ELECTRONIC PACKAGING TECHNIQUES IN THE MARS OBSERVER CAMERA

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Abstract

Volume constraints of small spacecraft place difficult packaging requirements on electronic designs. High component counts per unit area and stiff, lightweight boards with large surface to volume ratios will define the state of the art for PWB assemblies. The Mars Observer Camera, a high resolution imager on the Mars Observer mission, required innovative developments in these design areas to satisfy the difficult volume constraints placed on the instrument. These included qualifying a high-reliability "I-lead" surface mount technique used throughout the electronic system. This enabled a density with 4500 parts (including large DIPs and flatpacks), boards, and cabling in 900 cubic inches and a 14 inch diameter PWB/honeycomb board design. These PWBs were mounted through low frequency vibration isolators which provided dynamic and thermal strain isolation. This paper outlines the specific technical achievements gained with the Mars Observer Camera packaging design and the many design rules developed from it.

1. Introduction

The NASA Mars Observer mission is composed of a Mars polar orbiting satellite carrying a number of scientific instruments including a surface imager, the Mars Observer Camera. The MOC was designed and constructed by the California Institute of Technology, with the assistance of the Optics Corporation of America, Composite Optics, and Altadena Instruments.

Spaceflight instruments generally are designed to satisfy two sets of requirements. To gain the specified performance, certain technical requirements are created. To assure reliability and reduce development and operation risk, policy requirements are promulgated. In the case of the MOC, both were especially difficult, requiring a carefully applied system engineering approach.

Accommodating a large number of discrete, leaded components in a small volume is a difficult task. The use of these components in a spaceflight mission,

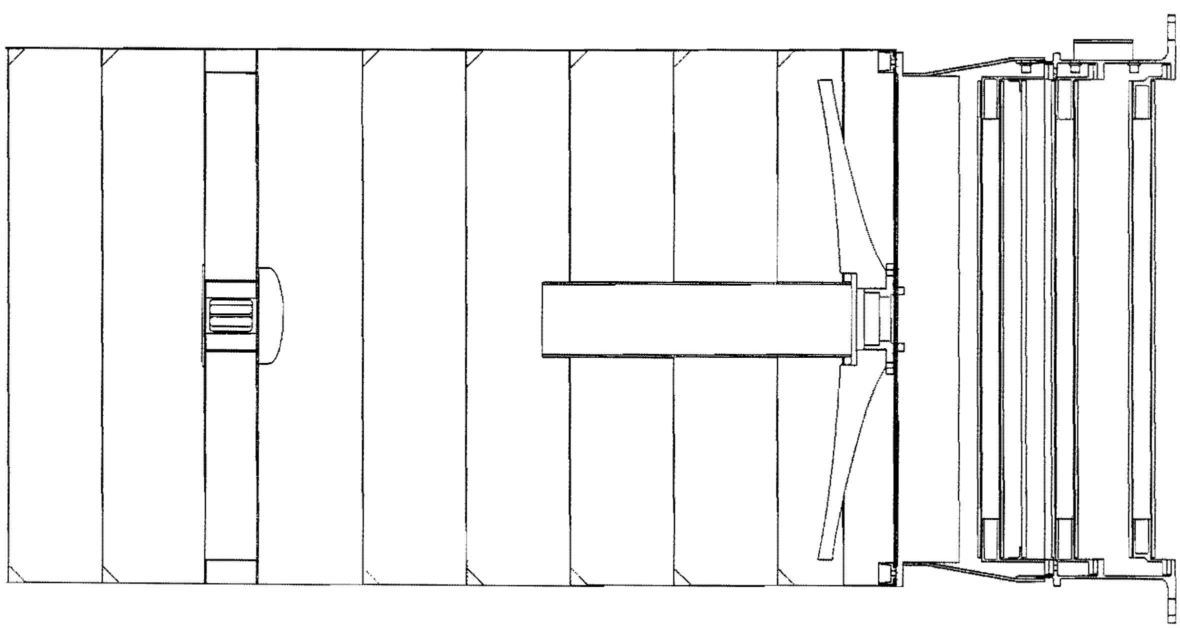

Figure 1. Cross-section View of the Mars Observer Camera

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however, may be dictated by reliability, availability, or policy constraints. The following paper discusses how the I-lead packaging method was used to successfully assemble the Mars Observer Camera (MOC) electronics. It will describe the requirements for the design, the packaging technology selected as the base of the design, and the engineering accomplished to extend the selected base to meet the requirements. As examples, case studies of how the three most common parts in the MOC are assembled will be given.

2. Requirements

2.1 Technical Requirements

The MOC is a narrow-angle Ritchey-Chretién telescope with a 3.5-meter focal length as shown in figure 1. It uses the spacecraft's motion to scan a line-array CCD across the Martian surface to create photographic swaths 3 km wide at 1.4-meter per pixel resolution from an altitude of 380 km. The average data acquisition rate of the narrow angle system is approximately 5 Mbytes/sec, a factor of 1000 greater than the bandwidth of the spacecraft data system. This requires the MOC to have a large image buffer. This in concert with a completely block redundant system leads to a component count of over 4500. As shown in Figure 2, the electronics were constrained to fit directly beneath the main telescope, while the height of the telescope base was limited by the surrounding instruments.

To help achieve the density, the Printed Wiring Boards (PWBs) were designed to be large circular edge-mounted boards in order to gain additional real estate and eliminate layout conflicts within the mass memory arrays. As a result, the packaging was required to accommodate the substantial vibration-induced curvature anticipated during launch. No packaging solutions in the JPL Design Manual directly supported significant board curvatures, so design extensions to highly compliant leads were required.

2.2 Policy Requirements

Three unusual circumstances placed heavy political pressure on the design of the MOC to be conservative. First, the MOC is the first non-facility camera to be flown in over 25 years. The principal investigator organized a team at the California Institute of Technology, using staff and a small group of subcontractors to design and build the flight hardware. JPL acted mainly as program managers. Second, cameras are the most publicly visible instruments on planetary missions and return of images is very important to public acceptance. Additionally, the MOC acts as a data buffer for the Mars Balloon experiment, a French instrument on a Russian mission. This increases the importance of reliability in the MOC.

Therefore, as a contractual requirement, the MOC electronics packaging needed to conform to the JPL design standards. A project waiver was required wherever the design rules were not covered by the JPL Design Manual for flight hardware. This document outlined the allowable packaging techniques for JPL sponsored assemblies. Solder assembly was

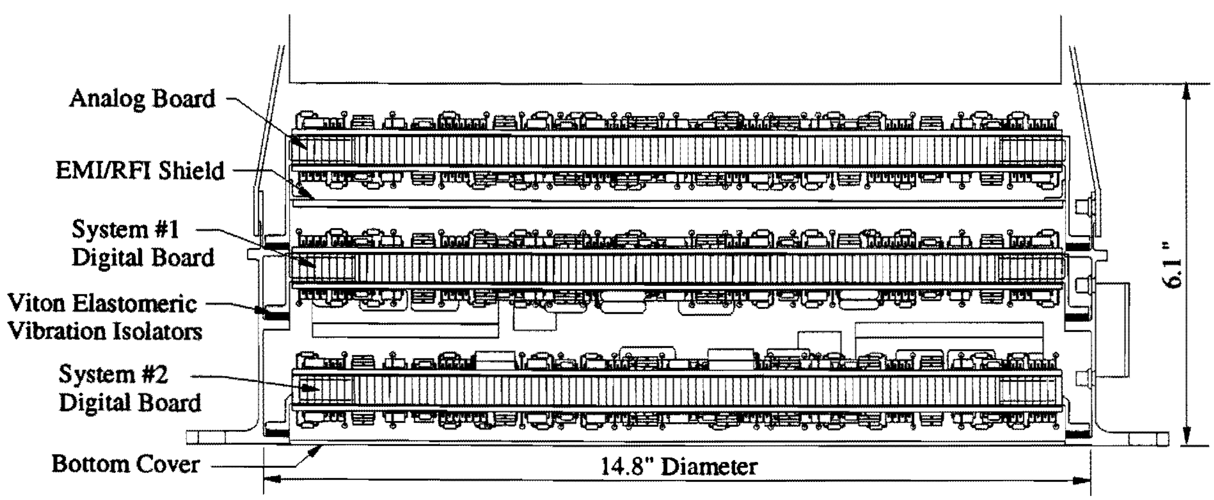


Figure 2. MOC Electronics Enclosure

acceptable, but with the additional constraint that the design be suitable for hand-soldering, 100% visual inspection, and rework/repair at any stage.

To accomplish its program management function, JPL formed design review and quality assurance teams to monitor the packaging design. Lacking the budget or schedule to develop truly new packaging technologies, we were constrained to remain within technologies at least somewhat familiar to most of the reviewers. The review boards mixed experts from development engineering and current programs with 'grey beard' specialists, creating a group suspicious of anything that was not already flight proven.

In practice, however, there are no truly 'qualified' packaging technologies. Each instrument subassembly, and preferably the entire instrument, should be subjected to a variety of environmental and fabrication stresses to assure proper application of the selected packaging technology. As such, the task was actually one of convincing the review board that the assembly could be expected to pass the qualification tests, and then agreeing on what tests constituted acceptance of the finished unit.

2.3 Additional Requirements

2.3.1 Flight Component Selection Constraints

Flight components were generally constrained to be off the shelf due to the extremely low production volumes. Parts from JPL's Preferred Parts List, especially from existing flight stores, were chosen wherever possible. If not available, industrial parts were purchased outright. This required accommodating both JPL and industry specifications for similar parts. Parts from flight stores were often quite old, requiring aggressive lead preparations and tinning verification.

Special fabrication lots for a preferred package type were generally not possible, leading to a mix of package styles for similar parts. Similarly, not all parts could be purchased with extra long leads; lead forming designs had to accommodate the shortest leads within that package style. Parts were either purchased to Class S specifications, or screened to a subset of Class S, as applicable. A few key parts were not available even to military specifications. These were subjected to rigorous physical analysis, and special screening tests were devised to assure reliable performance.

2.3.2 Quality Control and Inspection

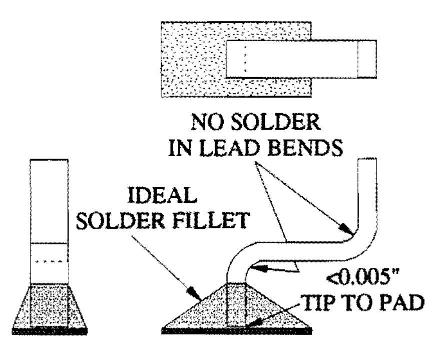
Although originally constrained to comply with the supplied JPL QA personnel, we ultimately retrained them for the unique reliability issues of the final design. Extensive engineering discussions were required to overcome the traditionally accepted views, but the end result was in fact much improved by the retraining process.

3. The Selected Packaging Technology

With the above constraints in mind, we reviewed possible packaging methods. An effort was made to compare costs and capabilities between candidate technologies. This led to the final selection.

Certain design candidates were eliminated early on. For instance, JPL's flight design rules prohibit thru-hole assembly. All components must be either surface mounted or wired to terminal posts. Epoxy or polyimide printed wiring boards are specified, requiring that components be mounted with compliant leads to withstand extended thermal cycle and launch vibration stresses. JPL requires special multi-layer PWB processing to fill all vias with epoxy. Blind and buried vias are not permitted. Leadless surface mount designs were not generally acceptable. Although hybrids have flown on virtually every spacecraft to date, hybrid packaging was considered too specialized for the Design Manual, and was not an acceptable solution for general electronics packaging.

The packaging technology ultimately selected, as described below, was initially spurred by recent development work at JPL. Previous applications had failed to address various key issues, however, and the resulting failures left a pre-judgment against our use



I-LEAD SOLDER JOINT (DIP)
SCALE 10:1
Figure 3.

of this technique. To further complicate the matter, JPL retracted the relevant sections from their Design Manual following our initial design reviews, forcing us to obtain waivers for virtually the entire instrument. Fortunately, manufacturing engineering was able to provide solutions to the historical shortcomings, most notably the ability to inspect the lead tip-to-pad gap with confidence.

The method selected for use throughout the assembly was the I-lead surface mount solder joint. In this joint, the lead is terminated normal to the pad (see Figure 3), minimizing joint area. Traditional terminal-mounting of parts clearly required too much real estate and overhead, while the drill holes for the terminal shanks would interfere with good circuit layouts. Gull-wing leads also required too much real estate, and most IC leads were too short to meet the highly compliant design requirement with enough lead left over for a gull foot.

J-lead and very minimal gull-wing solder joints could possibly have been made to fit the available real estate. However, I-lead pads were smaller still, providing some margin in the layout estimates. Further, development testing at JPL showed no reliability gains for J-leads, and there was no inheritance from previous flight instruments. Tooling for J-leads and gull-wing leads was also substantially more complex.

I-leads permit simple production tooling: a good lead bender to locate the leads precisely over the pads, and a flush-cut or shearing lead trimmer for proper coplanarity of the leads with the board. To reduce production complexity further, component packages were generally grouped into one of several standard lead forming specifications. The slight reduction in layout optimization was more than balanced by minimizing likely tooling and inspection errors.

I-leads also provided the smallest pad dimensions and shortest lead length requirements. The joints could be hand soldered to meet the reliability and longevity requirements, and the production tooling to ensure repeatable assembly results was inherently simple.

4. Applying the Selected Technology to the MOC Environment

As described above, the MOC contract required either compliance with the JPL Design Manual, or an approved waiver covering aspects outside the Design Manual. A notable engineering task involved determining where JPL's DM could be applied to the I-lead method without modification throughout the design.

The basics of instrument assembly and handling were applicable, as were general materials specifications and the specialized details for PWB fabrication. Many circuit board design issues were not covered in detail, but reliance on IPC and MIL specifications was generally accepted. Likewise, the most basic level of component mounting and soldering requirements were applicable to the design of reliable joints and assemblies.

Many fabrication-specific details required separate documentation to clarify and condense the applicable specifications. Assembly subcontracting required extraction of relevant paragraphs into a process specification, with direct references back to the originating JPL specification.

4.1 Creating Design Rules

Due to the lack of schedule or budget for an empirical development program, creating the design rules for the packaging engineering relied heavily on modeling and analysis. A high degree of conservatism was built into the design goals to cover the uncertainties of models that were not to be physically verified.

The basic design rules center around lead bending, part location, and bonding. Lead bending relieves board curvature stress while selection of the location of the part on the board is dictated by vibration loading. Thermal cyclic fatigue is mainly handled by ensuring solder fillets have the proper volume and shape, and that the lead is the proper height above the pad in the solder fillet. Where lead design and solder fillets were not sufficient to handle the mechanical loads, the part was bonded directly to the PWB. All of these rules are centered around the lead and fillet engineering detailed in the following sections.

Manufacturing concerns make up the rest of the design rules. Lead preparation for I-lead joints represents a substantial reliability concern. With gull-wing leads, a rather long portion of the lead is held within the joint, where a poorly tinned patch would represent a small portion of the overall joint strength. For an I-lead, however, the entire joint is concentrated within the last 0.020" of the lead; a poorly tinned patch would represent a substantial reduction in the overall joint strength. For added assurance, we incorporated a wetting balance solderability test for all I-leads in addition to 100% visual inspection of the lead tinning.

I-leads required several joint characteristics that were in direct conflict with traditional flight soldering rules. The most difficult I-lead requirement to enforce turned out to be the need for maximizing the solder volume. Traditional soldering rules call for concave joints where one can see the outline of the lead. In the case of an I-lead, this leaves virtually no joint at all. Both assembly technicians and inspectors required focused training and visual gauges to assist in keeping the joints nearly conical and at least 0.020" high.

A second critical process area was ensuring that the lead tips were within the required 0.005" of the copper pad. Icicleing, heavily tinned pads, etc. required touch-ups to ensure proper registration of the lead tips. Every joint required two stages: adhesive or solder-tack mounting with 100% visual inspection of the lead tip-to-pad gap, followed by final soldering with 100% inspection of the final joint appearance.

4.2 Packaging Engineering Process

The success of adapting a packaging technology to a very large variety of discrete components depends on carefully breaking down the environmental conditions into manageable pieces. After this is done, the different ways parts react to each of these environments can also be broken down into generic mechanisms. Table 1 outlines the different environmental inputs to the MOC electronics and the generic mechanisms by which reliability of the mounting scheme can be compromised:

Table 1. Environmental Inputs and Reaction Mechanisms

Environment	quasi-static stress	cyclic fatigue
Inertial loading		
Static acceleration	√	
Dynamic acceleration	√	√
PWB curvature		
Dynamic	√	√
Thermal Stress		
Deep cycle		√ (creep)
Small cycle		√

4.2.1 Failure Criteria and Modes

Two modes of mechanical susceptibility were identified for discrete components. The first was the quasi-static stress limitations in the leads and solder fillets, and the second was cyclic fatigue and creep in the solder. Each environmental input affected one or both of these areas.

In both cases, failure was defined as a discontinuity in electrical conductivity of the joint or the lead before the completion of the mission life plus margin. This allowed for fillets to experience partial cracking in life tests while still not being considered failed. This is significant, as fillets which incur vibration or thermal stress in test will often have surfaces that appear "frosty", a condition usually denoted as a failure. However, if the joint still maintains electrical continuity, it passes the test.

4.2.1.1 Quasi-static Stress

The quasi-static stress is the instantaneous stress in a part under dynamic load. Dynamic and static loading can be assessed in terms of the engineering values of yield and ultimate strength of materials. Margins of safety are developed which account for process and materials variations as well as unknowns in the mission environment. Generally, leads were designed such that the yield stress of the lead material was at least 1.5 times that of the stress developed under loading. While it can be argued that the energy present in dynamic loading may not be large enough to effect damage even if the quasi-static limit is exceeded, especially for soft materials such as solder, this method represented a simple and conservative way to select between candidate lead configurations.

4.2.1.2 Cyclic Fatigue

Cyclic fatigue and creep, on the other hand, represent the summation of stress or strain activity in a component. Low yield, low melting point materials such as solder absorb small amounts of energy at every application of stress. This has the cumulative effect of concentrating grain boundaries in the material which eventually lead to cracks. Therefore, the environmental history of a part plays a large role in its ability to resist further stress.

4.2.2 Stress/Strain Investigation

To adequately describe the stress/strain state of any of a wide variety of components when subjected to a

Table 2. Lead Stresses Due To Vibratory Loads and Thermal Distortion

ROUND LEAD / AXIAL PARTS

PART	MASS (#Force/G)	LEADS (qty)	HEIGHT (to C/L) (in)	E	CTE OF LEAD (per °F)	DIA OF LEAD (in)	Len. L1 B.C. (in)	Len. L2 BODY (in)	BENDING STRESS (PSI/G)	RES. FREQ. (Hz)	DIFF. EXP. (PSI/°F)	JNT/LD CRV (PSI/mC)	ADH
RN50	2.28E-07	2	0.167	1.60E+07	9.20E-06	0.016	0.290	0.170	18	2,653	4	333	
RWR81	6.85E-07	2	0.165	1.60E+07	9.20E-06	0.020	0.440	0.270	28	2,336	9	640	
LVR3	4.51E-06	2	0.234	1.60E+07	9.20E-06	0.032	0.822	0.570	63	1,368	18	1,349	*
CCR75	5.14E-07	2	0.165	2.80E+07	9.20E-06	0.020	0.320	0.170	21	3,637	8	815	
L1641	2.85E-06	2	0.238	1.60E+07	9.20E-06	0.025	0.615	0.420	85	1,069	10	777	*
DO35	4.00E-07	2	0.165	2.80E+07	9.20E-06	0.020	0.320	0.180	16	4,156	10	815	
DO7	8.56E-07	2	0.165	2.80E+07	9.20E-06	0.020	0.440	0.300	35	2,841	21	1,120	
TO18	2.28E-06	3	0.330	2.80E+07	9.20E-06	0.020	0.400	0.250	123	777	4	509	*
TO39	6.68E-06	3	0.330	2.80E+07	9.20E-06	0.020	0.520	0.370	361	454	7	662	*
TO99	6.17E-06	8	0.330	2.80E+07	9.20E-06	0.020	0.520	0.370	125	772	7	662	*

RECTANGULAR LEAD / DIP PARTS

PART	MASS (#Force/G)	LEADS (qty)	HEIGHT to C.G. (in)	E	CTE OF LEAD (per °F)	LEAD DIM 1 (in)	LEAD DIM 2 (in)	LEAD HEIGHT (in)	Len. L11 B.C. (in)	Len. L21 BODY (in)	Len. L12 BODY (in)
DIP8	5.88E-06	8	0.160	1.95E+07	2.44E-06	0.010	0.020	0.090	0.460	0.320	0.320
DIP14	1.22E-05	14	0.160	1.95E+07	2.44E-06	0.010	0.020	0.090	0.460	0.620	0.320
MFP14	2.11E-06	14	0.148	1.95E+07	2.44E-06	0.006	0.017	0.150	0.405	0.317	0.290
DIP16	1.26E-05	16	0.160	1.95E+07	2.44E-06	0.010	0.020	0.090	0.460	0.720	0.320
MFP16	2.11E-06	16	0.148	1.95E+07	2.44E-06	0.006	0.017	0.150	0.405	0.367	0.290
DIP18	1.55E-05	18	0.198	1.95E+07	2.44E-06	0.010	0.020	0.090	0.460	0.920	0.320
DIP24	2.43E-05	24	0.145	1.95E+07	2.44E-06	0.010	0.020	0.090	0.760	1.120	0.620
DIP28	4.40E-05	28	0.160	1.95E+07	2.44E-06	0.010	0.020	0.090	0.760	1.320	0.600

RECTANGULAR LEAD / DIP PARTS (cont)

PART	BENDING STR-1 (PSI/G)	BENDING STR-2 (PSI/G)	D-RES FREQ 1 (Hz)	S-RES FREQ 1 (Hz)	D-RES FREQ 2 (Hz)	S-RES FREQ 2 (Hz)	S-DIFF. EXP.-1 (PSI/°F)	D-DIFF. EXP.-2 (PSI/°F)	S-DIFF. EXP.-2 (PSI/°F)	JOINT STR-1 (PSI/mC)	JOINT STR-2 (PSI/mC)	LEAD STR-2 (PSI/mC)	ADH
DIP8	77	38	2,007	2,146	4,113	3,540	35	43	31	748	736	891	
DIP14	91	45	1,843	1,971	3,777	3,251	35	83	59	748	1,476	3,345	
MFP14	86	30	944	944	3,720	2,602	7	27	13	237	515	778	*
DIP16	82	41	1,939	2,073	3,973	3,420	35	97	69	748	1,734	4,511	
MFP16	75	26	1,009	1,009	3,977	2,782	7	31	15	237	600	1,042	*
DIP18	90	45	1,795	1,983	3,800	3,270	35	124	88	748	2,267	7,365	
DIP24	106	53	1,769	1,829	3,504	3,016	56	150	107	1,235	2,822	10,915	*
DIP28	164	82	1,381	1,468	2,455	2,250	56	136	109	1,235	2,843	11,608	*

NOTE: Leads are assumed to be DIM 2 for half the vertical run and all of the horizontal run, then 3x DIM 2 for the remainder of the vertical run.
NOTE: L11 is distance between joint centers, across the IC. L12 is the width of the IC body. L21 is the overall lead distance along the IC.
NOTE: Direction 1 (-1) is across the IC; direction 2 (-2) is along the IC.
NOTE: D-RES FREQ is more applicable for double-bend leads. S-RES FREQ is more applicable for single-bend leads.

SUMMARY	150 G			1.25 mC	1.25 mC		(sum)		153 °F	
	MX: 9.92	MN: 1.46		MX: 9.92	MX: 19.84		MX: 9.92		MX: 4.00	
PART	BENDING STRESS (KSI)	RES. FREQ. (KHz)	ADH	CURVE STRESS (KSI)	LEAD CRV (KSI)	% of DESIGN LIMIT	JOINT BND&CRV (KSI)	% of DESIGN LIMIT	DIFF. EXP. (KSI)	% of DESIGN LIMIT
RN50	1.37	2.65		0.21	0.21	1%	1.58	16%	0.07	2%
RWR81	2.08	2.34		0.40	0.40	2%	2.48	25%	0.14	4%
LVR3	4.75	1.37	*	0.84	0.84	4%	0.84	8%	0.28	7%
CCR75	1.56	3.64		0.51	0.51	3%	2.07	21%	0.13	3%
L1641	6.39	1.07	*	0.49	0.49	2%	0.49	5%	0.15	4%
DO35	1.22	4.16		0.51	0.51	3%	1.73	17%	0.15	4%
DO7	2.60	2.84		0.70	0.70	4%	3.30	33%	0.31	8%
TO18	9.25	0.78	*	0.32	0.32	2%	0.32	3%	0.06	1%
TO39	27.09	0.45	*	0.41	0.41	2%	0.41	4%	0.10	3%
TO99	9.38	0.77	*	0.41	0.41	2%	0.41	4%	0.10	3%

SUMMARY	150 G			1.25 mC	1.25 mC		(sum)		153 °F	
	MX: 9.92	MN: 1.46		MX: 9.92	MX: 19.84		MX: 9.92		MX: 4.00	
PART	BENDING STRESS (KSI)	RES. FREQ. (KHz)	ADH	CURVE STRESS (KSI)	LEAD CRV (KSI)	% of DESIGN LIMIT	JOINT BND&CRV (KSI)	% of DESIGN LIMIT	DIFF. EXP. (KSI)	% of DESIGN LIMIT
DIP8	6.42	2.01		0.93	0.93	5%	7.35	74%	1.19	30%
DIP14	7.62	1.84		1.39	1.39	7%	9.01	91%	1.80	45%
MFP14	6.80	0.94	*	0.47	0.47	2%	0.47	5%	0.51	13%
DIP16	6.88	1.94		1.55	1.55	8%	8.43	85%	2.01	50%
MFP16	5.95	1.01	*	0.52	0.52	3%	0.52	5%	0.57	14%
DIP18	7.53	1.80		1.88	1.88	9%	9.41	95%	2.42	60%
DIP24	8.85	1.77	*	2.54	2.54	13%	2.54	26%	3.15	79%
DIP28	13.73	1.38	*	2.55	2.55	13%	2.55	26%	2.93	73%

particular environment, it was necessary to create generic models which could be applied to any part. Simple beam models were created for the part leads which could be easily modified to fit any lead configuration. Finite Element Model (FEM) investigations of the solder fillet led to generalized elastic boundary conditions for the lead models forming a complete elastic description of the part. Stress and strain approximations could then be computed for any lead and body configuration. This was the method used to create spreadsheet models, as shown in Table 2, of each part for quasi-static stress analysis.

Analyzing fatigue began with a non-linear/plastic FEM of candidate solder fillets. The purpose was to determine the strain distribution in the fillet as a function of strain input. The largest values of strain were then used as the input into a solder fatigue law.

H. D. Solomon and the Sandia Corporation have published data for the fatigue behavior of eutectic solder for a variety of loading conditions and strains. In each case, the amount of strain accumulated in a solder sample could be correlated with the amount of "life" which had been consumed. The well known Coffin-Manson power law regressed fairly well to the Solomon data and was used as the function for analyzing the effect of each environment which contributed to fatigue, including thermal strain and board curvature.

The error of fitting the power law to the solder data, as well as the large variability in the data (not uncommon for fatigue testing) led us to adopt a cyclic fatigue life margin of 10 in the design. Unlike quasi-static stress, the exact mode of fatigue failure is relatively unknown, accounting for the larger margin.

Using the power law, qualification tests can also be designed which transform the differing cyclic fatigue environments into a small number of large thermal cycles which can be reasonably reproduced in a thermal test chamber. Fatigue life can be consumed at an accelerated rate using a smaller number of deeper cycles which are transforms, in terms of total fatigue, of the very large number of small cycles encountered during the mission. Tests which simulate the mission can be performed in the matter of a week, and tests which simulate multiple lifetimes can also be performed in a similar amount of time.

4.2.3 Environmental Conditions

With the models completed, the environments could be applied and the resulting stresses and fatigues analyzed.

4.2.3.1 Inertial Loading

When the PWB on which a part is mounted accelerates, the reaction of the inertia of the part mass creates a stress in the lead and fillet. The acceleration can either be static, such as the 6.5 g launch acceleration of the Titan III launch vehicle, or it can be dynamic, as in the 16.5 grms random vibration of the spacecraft during launch.

Determining the reaction loading in the static acceleration case is simply a process of applying the load factor to the simplified models. The vibration loading, however, requires an understanding of the harmonic nature of the part. The simple beam models were not capable of determining the fundamental mode directly, as several rigid body modes exist for multi-leaded (and hence high degree of freedom) components. FEM analysis was required to determine likely lowest mode shapes for several multi-lead configurations (from axial components to DIPs and flatpacks). With the mode shape determined for any class of part, the simple beam method could then be used to find the frequency of the lowest mode.

The vibration any part might experience depends largely on its location on the PWB. The construction of the circuit board assemblies attempted to mitigate the need for high stiffness and hence low curvature against the compliance needed for low vibration amplification and hence low reaction loads in the board mounting brackets.

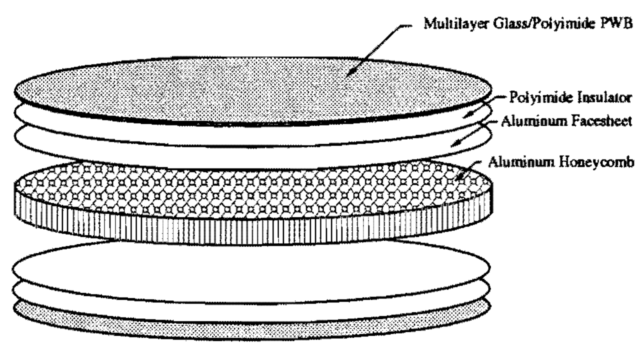


Figure 4, Circuit Board Assembly

The circuit board design uses two 14" diameter PWBs bonded to a 1/2" thick aluminum honeycomb core resulting in a very stiff assembly. The honeycomb sandwich construction constrained each cir-

Table 3. Mars Observer Camera Thermal Profile

MISSION PHASE		Tmin	Tmax	ΔT	# of cycles
ASSEMBLY (POST REFLOW)					
	Fabrication	20°C	70°C	50°C	4
	Ambient ON/OFF	20°C	35°C	10°C	100
	Rework (1major, 3 minor)	20°C	70°C	50°C	10
HANDLING/TESTING					
	INSTRUMENT TESTING				
	Bakeout	20°C	65°C	45°C	4
	Thermal/Vac I	-30°C	55°C	85°C	2
	Thermal/Vac II/III	-30°C	0°C	30°C	10
	Non-operating	-35°C	20°C	55°C	1
	Operating	20°C	75°C	95°C	1
	SYSTEM TESTING				
	Bakeout	20°C	65°C	45°C	4
	Thermal Balance	-20°C	20°C	40°C	3
	System T/V	-30°C	20°C	50°C	1
	GROUND HANDLING	20°C	25°C	5°C	1000
FLIGHT					
	Bakeout	-20°C	-15°C	5°C	1
	Cruise, inner -> outer	-30°C	20°C	50°C	1
	Cruise, rotation	-30°C	20°C	<1°C	4150
	MOI	10°C	15°C	5°C	87
	Mission	-5°C	15°C	5°C	8750
	Solar Orbit	-5°C	15°C	20°C	1
	MBR Ext. Mission	-5°C	15°C	5°C	2200

cuit board to a single surface for component assembly, but eliminated all mounting hardware from the layout area. The lack of obstructions in the layout area was a key element in achieving the required component density. See Figure 4.

In order to reduce the harmonic amplification characteristics of the board assembly from an unreasonably high value of 90 discovered in test, it was necessary to isolate the boards from the aluminum chassis of the MOC with Viton elastomeric vibration isolators. Without adding any unacceptable low frequency rigid body modes, the isolators effectively reduced the amplification of the board system to less than 20.

The result of this design is a circuit board system which floats as a rigid body on shock absorbers with a fundamental frequency of around 400 Hz. The rms acceleration components experience during launch range from 10 g's at the board edges to as high as 60 g's at the center. Parts could be moved to different areas on the PWB according to their susceptibility to vibration.

By taking the random vibration spectrum, determined by FEM of the boards, the quasi-static loads could then be determined by assuming the parts were rigid bodies below their fundamental frequencies. To insure no resonant amplification of vibratory inputs would occur at the parts, a design rule was created which insured each part had a fundamental frequency of at least 4 times that of the circuit board assembly or that its body was bonded directly to the PWB, relieving the leads of any structural responsibility.

4.2.3.2 Board Curvature

Quasi-static as well as cyclic fatigue is important here. Parts which have large spanning dimensions across the boards such as long DIPs and flatpacks are especially susceptible to board curvature. Although the board assembly is very stiff as mentioned, the PWBs do exhibit some curvature while vibrating. The extent of the curvature was estimated from a FEM model of the circuit board. Even with vibration isolators, substantial board curvature was expected due to launch vibrations. Component leads were thus required to include compliance in the mounting plane, effectively requiring every lead to have both a vertical and a horizontal run between the case and the solder joint. Unfortunately, more compliant leads lower the fundamental frequency of the parts. Curvature loading, therefore, can lead to a large number of parts being bonded directly to the PWBs.

4.2.3.3 Thermal Stress

The PWBs are constructed of a polyimide/glass fiber composite bonded in layers. The coefficient of thermal expansion (CTE) of the boards is generally larger than that of many of the ceramic or metal component packages. Changes in temperature over the mission create loads in the leads and solder.

The temperature profile of the MOC is composed mainly of two periodic components. One correlates to the orbital period of the spacecraft about Mars, and the other relates to the orbit of Mars about the sun. The first causes temperature swings on order 5° C while the other can be as high as 50° C. See table 3.

Interestingly, even though the temperature excursions are large, quasi-static stress is not an issue. Solder exhibits a large creep behavior even at very low stress levels, tending to relieve any load. Unfortunately, if thermal cyclic fatigue is a problem, making the component leads more compliant will not help. Any application of strain of a period longer than a few minutes will usually cause fatigue damage in solder.

The FEM model of the solder fillets was incorporated into a software package which took the fatigue environments listed above and systematically applied them to the part, accumulating a damage total. The solder fillet volume was sized in this way to ensure each part had adequate margin.

4.3 Test

Although dedicated test hardware could not be built, prototype hardware for engineering was assembled per the intended flight specifications. These boards were subjected to vibration and thermal cycle tests before being integrated into the prototype unit. Prototype test levels were used, intending to show suitability of the packaging but not its ultimate life.

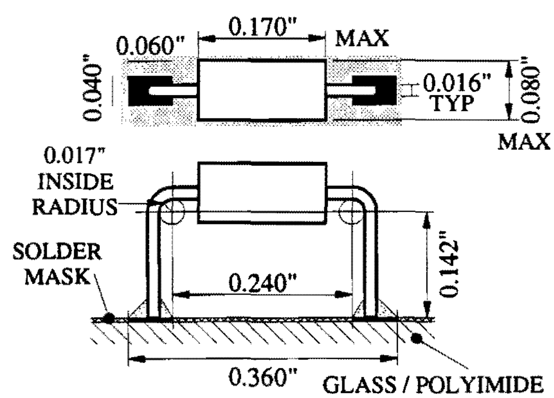
Based on the results of the prototype testing, process revisions were made to address observed weaknesses, mostly in improved soldering techniques and more quantitative inspection criteria. Some flight hardware was already in process, requiring rework or re-inspection.

Final hardware was subjected to "workmanship" and acceptance tests. Specifically, vibration and thermal cycle stresses were applied, followed by 100% re-inspection of the assemblies. In response to continuing skepticism within NASA, further testing was applied to the prototype units, including reworking hundreds of joints after application of the Parylene conformal coating followed by repeating the environmental tests. Final judgment of the JPL specialists was that the packaging was acceptable as presented.

5. Case Studies

RNC50 Case Study

Axial leaded parts, such as the RNC50 resistor, are generally characterized by a small, light body supported by two cylindrical leads. Exceptions include the occasional large inductor or capacitor, which require an adhesive mount to augment the leads, or rectangular cross-section leads which only affect the solder pad dimensions. Having only two leads, axial parts are inherently less stressed by board curvature than components such as a long DIP part with many leads in a row.



RNC50 I-LEAD MOUNTING EXAMPLE
SCALE 4:1

In spite of the low body mass, keeping a high (mechanical) resonant frequency is a concern for axial parts. To accommodate the wetting balance solderability testing, the leads were required to be relatively long. The basic analysis results, shown in Table 2, include the frequency of the lowest resonance. Those failing to meet the given design limit require an adhesive mount, and are so designated.

Table 4, below, lists key lead forming and trimming design rules, relevant to axial leaded parts, resulting from stress and manufacturing analyses. In addition, all the standard lead and lead tinning criteria apply, such as no nicks, tinning voids, icicles, etc. Table 5, below, lists key assembly and inspection criteria for installing axial I-leaded parts to maximize the assembly's reliability over vibration and thermal cycle. Again, conventional solder appearance criteria, such as no granulation, pits, etc., also applies.

Table 4: Key Leadforming Design Rules

- At least 2 lead diameters from body undisturbed.
- At least 1 lead diameter inside radius for bends.
- Bends should be fully 90°, after springback.
- At least 2 lead diameters between bend and joint.
- At least 0.12" below body for solderability test.
- Flush cut tips: <0.001" step, <0.001" ridge.

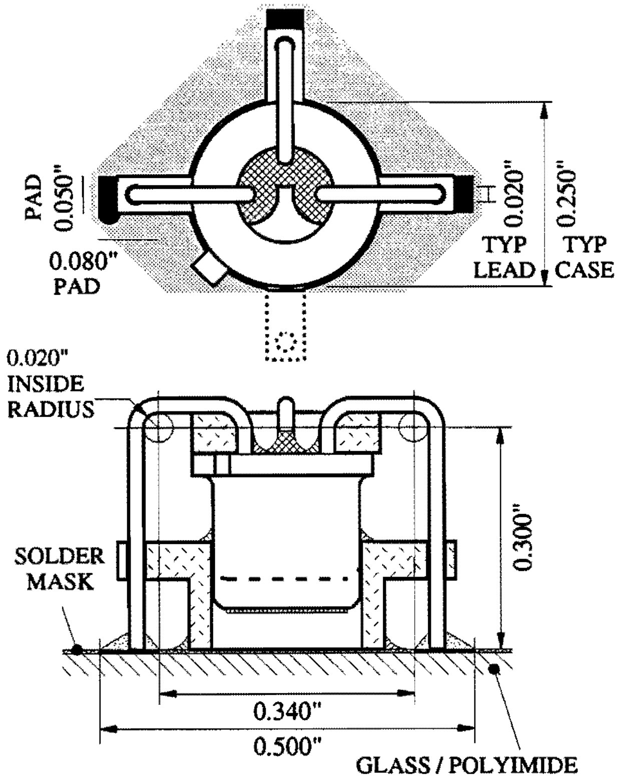
Table 5: Key Axial I-lead Installation Criteria

- Leads rise vertically from pads (within 10°).
- Lead tips must be within 0.005" of copper pad.
- Lead tips must be fully within pad (>0.005").
- 360° solder fillet, extending to edge of pad.
- Fillet Height: >0.020" average, >0.005" local.
- Fillet Shape: nearly conical, slightly concave
- Lead bends must be free of solder.

Finally, Table 6, below, gives a cursory description of the parts preparation and solder assembly steps developed for axial I-lead parts. Custom tooling was created to permit rapid and accurate lead forming and trimming. Solderability was tested using the wetting balance on a Multicore Universal Solderability Tester.

Table 6: Production Process Summary

- Clean and inspect parts; pre-tin gold plated leads.
- Form and trim leads using designated tooling.
- Test lead tip solderability within 8 hours of trim.
- Inspect workmanship; touchup tinning as needed.
- Bond mounting pedestal to PWB, as required.
- Solder tack lead tips to pads, stress-free.
- Bond body to mounting pedestal, as required.
- Inspect configuration and lead tip to pad distance.
- Final solder and clean, keeping leads stress-free.
- Inspect workmanship; 1 rework/joint permitted.



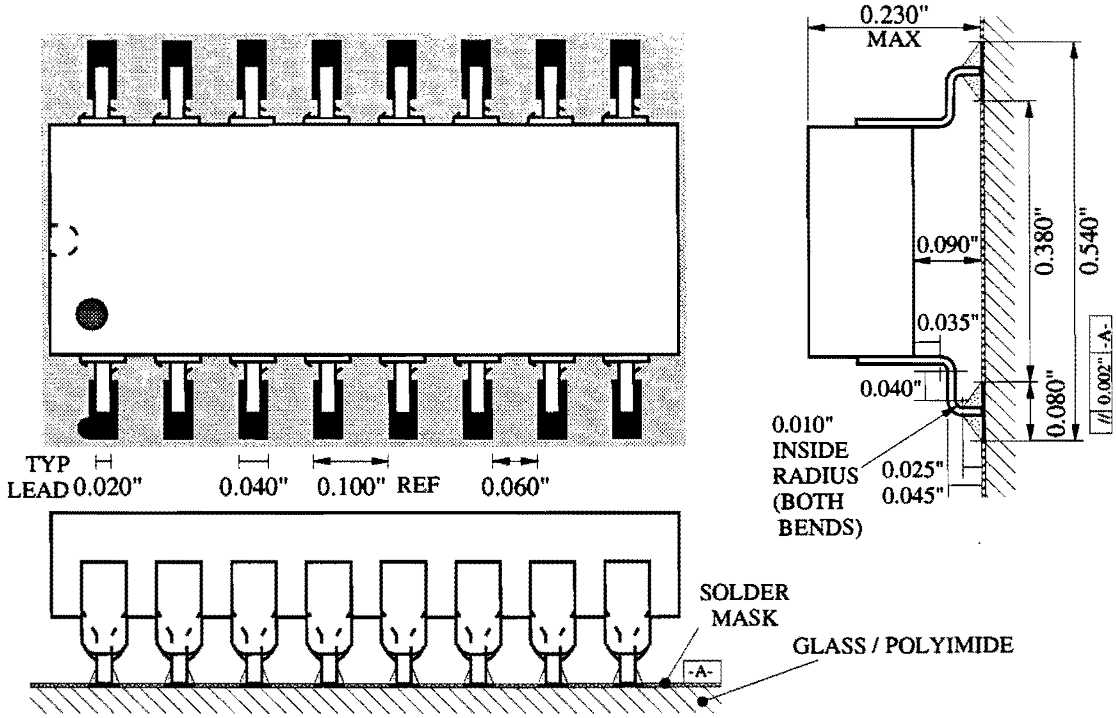
TO-18 I-LEAD MOUNTING EXAMPLE
SCALE 4:1

TO-18 Case Study

Devices packaged in TO-style cans, such as the TO-18 case for transistors, are generally characterized by a large, heavy body supported by two to eight leads. Exceptions include various high-power packages, which require unique mounting designs to increase heat dissipation. TO-can packages have all leads exiting from one end, arrayed in a circle. The leads are splayed out radially, then bend back towards the case. This mounting style is commonly referred to as "dead-bug" mounting. Alternate mounting styles were considered, but failed to meet all of the design constraints.

The device case requires mechanical support due to the long lead lengths. In addition, the long and springy leads were difficult to keep aligned with the solder pads without actually holding them during soldering (causing built-in stresses). The final solution involved adding a collar for the leads to the TO pedestal. The basic analysis results are shown in Table 2.

Tables 7 and 8 list the leadforming rules and installation criteria.



DIP I-LEAD MOUNTING EXAMPLE
SCALE 4:1

Table 7: Key Leadforming Design Rules

Transipad required to protect glass lead exits.
Form 1[ST] bend over the transipad.
At least 2 lead diameters from case to 2[ND] bend.
At least 1 lead diameter inside radius for bends.
Bends should be fully 90°, after springback.
Flush cut tips: <0.001" step, <0.001" ridge.

Table 8: Key TO-can I-lead Installation Criteria

Insulate metal case from PWB.
Use lead collars to align lead tips with pads.
Leads rise vertically from pads (within 10°).
Lead tips must be within 0.005" of copper pad.
Lead tips must be fully within pad (> 0.005").
360° solder fillet, extending to edge of pad.
Fillet Height: > 0.020" average, > 0.005" local.
Fillet Shape: nearly conical, slightly concave.

The production process for TO-can parts is similar to that for RNC50's, and is summarized in Table 9. These devices require adhesive mounting for mechanical support. Small tabs were added to the TO-can mounts to align the leads directly over the pads, eliminating the built-in stress that would have resulted from holding the leads during soldering.

Table 9: Production Process Summary

Clean and inspect parts; pre-tin gold plated leads.
Bond transipad in place before bending leads.
Form and trim leads using designated tooling.
Test lead tip solderability within 8 hours of trim.
Inspect workmanship; touchup tinning as needed.
Bond lead collar to PWB, aligned with pads.
Solder tack lead tips to pads, stress-free.
Bond case to lead collar as mechanical support.
Inspect configuration and lead tip to pad distance.
Final solder and clean, keeping leads stress-free.
Inspect workmanship; 1 rework/joint permitted.

DIP16 Case Study

Devices using DIP-style packages, such as the DIP16 package for integrated circuits, are characterized by a large, heavy body supported by 8 to 28 leads. DIP packages have half their leads exiting from opposite sides, forming a row. Two lead styles are common: side-brazing and frit-seals. Since the leads are arranged in rows, a horizontal run must be formed into the leads to accommodate board curvatures. Using an I-lead joint design maximizes the lead available for compliance.

Where additional mechanical support is required due to especially massive bodies or the need for spot radiation shielding, a mounting pedestal is employed.

The basic analysis results are shown in Table 2.

Tables 10 and 11 list the leadforming rules and installation criteria.

Table 10: Key Leadforming Design Rules
Leads must be clamped during forming.
Form 1^{ST} bend at least 0.030" below body.
Form 2^{ND} bend at least 0.030" from 1^{ST} bend.
At least 1 lead thickness inside radius for bends.
Bends should be fully 90°, after springback.
Trim leads at least 0.025" below 2^{ND} bend.
Flush cut tips: <0.001" step, <0.001" ridge.

Table 11: Key DIP I-lead Installation Criteria	
Lead tips must be within 0.005" of copper pad.	
Lead tips must be fully within pad (>0.005").	
360° solder fillet, extending to edge of pad.	
Fillet Height:	>0.020" average, >0.005" local.
Fillet Shape:	nearly conical, slightly concave.

Table 12 summarizes the production process. Many of these devices required spot radiation shields, which were installed after electrical test.

Table 12: Production Process Summary
Clean and inspect parts; pre-tin gold plated leads.
Form and trim leads using designated tooling.
Test lead tip solderability within 8 hours of trim.
Inspect workmanship; touchup tinning as needed.
Bond mounting pedestal to PWB, as required.
Solder tack corner lead tips to pads, stress-free.
Bond body to mounting pedestal, as required.
Inspect configuration and lead tip to pad distance.
Final solder and clean, keeping leads stress-free.
Inspect workmanship; 1 rework/joint permitted.

6. Summary

Engineering of a packaging design is always driven by a difficult combination of requirements. Often relegated to late in the design, packaging can be forced to fit within a stringent set of volume and environmental constraints. This, combined with a dizzying array of available packages, manufacturing techniques, training, and prejudices, creates a design statement that may seem impossible to physically realize.

We have found that a systems engineering approach to packaging design, where requirements and interfaces with other portions of instrument design are broken down and closely managed, can yield a workable design where inheritance from past tradition is married to innovation. The Mars Observer Camera, as an entire system, was created in this way. Future small satellite missions will find increasing pressure to meet the wisdom of the old and the possibilities of the new.

7. Acknowledgments

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