve is shown in Fig. 12.

The TOPS packaging concept allows many possible Assembly configurations. Because of resource limitations, only that previously described--the one having the most potential for advancement in packaging density and weight and cost savings in the packaging of digital circuits--was actively developed. Other Assembly types were studied conceptually. Figure 13 shows the packaging that was envisioned for the radio subsystem. High-power r.f. circuits would be mounted directly to the shear panel (an integral part of the upper half of the Assembly). The lower half of the Assembly would contain the receivers and other low-dissipation circuitry; it would also house the temperature controlled crystal oscillator, thermally isolating it from the high-power section. Figure 14 illustrates a sealed Assembly, which might be a tape deck or other equipment having similar requirements.

Choice of a larger Assembly envelope, with side fasteners outside the Mariner and Viking equipment envelopes, ensured that TOPS would be capable of utilizing residual equipment designs. This new Assembly size could incorporate Mariner and Viking subassemblies either by placing them in new chassis having the proper TOPS interface features or by adding brackets to existing flight equipment chassis. Some methods for accommodating existing equipment designs are shown in Fig. 15, for power subassemblies utilizing pigtailed Module connectors, and in Fig. 16, for "6 x 6" Mariner subassemblies.

"Black box" equipment could be accommodated in at least four ways; by mounting on part of a standard TOPS electronic chassis; by incorporating mounting supports and/or adapters; by mounting on a panel attached to the connector mounting rails in the EC, with pigtailed connectors from the system harness; and by mounting on the inside of the shear panel. These methods could be implemented with a minimum of engineering and testing if the black box equipment represented only a small portion of the total electronic equipment; say, no more than a bay on each side of the EC. However, the use of black box equipment will always result in losses in structural and volumetric efficiency, which usually increase spacecraft weight.

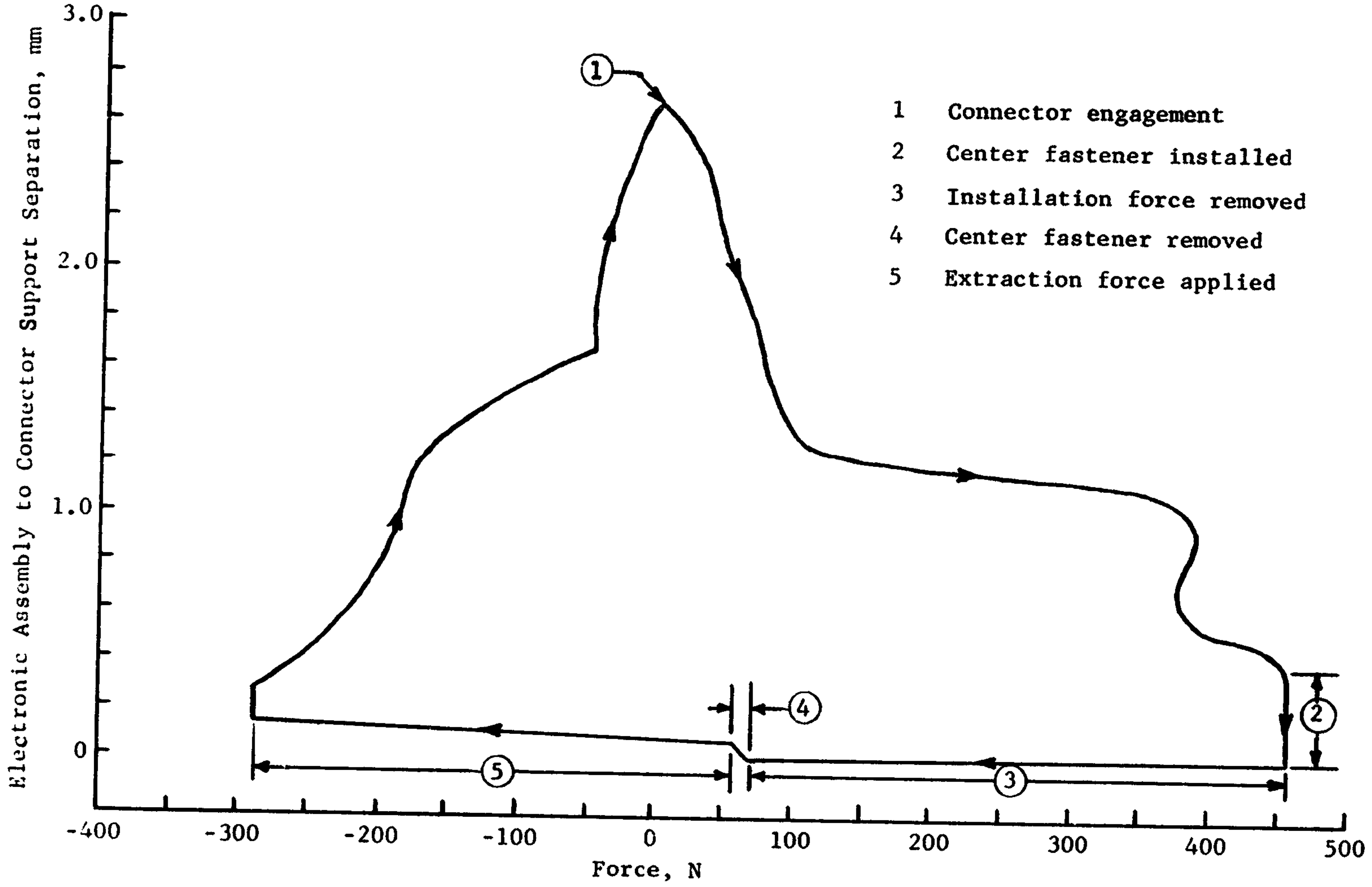


Fig. 12. Insertion Force vs. Separation for Electronic Assembly Installation and Removal

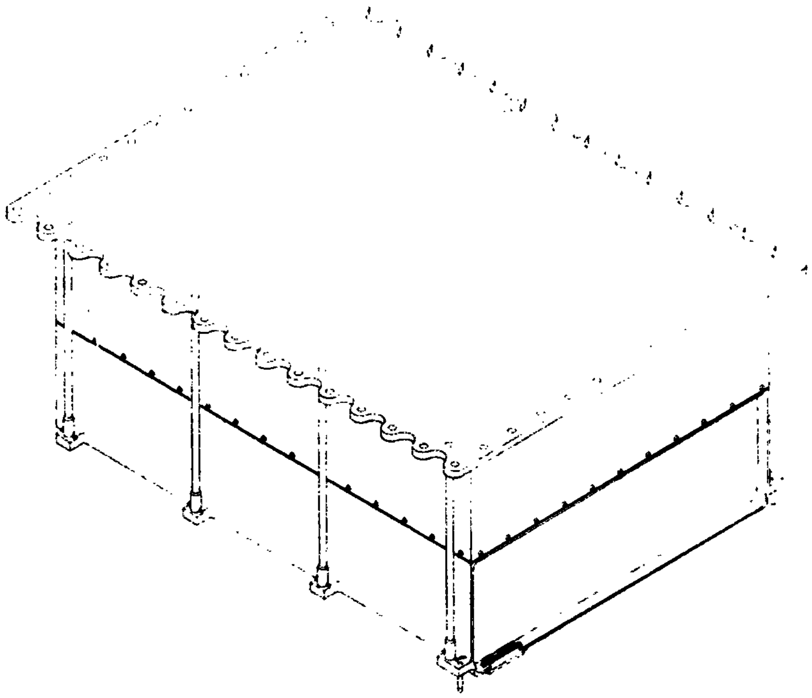


Fig. 13. Radio Subsystem Electronic Assembly Concept

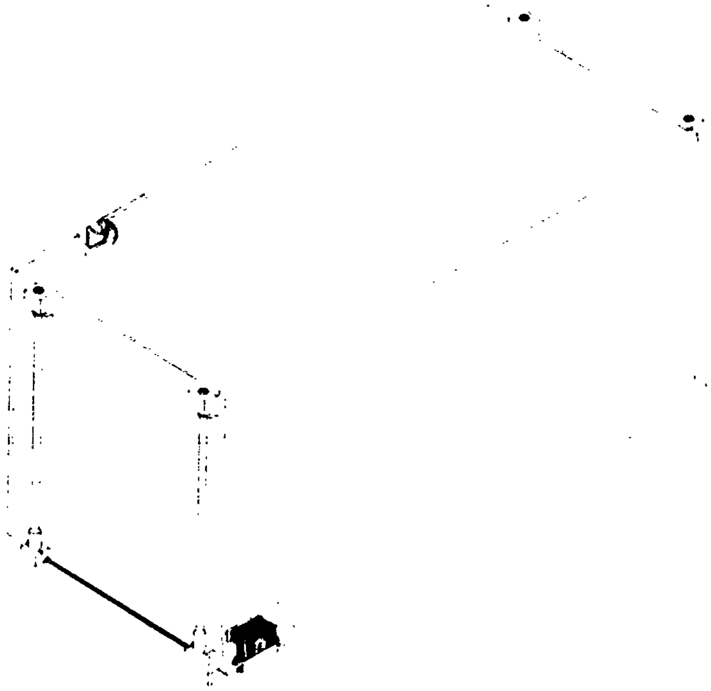


Fig. 14. Sealed Electronic Assembly Concept

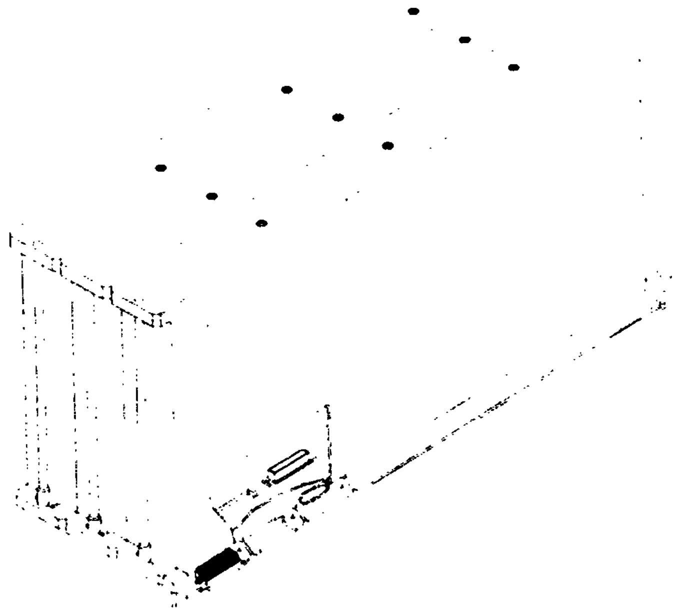


Fig. 15. Mariner Full-Width Subassemblies Adapted to TOPS Configuration

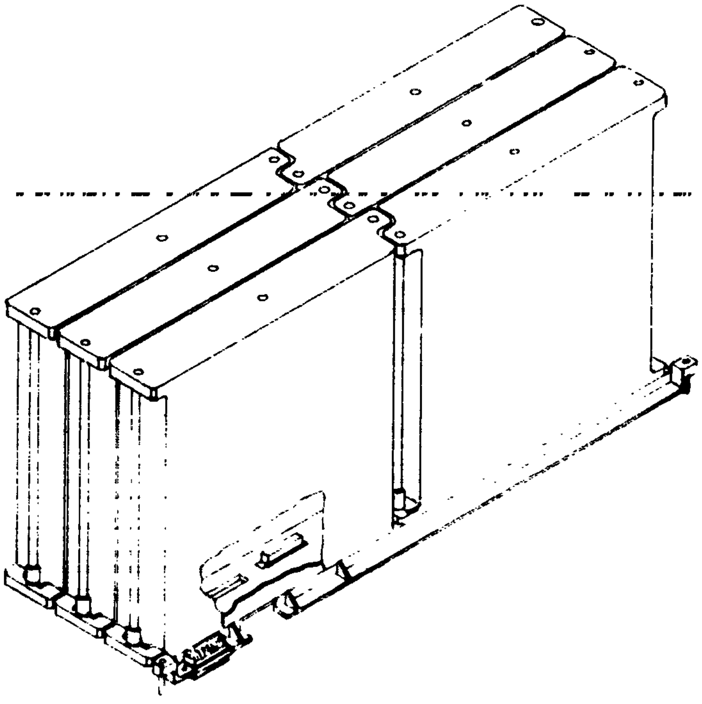


Fig. 16. Mariner "6 x 6" Subassemblies Adapted to TOPS Configuration

EAs would be installed and removed using tooling similar to that shown in Fig. 17, which is Mariner tooling as modified for the TOPS fit-and-function demonstration. Additional fixtures would be used to minimize weight, by reducing or eliminating structure that is not required in the flight configuration. Figures 15 and 16 show how all but the top and bottom shear plates of the Mariner chassis would be eliminated. Ground handling fixtures would be required for the resulting lighter weight flight Assemblies, to assure reliable handling during the fabrication, test, and transportation phases.

Achievement of 1.3 mm (0.050 in) interconnection spacing at each of the three levels of packaging (i.e., system, assembly, and module) was a development goal. Interconnection systems have trailed the state-of-the-art of part development for years. By reducing or eliminating the packaging density limitation imposed by interconnection capability, significant packaging gains could be achieved. In addition, large digital subsystems could be effectively packaged in functional groupings and incorporated into single Assemblies, further simplifying interfaces.

In the preliminary design phase, two possibilities were considered for the orientation of the Module within the EA. One is the design which has been described; in the other, the Module was rotated 90° in-plane. In the selected design, the Assembly interconnection plane is perpendicular to the shear panel, whereas in the latter design, it is parallel to the shear panel and at the surface adjacent to the system interconnection wiring. One of the obvious differences between these concepts is that the selected design fixes the width of all Modules in the EC at 17.3 cm, and thus the maximum number of contact pins per connector row at 100 (four 25-pin connectors), whereas in the alternate concept, this dimension is established by the variable dimension of the EA. Selection was based on: the desire to minimize attachments to the shear panel (for ease of Assembly installation and removal, and for the thermal decoupling which has been discussed); the belief that 100 contacts per connector row is sufficient; and the judgment that this design permits more flexibility in functional Module sizing than does the alternate.

The Electronic Assembly interconnection wiring is basically from contact to contact: that is, it interconnects those connectors on the EA chassis which mate with Modules with each other and with those which mate with the system wiring

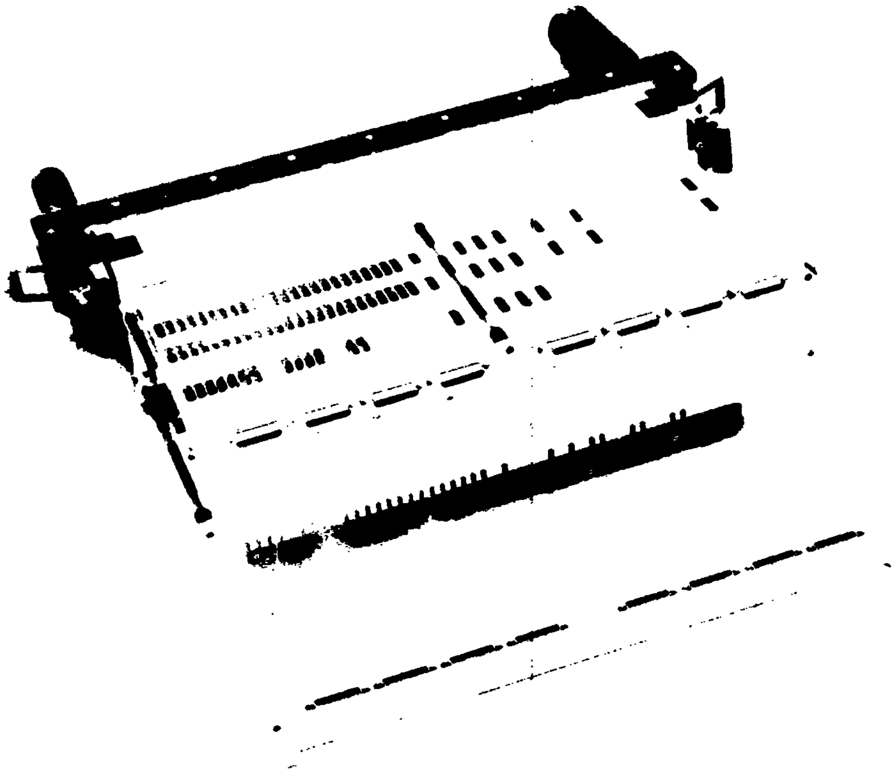


Fig. 17. Mariner Installation Tool Adapted to TOPS Electronic Assembly

harness. A number of variations were investigated. In one, the system connectors would be procured with pigtails and the Module connectors with insertable, crimp-type contacts. Contacts would be crimped to properly dressed and terminated pigtail leads and jumpers and would then be inserted into the proper Module connectors. Necessary busing and joining would be accomplished by splicing, as currently practiced on flight projects. Figure 18 shows the result of the first attempt at wiring a section of the EA interconnection harness. This used 24 AWG stranded wire (the largest that would fit in the contact) with the heavier (600 V) of the two flight wire insulations now in use. Although it did not meet the 1.3 cm height goal, it was otherwise feasible. Figure 19 illustrates another version, using 30 AWG stranded, Teflon insulated wire, which did meet the height goal. There is one major objection to these contact-to-contact wiring methods. If it were concluded that the wiring of the connectors is so critical that it should be done by the manufacturer, then the manufacturer would have to fabricate all the interconnection wiring, leading to possible interface problems.

The micro-D connectors are available with a variety of contact pin terminations. Figure 20 shows two types of film insulated magnet wire soldered into bifurcated contact terminations. Figure 21 shows the use of 30 AWG stranded, Teflon insulated wire with solder pot contact terminations, which requires a wiring height of 3.2 cm. This fabrication method is the same as that used for Mariner, except that it requires considerably more operator finesse because of the smaller gage wire and the closer spacing of the micro-D contacts.

Figure 22 illustrates yet another EA interconnection wiring scheme which was investigated. In this one, all EA connectors would be procured with pigtail leads. Interconnection and busing would be accomplished by making connections at a terminal strip, as shown. The rationale for considering this is that, in the pigtailing operation, contact attachment, installation, and inspection can all be performed under ideal conditions. It is thought that perhaps, even with the added joint (which can also be made and inspected under good conditions) per interconnection, this might be more reliable than contact-to-contact methods, which require making and inspecting at least one joint in each interconnection under less favorable conditions.

Three methods were investigated for mounting Module connectors on the EA. Figure 21 illustrates the use of two-row connector mounting brackets, each

Fig. 18. Point-to-point Wiring with 24 AWG Teflon Insulated Wire on Section of Electronic Assembly Chassis

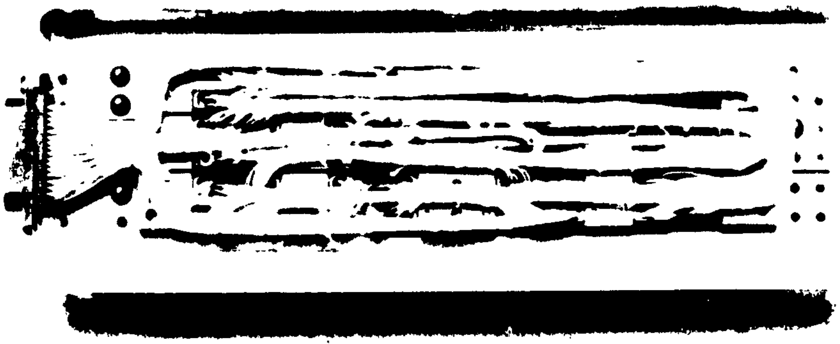


Fig. 19. Point-to-point Wiring with 30 AWG Teflon Insulated Wire

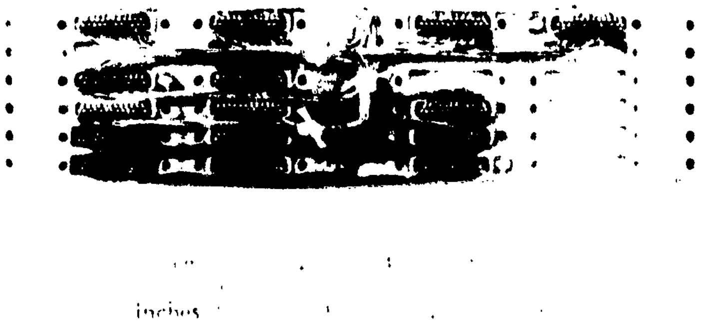


Fig. 20. Magnet-wire [illegible]
[illegible]

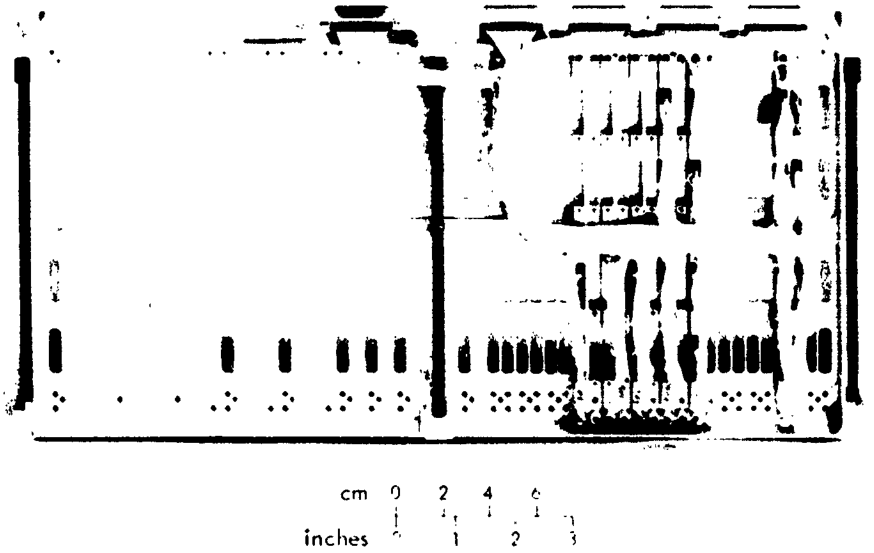
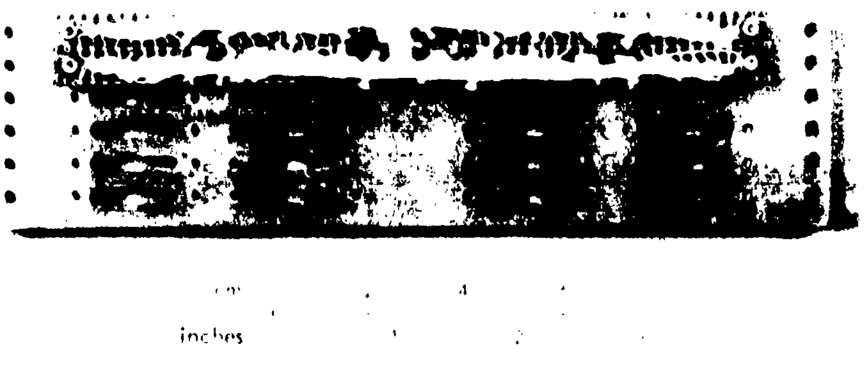


Fig. 21. Electronic Assembly Wiring Harness Using 30 AWG Teflon Insulated Wire With Solder Pot Connector Contact Terminations and Two-Row Connector Supports



[illegible]

capable of accommodating as many as eight 25-pin connectors. This is judged to be one of the most versatile connector mounting methods, in terms of flexibility in Module and connector arrangement, and has the advantage that the bracket could be a standard, low cost part. This method also tends to minimize tolerance build-ups that could adversely affect connector engagement length. It does have the disadvantages of using the most fasteners and of requiring bracket removal to gain access to the connector mounting screws. Two other methods were investigated which use a single connector mounting plate for the entire EA. Figures 23 and 24 show this plate with the connectors mounted on the back. This reduces the area available for wire routing, but is advantageous in that the connector mounting screws are readily accessible and that the harness could be removed and installed on another plate. Figure 25 shows a similar mounting plate with the connectors installed between it and the chassis. None of these connector mounting methods is clearly superior to the others; each has its limitations.

In retrospect, there is another connector mounting method which was not investigated, but which appears feasible and which might have certain advantages over those just discussed. In effect, the previously described connector mounting plate would be modified to incorporate the EA interface provisions; the part would be approximately 2.5 cm thick and would include provisions for the EA wiring harness. Except for rails along the sides, to permit attachment of this modified connector mounting plate and of the Modules, the bottom of the EA chassis would now be open. Redundant structure would be eliminated, both sides of the connectors would be accessible, and the wiring harness would be readily separable from the EA.

Several interconnection methods that have been used on subassemblies in the past are also candidates for this application. These include such methods as welded wire, printed wiring board with terminals (with pigtailed Module leads), through insulation welding (both opposed electrode and concentric electrode), and others.

C. Module/Subassembly and Discrete Multilayer (DML)

One of the goals of the TOPS packaging and cabling activity was the development of an improved Module that would provide significantly increased packaging density. Anticipating the introduction of medium- and large-scale integrated circuits (MSI and LSI) into the space program, with attendant increased part

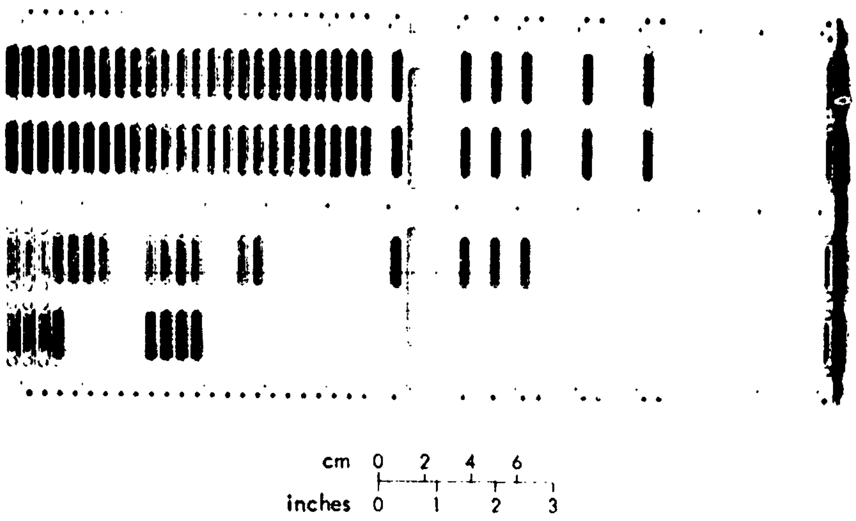


Fig. 23. Support Plate With Back Side Mounted Connectors (Back View

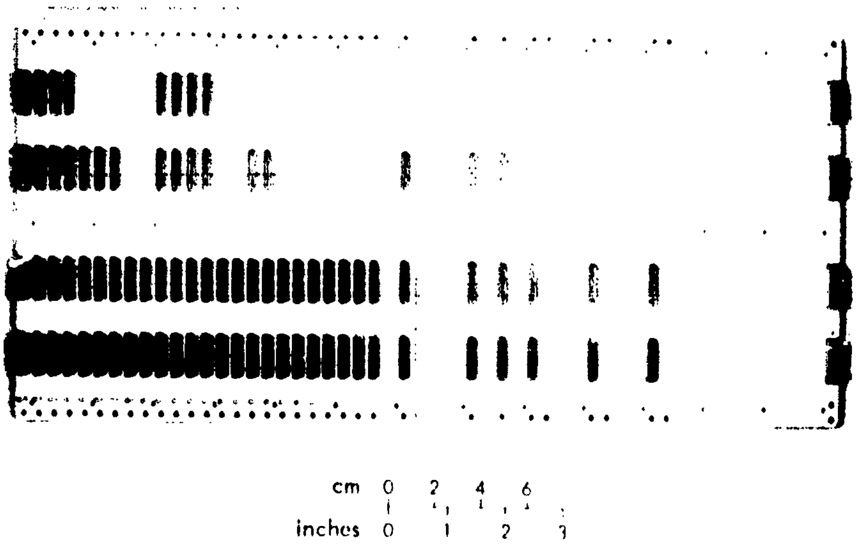


Fig. 24. Support Plate With Back Side Mounted Connectors (Front View

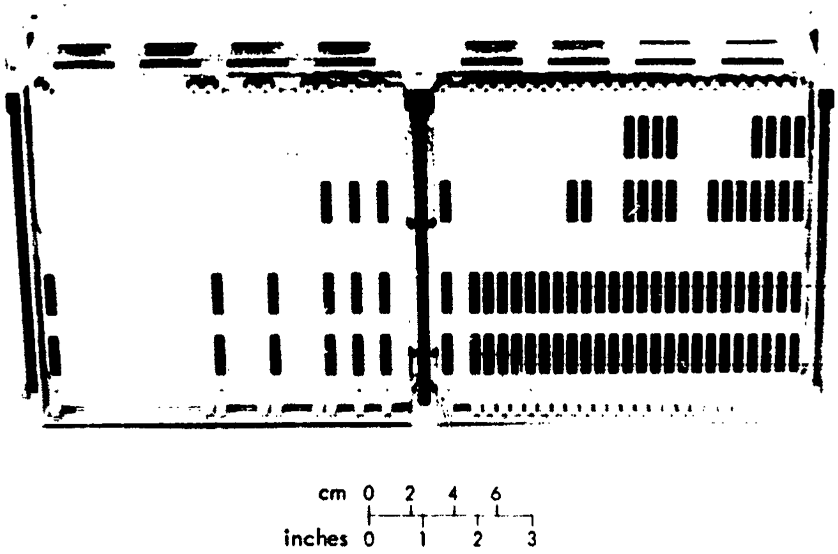


Fig. 25. Support Plate With Front Side Mounted Connectors, Installed in Electronic Assembly

costs, it was considered essential that this Module should use planar packaging techniques, the amenability of which to repair and/or part replacement and the general utility of which in limited production programs are both well established. The Composite Module--so named because it is an assembly of simple parts--was developed in response to this requirement.

The merits of the Composite Module include high packaging density, light weight, good part replacement capability, flexibility in sizing, and low cost, achieved through the use of standard hardware and simple fabrication and assembly processes. Figure 26 shows the parts that make up the Composite Module. The frame serves to mechanically integrate the other Module parts and is functionally sized to fit the requirements of the Assembly in which it is to be used. The part interconnection medium consists basically of a substrate, circuit conductors, and electrical insulation material. It could be a conventional or multilayer printed wiring board, or the DML interconnection system which was developed specifically for the Composite Module, but the choice is not limited to these. Input/output connections are nominally by means of micro-D connectors, using 1.3 mm (0.050 in) contact spacing. These provide a larger input/output capability than can be obtained with the conventional connectors now employed, without being a sizing constraint on the Assembly, as is sometimes the case with flight hardware using the latter connectors. Other possible input/output connection means include terminals and pigtails.

The evolutionary development of the Composite Module concept is illustrated in Fig. 27. The uppermost Module is the "green stick", a packaging technique originated by JPL and successfully employed in a number of space projects. With project experience and with the trend toward increasing circuit complexity, it is apparent that this has several shortcomings. The form factor is fixed, because the basic part is a molding. Input/output connections are hard wired, rather than plug connected, and their number has proven to be inadequate for many applications. (There have been instances in flight applications of the green stick where fewer than half of the component installation sites were used, because of the limitations imposed by the 39-pin input/output capability.)

The remaining Modules in Fig. 27 are Composite Module development units. The second Module from the top used a molded insulator strip derived from the

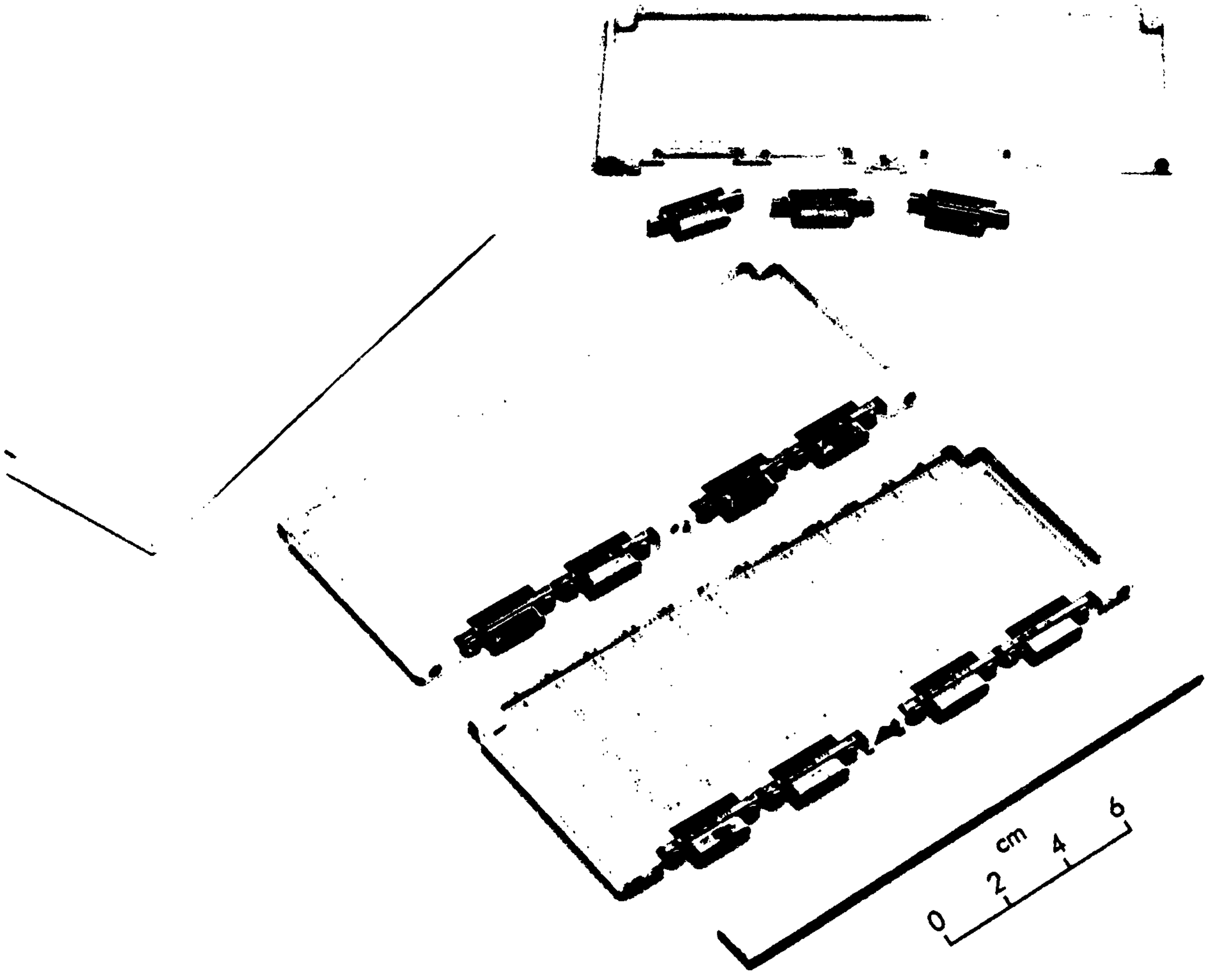


Fig. 26. Simple Parts of Composite Module

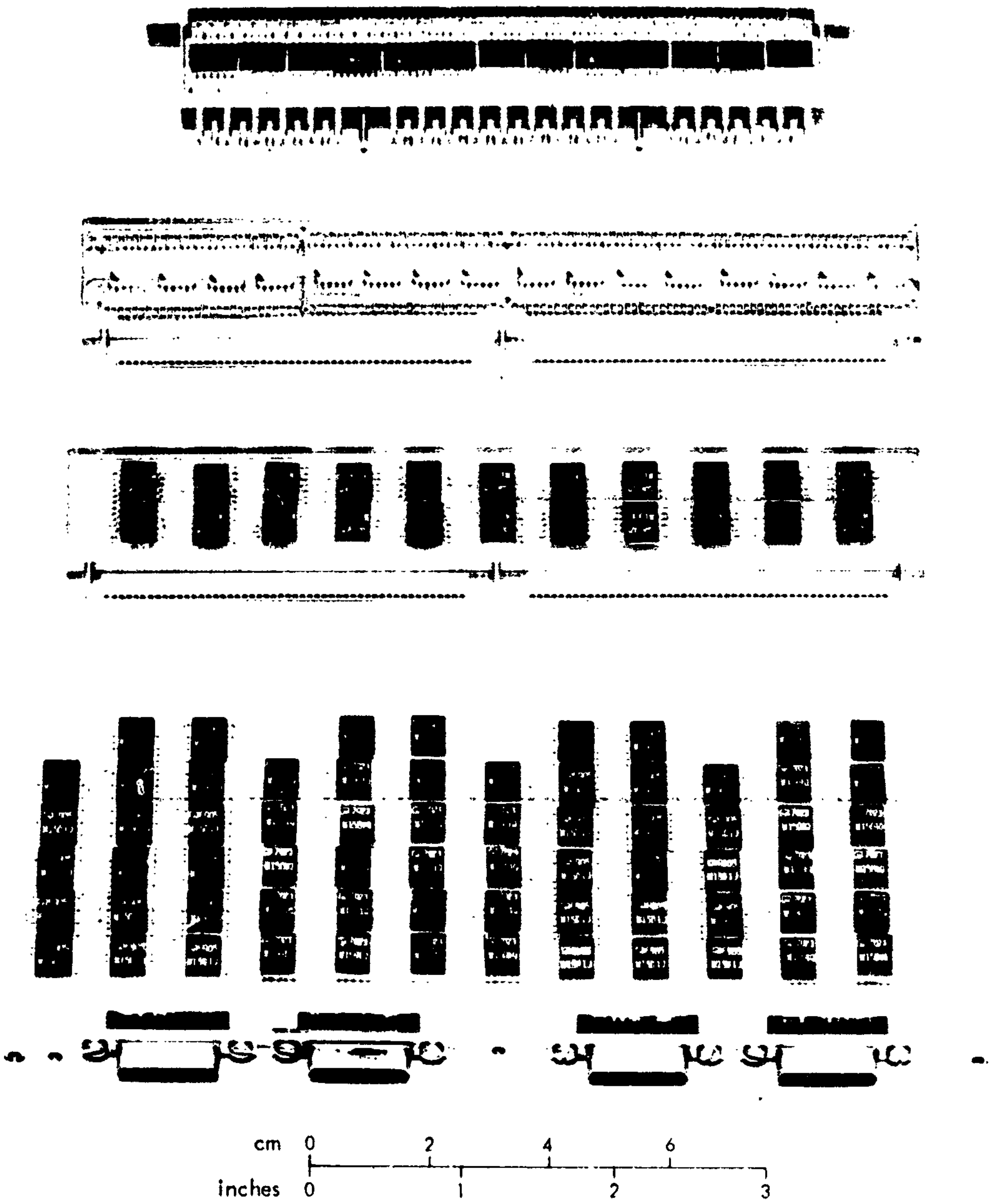


Fig. 27. Module Evolution

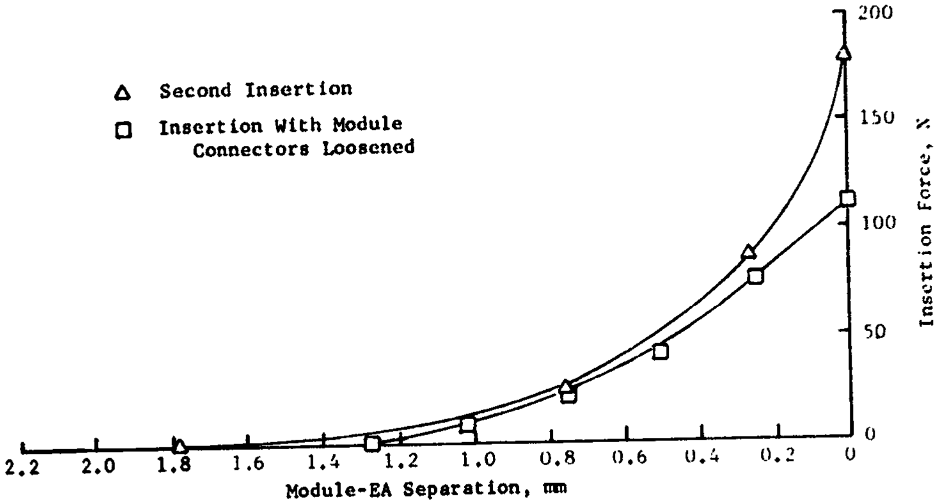
green stick. This was designed to be cut to length to fit into a metal frame, which in turn was sized for the EA chassis width and for functional partitioning. The Module was equipped with a plug-in connector strip, which increased the input/output connection capability and eliminated the requirement for hard wiring.

Estimates of functional interconnection complexity indicated that the 100-pin input/output capability would be adequate for anticipated Module designs. With this increased connection capability, it was then possible to consider ways to increase the number of parts which could be installed on the Module, including rearrangement of component locations and providing for Module growth to effect functional sizing. The lower two Modules in Fig. 27 are examples of development hardware which was used to investigate methods for attaining this increased component handling capability. They show the addition of microminiature connectors (for improved reliability) and the use of improved component installation and interconnection methods.

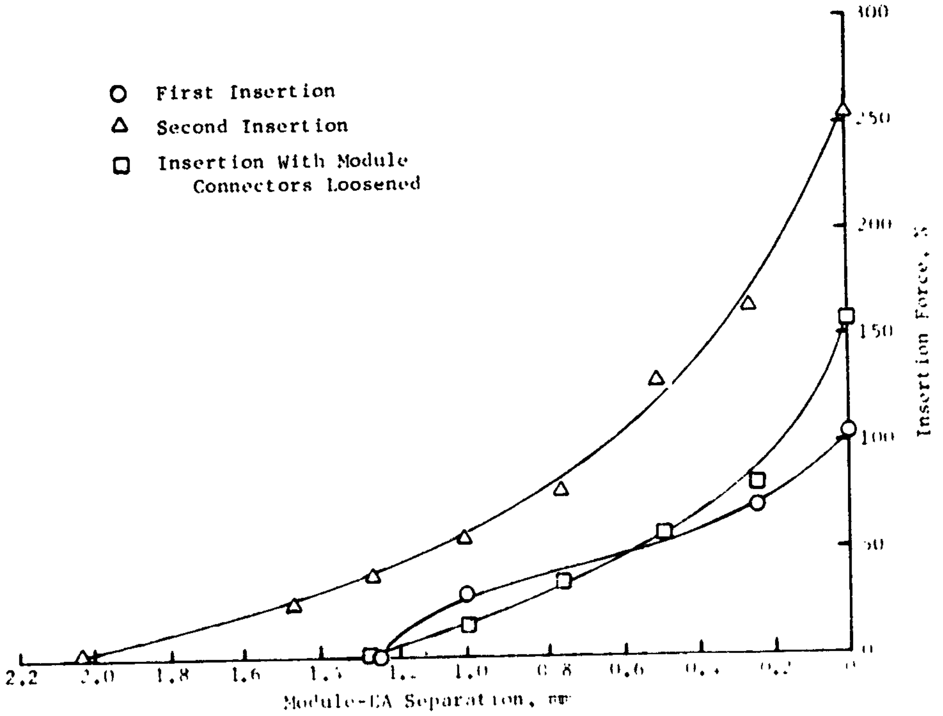
Incorporation of the plug-in capability into the Composite Module required dimensional tolerance analysis of the microminiature connector installation to ensure that insertion of the Modules into the EA would always provide 100 percent connector contact continuity. Allowances for tolerance build-up were made in the design of the EA-to-Module interface, and in close tolerancing of the connector supports.

To verify the design of the interface, a group of insertion force and continuity tests were performed. Figure 28 gives the results of these tests and shows that, for the nominal connector installation, all contacts are mated at least 1.3 mm (0.050).

The Discrete Multilayer (DML) interconnection system was developed especially for application to the Composite Module. It employs discrete, etched-foil circuit conductors, simple terminals for joining these conductors with part leads, and an insulating substrate which supports the circuit conductors and provides for the mounting of terminals and parts. The name is derived from the fact that the several conductor layers are discretely insulated from each other and from possible contact with terminals and part leads by the selective application of pressure sensitive insulating tape during the fabrication process. An interconnection node spacing of 1.3 mm (0.050 in) was chosen as



(a) First Location in Electronic Assembly



(b) Second Location in Electronic Assembly

Fig. 28. Module Insertion Force vs. Separation

the design goal, as this is conducive to high packaging density and is compatible with the lead spacing of a large number of components (e.g., IC, MSI, and LSI devices, and most discrete parts). Compared with other high-density interconnection systems, reliability against open circuits should be improved, as the number of interconnection joints is reduced and those that do exist are all visually inspectable (i.e., circuit conductors are continuous between the several part terminals which they interconnect; there are no vias or other intermediate joints). Non-proprietary manufacturing techniques are used, and repair/rework techniques are envisioned to be quite straightforward.

Figures 29 and 30 illustrate the use of the DML interconnection system in high-density packaging of integrated circuits. The circuit conductors are chemically etched traces (or ribbons), as shown in Fig. 31. Interconnection is from point to point, with multiple routing or busing being accomplished directly in the design of the trace and not altering the number of joints between components. Thus, for interconnection between any two components in the Module, there are always exactly four joints, and each is visually inspectable. By contrast, an interconnection run in a multilayer printed wiring board can have (due to required layer changes) a large number (never less than four) of joints which are not visually inspectable.

The circuit conductors are attached to the terminals by reflow soldering with a gold/tin solder or by welding. As the circuit layers are built up, the cross-overs are discretely insulated with adhesive-backed polyimide tape. The components are then attached to the terminal locations on the reverse side by reflow soldering with 63/37 tin-lead solder. The use of dissimilar joining techniques at the two ends of the terminals, with the low melting point solder being used for part attachment, ensures that installation and removal of parts will not affect the previously made joints on the interconnection side of the board.

The Module shown in Figs. 29 and 30 represents an adder unit for the STAR computer breadboard. It interconnects 71 ICs in a volume of 7.2×10^{-5} m^3 (4.29 in^3), to achieve a packaging density of approximately 10^6 ICs per m^3 (16 per in^3). The component layout is for the 14-lead flatpack ICs used in the adder. However, because of the flexibility of terminal location, other parts such as LSI devices and hybrid microcircuits can be placed and mixed in the Modules at will. Figures

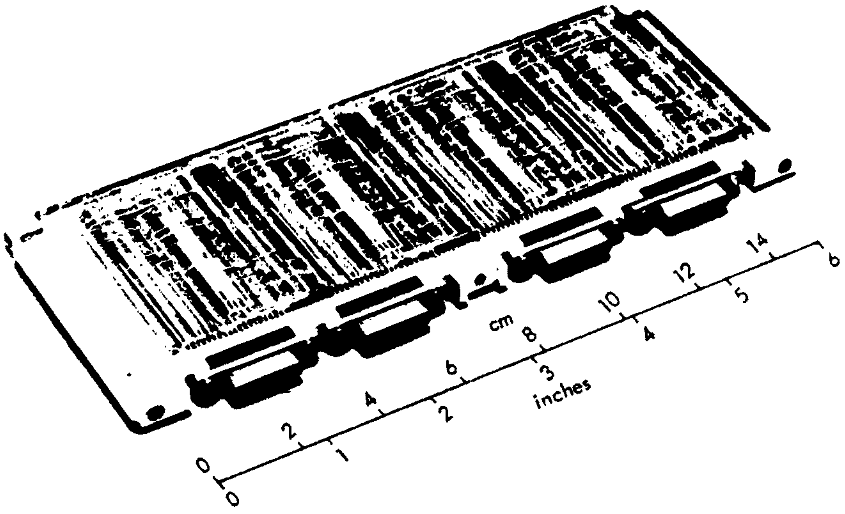


Fig. 29. Application of Discrete Multilayer Interconnection System, Interconnection Side

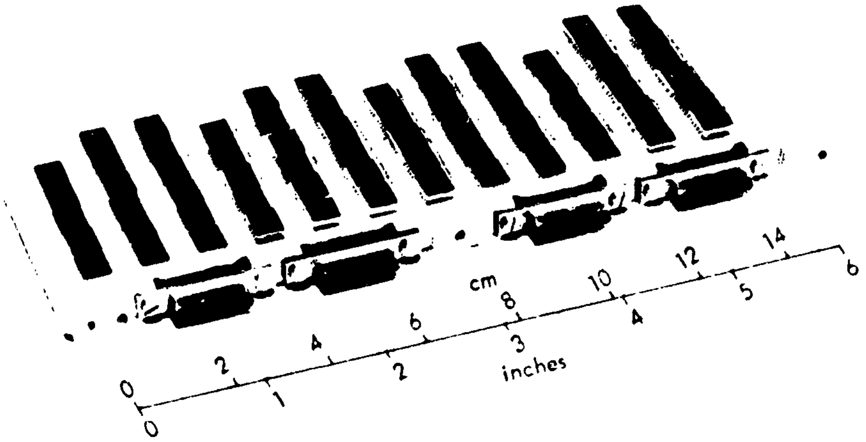


Fig. 30. Application of Discrete Multilayer Interconnection System, Electronic Part Side

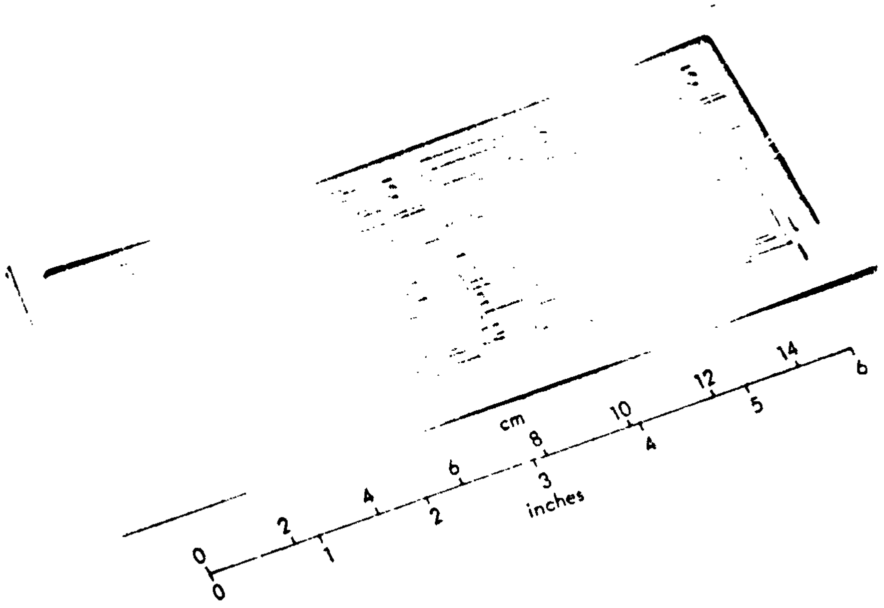


Fig. 31. Chemically Etched Discrete Multilayer Circuit Layer

32 through 36 illustrate some typical layout configurations which were studied.

Figure 37 illustrates some of the different possible modes of growth of the Module (Subassembly). Boards can be mounted back to back on double thickness Modules. Additional rows of connectors can be used on double thickness or larger Modules, if needed for additional access to the subsystem harness. A web may be added to provide heat sinking or support for larger components.

Flexibility in Module sizing is extremely important for efficient and cost effective packaging. The STAR computer employs a multi-processor system with stand-by redundancy; one of the vital elements is the power switch used to activate and deactivate each processor. Use of the special high-reliability switch developed under the TOPS project would require a Module thickness of at least 1.3 cm (0.50 in). A processor using one of these switches and 200 14-lead flatpack ICs could be constructed in a Module size of approximately 17.3 x 15.3 x 1.3 cm (6.8 x 6.0 x 0.5 in), using the DML interconnection system; this would fit in a 17.8 cm (7.0 in) high EA. Replacement of the conventional ICs with Custom Metallized Multi-gate Array (CMMA) LSI devices (the development of which was undertaken by TOPS) would permit reduction of the Module height from 15.3 to about 10.2 cm. In either case, the planned packaging approach was to package the flatpack devices in the basic 0.58 cm (0.23 in) Module thickness required for planar packaging of such devices; then to fold this back on itself, with hard wiring between the two sections, to approximate the 1.3 cm Module thickness required in the switch area.

It is worthwhile to observe that this processor could not have been packaged efficiently in the typical 16.5 x 35.6 cm (6.5 x 14 in) Mariner Module, because of the excessive area available and the minimum thickness required by the power switch. Also, on Mariner, the connector size and the required number of input/output connections frequently determine the Module thickness. The Module thickness required to accommodate large capacitors often reduces the volumetric packaging efficiency by a factor of 2 to 5. Table 5 shows the part densities that can be achieved with various packaging methods.

During the development of the Composite Module and DML, related fabrication and assembly processes were investigated. These included the application of reflow solder techniques to DML joint fabrication, methods for connecting the microminiature connector contacts to the circuitry on the Module, and installa-

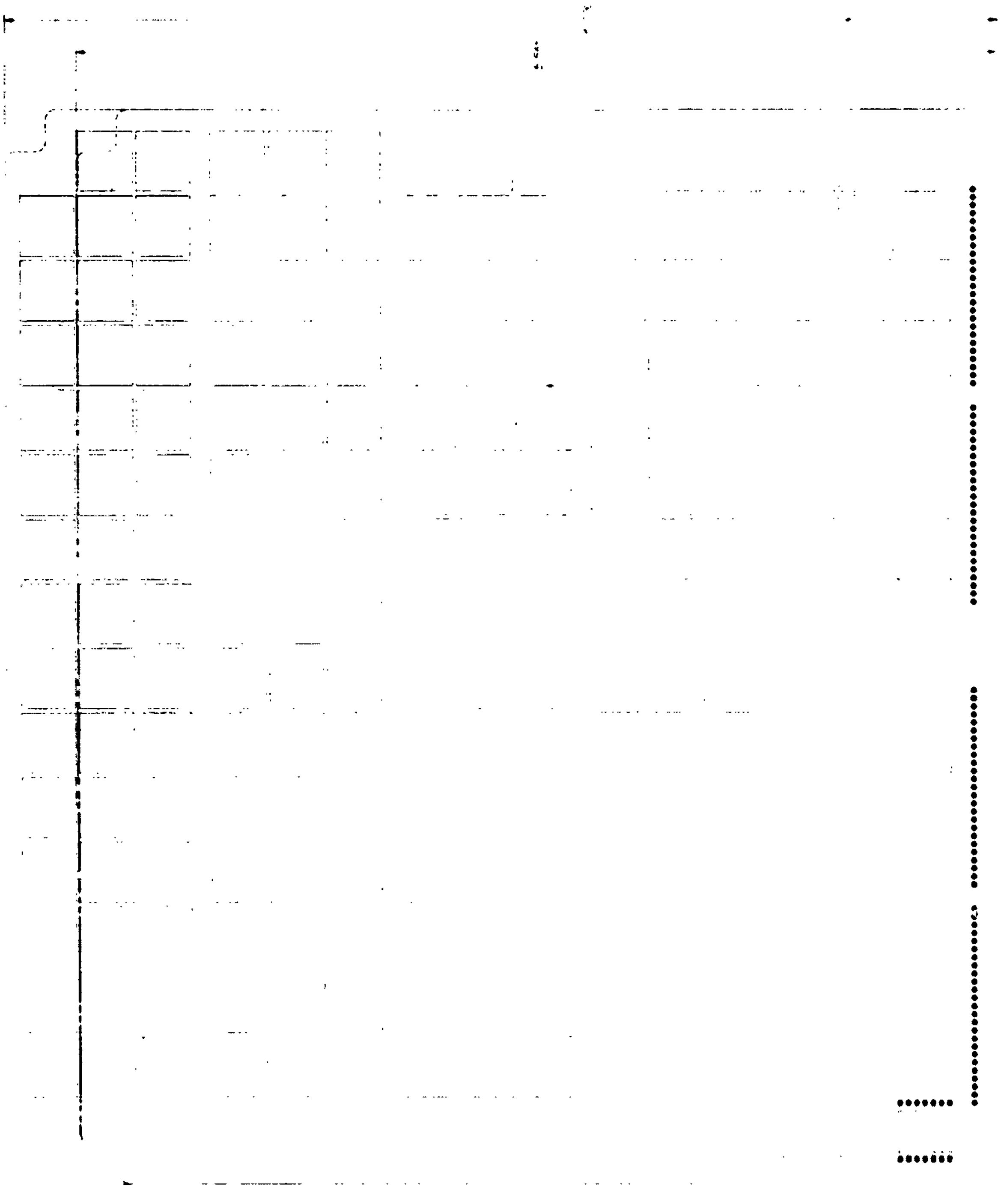


Fig. 32. Composite Module Layout with 14-Lead ICs and Discrete Multilayer Interconnections, Configuration 1

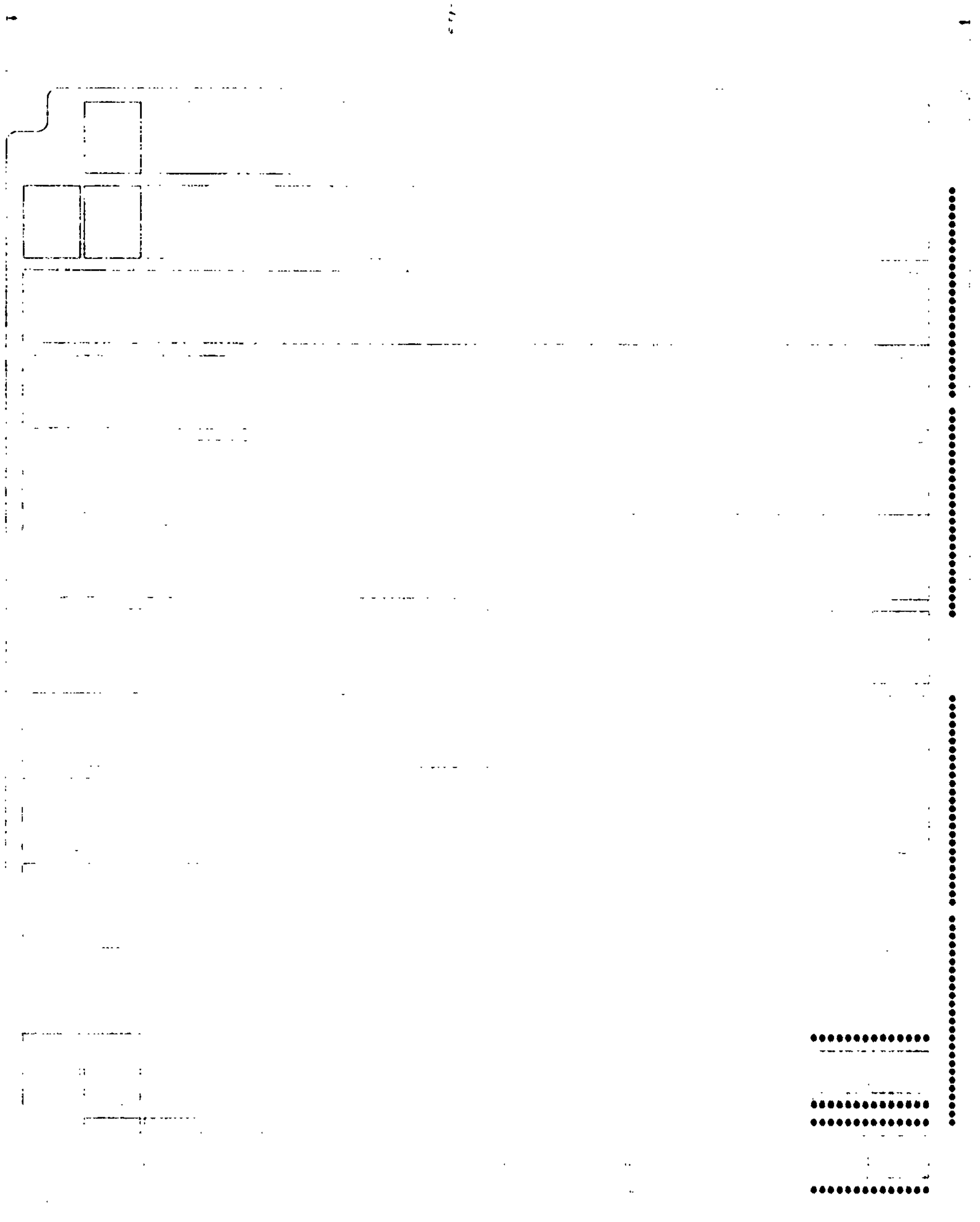


Fig. 33. Composite Module Layout With 14-Lead ICs and Discrete Multilayer Interconnections, Configuration 2

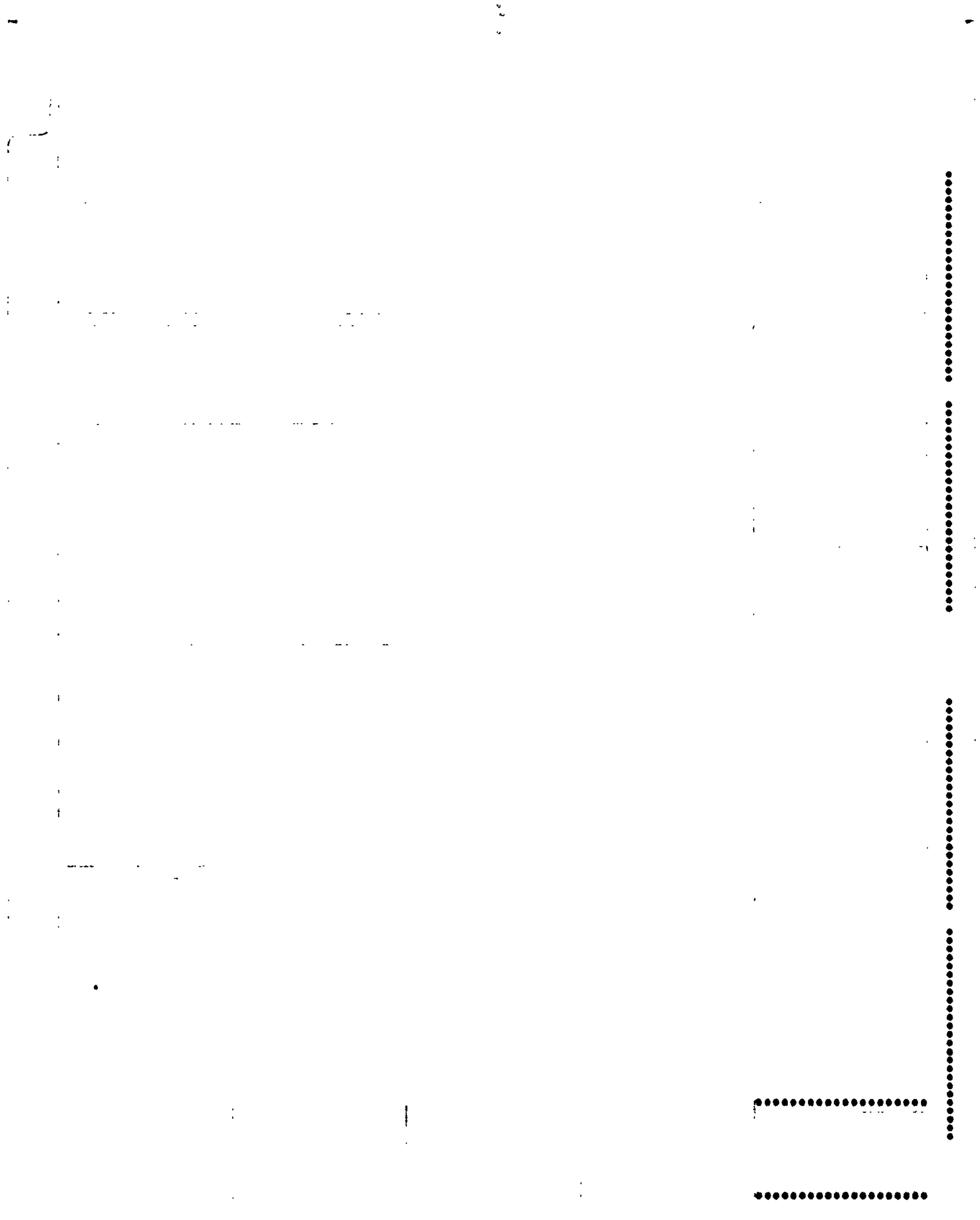


Fig. 34. Composite Module Layout With 40-Lead CMMAs and Discrete Multilayer Interconnections

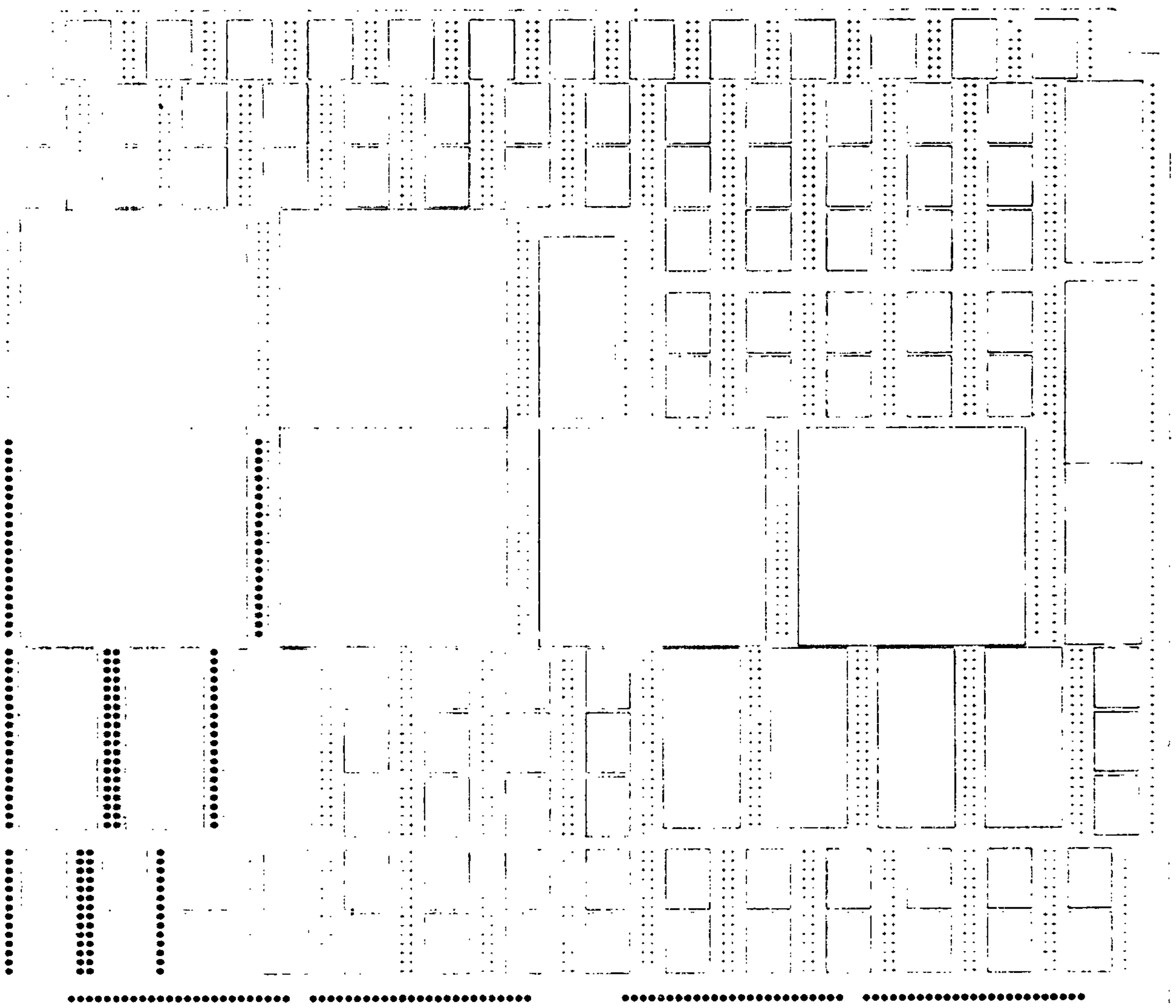


Fig. 35. Composite Module Layout with CMMAs, Hybrid Packages, and Discrete Multilayer Interconnections

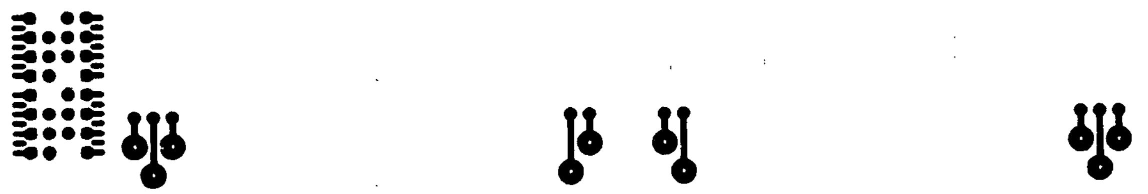


Fig. 36. Composite Module Layout With 14-Lead ICs and Multilayer Printed Wiring Board Interconnections

Fig. 37. Module Size Variations

Table 5. Packaging Density Estimates for TOPS Subsystems

Packaging Method and Assumptions	Estimated Density[a] parts/cm^3	(parts/in^3)
Planar		
Single-side printed wiring board; discrete parts	0.55-0.67	(9-11)
Power[b]	0.06-0.18	(1-3)
Cordwood module with discrete parts	1.5-2.1	(25-35)
Multilayer printed wiring board; discrete parts		
Mariner Mars 69	0.13	(2.15)
Mariner Mars 71	0.17	(2.85)
Mariner Mars 71[c]	0.34	(5.7)
"Green Stick" with 14-lead ICs	0.38	(6.3)
Expanded Stick with 14-lead ICs	0.64	(10.5)
Discrete Multilayer interconnection system with:		
14-lead ICs	1.06	(17.3)
Custom Metallized Multigate Arrays[d]	0.26	(4.3)
Hybrid microcircuits[e] using:		
IC chips	1.8	(30)
Transistor chips	2.4	(40)
Mixed parts, average	1.9	(32)

[a] A reasonable goal for mass density is 0.83 to 0.91 g/cm^3 (0.030 to 0.033 lb/in^3). For reference, the densities of Stycast 1090 and magnesium are 0.66 and 1.8 g/cm^3, respectively. Mass density estimates outside the range of 0.55 to 1.1 g/cm^3 (0.02 to 0.04 lb/in^3) are suspect and should be reviewed carefully.

[b] Mariner Mars 69 density was 0.022 parts/cm^3 (0.86 parts/in^3)

[c] Without limitation imposed by connectors.

[d] In 1.3 x 2.5 cm (0.5 x 1.0 in), 32-lead, hermetic package.

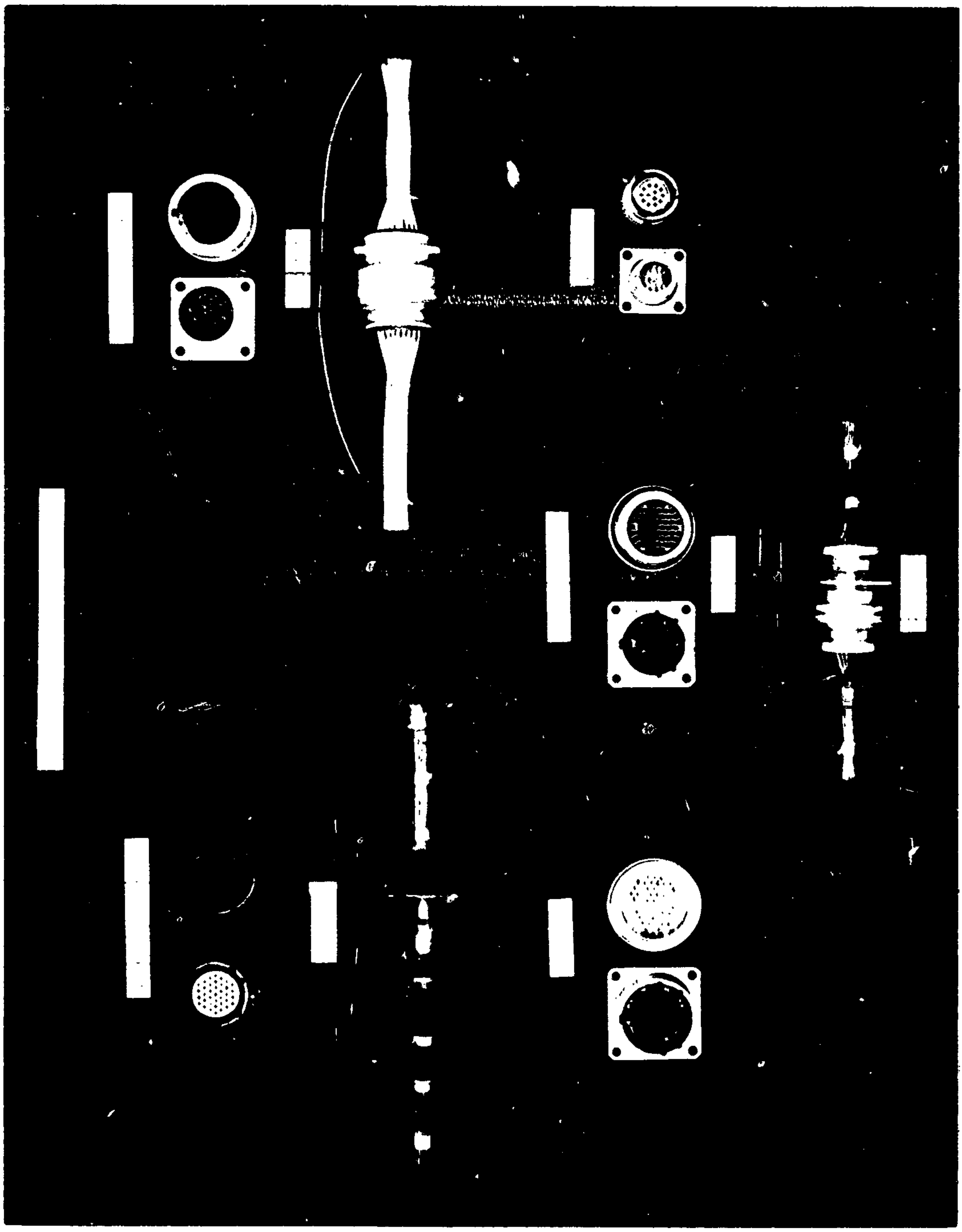
[e] Based on 2.5 x 2.5 cm substrate in 32-lead hermetic package.

tion and rework procedures for the chemically etched trace and its insulating tape.

D. Parts and Components

One of the keys to success in the design and fabrication of reliable electronic equipment is the establishment and maintenance of a list of selected parts, materials, and processes, the performance of which is known and predictable. JPL specification ZPP-2063-PMP, Preferred Materials, Fasteners, and Packaging and Cabling Hardware, is one such list. More than 90 percent of the parts and materials (exclusive of electronic components) used in the fabrication of JPL spacecraft electronic equipment are covered by this document. A predecessor to this, JPL specification ZPP-2011-PML, Preferred Parts and Materials List for Electronic Equipment, was in effect at the time of the TOPS project. Since this was a general purpose document and did not consider the natural and RTG-induced radiation environments forecast by TOPS, nor the magnetic cleanliness requirements of the project, it was reviewed to ascertain the possible effects of these new considerations. This review by materials specialists disclosed no problems other than the likelihood of radiation damage to Teflon and parts made therefrom. Based on available literature, TFE Teflon was considered unsatisfactory and FEP Teflon marginal. (Later, the predicted radiation levels were revised downward, making both forms of Teflon marginally acceptable.

Satisfaction of the TOPS packaging and cabling objectives required the obtaining of high-density connectors, of flightworthy design, in both rectangular and circular configurations. To obtain four times the contact density of Mariner 69 required a pin spacing of 1.3 mm (0.050 in). From the available connectors in this category, the groups shown in Figs. 38 and 39 and listed in Table 6 were selected and procured for evaluation. Connectors were selected for use in the TOPS packaging and cabling developments based on the evaluation data. The circular connectors chosen were the Bendix JT series, which utilize aluminum shells and rigid diallyl phthalate inserts in both mating connectors. Only minor modifications would be required to obtain the required nonmagnetic and contact plating properties. This connector is available with either solder cup or crimp contacts. The rectangular connectors selected were the microminiature Microdot MCD Micromate series with metal shells, diallyl phthalate inserts, and



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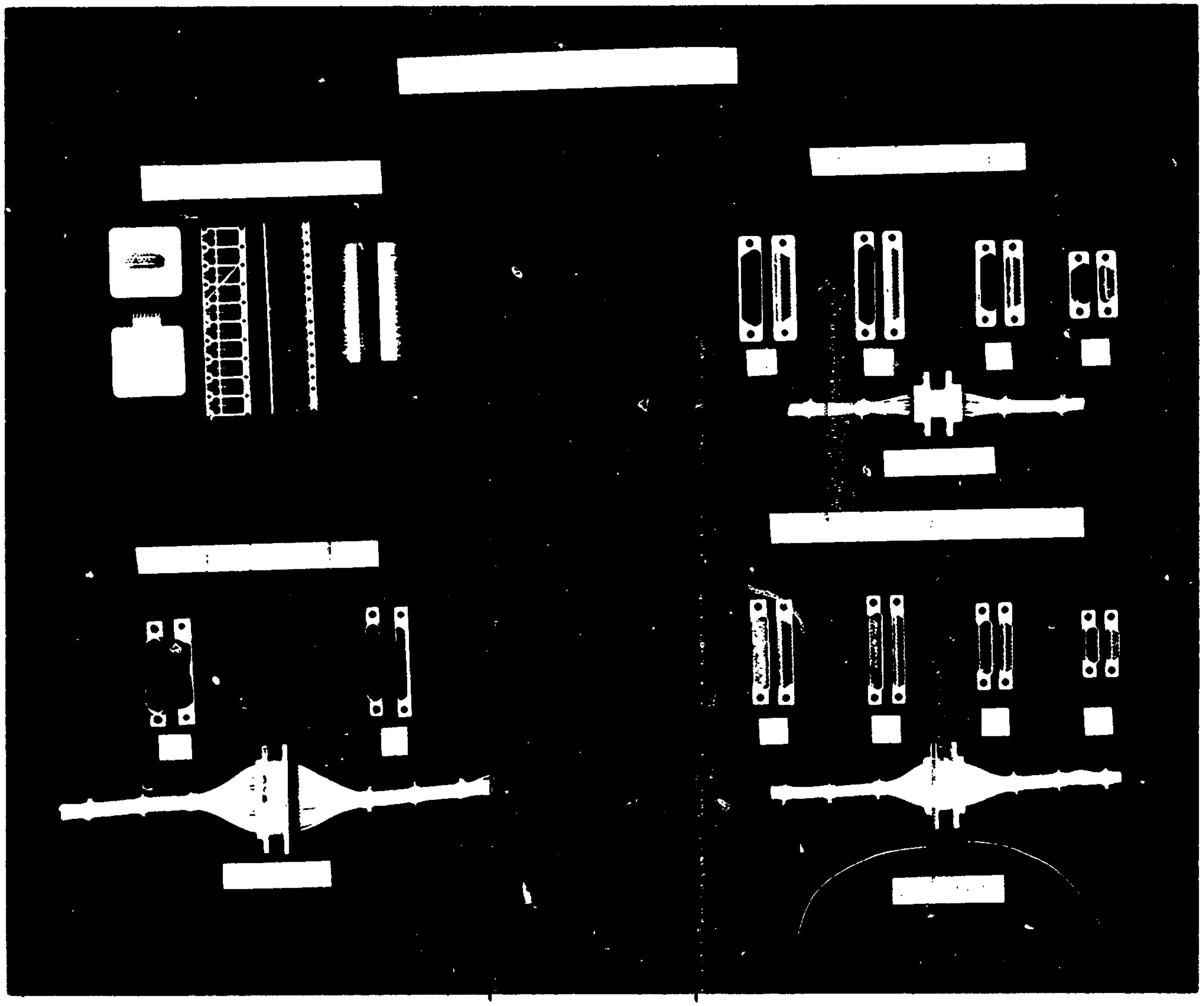


[illegible]. Microminiature Rectangular Connectors (contd)

Table 6. Connector Evaluation Candidates

Connector Type	Packaging Level[1]	Mfr. Code	Contacts			
			Number	Spacing, mm (in)	Contact Size, AWG	Wire Attachment
Subminiature circular	III	1	37 to 85	1.5 to 1.8 (0.060 to 0.070)	22 & 22M	Crimp[3]
		2	4 to 128	1.5 to 2.0 (0.060 to 0.080)		Crimp[3] or solder[2]
		3	61		26 to 30	Crimp[3]
Subminiature rectangular	II & III	4	6, 28, & 100	1.8 (0.070)	22	Crimp[3]
Microminiature circular	II	5	19, 31, & 61	1.3 (0.050)	22	Crimp
		6	7, 12, & 22		26	Solder
Microminiature rectangular	I, II & III	7	16, 32, & 64	0.6 or 1.3 (0.025 or 0.050)	26 to 30	Crimp or solder
		8	9 to 51	1.3 (0.050)	24 (Twist pin)	Crimp
		9				
		10				Crimp[3]

1. Levels: I, System; II, Assembly; III, Module.
2. Available on some sizes.
3. Contacts not installed.

Twist/Con contacts. These contacts utilize a crimp connection to any of various terminations, including solder cups and wire pigtails.

Wire of smaller gage and lighter weight than that now used for flight was also needed. Several available types, as listed in Table 7, were selected and procured for evaluation. The results of the initial evaluations are reported in Refs. 3 and 4. The initial evaluations did not include insulation stripping and radiation exposure tests; these were performed subsequently. Radiation exposure tests were inconclusive; a new test plan and new samples were prepared, with the expectation that the testing would be performed on the Outer Planets Project. Based on the limited testing that was accomplished, two wire types, having tape-wrapped Teflon and polyimide insulations, respectively, were considered potentially acceptable.

The reliability history of hermetic packages for integrated circuits and other microcircuit and hybrid devices has been one of high package rejection rates and poor-to-marginal overall quality. Deficiencies exist in plating quality, bondability, sealing capability, and adequacy of the cavity geometry for specific die applications.

One of the tasks undertaken on TOPS had as its initial objective the definition of the engineering requirements and manufacturing controls necessary to obtain reliable hermetic packages of the conventional flatpack configuration. Readily available manufacturing techniques were to be used. JPL specification CS 594932, defining certain improvements (primarily dimensional) to an otherwise readily available, commercial-type, Kovar-glass sealed IC flatpack, was generated in response to this requirement. Subsequent review by the JPL Microelectronics Committee resulted in the decision to pursue the development of a package specifically tailored to the needs of TOPS: a nonmagnetic, all-ceramic package.

The objective was redefined to include the preparation of drawings and specifications for a family of flatpacks, having 1.3 mm (0.050 in) lead spacing, that would: be nonmagnetic; be radiation resistant; be capable of reliable hermetic sealing; minimize the risk of failure of the die bond; and maximize the integrity of the wire bonds. Specification CS 505390 was generated, along with detail drawings for three package types: a 14-lead IC package, 7.1 x 8.9 mm (0.280 x 0.350 in); a 40-lead LSI package, 1.12 x 2.54 cm (0.440 x 1.000 in); and a 44-lead hybrid circuit package, 3.05 x 3.21 cm (1.200 x 1.260 in), for

Table 7. Wire Evaluation Candidates

Mfr. Code	Applicable Specification	Primary Insulation		Conductor Size, AWG	Voltage Rating, Volts	Construction
		Material	Thickness, mm (in)			
1	JPL - DS 9000 series	Wrapped and sintered TFE	0.20 (0.008) 0.25 (0.010) 0.25 (0.010)	28 28 30	350 600 600	Single conductor
			0.25 (0.010) 0.20 (0.008)	26 30	600 350	Twisted, shielded, and jacketed pair
2	MIL-W-16878, Type E	Extruded and sintered TFE	0.25 (0.010)	28 30 32	600 600 600	Single conductor
3	MIL-W-16878, Type ET	Extruded and sintered TFE	0.15 (0.006)	28 30 32	300 300 300	Single conductor
4	MIL-W-81381	Polyimide, tape wrap	0.25 (0.010)	26 28	600 600	Single conductor
				26	600	Twisted, shielded, and jacketed pair
5	None	Extruded cross-linked alkane-imide polymer	0.25 (0.010)	26 28 30	600 600 600	Single conductor
				26	600	Twisted, shielded and jacketed pair

2.54 x 2.54 cm substrates. All bonding surfaces were to be gold plated, with the exception of the wire bond pads in the LSI package, which were to be aluminized for compatibility with the metallization of the CMMA device mentioned in Section III-C. These specifications and drawings were released following review by prospective suppliers and by a special JPL review board. Figure 40 shows the salient geometrical features of the 14-lead IC package.

A Request for Quotation (RFQ) covering the fabrication and predelivery acceptance testing of a total quantity of 550 (50 proof parts and 500 prototypes) of each of these package types was sent to seven prospective suppliers in December 1970. This produced one responsive quotation; however, during the negotiating period, this firm went into bankruptcy. Subsequent negotiations with a number of companies, including several who were not included in the original RFQ, resulted in no quotations which were both responsive and within the funding available for this task.

Finally, an order was placed for a modified commercial package similar to the 40-lead LSI package. The modifications consisted of replacing the manufacturer's normal Kovar lead frame and Kovar package seal ring, respectively, with a copper lead frame and with gold plated tungsten package metallization. The manufacturer was also to supply a ceramic lid with gold plated tungsten metallization on the sealing surface, in lieu of the usual Kovar lid. This was done with the intent of establishing the feasibility of the nonmagnetic aspects of the package, which appeared to be the item of greatest concern to prospective suppliers.

The receipt of the modified commercial packages and their subsequent evaluation is covered in Ref. 5. These parts were found to be essentially completely nonmagnetic. Test results showed the feasibility of a nonmagnetic package, but emphasized the need for improved controls in microcircuit package procurements.

E. Joining Techniques

The selection of joining techniques used to interconnect electronic parts is an important aspect of electronic packaging development. The joining technique establishes one of the limits on achievable part density. Because of the large numbers of components and of joints in the spacecraft, both the reliability

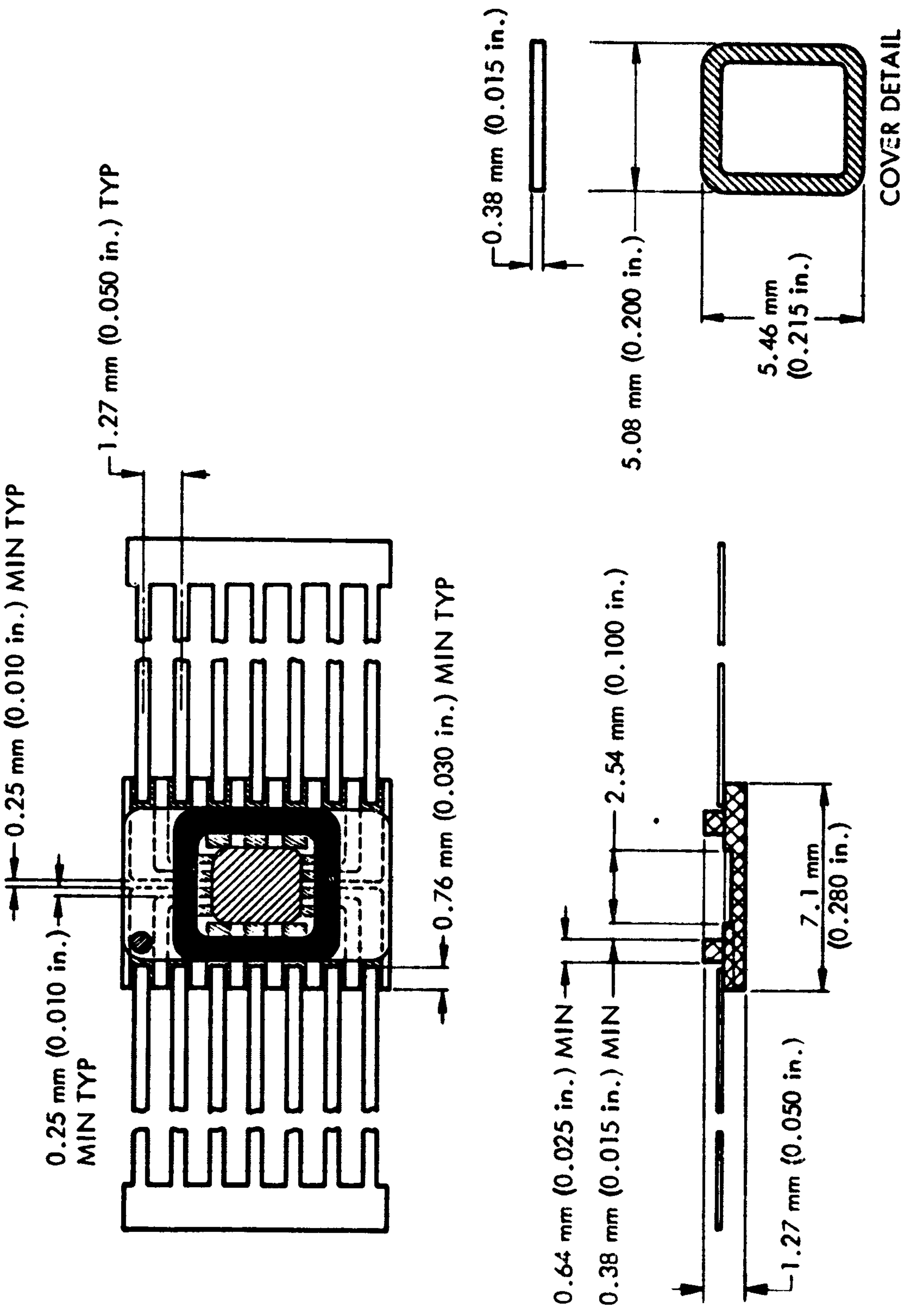


Fig. 40. 14-Lead IC Package

of the joint and the effects of the joining process on part reliability are crucial to system reliability. The ability to readily make, inspect, and repair joints also has a significant impact on hardware costs.

Two joining techniques under development at the start of the TOPS project were reflow soldering, for attachment of ICs to printed wiring boards, and concentric electrode through-insulation welding of interconnections. Reflow solder joining allows equipment maintenance at the component level. Figure 41 illustrates reflow solder attachment of flatpack devices to a multilayer printed wiring board on an experimental module. Computer controlled routing and through-insulation welding of magnet wire is attractive for use in fabrication of light-weight Module interconnection systems, having the potential for being accomplished directly from subassembly wiring lists. Concentric electrode through-insulation welding development is illustrated in Fig. 42 and is reported in Ref. 6.

Joint parameters for both electronic part and circuit conductor attachment were developed in support of the DML interconnection system development. Two different material systems and their associated joining processes were investigated. One system used stainless steel foil interconnection circuitry, which was welded to gold plated stainless steel or Monel terminals. The second system combined gold plated brass terminals with gold plated copper foil circuitry, with the joint being made by reflow soldering with a high melting point gold-tin solder, applied in paste form. In both systems, the part leads and the part ends of the terminals were tinned with 63/37 tin-lead solder and these were then joined by reflow soldering. A typical chemically etched circuit conductor is shown in Fig. 31.

Thick film hybrid interconnection processes were also investigated. Figures 43, 44, and 45 show substrates that were developed for the TOPS tree switch; Fig. 46, a CCS interface circuit; and Fig. 47, a tape head driver.

Beam lead attachment methods were also investigated briefly. A method for mounting beam leaded devices to carriers, to permit testing and burn in, was suggested to radio subsystem cognizant personnel. The beam leaded devices which were being developed for their use could be designed with extra long [illegible] beams. The devices would be mounted to the carriers by thermocompression bonding of just the tips of the beams. Cutting the beams at about their midpoints [illegible]

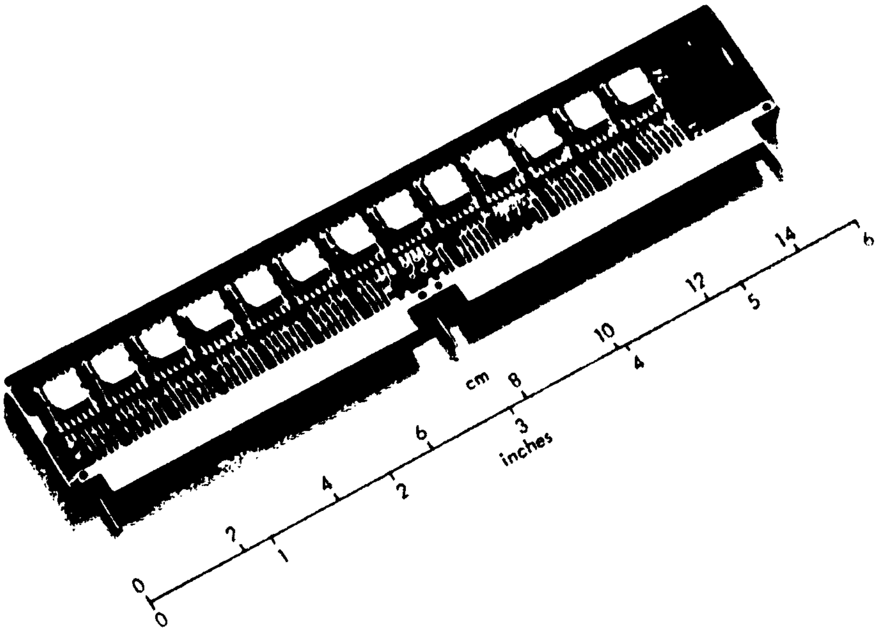


Fig. 41. Experimental Module With ICs Reflow Soldered to Multilayer Printed Wiring Board

Fig. 42. Close-up of Automatically Routed, Through-Insulation Welded Interconnections

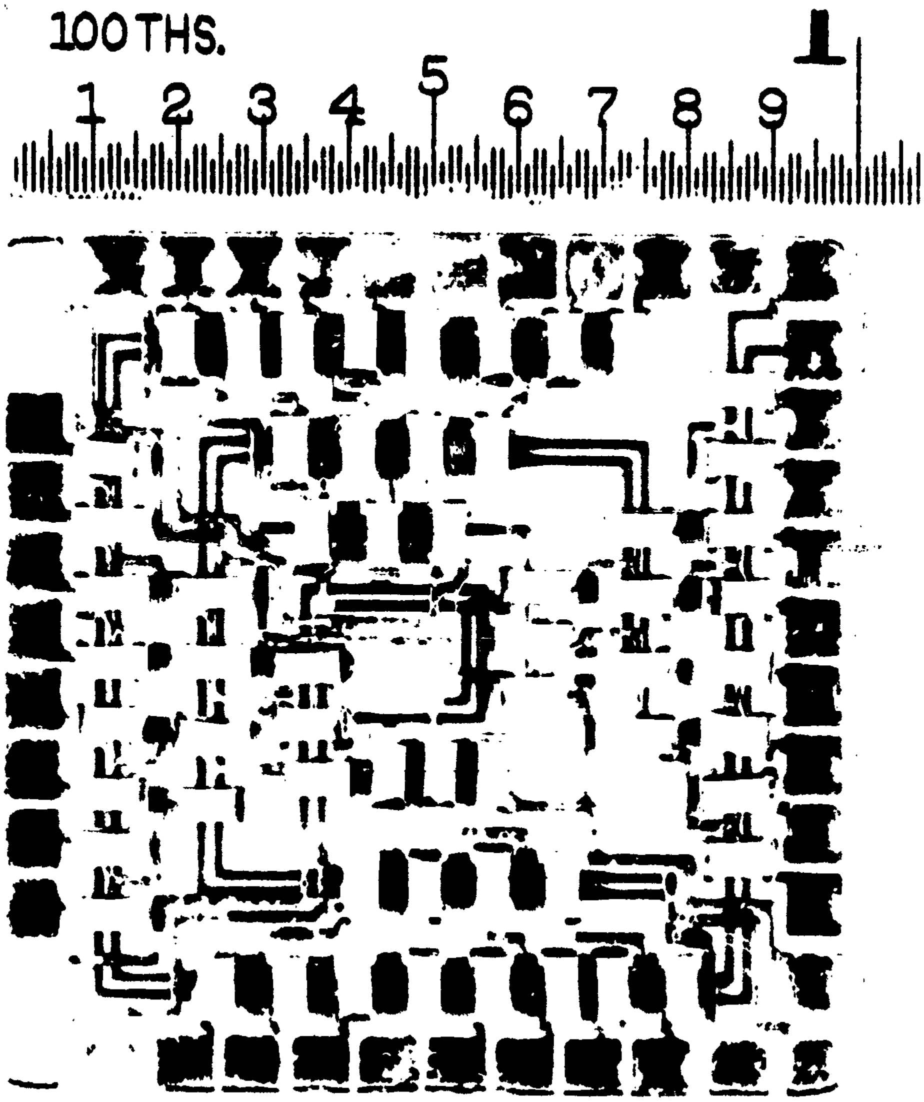


Fig. 43. Third Flip-Flop Switch Module, Early Version

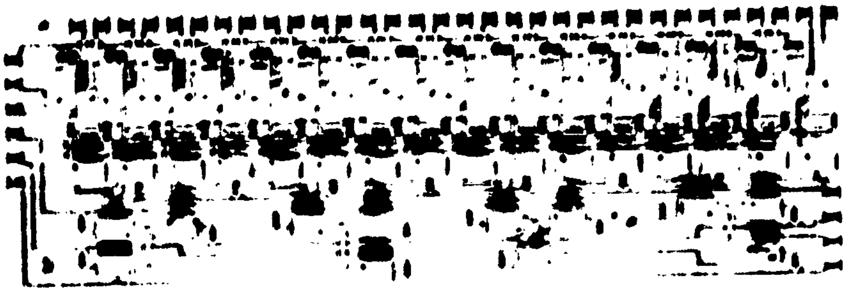


Fig. 44. Thick Film Tree Switch, Improved

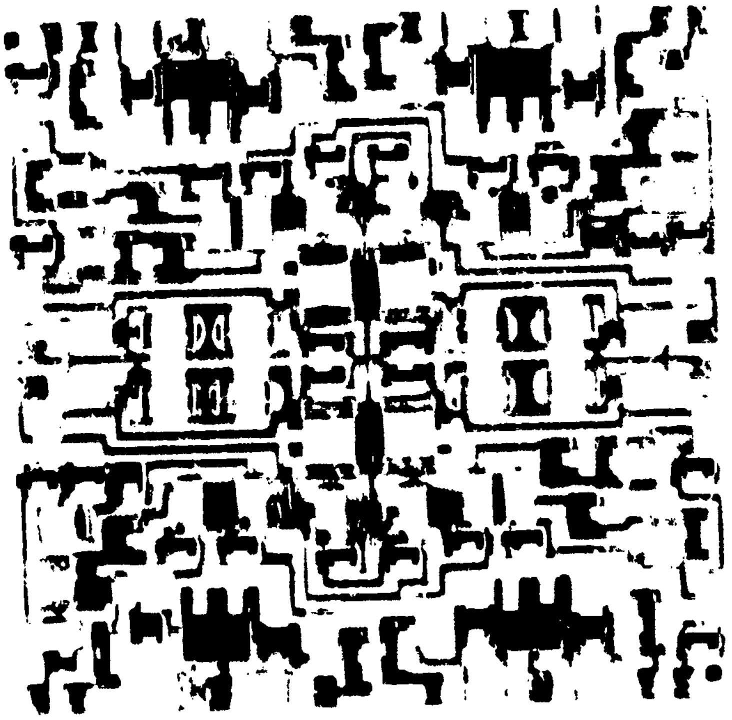


Fig. 45. Thick Film Redundant [illegible]
Tree Switch Driver Module

Fig. 46. Thick Film CCS Interface Circuit

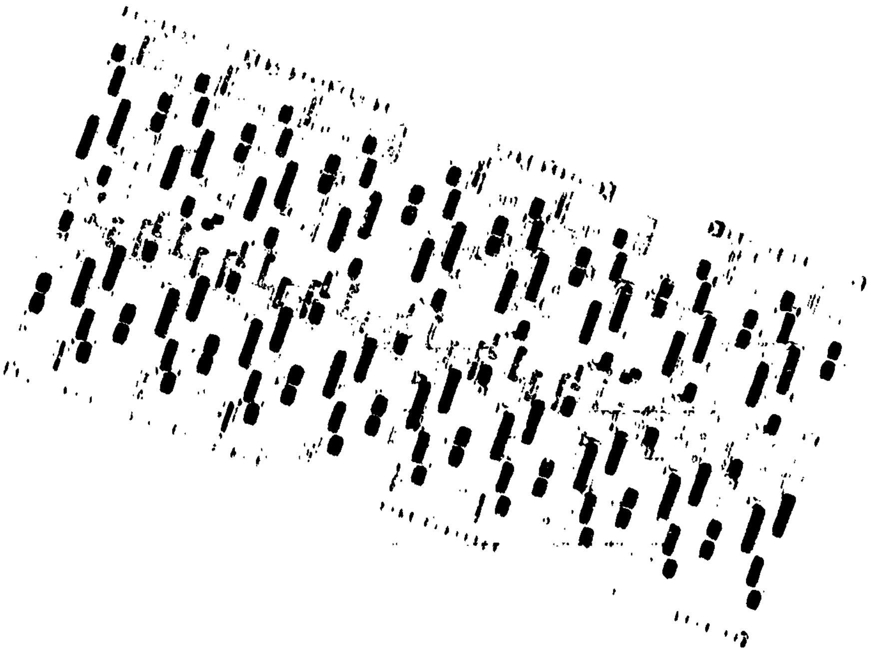


Fig. 47. Thick Film Tape Head Driver Circuit

allow the devices to be removed from the carriers, leaving them with normal length beams, and permitting them to be used in the usual manner. Development of this and other methods for mounting of beam leaded devices for test purposes should be continued.

IV. PROJECT SUPPORT

A. System

Packaging and cabling support at the system level consisted of participation on the Design Team and the Microparts Committee, presentations at design reviews, writing Functional Requirements (FR) documents, supporting the Functional Engineering Model (FEM) activity, and providing cost estimates for proposed outer planets missions.

As part of the Design Team activities, the volume requirements of the electronic equipment were developed to permit sizing the Electronic Compartment for configuration studies. Table 1 summarizes this information and compares it with Mariner 69 data. A packaging layout drawing was developed as part of this activity, and is shown in Fig. 5.

A set of guidelines was distributed to the subsystem engineers for their use in developing estimates of weights and volumes. These guidelines, shown in Table 5, are based on the use of a 15.2 cm (6.00 in) EA width.

B. Subsystems

In addition to the continuing activity of defining and refining subsystem weights, volumes, and packaging interfaces, several specific subsystem development support tasks were accomplished.

Liaison was maintained with the development contractor for the miniature radio receiver. A subchassis, having integral r.f. seals machined into the covers, was designed for mounting of the contractor-developed circuit boards; the subchassis, in turn, were attached to a structural plate provided with integral, r.f. shielded wireways. Subchassis were procured and supplied to the Telecommunications Division. The follow-on development of a microminiature receiver, using beam leaded parts and hybrid microcircuit packaging techniques, was also supported.

Elements of several of the TOPS subsystems were used as applications test vehicles in ongoing hybrid microelectronics R/AD tasks. Figure 43 is a 32-input, two-output switch module which represents a portion of the tree switch used in the Flight Telemetry Subsystem; Fig. 44 is a revised version having thick film resistors in series with the gates of the JFETs. Figure 45 is a redundant complementary driver for the tree switch. The complete 512-input tree switch requires 18 of the switch modules and 10 of the drivers, and could be packaged on a single 17.8 x 36.8 cm (7 x 14.5 in) subchassis. Figure 46 shows an early developmental CCS interface circuit. Figure 47 is a head driver circuit which was built for test with a developmental multi-head tape recorder.

V. CONCLUSIONS AND RECOMMENDATIONS

The TOPS packaging and cabling development and support activities covered a period of approximately 30 months. The hardware development objectives were to conceive, design, fabricate, and test a packaging and cabling system for reliable flight electronic subsystems that would provide significant improvements in weights and volumes. Within the constraints of the system development project structure, a concept was developed, hardware was designed and fabricated, and the fit-and-function of the hardware was demonstrated. Specific accomplishments include:

(1) Design and fabrication of the Electronic Compartment, including the mechanical features required for interfacing with the Electronic Assembly.

(2) Design and fabrication of an Electronic Assembly for high-density digital circuits, having a plug-in interface to the Module/Subassembly.

(3) Investigation of several interconnection methods for use at the Assembly level.

(4) Fabrication of a Composite Module employing the Discrete Multilayer interconnection system; the test item being a portion of the STAR computer.

(5) Fit-and-function and insertion force tests of the Module-to-EA interface.

(6) Evaluation of connectors and wires, selection of candidates for outer planets missions, and preparation of documentation suitable for procurement of samples for flight qualification.

(7) Procurement and testing of a nonmagnetic, ceramic, microcircuit package.

(8) Development of selected thick film hybrid circuits.

A list of drawings generated during the program is included as Appendix A.

Most of the goals and objectives initially set were achieved. However, due to programmatic funding limitations, the development was accomplished in three related, but noncontiguous, periods. Supporting technology developments that were anticipated from other R/AD programs were severely curtailed and their funding completely eliminated during the last five months of the TOPS project. Some of the needed technology was developed on TOPS, and support for portions of the environmental testing and applications development needed to demonstrate the evolving technology was obtained at the expense of other planned TOPS work.

The TOPS subsystem functional definitions were sufficiently refined by the end of the project that realistic definitions of subsystem weights and volumes, reflecting the full impact of the packaging and cabling developments, could have been made. Although some of the savings available from these developments were included, the final subsystem weight and volume estimates still contained substantial pads.

Applying the packaging and cabling developments to a digital subsystem could have been very helpful and illuminating in demonstrating the improvements possible with TOPS technology. For example, the Mariner 69 DAS used 653 ICs in three subassemblies; with TOPS technology, 1500 ICs could be packaged in the envelope of one Mariner 69 DAS subassembly. Weight and volume could potentially be improved by factors of two and three, respectively, along with the possibility for improving reliability and cost.

At the conclusion of this study the following items are recommended for further development:

(1) Completion of procurement documentation and qualifications for small gage light weight wire, in two voltage ratings, and addition of these items to the Preferred Packaging & Cabling Hardware, Spec. (Ref. 7).

(2) Completion of procurement documentation and qualification for sub-

miniature circular connectors and addition of these to the Preferred Parts Specification (Ref. 7).

(3) Completion of procurement documentation and qualification for microminiature rectangular connectors and addition of these to the Preferred Parts Specification (Ref. 7).

(4) Upgrading of the Electronic Compartment to test model status; proof testing and refining of the design to qualify it for flight.

(5) Proof testing and refining of the Electronic Assembly design to qualify it for flight.

(6) Completion of the development of the Electronic Compartment (EC) cabling system. This would include the establishment of the flight design, fabrication and test of a proof model.

(7) Completion of the development of the EA interconnection system, establishment of the flight design, fabrication of a proof model, and inclusion of this in the EA proof test.

(8) Documentation of the DML interconnection technique sufficiently to permit fabrication of flight qualification and proof test hardware.

(9) Development and qualification of the design and process requirements for fabrication of thick film hybrid circuits. This should include policy positions on electronic part types and hermeticity and "package" level for semiconductor devices.

(10) Establishment of a list of approved parts for use in hybrid microcircuits.

(11) The need for a reliable hermetic microcircuit package still exists. In particular, the development of such a package in a nonmagnetic version should be vigorously pursued. It is suggested that this be done first for a 14-lead package, and that larger packages be added following completion of the learning process on the smaller package.

APPENDIX A

TOPS ELECTRONIC PACKAGING DRAWING LISTS

A number of electronic packaging drawings were generated under the TOPS project. Some of these deal with the configurations of the Electronic Compartment and of the digital-type Electronic Assembly that was extensively studied. Others cover details, such as those relating to the improved microcircuit packages that were documented, the key features of the Discrete Multilayer interconnection concept, and mechanical hardware, such as guide pins and connector mounting brackets. For historical reasons, and in the belief that certain of these may yet find flight project use, these are listed in Tables A-1, A-2, and A-3, for Module, Assembly, and Compartment level drawings, respectively.

Table A-1. TOPS Electronic Packaging Drawings, Module Level

Dwg. No.	Drawing Title	Description and Remarks
10034560	Terminal, Integrated Circuit, DML	Detail drawing of terminal for use with Discrete Multilayer interconnection system. Two dash numbers have heights of 0.89 and 1.65 mm (0.035 and 0.065 in) on component installation end.
10036203	Module Handling Tool	
10036205	IC Module Assembly	Obsolete
10036207	Electronic Subassembly TOPS Development	
10036208	Frame Assembly IC Module	Early version with Module-EA interface.
10036506	14-Lead Ceramic Package	7.1 x 8.9 mm (0.280 x 0.350 in) flatpack with leads on 1.3 mm (0.050 in) centers.
10036589	44-Lead Ceramic Package	3.10 x 3.25 cm (1.220 x 1.280 in) flatpack with leads on 1.3 mm centers. Has 2.69 x 2.74 cm (1.060 x 1.080 in) substrate mounting cavity. For hybrid circuit applications.
10037884	Cover Seal Preform, Ceramic Package	Gold-tin alloy with 296°C (566°F) melting point. Dash numbered sizes for different packages.
10037885	40-Lead Ceramic Package	1.12 x 2.54 cm (0.440 x 1.000 in) flatpack with leads on 1.3 mm centers. Has 5.3 x 5.8 mm (0.210 x 0.230 in) die cavity and aluminized bonding pads. For Custom Metallized Multigate Array.
10038456	Gasket, RFI, Receiver Module	Gasket for 10045870 chassis.

Table A-1. TOPS Electronic Packaging Drawings, Module Level (contd)

Dwg. No.	Drawing Title	Description and Remarks
10038959	Receiver Modules, Assembly, Typical Layout	Shows method of assembly and interconnection of receiver Modules.
10039247	Module Frame, Standard Blank	Stock, blank frame from which Module frames are completed by machining connector mounting locations (1 to 4) and guide pin receptacles. Dash numbers for 0.6 and 1.3 cm (0.25 and 0.50 in) widths in both 7.6 and 15.2 cm (3.0 and 6.0 in) heights.
10039640	Terminal Board Assembly, Small DML Module	Insulator board for 7.6 cm high Module accepting 76 14-lead ICs. Terminal layout is used as basic spacing pattern for STAR breadboard circuit artwork. Shows terminal installation.
10039710	Frame Assembly, DML Module	Details connector configuration, keying, insert locations, and final machining of the 10039247 blank to provide 19 different Modules of various widths, heights, and connector capability.
10039823	Subchassis, Electronic Module, Standard Blank	Machined blank from which 2.5 cm (1.00 in) wide Modules are made. Both 7.6 and 15.2 cm heights. 1.0 mm (0.050 in) thick component mounting web.
1003982[illegible]	Subchassis, Assembly, 1" Wide, Module	Finish machining details for 2.5 cm wide Module including connector locations, keying, and inserts.
10039825	Subchassis, Assembly, Expanded Electronic Module	Complete machining drawing for a 7.6 cm wide Module typical of a plug-in unit using larger components (e.g., transformers).

Table A-1. TOPS Electronic Packaging Drawings, Module Level (contd)

Dwg. No.	Drawing Title	Description and Remarks
10039867	Guide Pin, Electronic Subassembly	
10040196	Terminal Board Assembly, Large DML Module	Similar to 10039640, but fits the 15.2 cm high Module and accepts 193 flatpacks.
10040198	DML Module Subassembly, Pictorial Configuration	Exploded view of DML Composite Module.
10044656	Subchassis Assembly, Expanded 6 in. Electronic Module	Similar to 10039825, but with more machining variations.
10045867	STAR/FTS Adder Functional Interconnect List	Interconnection definition for test Module.
10045870	Chassis, Receiver Module Development Proposal	Chassis for mounting miniature receiver printed wiring boards made by Motorola for the Telecommunications Division.
10054833	Component Board Layout Composite Module	Illustrates various part layouts: ICs; mixed IC, LSI, and hybrid parts; and multilayer printed wiring board with ICs.
10054843	Circuitry Pattern, Layer 1 thru 9	DML artwork used in fabrication of the 0.1 mm (0.004 in) thick, gold plated, copper traces used to build up the DML interconnection system. Circuit represents four iterations of the breadboard schematic STAR/FTS 3-input adder. 9 sheets.
10056156	.050 Matrix Master Pattern	
10056157	IC Module Removal Layout	Illustrates use of 10036203 tool.

Table A-2. TOPS Electronic Packaging Drawings, Assembly Level

Dwg. No.	Drawing Title	Description and Remarks
10034509	Typical Electronic Assembly Pictorial Configuration	An early development configuration.
10039963	Guide Pin, Module	Located in EA connector bracket or plate to control Module-EA interface; also provides keying of Module through location.
10041302	Tube, Screw Access	Epoxy-fiberglass which guides tool used to secure screws which fasten connector brackets (10036204) or plates (10041303) to chassis. Tube also insulates and protects the wire harness as it breaks out of the interconnect volume and runs to the compartment interface connectors.
10041409	Keying Guide Pin, Electronic Assembly	Helper pin located at opposite end of the EA-EC interface to aid the keying pin in proper positioning of the EA for plug in. Clearance hole in EC structure permits alignment with mating part of the EC connector support (10041394).
10041495	Access Tube, Electronic Assembly	Epoxy-fiberglass tube which provides access to and provides the captive feature for the spring-loaded screws used to pull the EA into full engagement with the EC.
[illegible]	Electronic Subassembly Pictoral Configuration Alternate Concept	Shows alternate Module arrangement where Module height is fixed and width is variable.
[illegible]	Wiring Harness Diagram	Wiring diagram used for development of EA interconnections.
[illegible]	TOPS EA Configuration	Isometric drawings of TOPS EA.

Table A-2. TOPS Electronic Packaging Drawings, Assembly Level (contd)

Dwg. No.	Drawing Title	Description and Remarks
10056153	Alternate TOPS EA Configuration Sheets 1 through 4	Isometric views showing full bay with integral shear plate, sealed unit, full length subassemblies with integral connector plate, and 6 x 6 subassemblies with integral connector plate

Table A-3. TOPS Electronic Packaging Drawings, Compartment Level

Dwg. No.	Drawing Title	Description and Remarks
10034265	TOPS Packaging Arrangement Electronic Assembly Compartment	Views of +Y, -Y, +X, and -X sides of Electronic Electronic Compartment
10041344	Connector Support Assembly	
10045868	Electronics Subassembly and Compartment Interface Layout	Shows three views of Electronic Compartment assembly
10056151	EC Assembly Pictoral	Isometric view of EC showing EA and louvers

APPENDIX B

ELECTRONIC ASSEMBLY FIT-AND-FUNCTION DEMONSTRATION

Fit-and-function tests were performed to demonstrate the feasibility of single-side access installation of the Electronic Assembly (EA) into the TOPS Electronic Compartment (EC), using fixed-mounted microminiature connectors. Besides the obvious objective of physically installing the Electronic Assembly, it was planned to determine: the ability to align the connectors, and the effect of alignment on insertion forces; deflection of the connector support system; installation tooling requirements; and fastener torquing characteristics.

The installation/removal tests were performed in two setups. Figure B-1 shows one setup, with the load cell used to measure insertion and removal forces versus connector support separation (at the center of the support bar). The second setup was in the center of an end bay of the Electronic Compartment shown in Fig. B-2. Deflections of the center of the connector support were measured and single-side access installation demonstrated in the Compartment. Both setups used the Mariner installation tool, with appropriate adapters. Figures B-3 and B-4 show the tool modifications, which consist mainly of spacers that establish the position of clamping to rails fastened to the Compartment and test fixture.

A total of 16 tests, as summarized in Table B-1, were performed in the fixture and in the EC mock-up. Three connector alignment conditions were investigated. In the first, the connectors on each side of the interface were manually aligned and secured within 0.025 mm (0.001 in) of true position and verified by inspection. In the second, the connectors on the EA were loosely attached, such that they could float. The third condition was established by using the connectors mounted in the support bracket as an alignment fixture, and aligning the EA connectors to this. Figure B-5 shows a typical curve of insertion and extraction forces versus connector separation, for mating the eight 37-pin MCD microminiature connectors (a total of 296 contacts).

Six tests were made measuring insertion force for the Module having ten 25-pin MCD connectors. These were not initially planned, but were made following the tests on the EA, to provide a quick look at Module insertion force and at the Module connector support system. These tests were made using the EA installation tool and load cell setup, but with improvised blocking, hand-holding of the EA

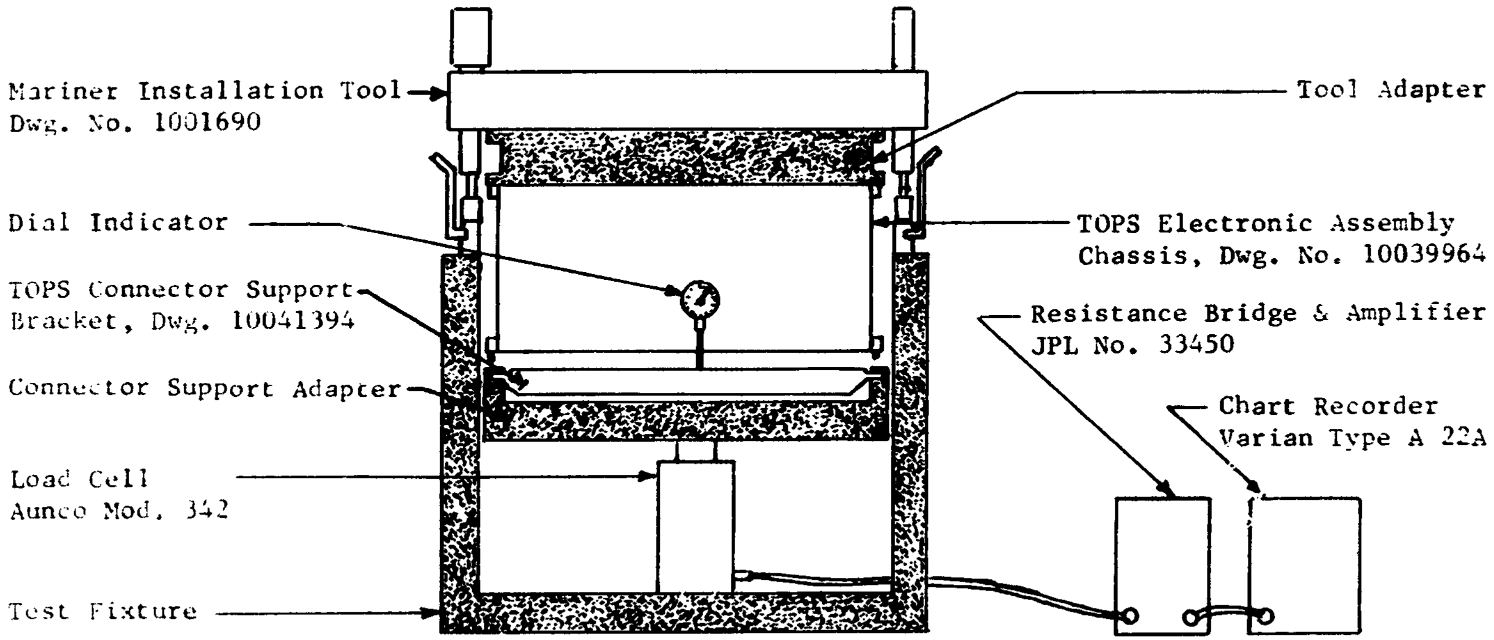


Fig. B-1. TOPS Electronic Assembly Insertion Force Test Setup

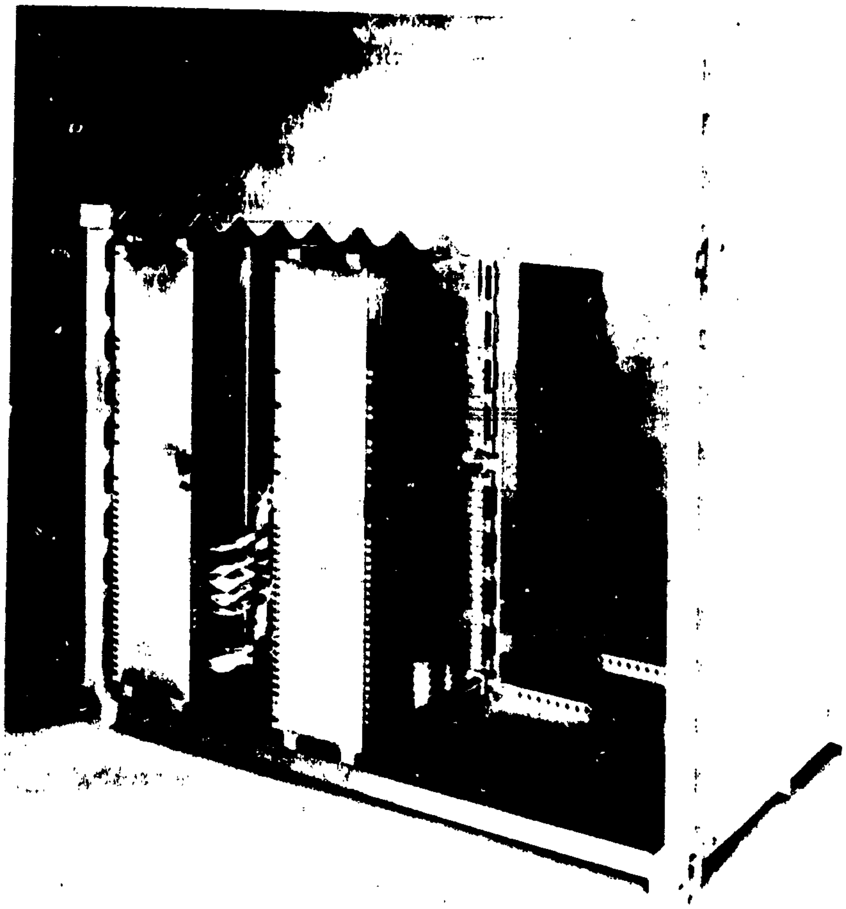


Fig. [illegible]. Location [illegible]
[illegible]

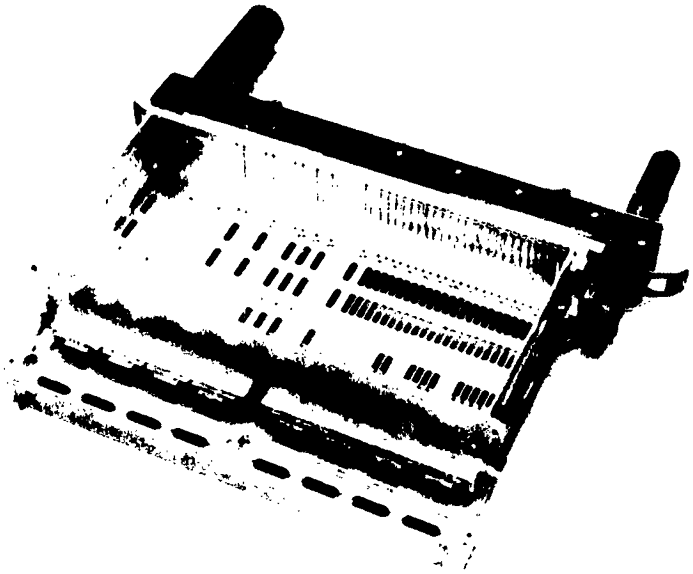


Fig. B-3. Mariner Installation Tool Modified for Insertion Force Test

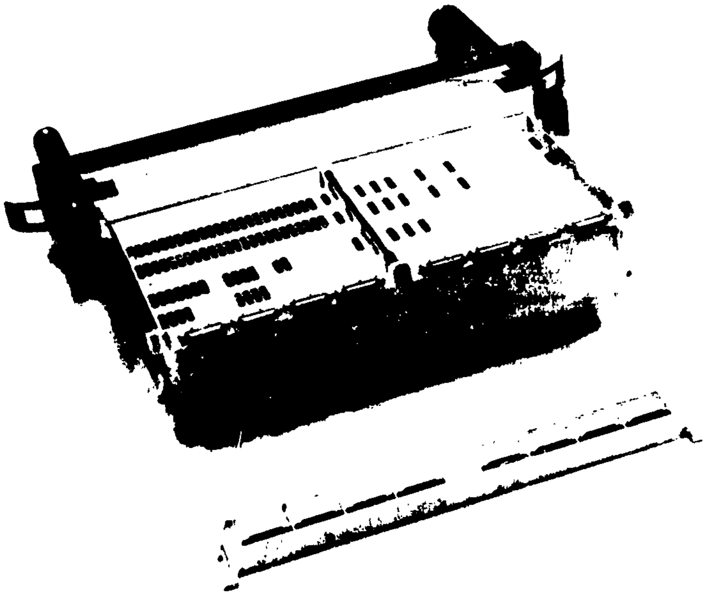


Fig. B-4. Mariner Installation Tool Modified for EC Fit-and-Function Verification

Table B-1. Electronic Assembly Insertion/Removal Test Summary

Test No.	Test Location[a]	Connector Alignment[b]	Deflection Measurement[c]	Maximum Insertion Force		Remarks
				N	lb	
1	A	1	1	512	115	Note d
2	A	1	1	467	105	Note d
3	A	1	1	494	111	
4	A	1	1	681	153	Note e
5	A	2a	3	545	122.5	
6	A	2b	3	534	120	
7	A	2b	3	492	110.5	
8	B	2b	2	---	---	
9	B	2b	2	---	---	
10	B	2b	2	---	---	
11	A	2b	3	521	117	
12	A	2b	3	623	140	
13	A	2b	3	578	130	
14	A	2b	3	452	101.5	Note f
15	A	2b	3	496	111.5	Note f
16	A	3	3	512	115	
17	A	3	3	567	127.5	Note g

[a] A. Force fixture setup
B. Electronic Compartment

[b] 1. Mating connectors aligned and secured within 0.025 mm (0.001 in) of true position.
2a. Connectors on EA loosened to snug sliding fit.
2b. Connectors on EA loosened to sloppy fit.
3. Connectors aligned and secured, using support side as alignment fixture.

[c] 1. Movement of center of connector bracket relative to adapter, and EA chassis flange deflection.
2. Movement of center of connector bracket relative to EA chassis and to surface plate.
3. Movement of center of connector bracket relative to EA chassis.

[d] Gap between chassis and center of connector support, 0.28 mm (0.011 in); flange deflection, -0.051 mm (0.002 in) on test 1 and -0.069 mm (0.0027 in) on test 2.

[e] Gap of 0.61 mm (0.024 in) on left side, due to tilted load cell beam.

[f] Connector bracket shimmed and clamped to reduce deflection.

[g] Installed blocks to prevent tilting of load cell.

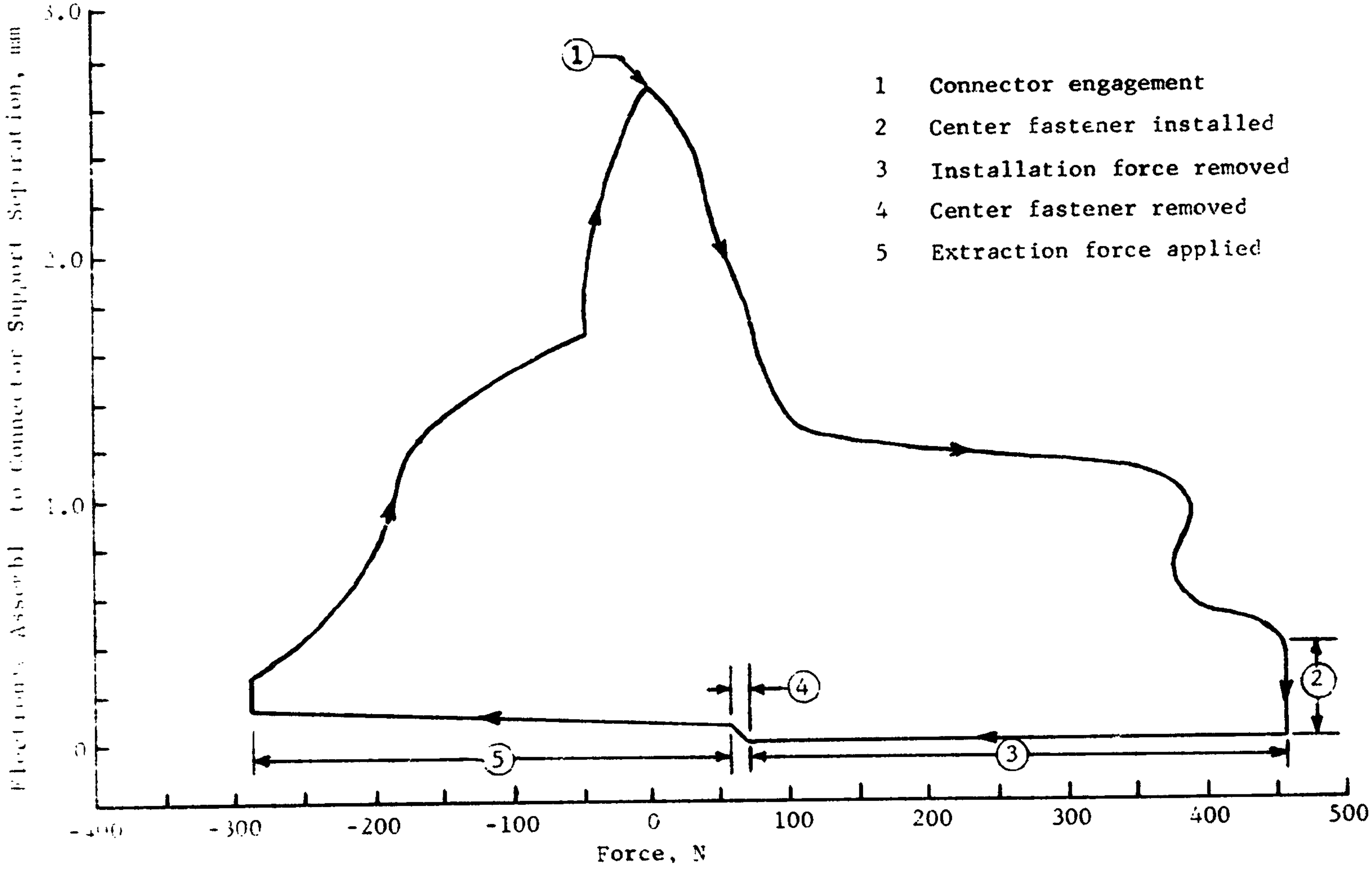


Fig. 8-5. Insertion Force vs. Separation for Electronic Assembly Installation and Removal

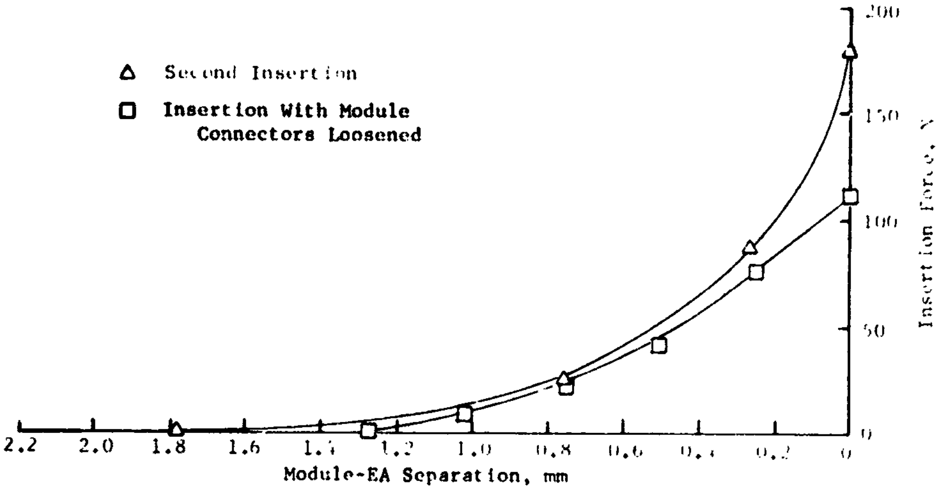
chassis, and the use of a scale for measuring Module position. The resulting data, shown in Fig. B-6, are considered representative of Module insertion force for this condition.

The wired Composite Module and the cabled EA connectors were located only by the nominal machined mounting features; no attempt was made to precisely align the mating connector interface, as would be done in actual usage. The tests were performed satisfactorily at two randomly selected locations in the Assembly. It is believed that insertion forces lower than the observed 1.1 to 1.9 N (4 to 7 oz) per contact could readily be achieved with the fixed connector alignment in this application.

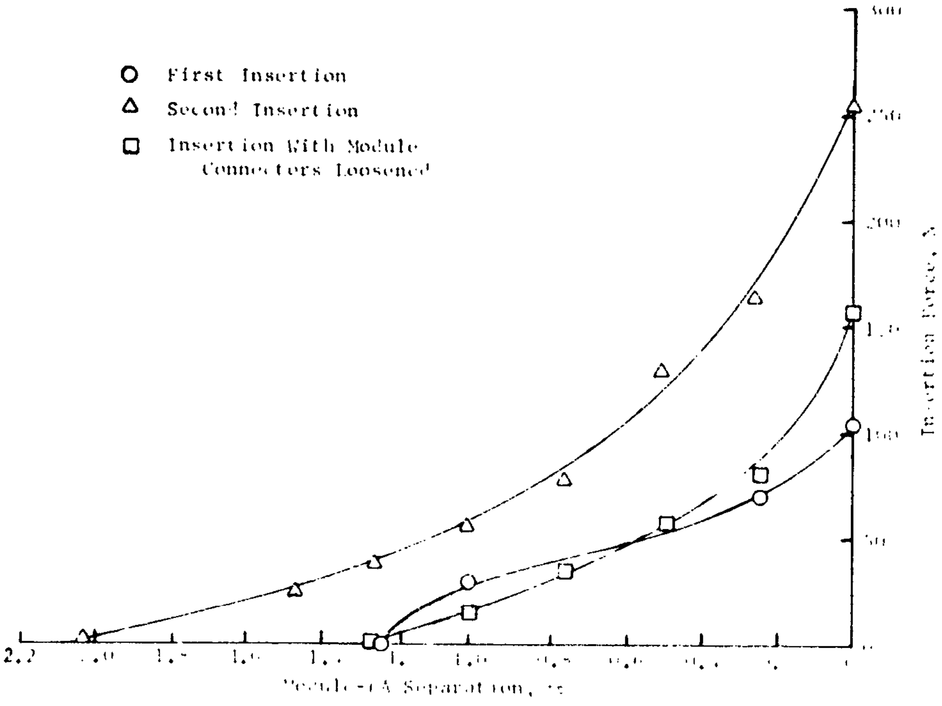
The EA insertion test results were satisfactory for all three alignment conditions. The EA connector cutouts were enlarged from their original size to permit connector movement of approximately ±0.25 mm (0.010 in). For the tests where the EA connectors were allowed to float, they were positioned at extreme locations in the cutouts and the EA was then installed into the EC. No difficulty was experienced, the tapered extensions of the connector shells being capable of properly engaging the connector sockets and correcting the initial misalignment. The lowest insertion forces and smoothest operation were observed with the third condition, where the EA connectors were hard mounted and were initially aligned to those on the connector support bracket. This condition most closely approximates the use of precision alignment tooling, as in the baseline proposal.

The deflection of the center of the connector support for the eight 37-pin connectors ranged from 0.66 mm (0.026 in), for EA installation, to 0.51 mm (0.020 in), for EA removal, in the various tests performed with the Compartment. Fig. B-7 shows the results of two cycles of insertion and removal. The deflection is within an acceptable limit (approximately 0.76 mm) to allow electrical testing without requiring installation of the center support fastener. With the center support fastener installed, no problems are anticipated with operation in dynamic environments.

Supports for eight 51-pin connectors would require additional stiffening, to assure electrical contact without installation of the center fastener. It was anticipated in the baseline design that a support perpendicular to and between opposing EA connector supports would reduce deflections and allow some

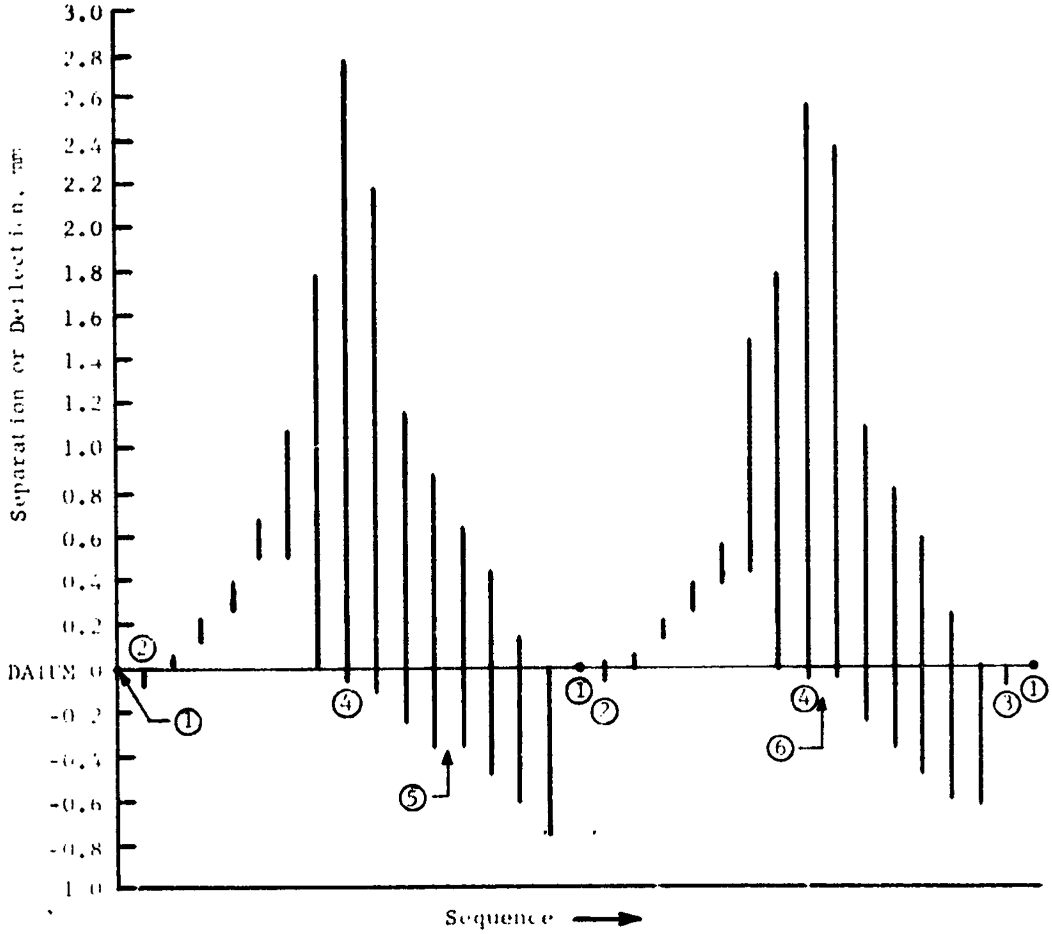


(a) First Location in Electronic Assembly



(b) Second Location in Electronic Assembly

Fig. B-6. Module Insertion Force vs. Separation



General Notes

(a) **Each vertical** line depicts the relative positions of the EA and the connector support bar at one point in the installation removal cycle. The positive-most end of the bar represents the position of the EA, and the more negative end, that of the connector support, both with respect to a fixed datum. Thus the length of the bar represents the separation between the EA and the connector support bar, at their midpoints.

(b) The installation removal cycle proceeds from left to right, however there is no scale applicable to the abscissa.

(c) Circled numbers refer to the following conditions of operation: ① center fastener installed, no tool load; ② center fastener removed; ③ center fastener installed; ④ connector [illegible] separated; ⑤ tool intact and aligned; ⑥ EA removed and replaced. Thus, ① to [illegible] sequence is [illegible] and [illegible] to [illegible] sequence is installation.

Fig. B-7. Connector Support Deflection and Separation During Electronic Assembly Installation and Removal lightening of these elements. This transverse support, extending between the Compartment side frames, would also act as a cable support and separator.

The EA was inserted into the Electronic Compartment mock-up and secured to the structure by four captive no. 6 screws and to the connector support by one captive no. 6 screw. Use of the 19 cm (7.5 in) long, 2.4 mm (3/32 in) hex tool for torquing the captive screws through the screw retainer/access tubes was demonstrated. The torsional deflection of this long hex tool was approximately 130° at 2.04 N·m (18 in-lb). To investigate possible effects of this large deflection on fastener torquing, fasteners were first torqued to 2.04 N·m, using the long hex tool, and were then checked by re-torquing with a conventional short hex tool. This was done several times, without any movement of the fastener being observed when re-torquing with the short tool. However, if this large torsional deflection were considered objectionable, a stiffer shaft could be realized within the present dimensional limits. The technician observed that the use of the epoxy-fiberglass screw retainer/access tubes was a significant improvement over previous methods for accomplishing blind installation of the captive fasteners.

The required adapters for the Mariner Assembly installation tool made it somewhat awkward to use, but it otherwise functioned very satisfactorily in the tests. With a plug-in system of this kind, the tool-EA interface should be defined early and the following features should be incorporated into the system:

(1) There should be a gross Assembly location and insertion guide. This could be provided by using rods from the EC support flanges, referenced to the EA guide pins.

(2) The tool should incorporate an "outrigger" capability, to provide control of large eccentric loads relative to the connector engagement centerlines.

(3) There should be clearance through or around the tool for access to the EA attachment fasteners.

(4) The installation tool should be coordinated and compatible with the EA handling and assembly fixture.

In summary, the EA installation tests demonstrated the feasibility of the single-side access concept using the microminiature connectors. The fit-and-function demonstration of the EA installation into the EC verified the basic mechanical and dimensional aspects of the concept. The alignment capability required for plug-in installation of multiple, microminiature connectors was demonstrated, and support member deflections were measured. Engagement forces and dimensional tolerances of standard microminiature connectors are acceptable.

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