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Manufacture of Aluminum Custom Hybrid Microwave Packages

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Manufacture of Aluminum Custom Hybrid Microwave Packages

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Abstract

Five aluminum-based materials were explored for fabrication of custom microwave hybrid packages for spacecraft electronics applications. Machining, plating, matched-glass feedthrough installation, substrate attach and laser lid-weld assembly operations were addressed. Test packages passed MIL-STD-883, Test Method 2009.8, Class-K, thermal-shock and thermal-cycle stress-tests from -65°C to + 150°C with no change in He leak-rate; packages remained in the less than 1×10^{-9} atm-cc/ sec He range.

Key words: Custom hybrid microwave packages, hermetic modules, 6061 aluminum, A-40 aluminum/silicon alloy, A-390 high-silicon aluminum alloy, Al/SiC metal matrix composite materials, (4 volume-% ranges detailed) matched-glass feedthroughs, gold/tin eutectic solder, low-labor feedthrough installation, removal and replacement of FT's, polycrystalline diamond machining, casting to near-net shape

Introduction

This aluminum-based package work was undertaken to provide dramatically improved thermal transfer, lighter weight and controlled C_{TE} custom microwave hybrid packages for spacecraft/avionics electronics using GaAs IC's. The primary aerospace electronics package material has typically been one of the nickel-iron materials. Kovar^R, for instance, is often used to allow direct-glassing of matched-glass feedthroughs (FT's). Some designers use Alloy 46 with brazed-in FT's. While both Kovar^R and Alloy 46 have excellent C_{TE} properties, neither have acceptable thermal transfer properties for use in direct contact with GaAs chips, nor are they light-weight materials.

Custom Hybrid Package Materials

We examined and processed 6 types of aluminum-based materials:

- "Plain" 6061 T6 aluminum served as a baseline material
- Sumitomo's proprietary A-40 high-silicon hypereutectic sintered metal alloy
- Reynold's A-390 casting alloy
- DWA's bulk-reinforced 6061 Al/SiC metal matrix composite materials (MMC) (both 40 vol-%SiC and 55 vol-% SiC, extruded and forged)
- British Petroleum Research's squeeze-cast, selectively-reinforced 6063 Al/ 59 vol-% SiC MMC material, a near-net shape approach
- Alcoa Innometalx's 65 vol-% Al/SiC, 10% Si, vacuum-assisted high-pressure diecast MMC, another near-net shape approach

Approach

We initially designed and fabricated a test-vehicle we called the "Model Package". Figure #1 shows an array of 6061 Model Packages after initial thermal shock and cycling. We made Model Packages in 6061, A-40 and started to make them in A-390. Figure #2 shows a plated 6061 Model Package in the copper solder fixture, an A-390 rough-machined Model Package blank to the left and a finish-machined, unplated A-40 Model Package to the right.

The A-390 material we were presented with was found to be too porous to be even marginally acceptable and was dropped. Figure #3 shows a "close-enough" view of a typical A-390 rough-machined blank to determine extensive porosity. Several casting houses would like to cast A-390 to near-net shape and insist that porosity isn't an issue. If fully dense A-390 material becomes available, it may be able to be utilized as a package material.

As a result of time constraints, we adopted a package that had been designed and had a mold made for squeeze-casting by British Petroleum Research, Warrensville OH. BP's Transmitter/Receiver Package (T/R Module) is smaller than our "Model Package" but is adequate to allow FT emplacement, substrate attach, lid-weld and preliminary thermal shock and thermal cycling to conducted. Figure #4 shows the as-received selectively-reinforced BP T/R module and a selectively-reinforced cover made by machining away the side-walls from one of the cast modules. Figure #5 shows a T/R module with FT's Au/Sn soldered into each end, a pair of matched-glass FT's and a T/R module in a copper solder installation fixture ready for solder reflow.

Using polycrystalline diamond (PCD) endmills, another simple "box-package" was machined from DWA's bulk-reinforced Al/SiC MMC material. Figure #6 shows this simple package after installation of one FT. We purchased PCD endmills and drillbits from 3 vendors, todate: Precorp, Provo UT, Robb-Jack, Lincoln CA and Norton Co., North Attleboro MA. Tool design and construction varies widely from these vendors; but, performance of these tools has been generally quite acceptable for the very fine details of custom hybrid microwave packages.

We then made slight modifications to a third test article: a solid state amplifier Driver Module shown in Figure #7. This package was PCD-machined from DWA's bulk-reinforced, 55 vol-% Al/SiC material that had been forge-clad with 6061 Al to allow direct laser lid welding of 4047 Al lids.

Our final test article was this same Driver Module modified for "insert-casting" by Alcoa using a SiC preform or insert to result in 65 vol-% Al/SiC. This near-net shape part is shown, as-cast, in Figures #8 & 9.

Table #1 shows some selected physical properties of the 5 materials. The 4th column, coefficient of thermal expansion, C_{TE}, shows why we were interested in each material and what weighting we might give to each of the materials in selecting for a composite value in terms of best thermal transfer, light weight, controlled C_{TE}, cost, availability, machineability, and ready plateability.

Tables #2 and #3 show some of the machining results and milling parameters for the 6 materials. Our initial attempts to cut Al/SiC MMC materials with coated-carbide endmills rapidly produced badly eroded tools. Fortunately, much is being done with PCD and single-crystal diamond cutting tools today. We used both two-fluted, straight-flute PCD endmills and spiral-fluted polycrystalline diamond insert endmills quite successfully. We PCD-machined 3 packages made of 40 vol-% SiC/6061 Al and 12 SSA DM's to print specifications with no significant problems using PCD endmills and drillbits from 3 vendors. This PCD "tool-set" of some 20-odd tools is still functional after making the test-articles More remains to be learned about using these expensive new tools for package machining, but it is an understatement to say that they're "pretty interesting"!

Package Fabrication Procedure

The 6 package materials were obtained in bulk form, squeeze-cast form, and insert-diecast form and were then rough-machined, finished machined, deburred, zincated, electroless Ni-plated, Au-electro-plated and then matched-glass FT's were installed using an 18-minute fluxless 80Au/20Sn solder reflow cycle in one of two DAP 2200 thermal processors.

Matched-Glass Feedthroughs

TRW has an in-house feedthrough-glassing capability that has been reported in a paper presented at the 1990 Chicago ISHM Symposium. Work-in-progress now includes the fabrication of quasi-matched-glass FT's using Kovar ferrules and pins and Corning's #7070 glass beads. #7070 glass allows fabrication of somewhat smaller RF FT's than does Corning's #7052 glass. Details of this newer FT effort will published at a later date.

Using our standard glassing procedure, we designed and made 5 different configurations of matched-glass (Corning's #7052 glass) FT's to install in the 3 companion packages using a fluxless gold-tin (Au/Sn) solder reflow process. Figure #10 shows a macrophotograph view of some of the FT's used.

The packages are placed in a simple copper fixture (Figure #2, above) that constrains the FT's and preforms in their socket-holes. Figure #11 shows a macrophotograph view of both wound wire and stamped flat preforms. The assembled fixture, loaded with the package, preforms and FT's, is placed in the graphite heater-cavity of a DAP 2200 thermal processor and an 18-minute, vacuum-assisted reflow profile is run. Figure # 12 shows a sketch of a fixtured package in the graphite heater cavity of a DAP 2200 system.

Solder Composition

The solder chosen is an old semiconductor die-bonding standby: 80% Au/20% Sn, liquidus 280°C. We used both wound-wire preforms and purchased flat-washer preforms. In some cases of looser fit-up we used both types to compensate for a larger than desired fit-up gap.

Reflow Procedure

The process overview is:

- solvent clean FT's, preforms and plated packages in ultrasonically agitated acetone
- blow components dry with house N_2 and store in N_2 drybox.
- assemble FT"s and preforms in solder fixture wearing clean white nylon gloves with clean SS tweezers
- place assembled package/fixture in DAP graphite cavity, close system
- run profile from Eeprom
- remove fixtured package from DAP and then remove package from fixture
- visually inspect, He leak-test package and store for future substrate-attach step

Notes:

Packages were fixtured in one building on our campus and carried to another building in a Pyrex Petrie dish for solder reflow; this is one measure of a robust process.

This is a "green process": no CFC's were used or are needed for excellent solder-joints despite assembly in one building and solder-reflow in a remote location.

Reflow Profile

The solder reflow profile shown in Figure #13, was adapted from a profile developed by Darrell Dickinson of SST, maker of the DAP system. We wanted a relatively rapid heating cycle, we wanted to vacuum-outgas the surfaces of the plated package, the plated FT's and the preforms for some appreciable time at an elevated temperature just below the melting point. This reduces the tendency to form gas bubbles in the molten solder. Table #4 shows some common solder alloy physical properties. We reflowed our preforms in flowing house-N_2 as the fixtured part temperature rises to the 280°C melting-point of Au/Sn solder.

An improvement might be to reflow in pressurized N_2 to further collapse gas bubbles in the molten solder joint. Another fillip might be to use 3% H_2/97% N_2 forming gas. This somewhat reactive gas might help further clean all the surfaces to produce cleaner joints and promote even better solder flow.

Removal and Replacement of FT's

Using Kestor's high-temperature #1587-HT flux, and Sikama's linear µ-processor-controlled hotplate, we were able to remove a "bad" FT from a test package and replace it with new FT, maintaining full open-face package hermetic integrity. Alpha Metals 564 Reliasolv^R solvent was then used to immediately remove all traces of the flux. This is a somewhat involved process and will not be fully detailed here.

Joint Design Discussion

16 6061 "Model Packages", 16 A-40 "Model Packages", 9 selectively reinforced BP "T/R Modules", one DWA bulk-reinforced "box-package" and some 30+ program-specific Integrated Microwave Assembly, "IMA" packages, were populated with in-house fabricated, matched-glass FT's using the DAP profile shown. We worked through some solder-joint design problems on the path-finder 6061 Model Packages and developed tolerancing/preform-volume guidelines for solder joints in aluminum materials. These lessons are being successfully applied to A-40 and Al/SiC packages that are now in-work.

Results and Conclusions

16 6061 Model Packages, 16 A-40 Model Packages, 9 selectively-reinforced Al/SiC T/R Modules and one bulk-reinforced Box Package had a total of 122 FT's installed. A sixth and smaller 6061 Al package, the smallest shown in Figure #14, had been designed, fabricated and populated with 3 FT's each in an earlier Au/Sn solder study performed in 1990.

This earlier Au/Sn solder effort had emplaced 36 in-house matched-glass FT's in 12 smaller 6061 plated-aluminum IMA packages using the same preforms and joint fit-up but using Kestor's 1589-HT flux. These FT's were solder-reflowed on a µ-processor controlled Sikama Linear Hotplate in a 2-minute profile in air. These 12 packages were subjected to the same thermal shock/thermal cycling tests and showed exactly the same excellent results.

Two of the fundamental requirements of this effort were that no solder maskants and no fluxes be used. Elimination of solder masking, flux-application, hand-feeding of solder and subsequent flux/maskant removal and clean-up is a reduction in touch-labor of at least 60%.

Another group of A-40 test-strips and IMA's were populated with some 150+ custom FT's using the exactly the same Au/Sn process, preforms and procedures but will not be discussed in detail in this report. FT's have been emplaced in packages in both the pin-horizontal and pin-vertical orientations in this effort.

When the joint fit-up is properly sized with controlled clearances of approximately .001"-.0015" gap on the radius, no change in leak-rate was seen on any of the 150+ FT's. Packages gave measured open-face He leak-rates in the less-than 1×10^{-9} atm-cc/sec range both before and after 15 thermal shocks, liquid-to-liquid, 10-second-transfer, 5-minute-dwell from -65°C to + 150°C and then a subsequent 100 thermal cycles from -65°C to + 150°C, air-to-air.

Two A-40 Model Packages have now survived 45 thermal shocks and 300 thermal cycles and 45 thermal shocks and 400 thermal cycles with no change in He leak-rate. These two packages are still in the less than 1×10^{-9} atm-cc/sec He range. We routinely see no measurable He leak-rates on any of 2 DuPont #120 SSA's and one Veeco Model #170 leak detectors with both direct-glassed Kovar packages and in any of these aluminum-based packages with Au/Sn-installed FT's.

The PCD-machined 55 vol-% Al/SiC are plated and ready for FT emplacement. The copper solder fixture specification is detailed, ready for fabrication. Two of these units have been passed forward in the assembly process to verify laser lid-weld to the clad 6061 sealing surface. The diecast 65 vol-% driver modules are in-queue to be finish-machined and plated for FT emplacement in the same solder fixture.

Figures #15 and #16 show two different approaches to preform placement during mechanical assembly. We recommend the latter for greater ease of assembly and uniformity of reflow.

Cross-sections through the FT's, as shown in Figure #17, show excellent wetting throughout the solder joint volume; the joints are not uniformly bubble-free, but are certainly RF-acceptable and He leak-free. Figure #18 shows a macrophotograph of a fluxed Au/Sn FT meniscus. Figure #19 shows a macrophotograph of a non-fluxed Au/Sn FT meniscus.

Conclusion

Solder attachment of a low C_{TE} material such as Kovar, to even a high-C_{TE} material such as 6061, can be readily and routinely accomplished and will withstand the severe stresses of successive thermal excursions from room temperature (RT) to -65°C to +150°C and back to RT for an impressive "duty cycle" with no hint of loss of hermeticity.

The tooling or fixturing costs are modest, the labor cost of mechanical assembly is modest. The elimination of the need for hand-applied solder-masking, hand-applied flux application, hand application of solder and then flux removal, followed by maskant removal, is eliminated.

References

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"Manufacture of Robust Matched-Glass Feedthroughs" by M. D. Grgas and G. G. Pinneo, **TRW**, Redondo Beach CA ,1990 ISHM Symposium - Chicago IL

"New Group of Tools With Thick Diamond Film Made by Chemical Vapor Deposition" by F Okuzumi, J. Matsuda, and K O-Oka, Genasystems/Ashai, Superabrasives '91, - Chicago IL

"Tool Applications of CVD Diamond", by T. Nakamura, N. Fujimori, Dr. T. Nakai, S. Nakatani, Sumitomo Electric Industries, Superabrasives '91, - Chicago IL

Table #1 - Packaging Materials, Selected Physical Properties

Material Name	Physical Description	Vendor Name	TCE	Density	Thermal Conductivity	Electrical Resistivity
Kovar^R (ASTM F-15 Alloy)	29%Ni/17%Co 54%Fe	Fagin -- Carpenter	5.1 X 10^{-6}/°C	8.36 g/cc	17.3 W/m K	490 µ ohm-mm
oy 46 (ASTM F-30 Alloy)	46%Ni/54%Fe	various	7.4 X 10^{-6}/°C	8.+		--
6061 Alum	wrought	various	23.6 µm/m K	2.70 g/cc	201 W/m K	40. n ohms m
6063 Alum	wrought	various	25.6 µm/m K	2.69 g/cc	167 W/m K	33 n ohms m
A-40 Alum	powdered metal (consolidated)	Sumitomo	13.5 X 10^{-6}/°C	2.53 g/cc	130 W/m K	--
A-390 Alum	casting alloy	Reynolds	18.5 X 10^{-6}/°C ?		-- --	--
Al/SiC	metal matrix 59 v-%/6063	BP Research DWA Composites	8.5 X 10^{-6}/°C	3.00 g/cc	200 W/m K	--
Cu/W	sintered Cu/W (powder metal)	Sumitomo 80/20 CMW 76	8.5 X 10^{-6}/°C 7.6 X 10^{-6}/°C	15.65 g/cc 15.56 g/cc	240 W/m K 180 W/m K	-- --
Beryllium	E-60 grade (metal)	Brush Wellman	6.1 X 10^{-6}/°C	2.52 g/cc	240 W/m K	--
Molybdenum	(metal)	various	5.1 X 10^{-6}/°C	10.22 g/cc	132 W/m K	--
Alumina	Al_2O_3 (substrate)	various	6.7 X 10^{-6}/°C	3.6 g/cc	12.0 W/m K ?	--
Beryllia	BeO (substrate)	various	7.6 X 10^{-6}/°C	2.69 g/cc	170 W/m K	--
uminum Nitride	AIN (substrate)	various	4.7 X 10^{-6}/°C	3.24 g/cc	170 W/m K	--
Gallium Arsenide	GaAs active devices	various (TRW)	6.5 X 10^{-6}/°C	5.3 g/cc	54 W/m K	
Silicon	Si	various	4.2 X 10^{-6}/°C	2.3 g/cc	151 W/m K	

Table #2: Summary of Machining Results

aterial ested	Cutting Tooling Material	Coolant	Machineability	Cutting Tool Wear	Surface Finish	Able to EDM	Tap Material	Tap Lubricant	Thread Quality	Tap Wear	Comments
6061-T6	Carbide	Flood, H_20-soluble oi	Excellent (Conventiona and climb-cut)	Low	Excellent	Yes	HSS		Good	Low	Baseline Material
A-40	Carbide	Flood, H_20-soluble oi	Good (climb-cut)	Moderate	Good	Yes	HSS		Good	High	Brittle; Requires Carbide Taps
A-390	Carbide	Flood, H_20-soluble oil	Satisfactory (climb-cut)	High	Satisfactory (very porous)	Yes	HSS		Good	High	Tough, Abrasive Brittle, Requires Carbide Taps
Al/SIC	Carbide/PCD	Flood, H_20-soluble oi	Unable to machine w/o PCD	Very High (Carbide	Poor	Yes	Not Attmpted		Not Attempted	----	Extremely Abrasive, Requires Diamond Tooling Tapping Method unknown

Table #3: Machining Parameters

Mat'l/Type of Cut/Tool Type	RPM	Feed	Direction	SFPM	Chipload
A-40 Roughing					
3/8Ø, 4 Fl, TiNiCarbide EM	4,000	10 ipm	Climb	392.7	.0006/tooth
1/4Ø, 2 Fl, TiNiCarbide EM	3,500	20 ipm	Climb	229.1	.0029/tooth
1/8Ø, 2 Fl, Carbide EM	3,000	10 ipm	Climb	98.2	.0017/tooth
A-390 Roughing					
3/8Ø, 4 Fl, TiNi Cobalt EM	3,000	20 ipm	Climb	294.5	.0017/tooth
1/4Ø, 2 Fl, TiNiCobalt EM	3,500	20 ipm	Climb	229.1	.0029/tooth
A-40 and A-390 Finishing					
3/16Ø, 2 Fl, Carbide EM	3,500	20 ipm	Climb	172.3	.0029/tooth
1/8Ø, 2 Fl, Carbide EM	3,000	8 ipm	Climb	98.2	.0013/tooth
1/16Ø, 2 Fl, Carbide EM	4,000	5 ipm	Climb	64.9	.0006/tooth
1/32Ø, 4 Fl, Carbide EM	5,000	3 ipm	Climb	41.9	.0002/tooth
3/16 Ø, Center Drill	3,500	2 ipm	--	--	--
.100 Ø Drill	3,500	2 ipm	--	--	--
1/4 Ø x .03 Thk. T-slot cutter	2,500	5 ipm	--	--	--

TABLE #4

Solder Alloys Composition and Melting Point

Solder Description	Composition	Melting Point	Flux Required	Maskant Required
Gold/Tin Solder	80%Au/20%Sn	280°C	no	no
Gold/Germanium Solder	88%Au/12%Ge	365°C	no	no
Sn96 Solder	96%Sn/4%Ag	230°C	yes	yes
Sn63 Solder	63%Sn/37%Pb	182°C	yes	yes

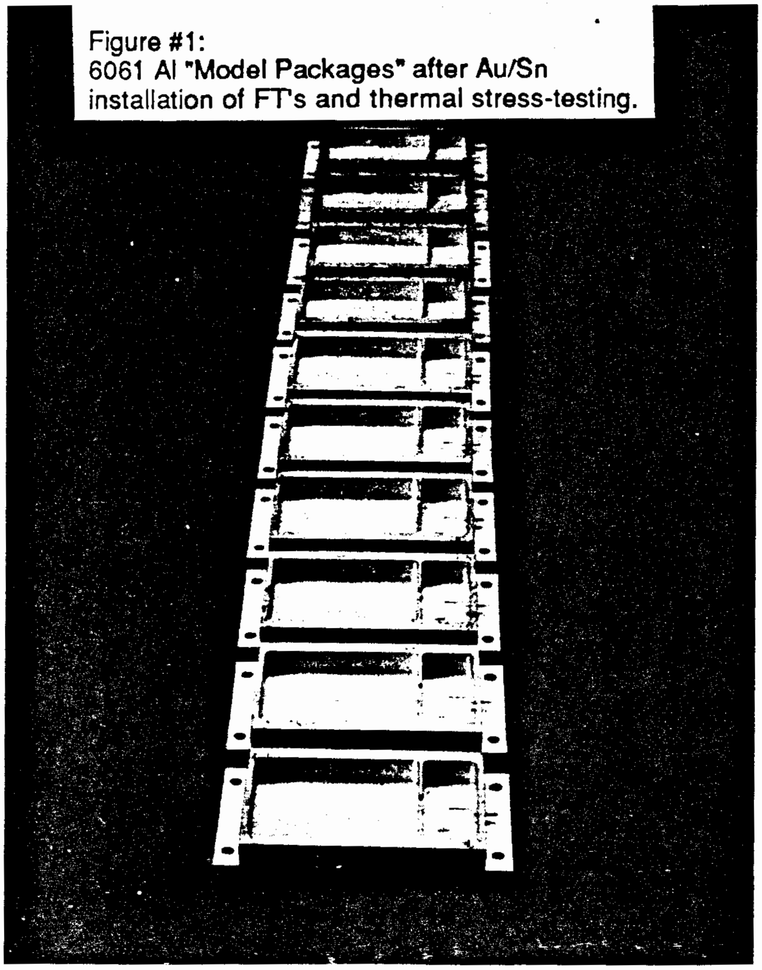


Figure #1:
6061 Al "Model Packages" after Au/Sn installation of FT's and thermal stress-testing.

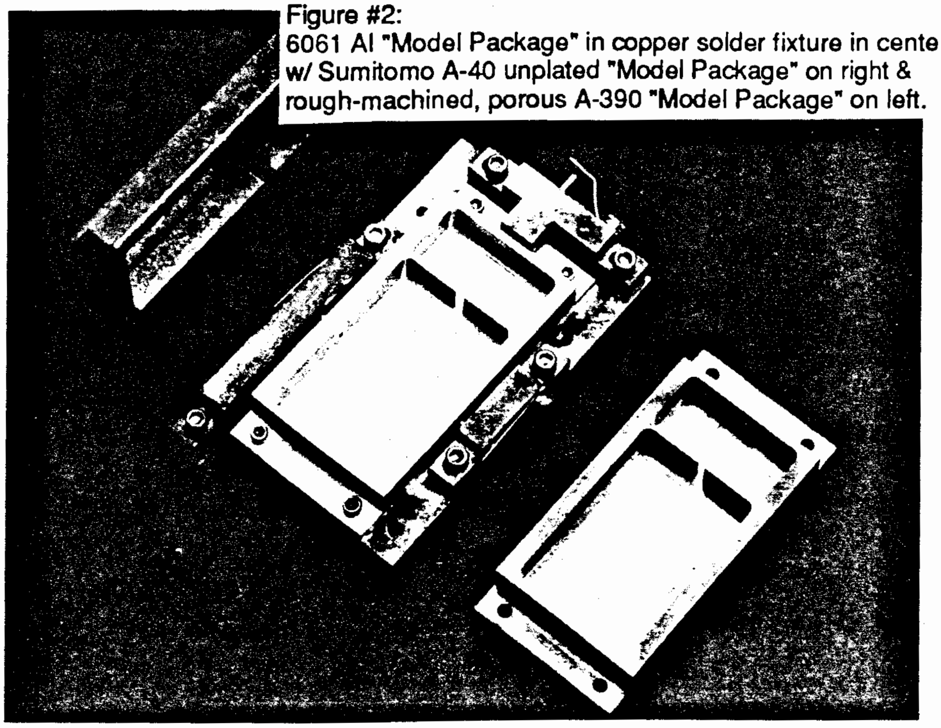


Figure #2:
6061 Al "Model Package" in copper solder fixture in center w/ Sumitomo A-40 unplated "Model Package" on right & rough-machined, porous A-390 "Model Package" on left.

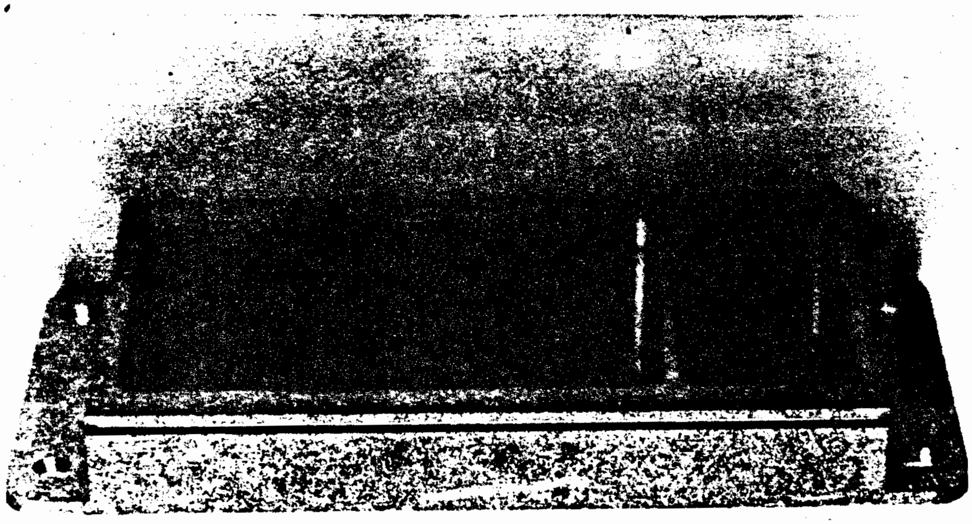


Figure #3:
Reynolds A-390 rough-machined "Model Package" shows surface roughness & porosity: poor casting density

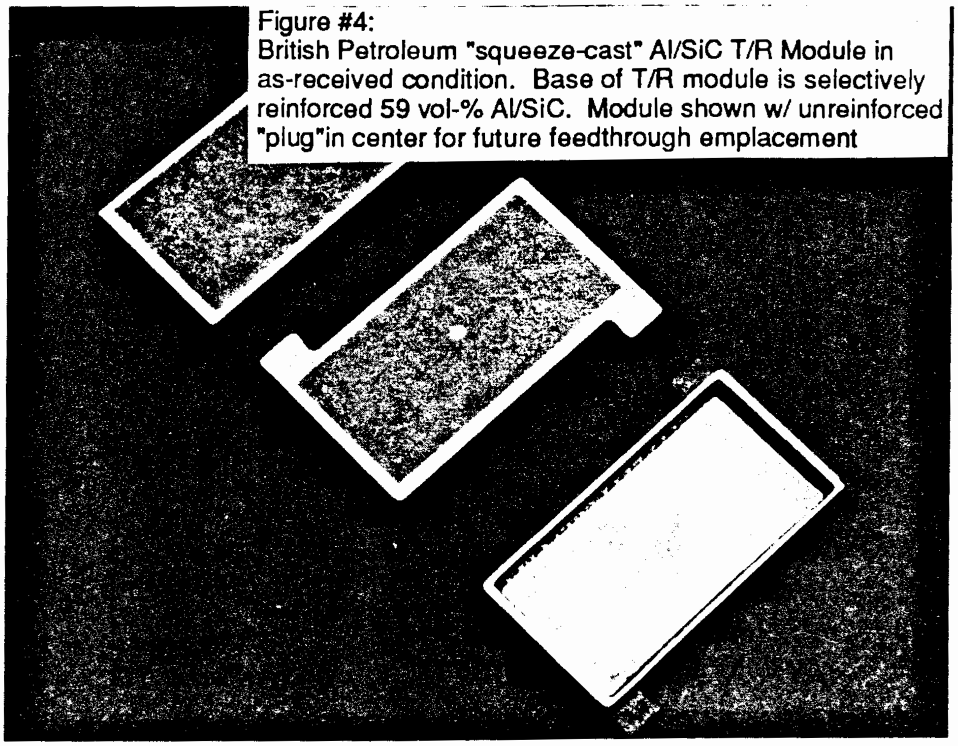


Figure #4:
British Petroleum "squeeze-cast" Al/SiC T/R Module in as-received condition. Base of T/R module is selectively reinforced 59 vol-% Al/SiC. Module shown w/ unreinforced "plug"in center for future feedthrough emplacement

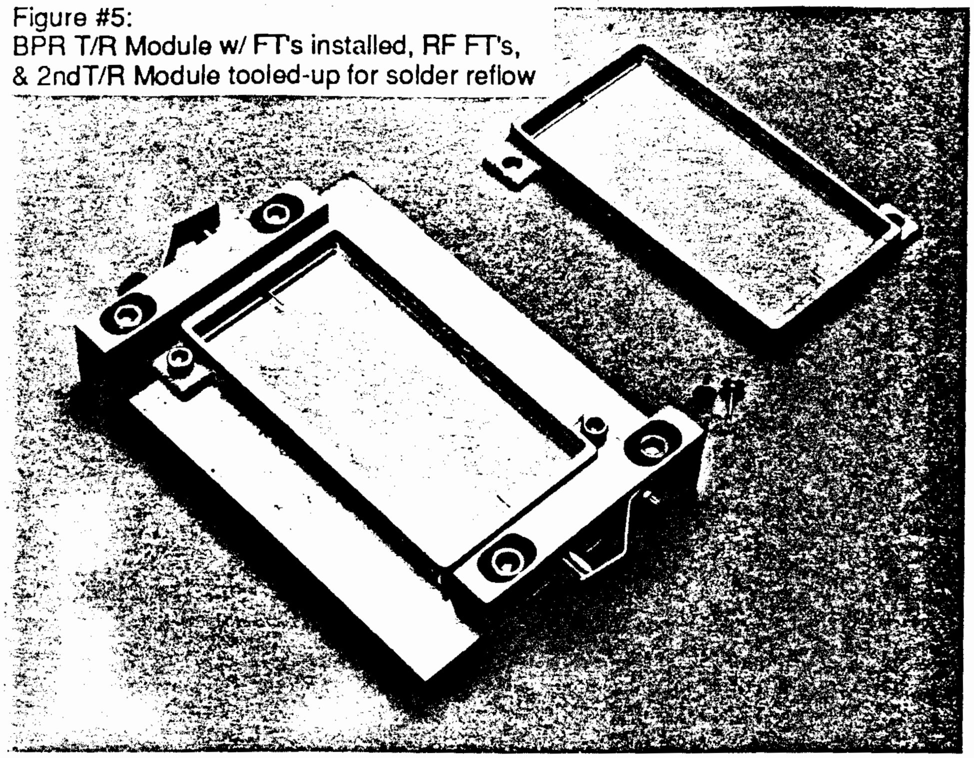


Figure #5:
BPR T/R Module w/ FT's installed, RF FT's,
& 2ndT/R Module tooled-up for solder reflow

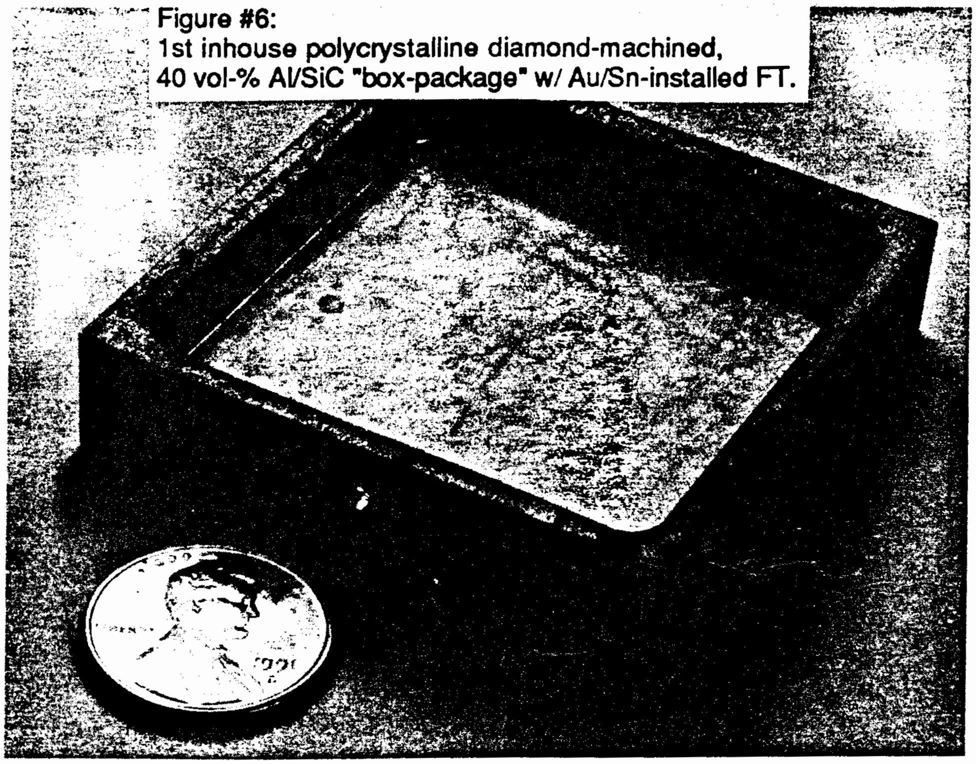


Figure #6:
1st inhouse polycrystalline diamond-machined,
40 vol-% Al/SiC "box-package" w/ Au/Sn-installed FT.

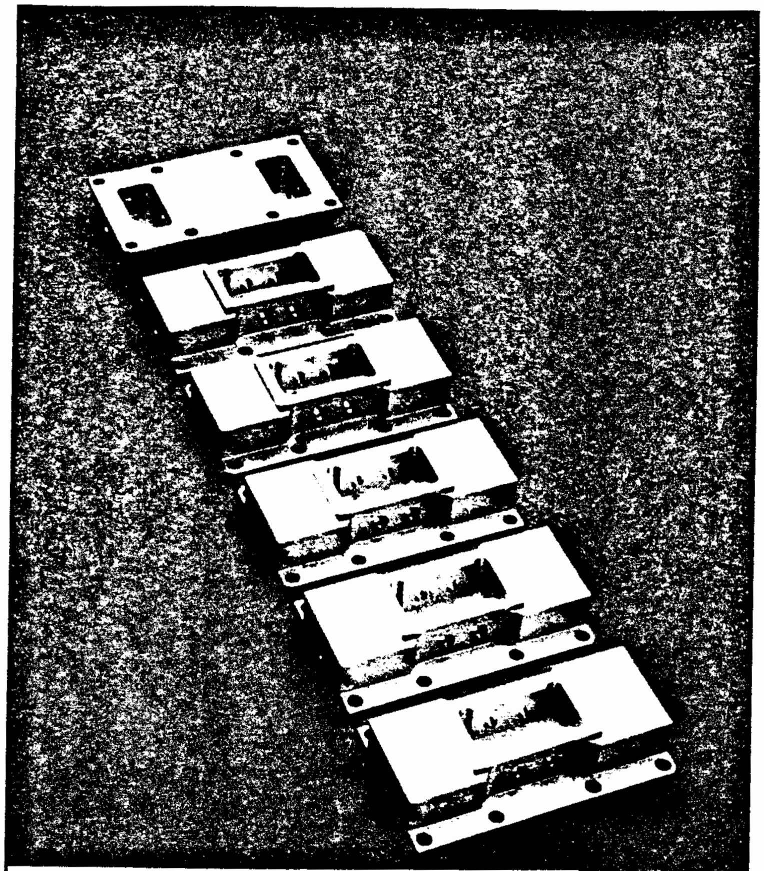


Figure #7:
55 vol-% Al/SiC Driver Modules PCD-machined from forge-clad bulk material.

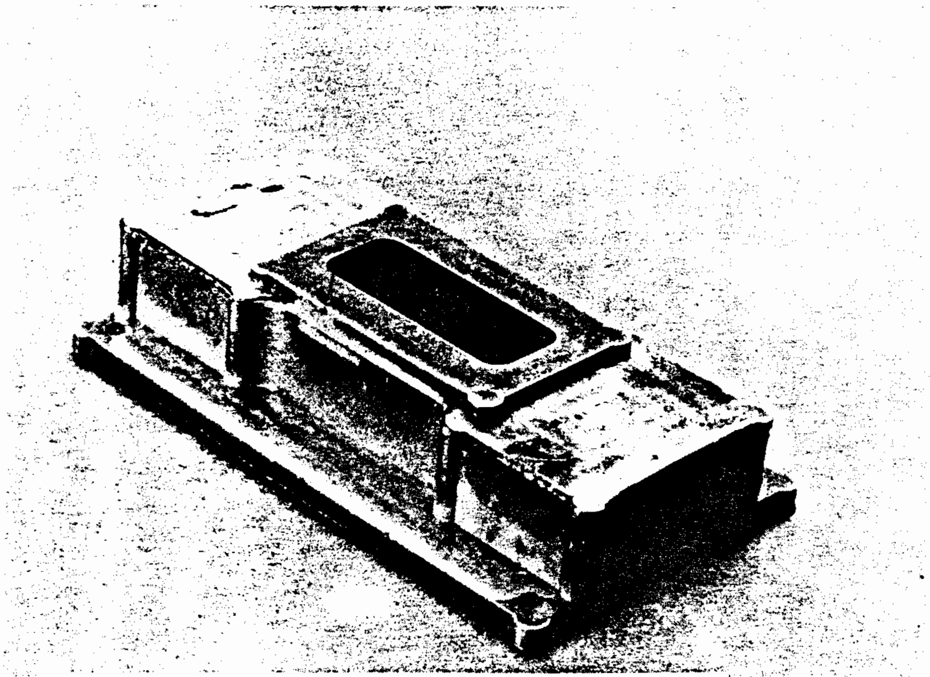


Figure #8:
Top view, Alcoa die-cast 65 vol-% Al/SiC Driver Module.

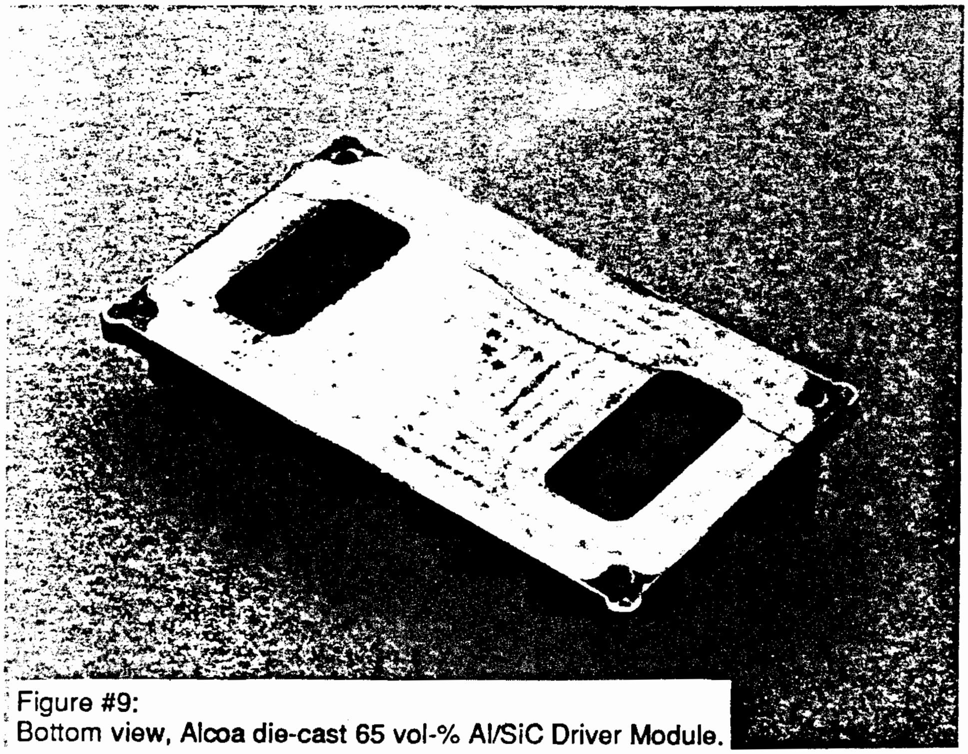
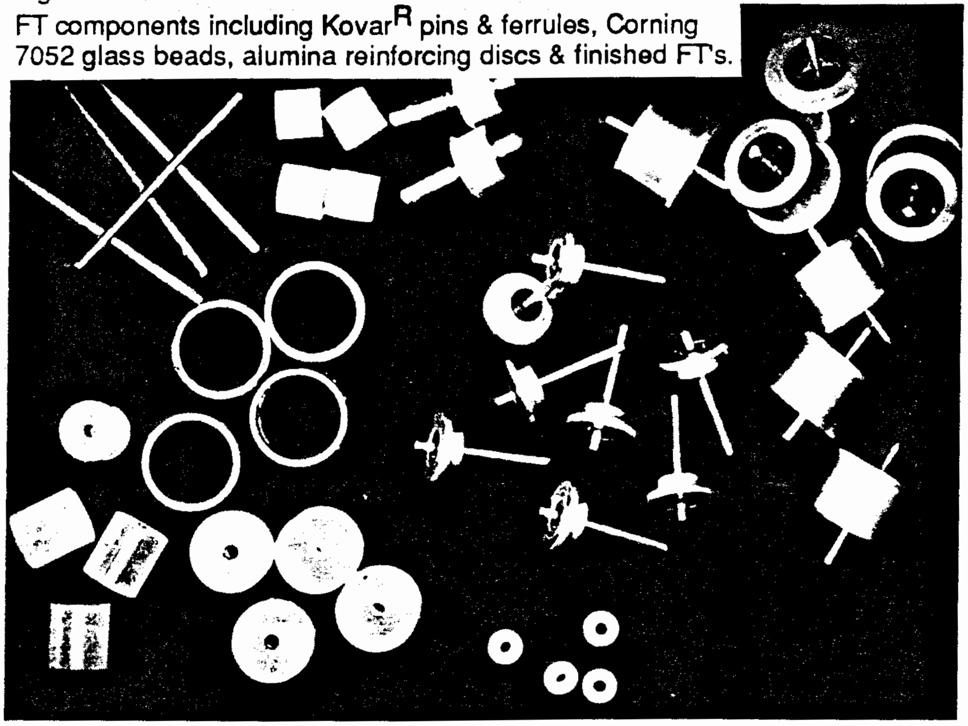


Figure #9:
Bottom view, Alcoa die-cast 65 vol-% Al/SiC Driver Module.

Figure #10:
FT components including Kovar^{R} pins & ferrules, Corning 7052 glass beads, alumina reinforcing discs & finished FT's.



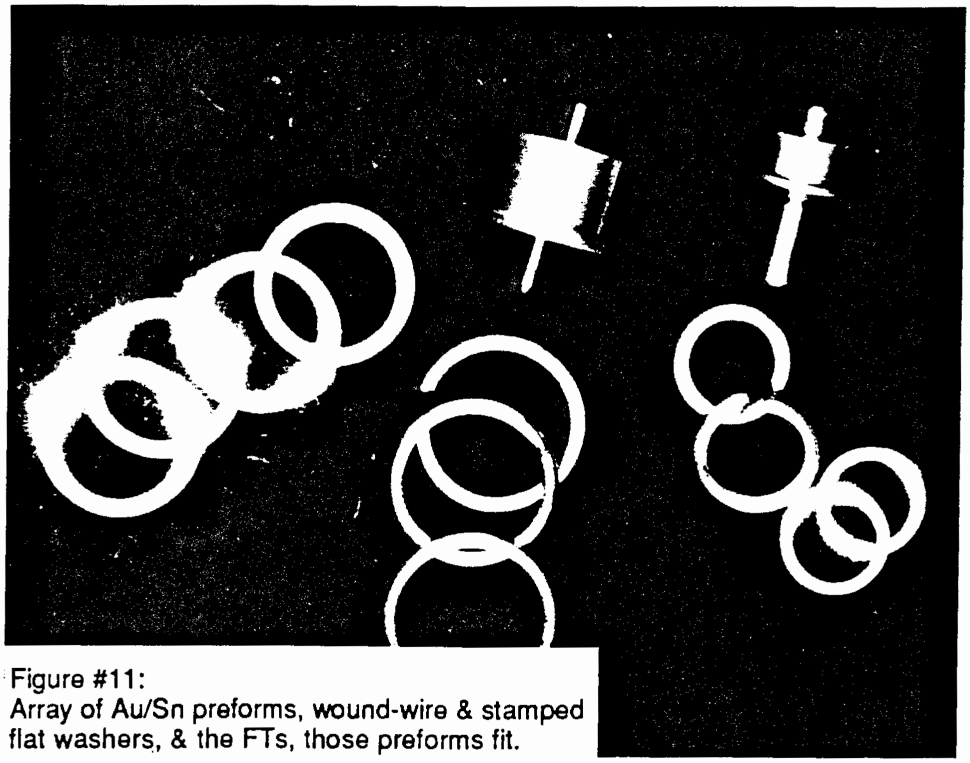
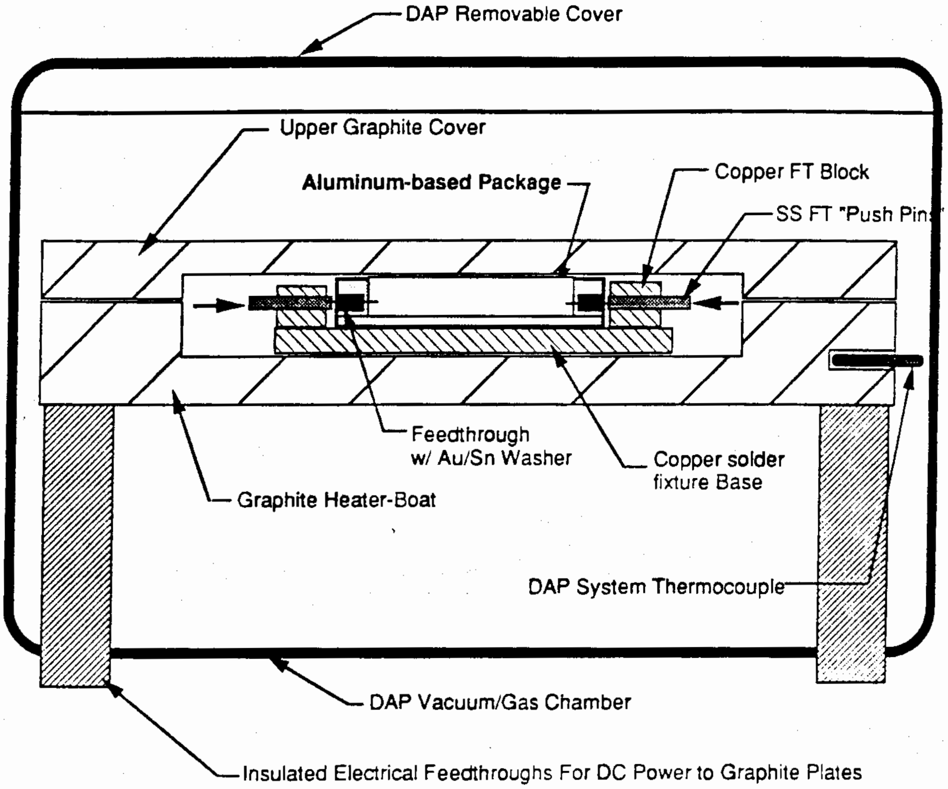
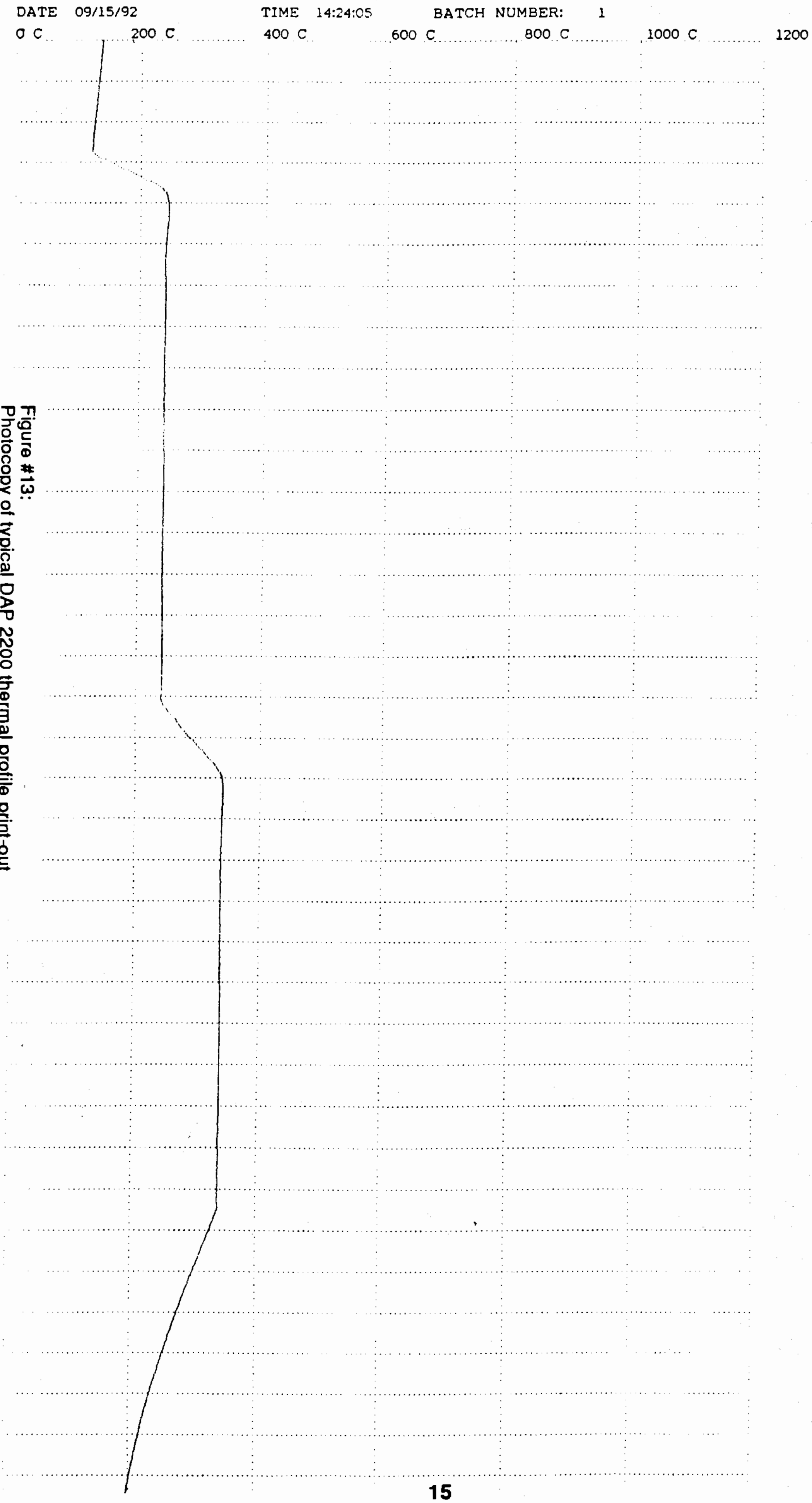


Figure #11:
Array of Au/Sn preforms, wound-wire & stamped flat washers, & the FTs, those preforms fit.

Figure #12: Cross-Section of Fixtured Package in DAP Graphite Heaters





DATE 09/15/92 TIME 14:24:05 BATCH NUMBER: 1

Figure #13:
Photocopy of typical DAP 2200 thermal profile print-out for reflow of Au/Sn. 1st plateau is 240°C vacuum bake-out; 2nd plateau is 325°C N2 reflow, followed by solidification

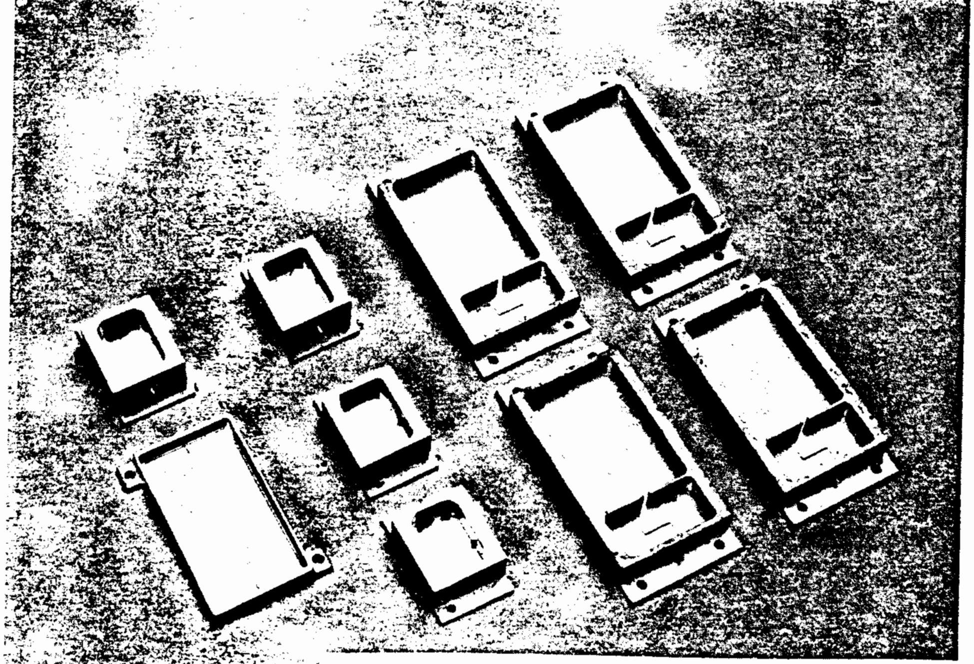


Figure #14:
Various Al-based custom hybrid microwave packages

Figure # 15: FT Au/Sn Solder Assembly Prior to DAP Reflow

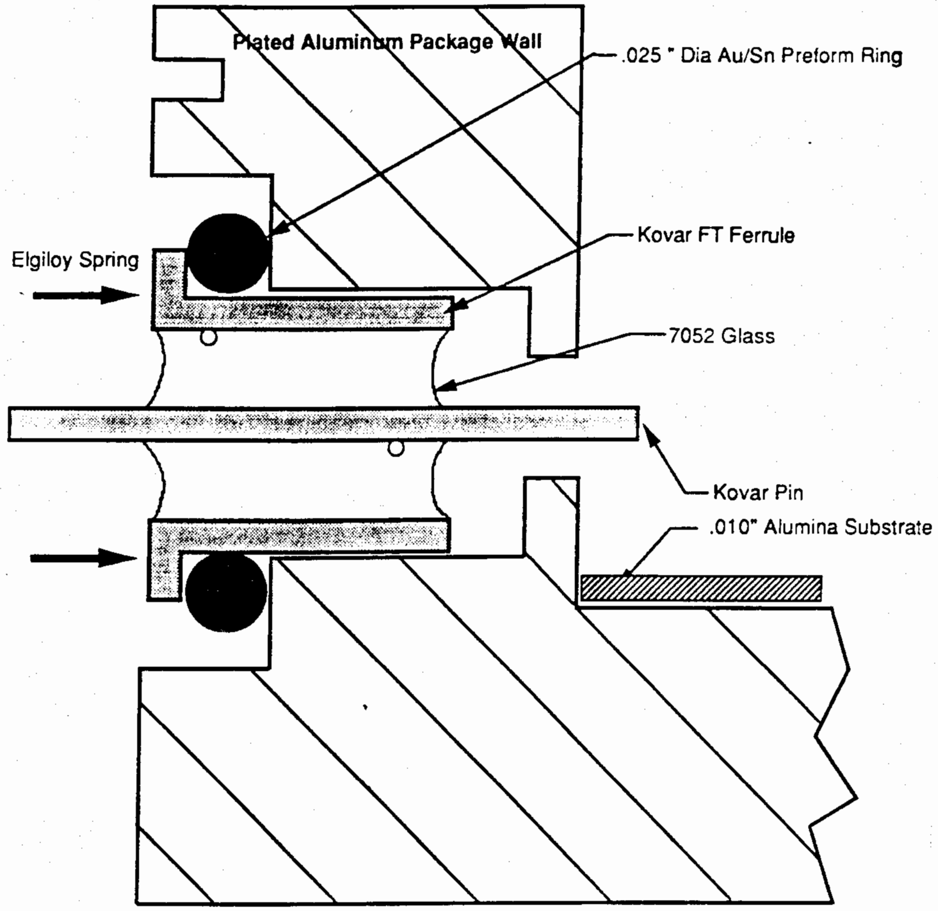
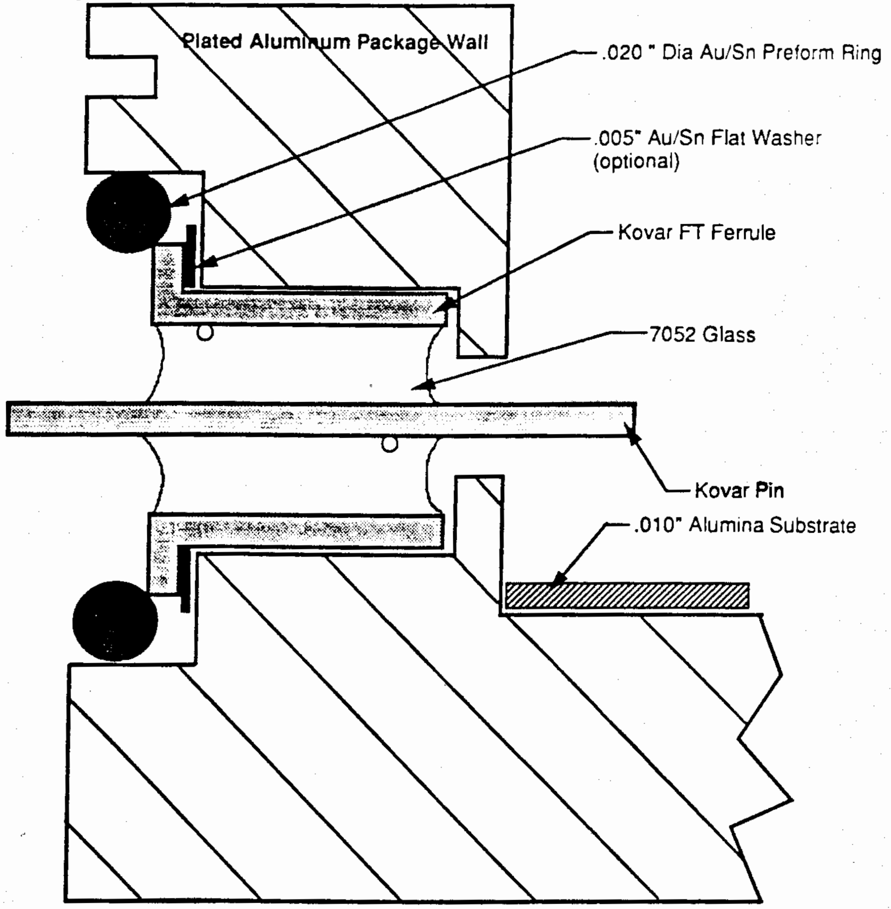


Figure #16: Alternate FT Au/Sn Solder Assembly Prior to DAP Reflow:



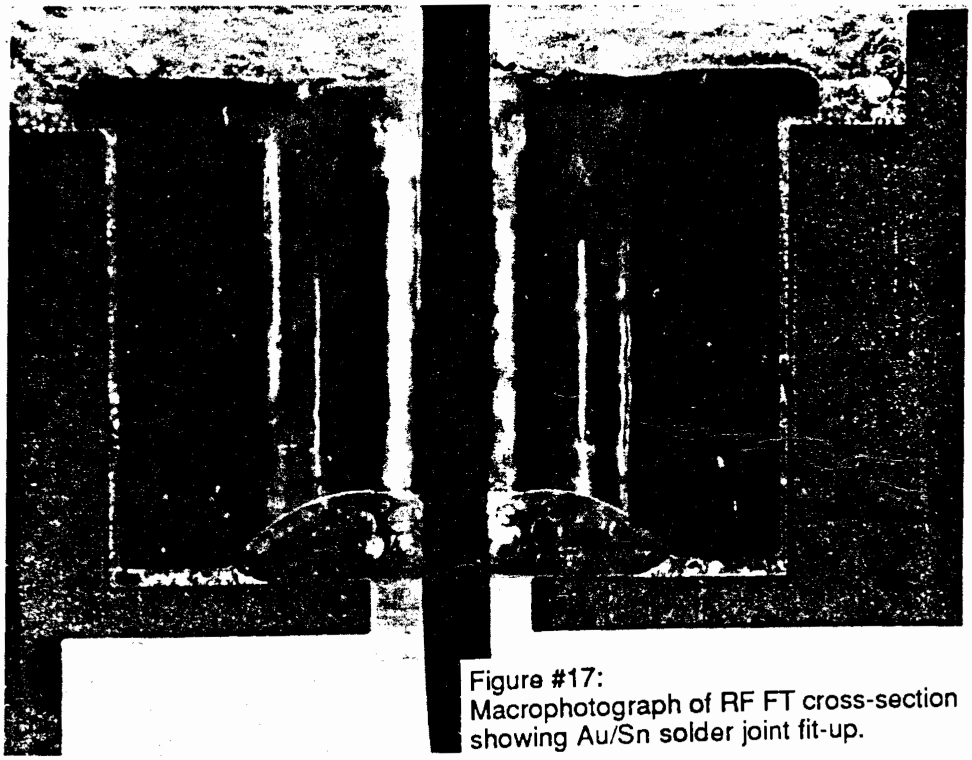


Figure #17:
Macrophotograph of RF FT cross-section showing Au/Sn solder joint fit-up.

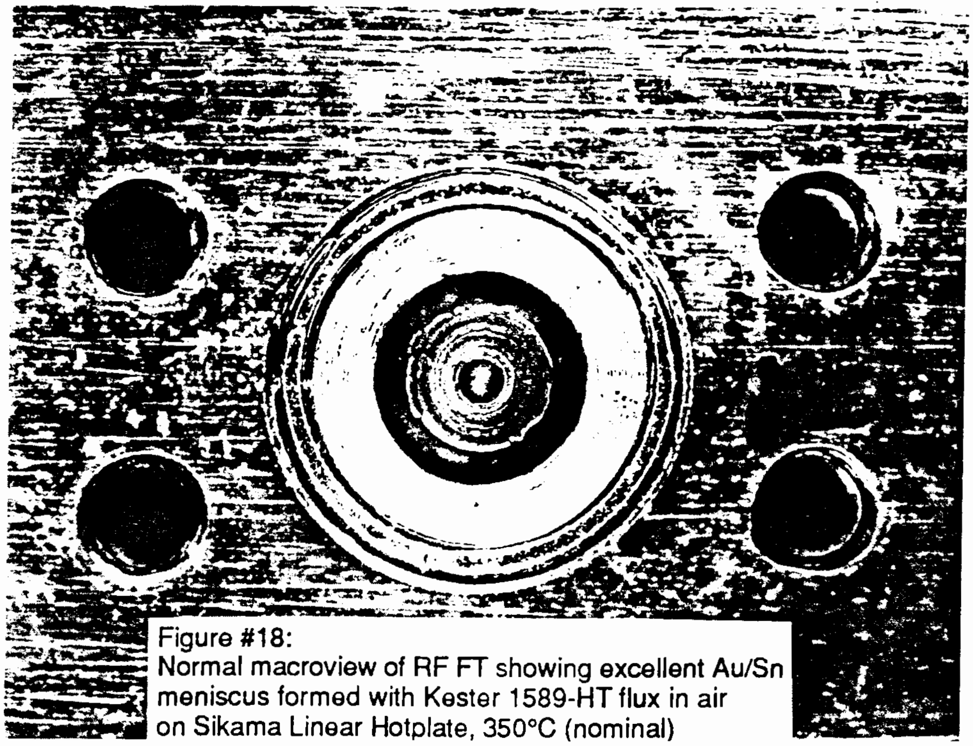


Figure #18:
Normal macroview of RF FT showing excellent Au/Sn meniscus formed with Kester 1589-HT flux in air on Sikama Linear Hotplate, 350°C (nominal)

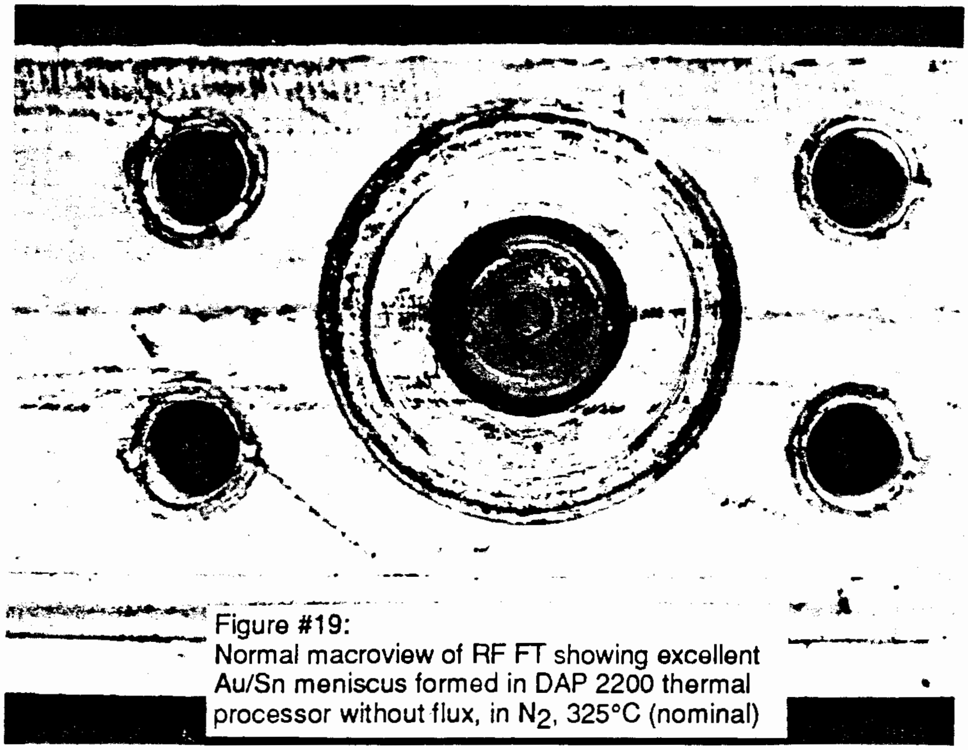


Figure #19:
Normal macroview of RF FT showing excellent Au/Sn meniscus formed in DAP 2200 thermal processor without flux, in N_2, 325°C (nominal)