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DESIGN AND FABRICATION OF TITANIUM MULTI-WALL THERMAL PROTECTION SYSTEM (TPS) TEST PANELS

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

TASK 1 REPORT

DESIGN AND FABRICATION OF TITANIUM MULTI-WALL THERMAL PROTECTION SYSTEM (TPS) TEST PANELS

Prepared for:

NASA LANGLEY RESEARCH CENTER

Hampton, Virginia 23665

CONTRACT NAS1-15646

ROHR INDUSTRIES, INC.
Chula Vista, CA.

FOREWORD

This is the interim report on work being performed by Rohr Industries - Design and Fabrication of Titanium Multiwall Thermal Protection System (TPS).

This program is administrated by the National Aeronautics Administration Langley Research Center (NASA LaRC). Mr. John Shideler of the Thermal Structures Branch, Structures and Dynamics Division, is Technical Monitor for the program.

The following Rohr personnel were the principal contributors to the program during this reporting period: Winn Blair, Program Manager; T. C. Atkinson, Manufacturing Technology; J. E. Meaney, Structures; R. M. Martinez, Project Engineer; H. A. Rosenthal, Thermal Testing; R. H. Timms, Preliminary Design; and L. A. Wiech, Engineering Laboratory. Overall program responsibility is assigned to the Rohr Aerospace R&D Engineering Organization with U. Bockenhauer, Manager.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

A Titanium Multiwall Thermal Protection System (TPS) panel conceived by NASA was designed. An acceptable fabrication process was developed, and the panel design was verified through mechanical and thermal testing of component specimens.

INTRODUCTION

Rohr Industries was awarded a contract January 1979 to design and fabricate titanium multiwall thermal protection panels for testing by NASA. Progress, current activities, and future milestones are shown in Figures 1 and 2.

The primary objective of this program is to design and fabricate metallic multilayer sandwich panels for test and evaluation by NASA. The program consists of two tasks:

Task 1 - Design Definition

Task 2 - Test Model Design and Fabrication

Task 1 consists of a preliminary design of panels and tools, fabrication of test panels and testing in face tension, flexural strength, creep, thermal conductivity and emittance.

In Task 2, a nine panel array shown in Figure 3, will be fabricated for testing in the Langley Research Center 8-foot High Temperature Structures Tunnel. A two-panel array shown in Figure 4 will be fabricated and delivered to the Langley Research Center for vibrational and acoustical tests. A second two-panel array will be delivered to Johnson Space Center for radiating tests.

Only the activities of Task 1 will be described in this report.

DESIGN DEFINITION

The configuration and construction details for a titanium multiwall panel is shown in Figure 5. The panel is a nine-sheet sandwich structure consisting of an upper and lower face sheet, four dimpled sheets, three septum sheets, and clips for attachment to the test fixture. The material for all detail parts is Ti-6Al-4V. The joining system used is a Rohr proprietary process in which the interfaces of the parts to be joined are plated with two or more elements. When put in contact with each other and heated to approximately 1214K (1725°F), the plating material melts creating a short time eutectic with the Ti-6Al-4V. While holding at this temperature for a specified time the plating material is diffused into the Ti-6Al-4V creating a bond at all plated interfaces.

DESIGN

Panel Design - The panel assembly shown in Figure 5 was designed from a sketch and information supplied by NASA Langley Research Center, Hampton, Virginia. Particular attention was given to the fabrication problem encountered with forming of the dimpled sheets. The design in Figure 5 shows a 25.75 angle on all sides of the panel. The angle slope is in the flow direction and also permits the use of a common dimpled sheet used in each of the four layers. The design is also unique inasmuch as the outer skins are formed on the 25.75° angle and are joined to each other by Liquid Interface Diffusion bonding to close out the panel's four sides. The panel sides are corrugated to give stiffness and to allow the panels to nest during the time they are being thermally expanded during service.

Skin Forming Tool Design - The tool design shown in Figure 6 takes into account the possibility of mass producing the skins. The design allows for multiple loading parts into mirror image die halves and forming as many as six skins simultaneously. Argon gas is used as the pressure media for superplastic forming the skins.

Dimpled Sheet Forming Tool Design - The design shown in Figure 7 takes into account Ti-6-4 material size availability, thermal expansion and part quantity. The die plates were designed to permit economic installation of a large number of pins. A shim plate was added to permit some adjustment of the dimple height by adding to or removing from the plate.

TEST PANEL FABRICATION

Panels for Structural and Thermal Tests - The dimpled sheet shown in Figure 8 was superplastically formed in a vacuum furnace using 8.27 KPa (1.2 pounds per square inch) dead weight pressure. Figure 9 shows the dimpled sheet forming tool being loaded into the vacuum furnace. After it was formed, the dimpled sheet was trimmed by chem blanking, (see Figure 10), and was plated on the nodes only using the Rohr proprietary process. The plating parameters were established using full sized sheets 305 mm (12") by 610 mm (24"). Figure 11 shows a plated sheet with cut-outs made for microexamination.

The layup for LID bonding was accomplished by aligning the nodes opposing each other through the septum sheets, and by resistance welding at each of the four corners. This procedure held the dimpled sheets, septum sheets and skins in position for LID bonding. For LID bonding, the layup was placed on a flat graphite reference block, with 18 mm (.7") thick blocks placed on each of the four sides. The side blocks control the panel height and prevent the panel from being crushed by a graphite block that was placed on top of the layup for bonding pressure. The assembly was then placed into a vacuum furnace for LID bonding. The furnace was evacuated to 1 x 10^{-5} torr, heated to 1214K (1725°F), and held for a specific period of time. During this period the plated material is melted and diffused into the Ti-6Al-4V creating a bond joint at all plated interfaces.

All panels were fabricated without clips and doublers. All panels for testing in flatwise face tension, beam flexure, creep and thermal conductivity were LID (Liquid Interface Diffusion) bonded in sizes of 152 mm (6") by 305 mm (12") and 305 mm (12") by 305 mm (12"). Figure 12 shows three of these panels.

After the panels were LID bonded a layout for cutting of all the test specimens was made. The layout for the structural test specimens is shown in Figures 13, 14 and 15. The test specimens were cut using an electric discharge saw. Specimens for static creep test were taken from each material gage used in the sandwich. Two thermal conductivity test specimens were cut to a size 1.8 by 203 by 203 mm (.7" x 8" x 8"). The emittance test specimen, .076 by 50 by 100 mm (.003" x 2" x 4"), was polished to a very high luster on one end and processed through two thermal cycles, duplicating the fabrication process, then checked for emittance on both the polished and unpolished areas. One specimen was oxidized for 30 minutes at 810K (1000°F) and checked for emittance.

<u>Vacuum Tight Panel Fabrication</u> - This was a test to determine if a vacuum tight panel can be produced. The dimpled sheets and septum sheets were produced in the same manner as for the structural test panels. The skins which also close out the vacuum tight panel sides shown in Figure 16 were superplastically formed two at a time in a mirror image die, shown in Figure 17. The forming was also accomplished in a vacuum furnace using 34.5 KPa (5 pounds per square inch) argon gas pressure. The skins for the vacuum tight panel were plated around the periphery 5.1 mm (0.2") wide shown in Figure 18.

After plating had been accomplished the skins, septum sheets, and dimpled sheets shown in Figure 19 were assembled for LID bonding. The nodes were aligned opposing each other through the septum sheets, and resistance spot welded five places at each corner. This procedure held the detail parts in place until the joint had been achieved by the LID bonding process. For LID bonding, the assembly was placed on a flat graphite reference surface shown in Figure 20. Also shown in Figure 20 are the graphite aids that are used to control the panel height and bonding pressure. The panel was isolated from the graphite by commercially pure titanium slip sheets. The assembly was then placed into a vacuum furnace for LID bonding. The furnace was evacuated to 1×10^{-5} torr, then heated to 1214K (1725°F) and held for a specific time. During this time period the plated material is melted and diffused into the Ti-6Al-4V creating a bond joint at all plated interfaces. Figure 21 shows a LID bonded panel for vacuum tight evaluation.

THERMAL TESTING

Emittance Tests - The samples tested were:

Sample #7910 - as received foil.

Sample #7911 - foil run through sandwich manufacturing process.

Sample #7912 - foil was polished, then run through sandwich manufacturing process.

Sample #7904 - foil oxidized at 810K (1000°F) for 30 minutes.

These samples were supplied to General Dynamics for wavelength-reflectivity measurements in their test apparatus described in the appendix. All tests were made at room temperature. Reflectivity data were entered into their computer program which determined total normal emittance at various temperatures. Results are given in Table I and graphed in Figure 22. Note that the term emissivity is the same as total normal emittance.

For the most part only minor differences are shown between the samples. There appears to be a slight increase in emittance when the sample goes through the manufacturing process, i.e. compare 7910 and 7911. But polished foil 7912 shows an even smaller difference. As expected, the foil oxidized for 0.5 hours at 810K (1000°F) has a higher emittance. Additional tests have shown that emittance continues to increase as oxidation time increases above 0.5 hours.

In summary, one can conclude that little is gained by polishing the foil, and that manufacturing the sandwich out of as received foil is satisfactory. Furthermore, additional data will be required to determine emittance as a function of oxidation time.

Conductivity Tests - Thermal Conductivity testing was subcontracted to General Dynamics Convair Division. Tests were performed on two panels having approximate dimensions of 17.3 by 203 by 203 mm (.68" by 8" by 8") using a guarded hot plate apparatus, see Appendix A.

The test results showed higher conductivity than had been predicted. After analyzing the test data and test conditions, it was concluded that:

1. The test panel was too small.

2. Tests should be re-run by Rohr using a larger test panel, 17.3 by 305 by 305 mm (.68" by 12" by 12").

3. The test should use a standard material (MIN-K) with a known thermal conductivity next to the test panel.

4. The heating instrument should be capable of holding finite temperature control over the test area.

(Data from these Rohr tests have been added to the figure in the Appendix. This data fall about 10 percent higher than that predicted from NASA CP-2065).

STRUCTURAL TESTING

Flatwise Tension Tests - Test specimens were approximately 50 by 50 mm (2" by 2") and consisted of full depth sandwich and individual layers. These specimens were bonded with Hysol EA934 adhesive to aluminum loading blocks. The blocks with the specimen were loaded into the test fixture as shown in Figure 23. This fixture was located in the Instron test machine. This set-up has swivel joints at both ends to account for misalignments of load. However this device must overcome friction loads and these small loads can be very significant if they apply peel loads to this sandwich configuration (see test results). Therefore for future testing it is recommended that fixtures more sensitive to alignment be used.

The test results are summarized in Tables 2 and 3. The lower values in the full depth sandwich (Table 3) are indicative of predominant LID bond failures rather than node metal failures. However the three very low values in the individual layer testing (specimens 16-2, 22-2, and 24-4) are not indicative of weakness in the bonding. These specimens had significant metal failures, and it is suspected that their premature failure was caused by a peel load introduced by the loading fixture (see above discussion). There was a range in the number of nodes per specimen, however there did not appear to be any correlation between their number and the failure stress.

Basic Face Sheet Tension Tests - The specimens are standard ASTM E8 size with a 12.7 mm (.50") wide test area. The specimens were of three different thicknesses: .038, .076 and 0.10 mm (.0015", .003" and .004"), and were tested in three physical conditions: a) as received from the mill, b) after being run through the LID thermal cycle 1200K (1700°F) for approximately 90 min., and c) sheets taken from actual bonded sandwich panels. These specimens were tested at room temperature in the Instron test machine and the following properties were determined:

yield and ultimate stress, percentage elongation, and modulus of elasticity.

The test results are summarized on Table 4. As shown, the as received strength properties are significantly higher than those for standard annealed Ti-6Al-4V sheet. These increases are attributed to the rolling operations these sheets received before being sent to Rohr. The specimens after the LID thermal cycle produced strength properties close to annealed sheet values. The low elongation value in the 0.038 mm (.0015") foil indicates some contamination during the thermal cycle. The .038 mm (.0015") and .076 mm (.003") specimens from the LID bonded panels exhibited lower strength and very low elongation properties. This did not occur in the 0.10 mm (.004") sheet. It is surmised that the .10 mm (.004") sheet is not as sensitive to surface contamination from the furnace and to the diffusion bonding as the thinner sheets.

Beam Flexure Tests - The seven test specimens had the following approximate dimensions: 305 by 76 by 17 mm (12" by 3" by .65"). All seven specimens were tested in the test setup shown in Figure 24. This setup was designed to provide a temperature gradient across a specimen while it is being subjected to a four point beam flexure test. As shown, the hot side of the specimen was heated by quartz lamps while the other side was cooled by shop air. The heat in the lamps may be regulated by altering the input current and shop air flow is metered by a valve. Ti-6Al-4V pads 12.7 mm (1/2" wide by .050" thick) were used to distribute applied and reaction loads into the specimens. Two of the specimens were tested at room temperature and did not require thermocouple instrumentation. Each of the other five specimens had eight thermocouples installed.

Two room temperature specimens were loaded in 89.0 N (20 lb.) increments with a return to zero load after each increment. The loads were applied with a crosshead movement of .05 in/minute and the load was held for

30 sec. Deflection readings at the center of the specimen were taken at each loading and unloading.

Four of the five remaining specimens were tested to failure in the same manner as described above except a temperature gradient was imposed. Two specimens had a 422-700K (300°-800°F) gradient and the other two had a 422-811K (300°F-1000°F) gradient. These specimens were brought to temperatures before the loads were applied. The seventh specimen was brought to a temperature gradient of 422-811K (300°-1000°F) and then a total load of 120.0 N (27 lbs.) was imposed and left for one hour. There was a negligible amount of creep during the test.

The results are shown in Table 5. Note the very small temperature gradients along the lengths of the specimens. The disbond failure mode on the room temperature specimens occurred only after very severe buckling waves took place in the face sheet. Deflection readings indicate that permanent set and creep values were negligible.

Creep Tests - A total of eight specimens were tested for elevated temperature creep. The specimens were .076 mm (.003 in.) foil which had been diffusion bonded to corrugated core. After the core had been cut away, the foil was cut into tensile specimens. The specimens were dead weight loaded and a portable wrap around furnace supplied the temperature. Deflection was measured using a dial gage and a microscope. Three of the eight specimens were tested at 811K (1000°F) and 68.95 MPa (10,000 psi) for 100 hours without failure. The other five specimens were tested at higher stress levels and the results are plotted on Figure 25. Comparison of the data for LID bonded foil with published rupture data for annealed sheet indicates about a 25 percent reduction in creep rupture due to the LID bonding process and loss of work hardening imposed on the material by the rolling operation.

CONCLUSIONS

1. A design was completed which takes into consideration fabrication techniques, thermal properties, mechanical properties, and material availability.

2. An acceptable fabrication process was developed.

3. The design was verified through mechanical and thermal testing of the materials and sandwich test specimens.

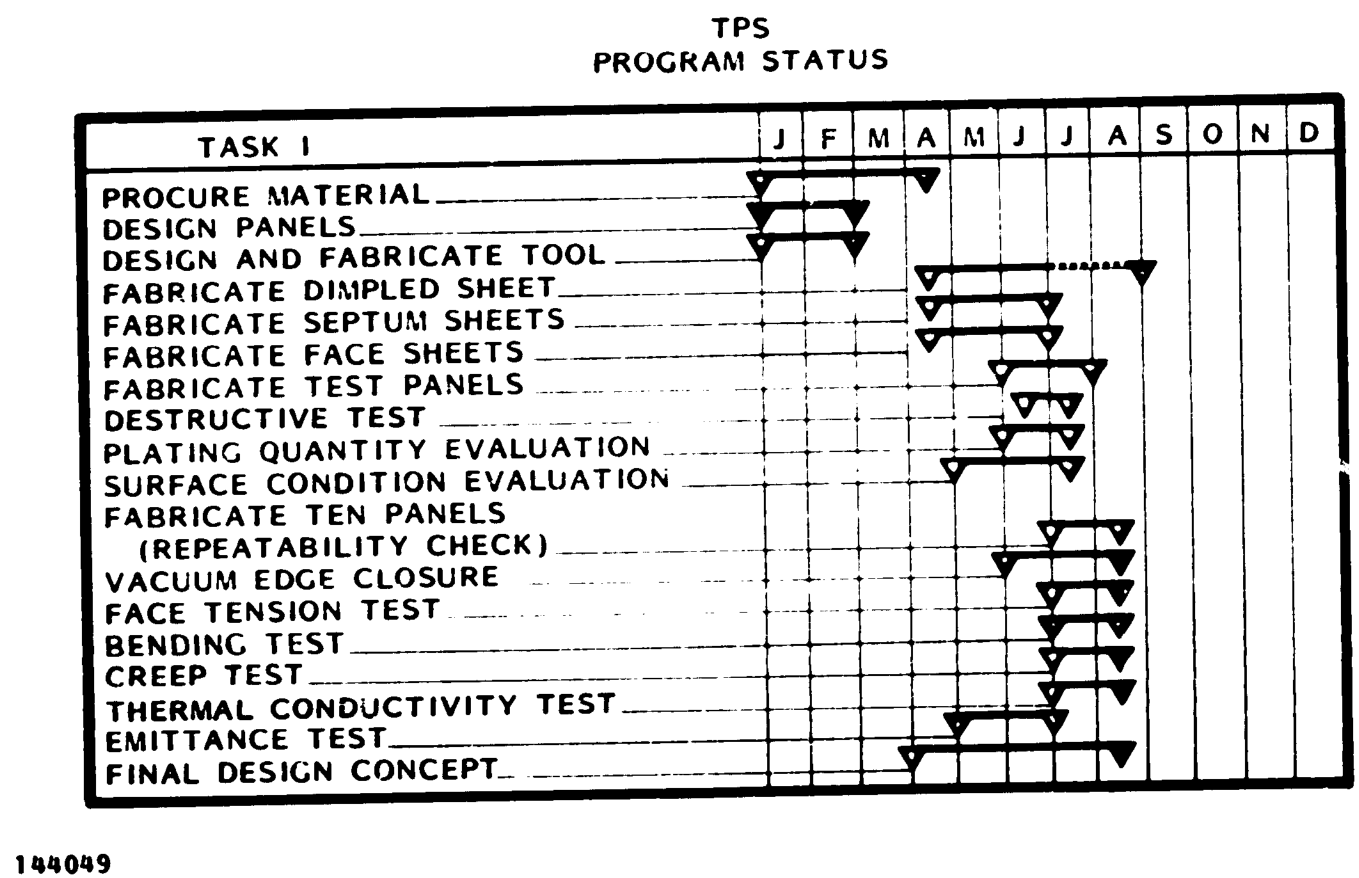

Figure 1. Task 1 Program Status

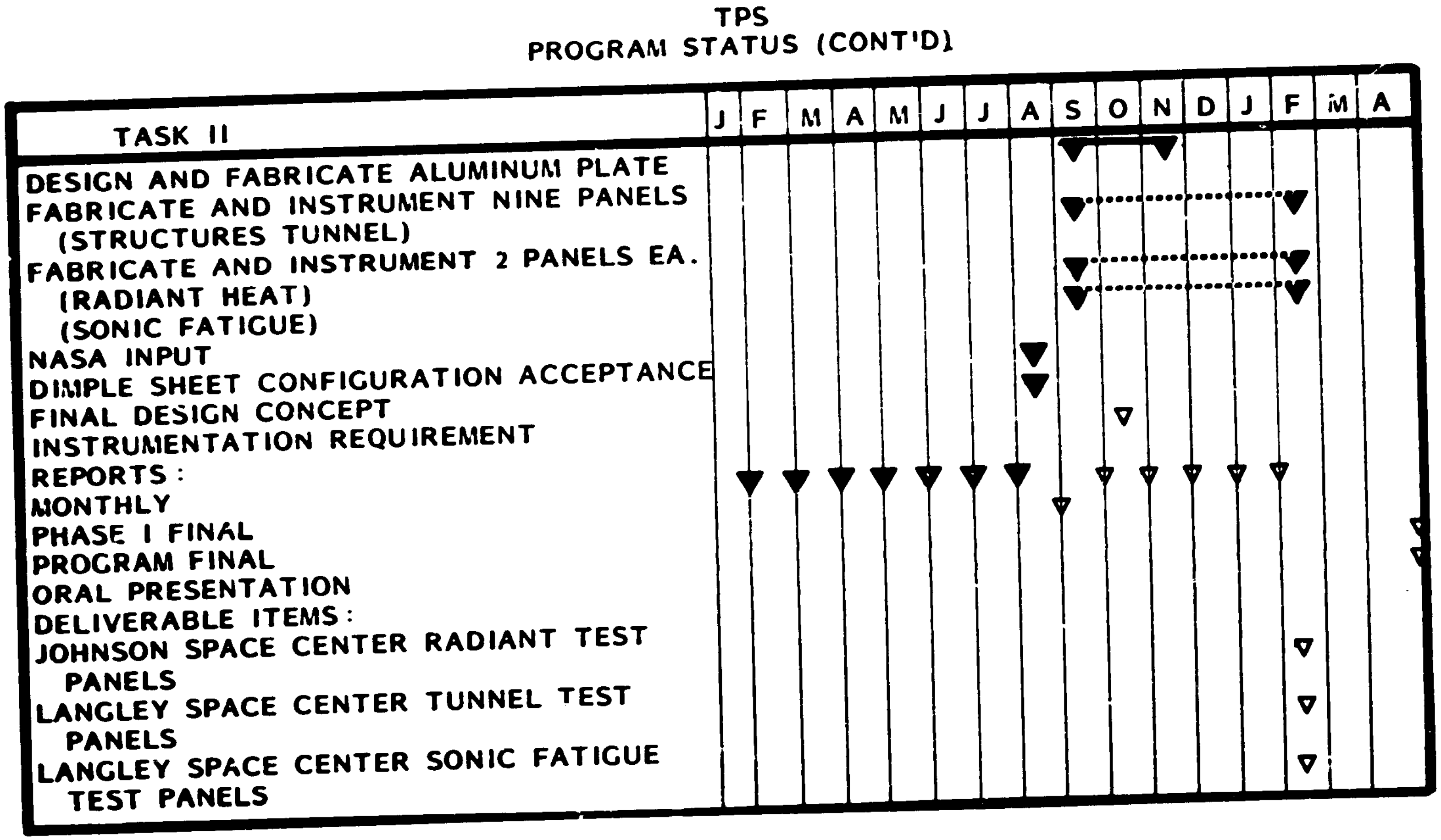

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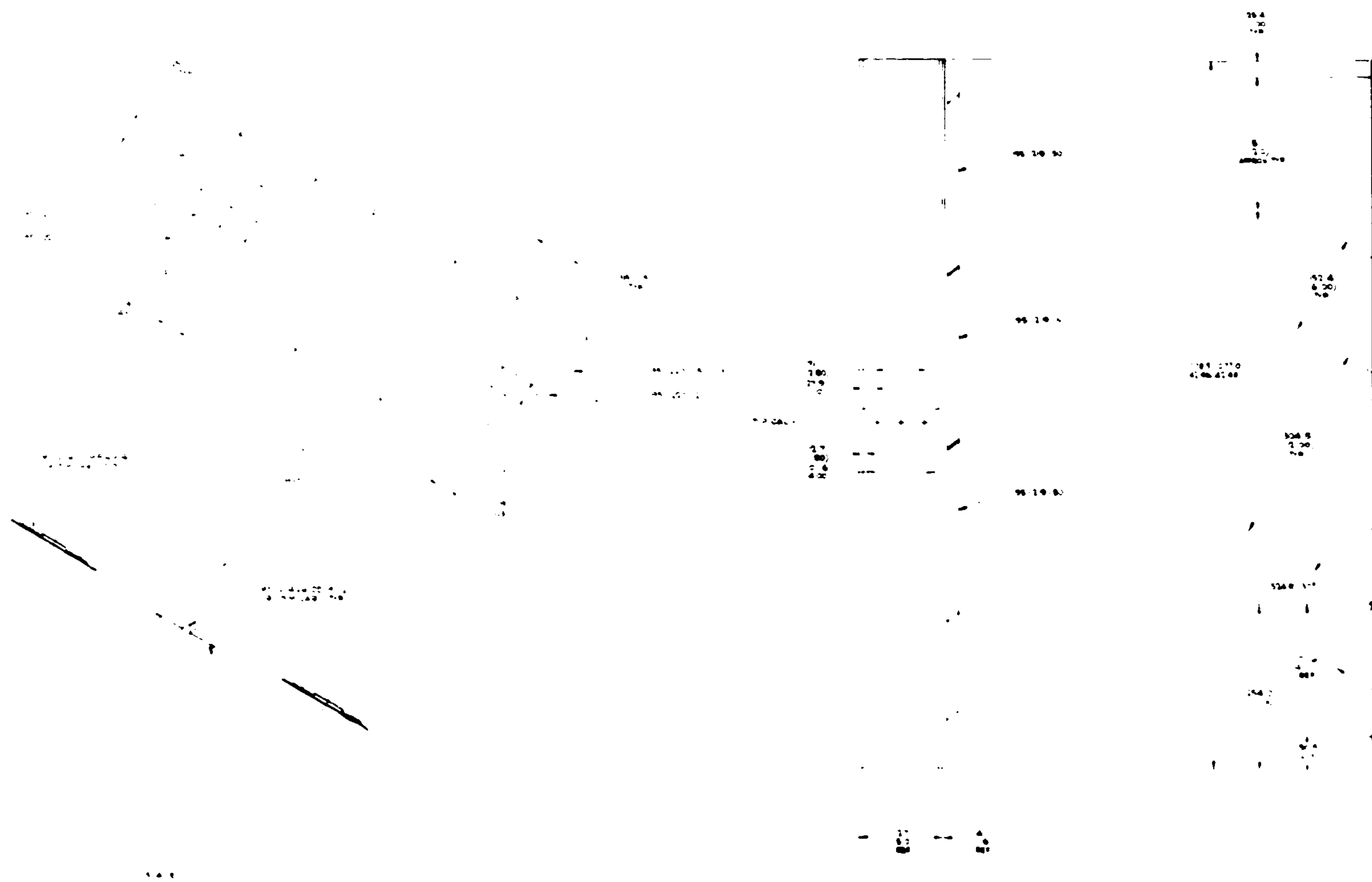
Figure 2. Task 2 Program Status



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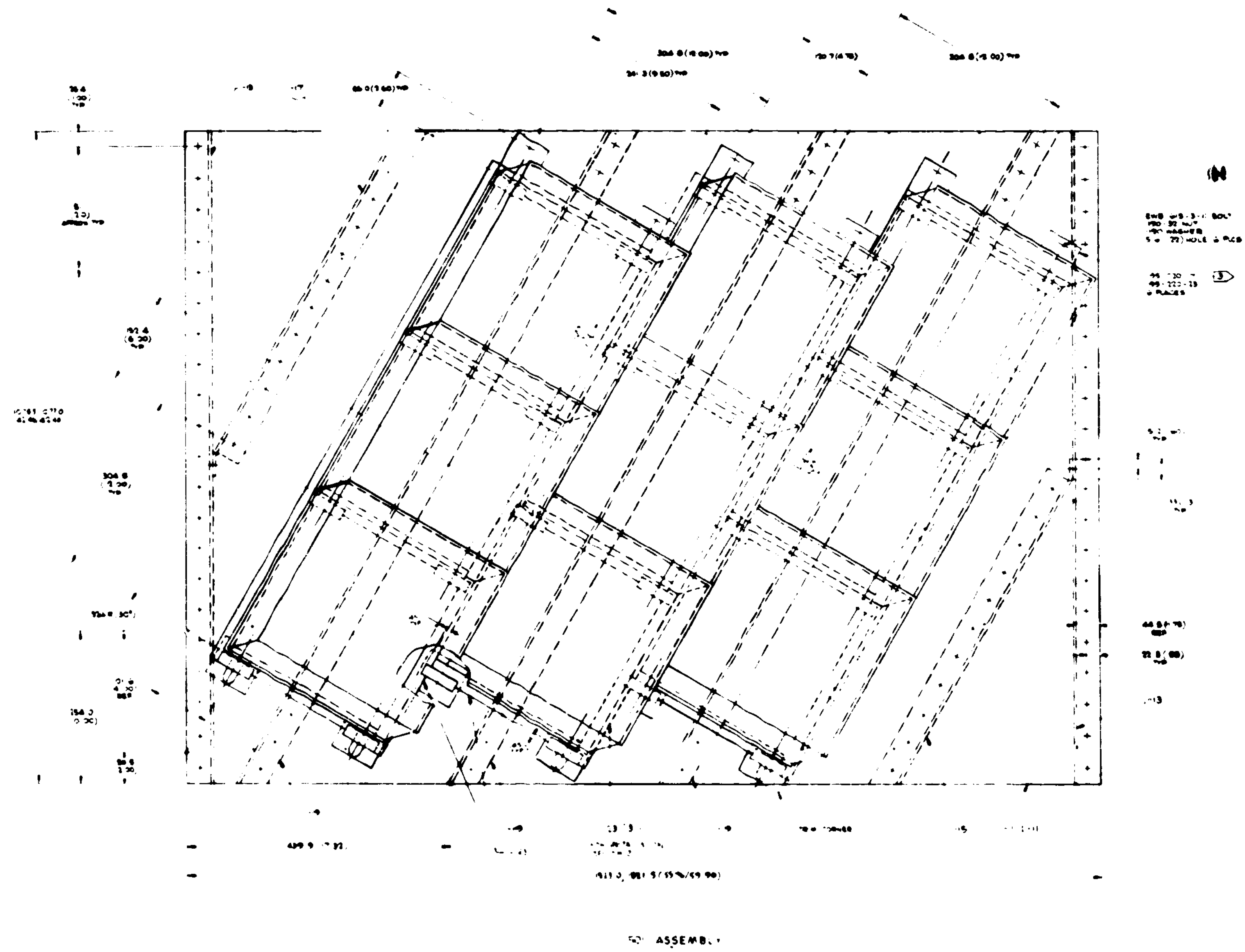

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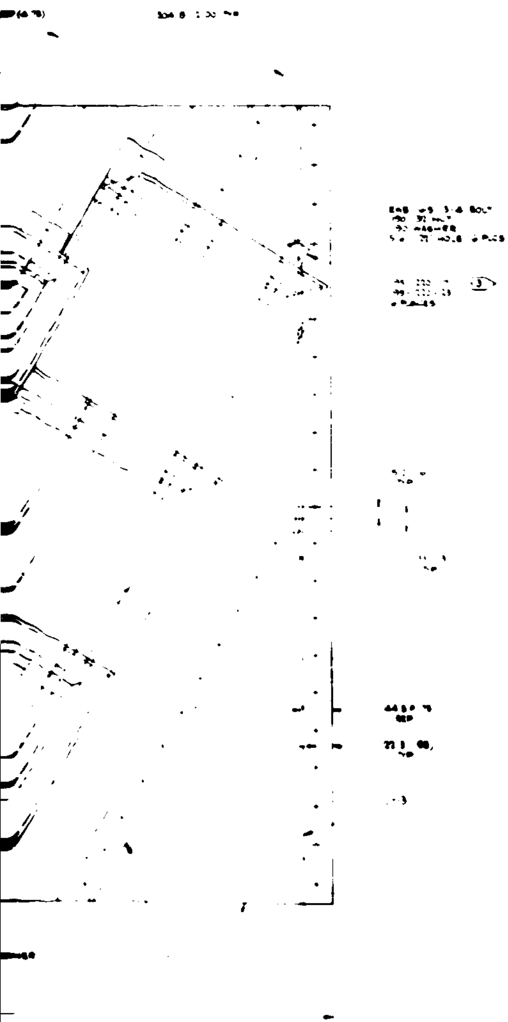

NOTES

1. DIMENSIONS IN SI UNITS AND (CUSTOMARY UNITS) mm (in), deg.

2. TOLERANCES LINEAR / ANGULAR

96		[illegible]	RIVET, BLIND				
160		[illegible]	RIVET, CSK				
	6	-90	WASHER				
	6	-90-92	NUT				
	6	[illegible]	BOLT (OR SIMILAR)				
	9	[illegible]	PANEL ASSY				
	6	198-220-23	TONGUE				
12		-21	CLIP				
12		-9	CLIP				
6		-7	PACKING				
24		198-220-19	DOUBLER				
AR		-23	FELT TAPE	NOMEX	[illegible]		[illegible]
AR		-21	TAPE	TEFLON	[illegible]		DUPONT
3		-19	STIFFENER	AL AL	[illegible]	6061-T6	CHANNEL
		-17			-27		
		-15			-26		
2		-13	STIFFENER		[illegible]	6061-T6	CHANNEL
		-11	PANEL	AL AL	[illegible]	2024-T3	
		-1	PANEL ASSY				
		-90	ASSEMBLY				
QTY REQUIRED		PART NO	DESCRIPTION	MATL	SIZE (in)	SPEC.	

Figure 3. Design, Kine-Panel Array (Construction Details) (Sheet 1 of 2)

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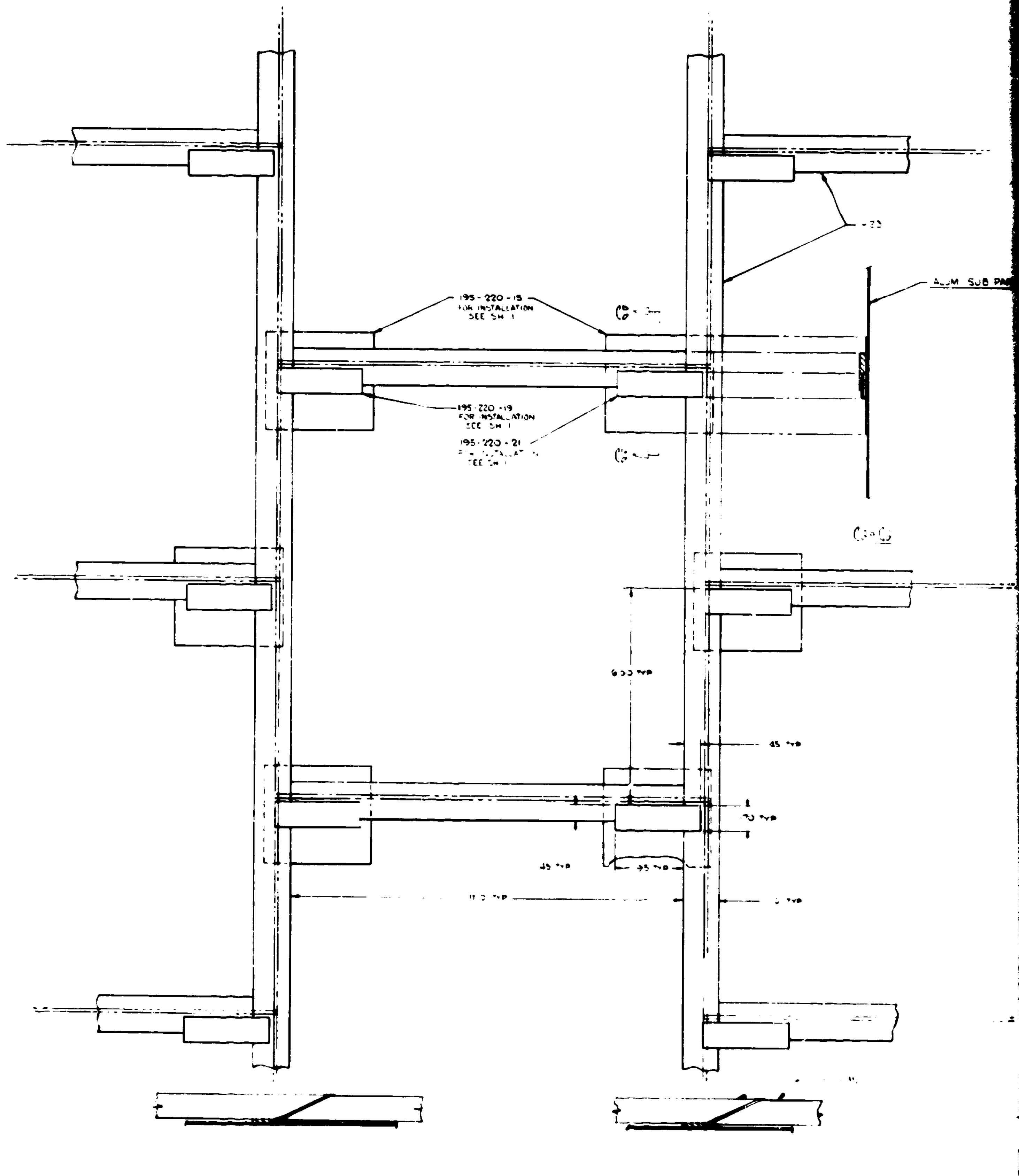
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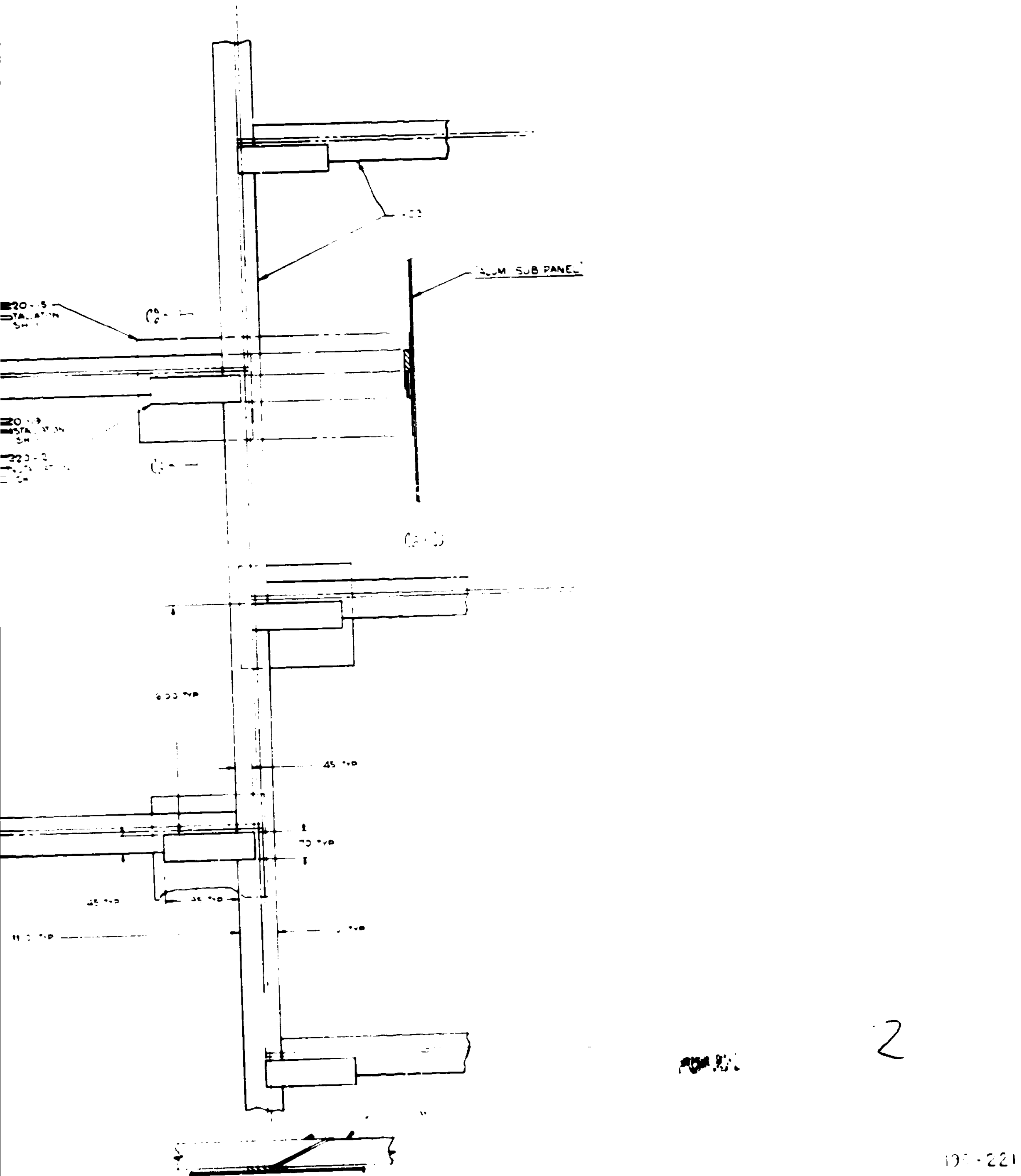
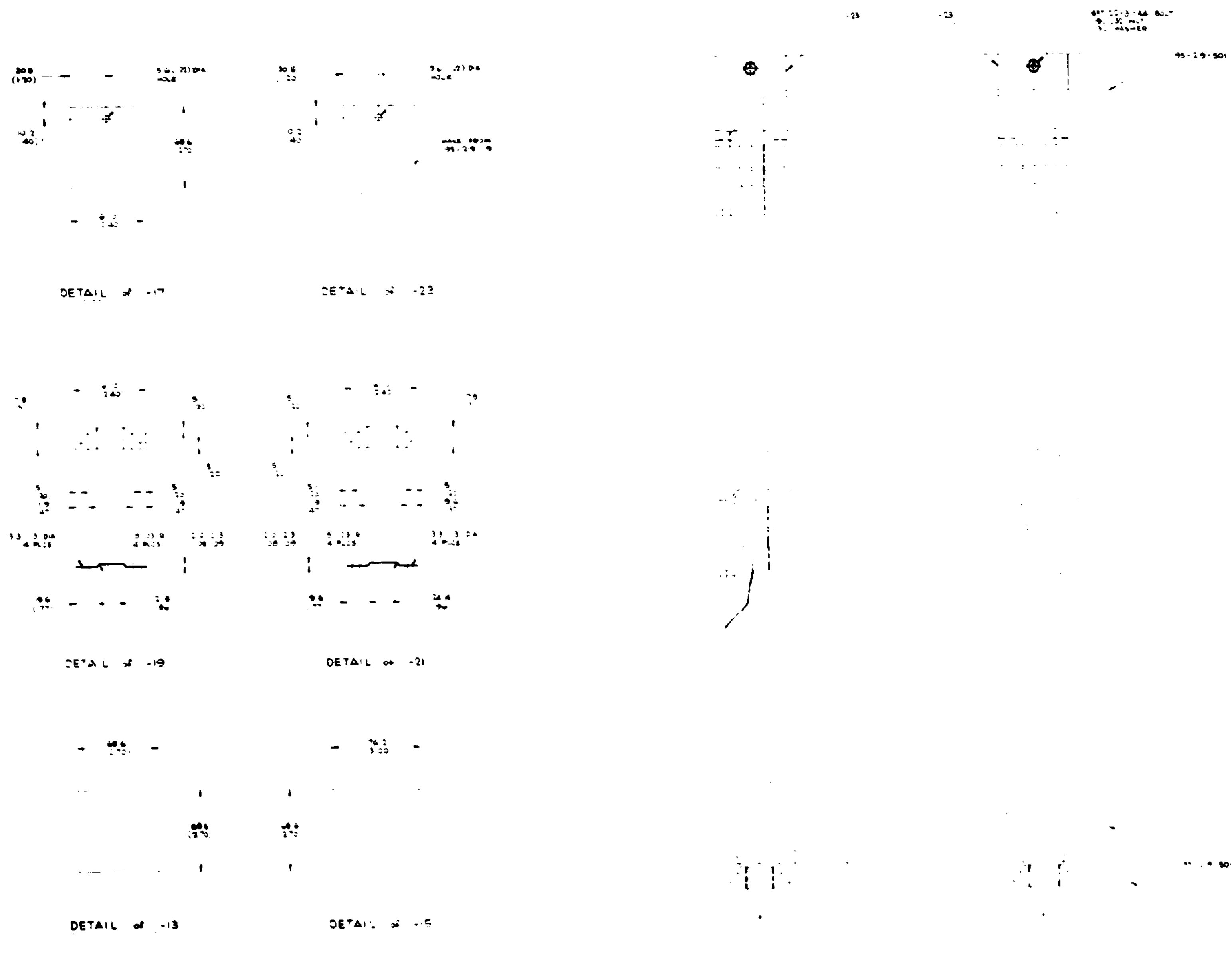


Figure 3. Design, Nine-Panel Array (Construction Details) (Sheet 2 of 2)



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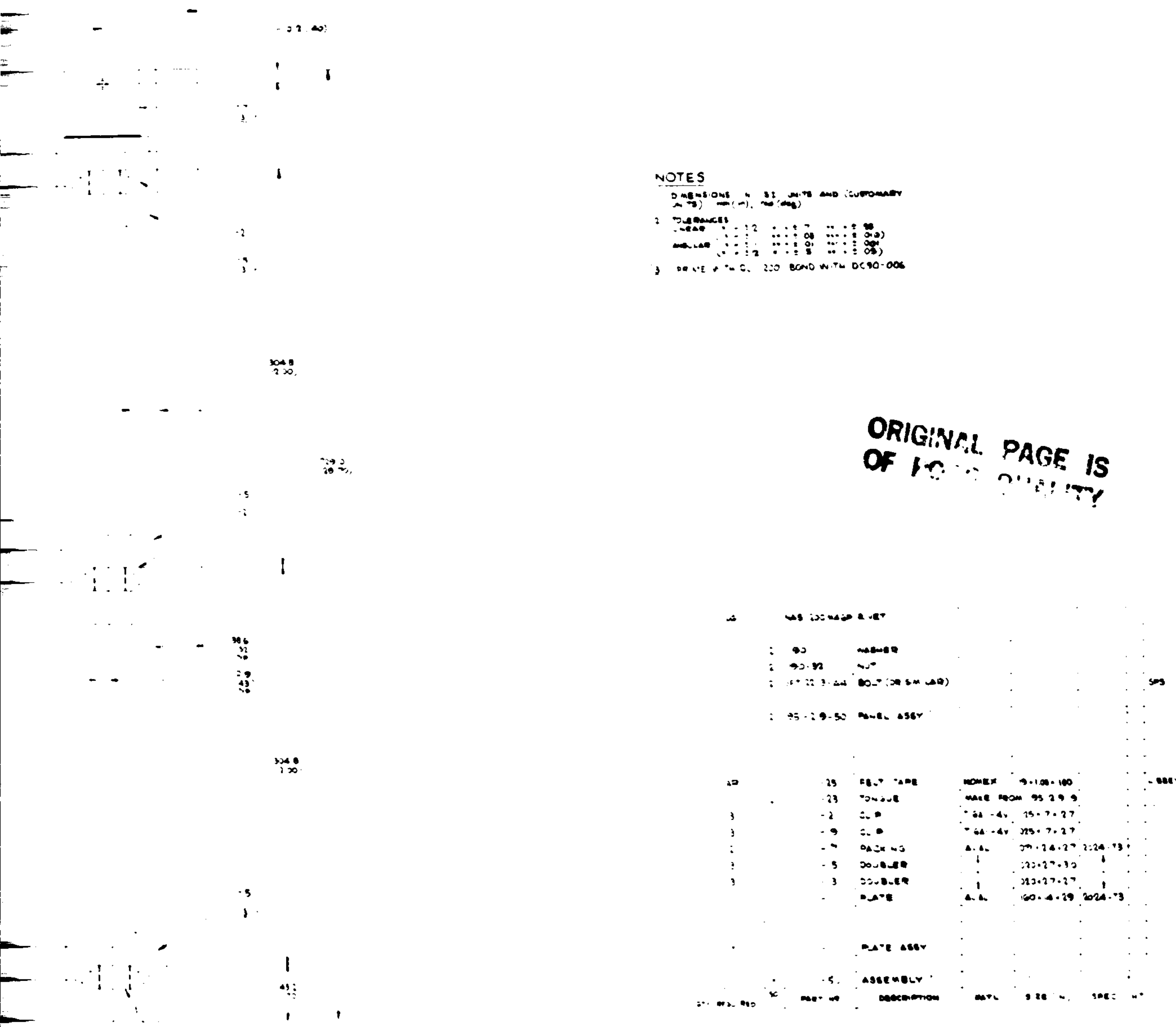

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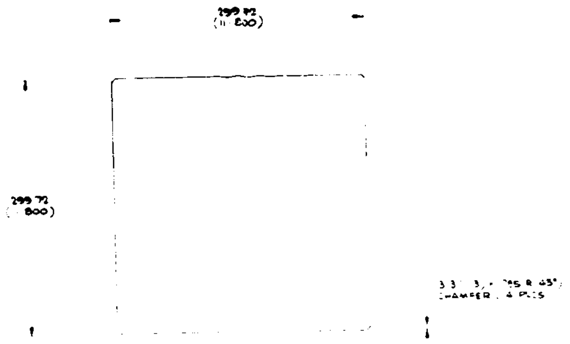
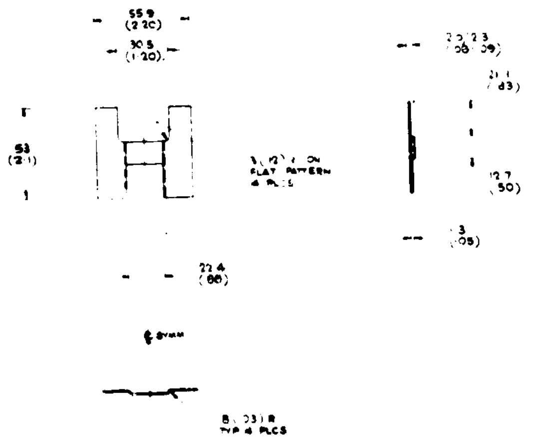
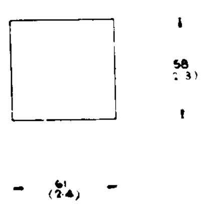
Figure 4. Design, Two-Panel Array (Construction Details)



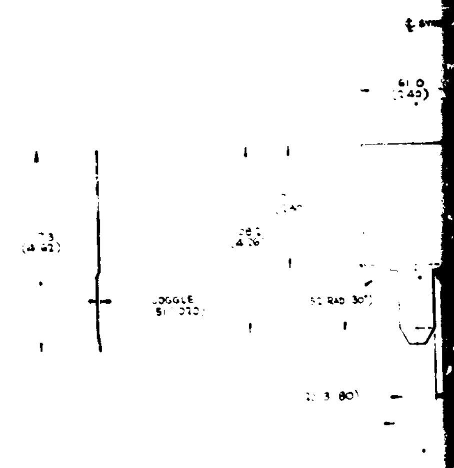
DETAIL of -17
SCALE 1:2



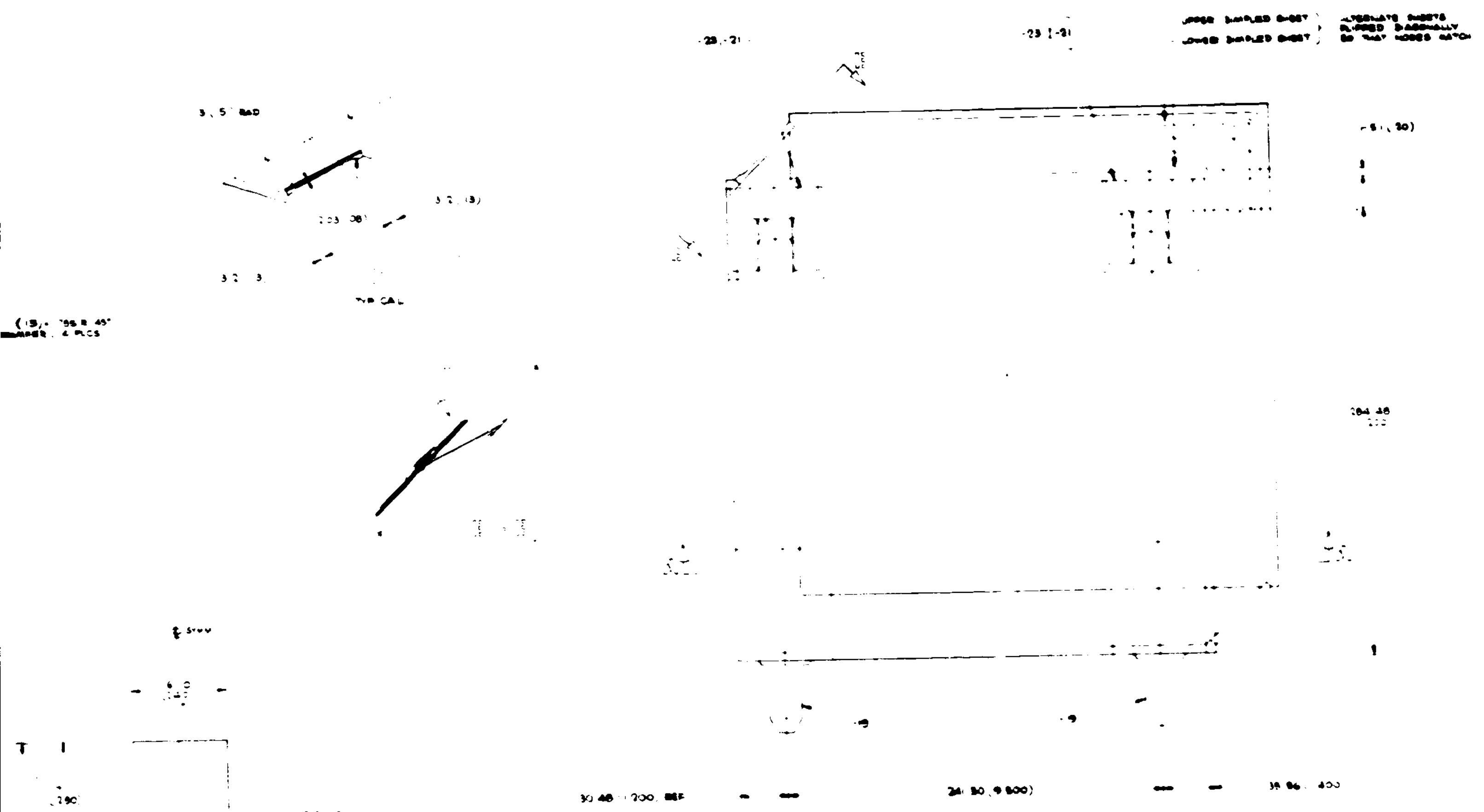
DETAIL of -23



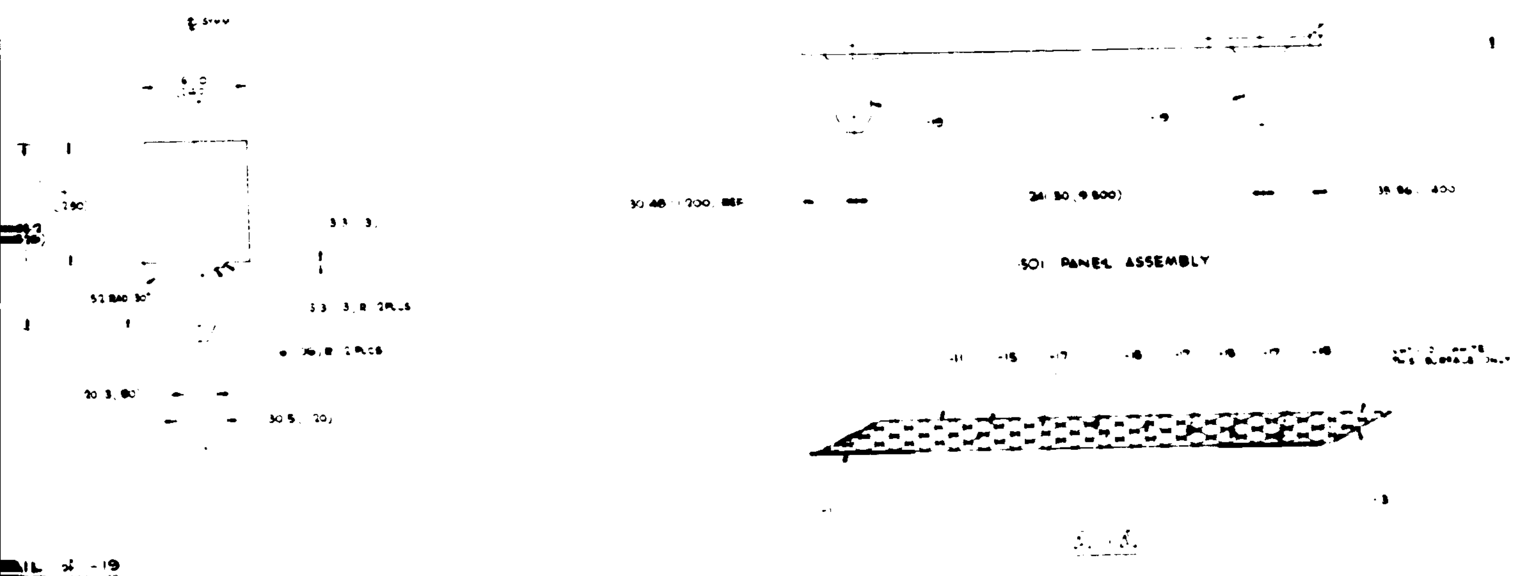
DETAIL of -21



DETAIL of -19



-501 PANEL ASSEMBLY



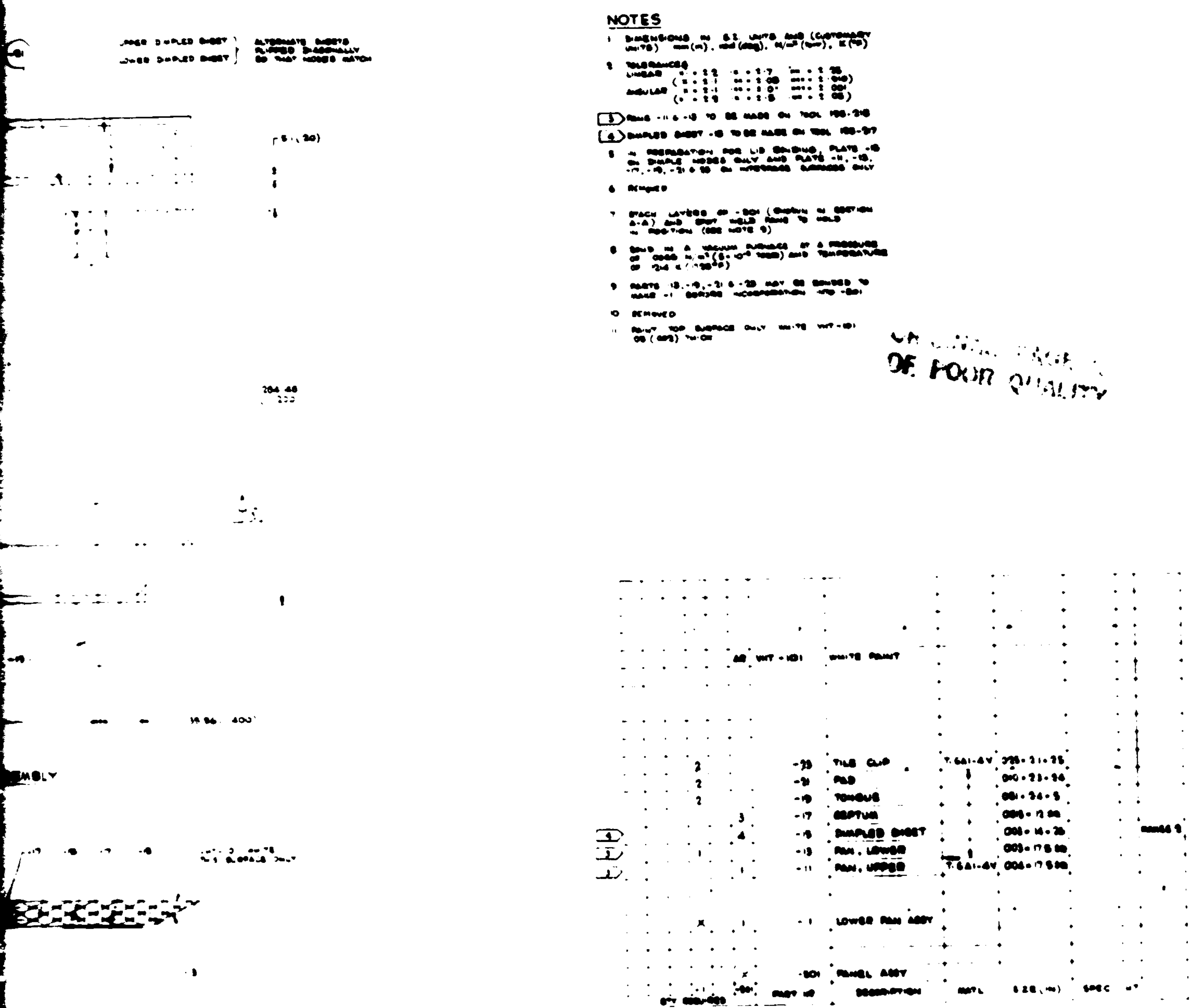


Figure 5. Design, Panel Assembly (Shows Construction Details of the Individual Panel)

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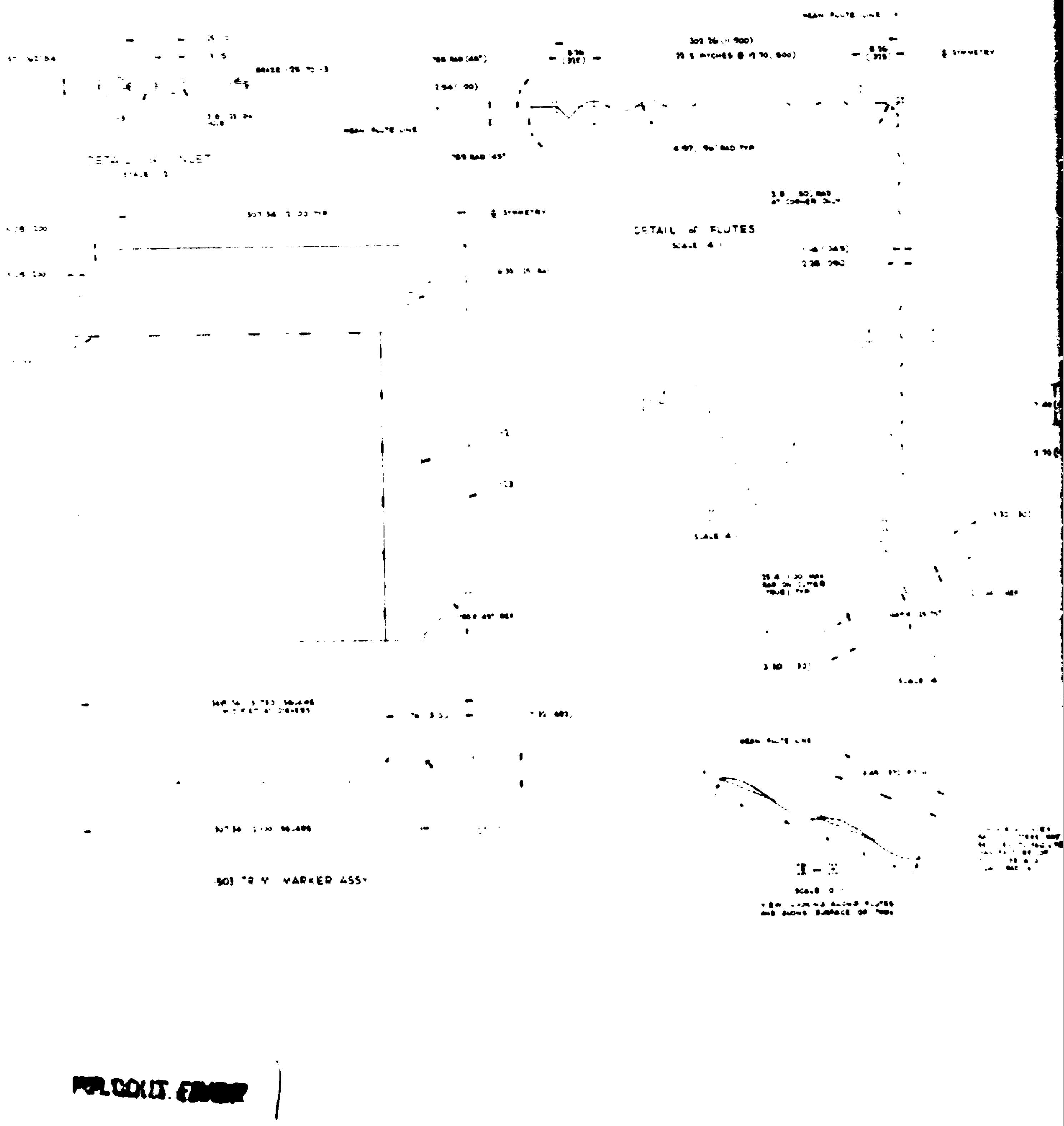
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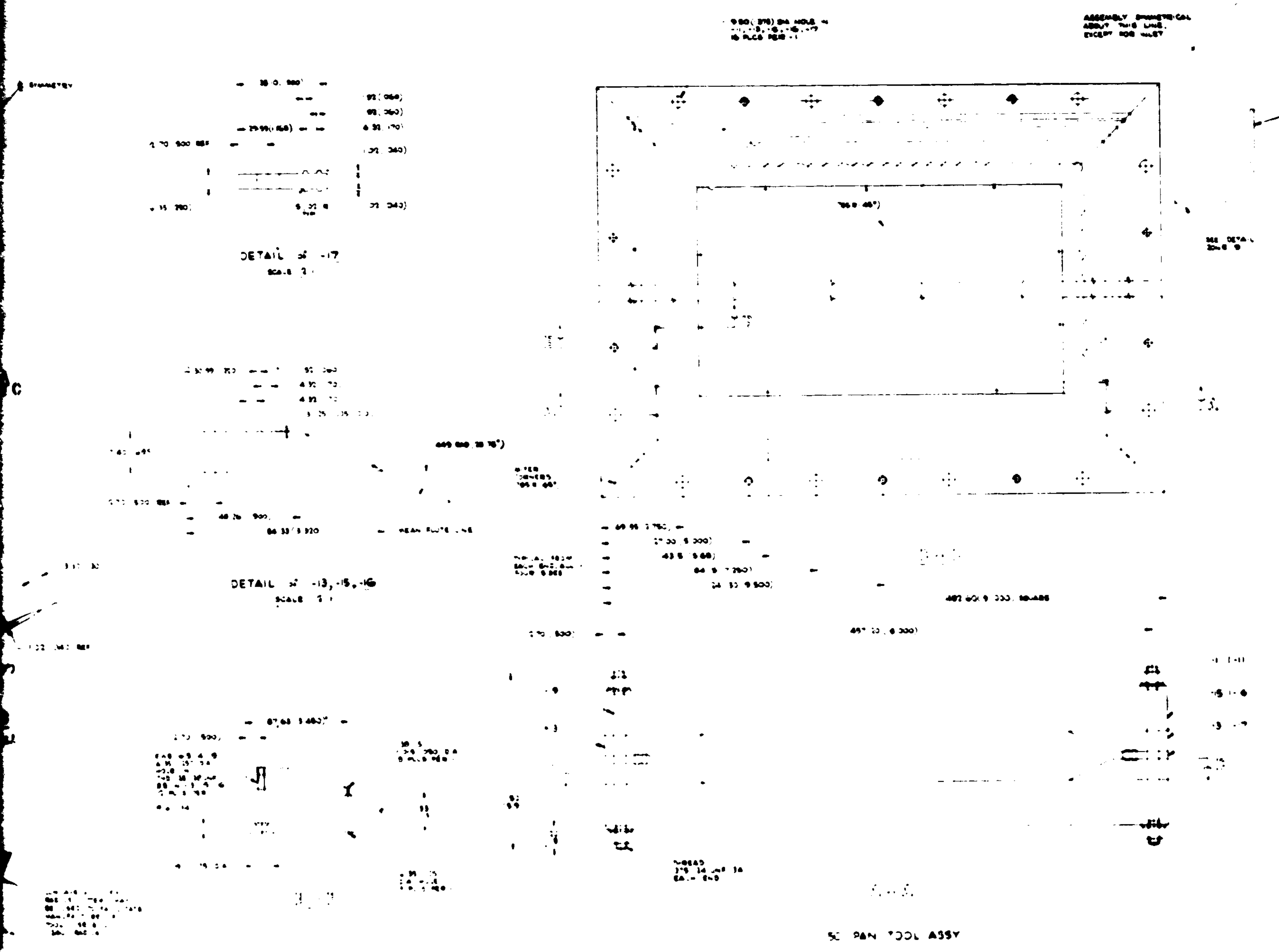

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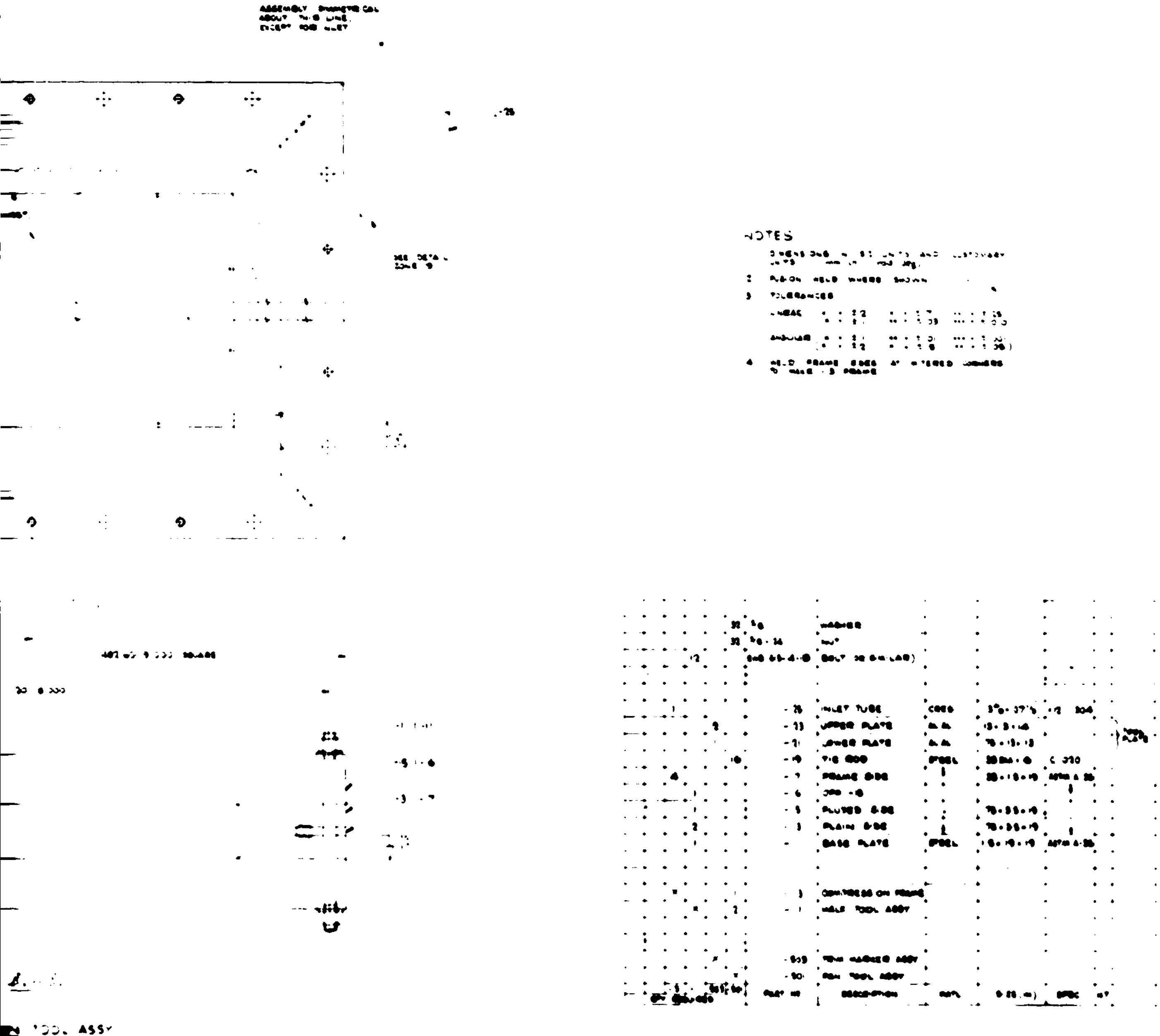

Figure 6. Design, Skin Forming Tool

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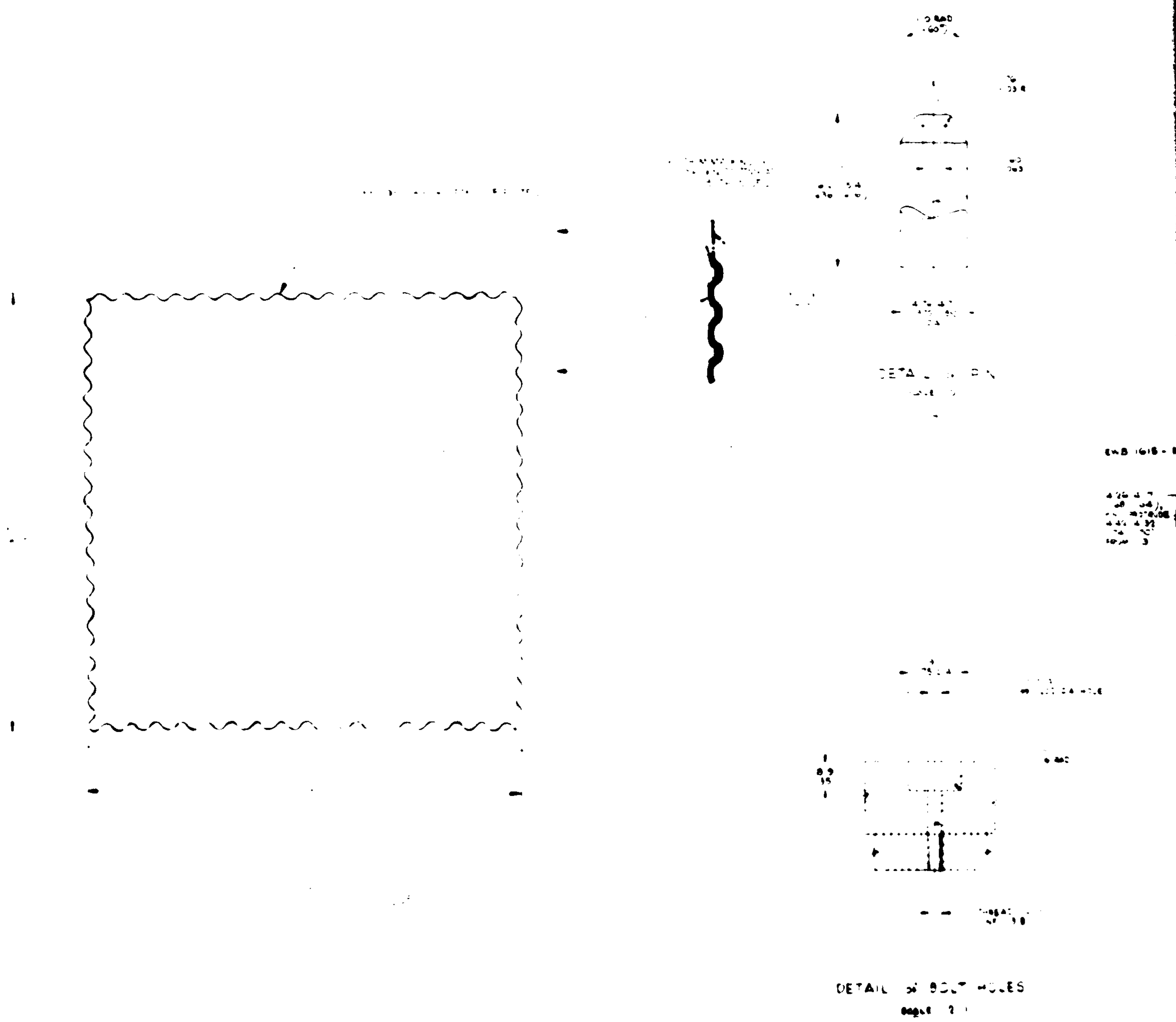

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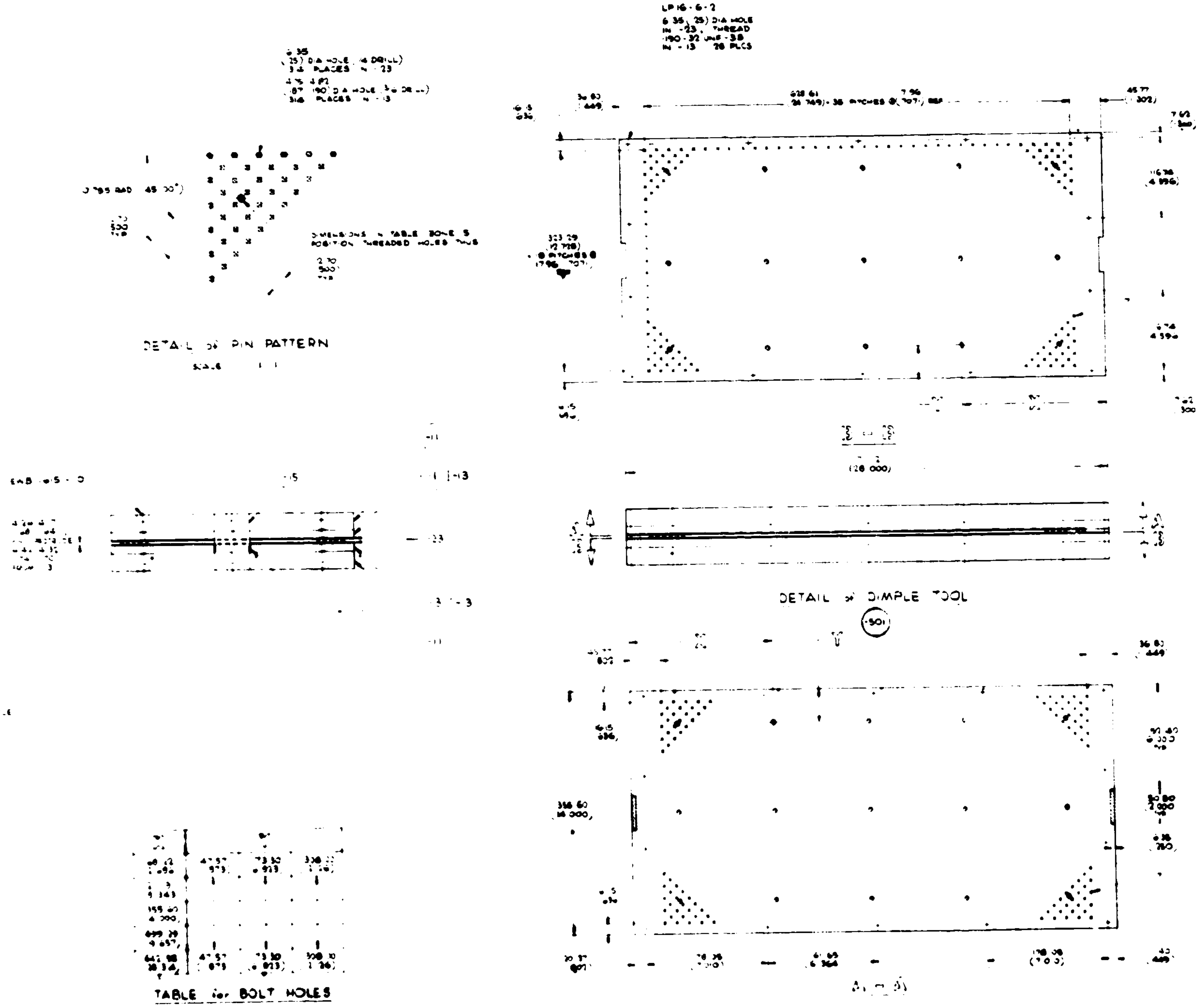

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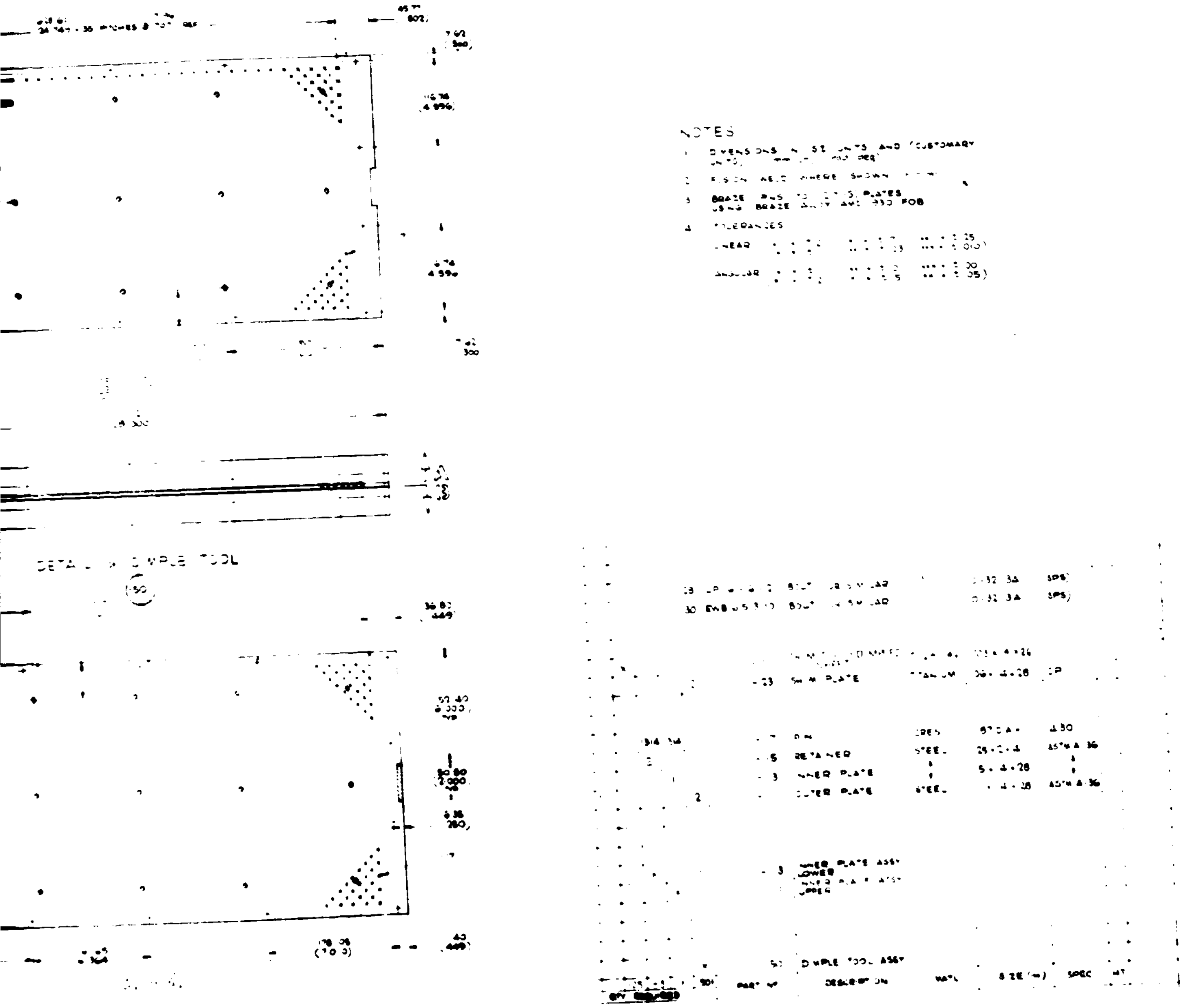

Figure 7. Design, Dimpled Sheet Forming Tool

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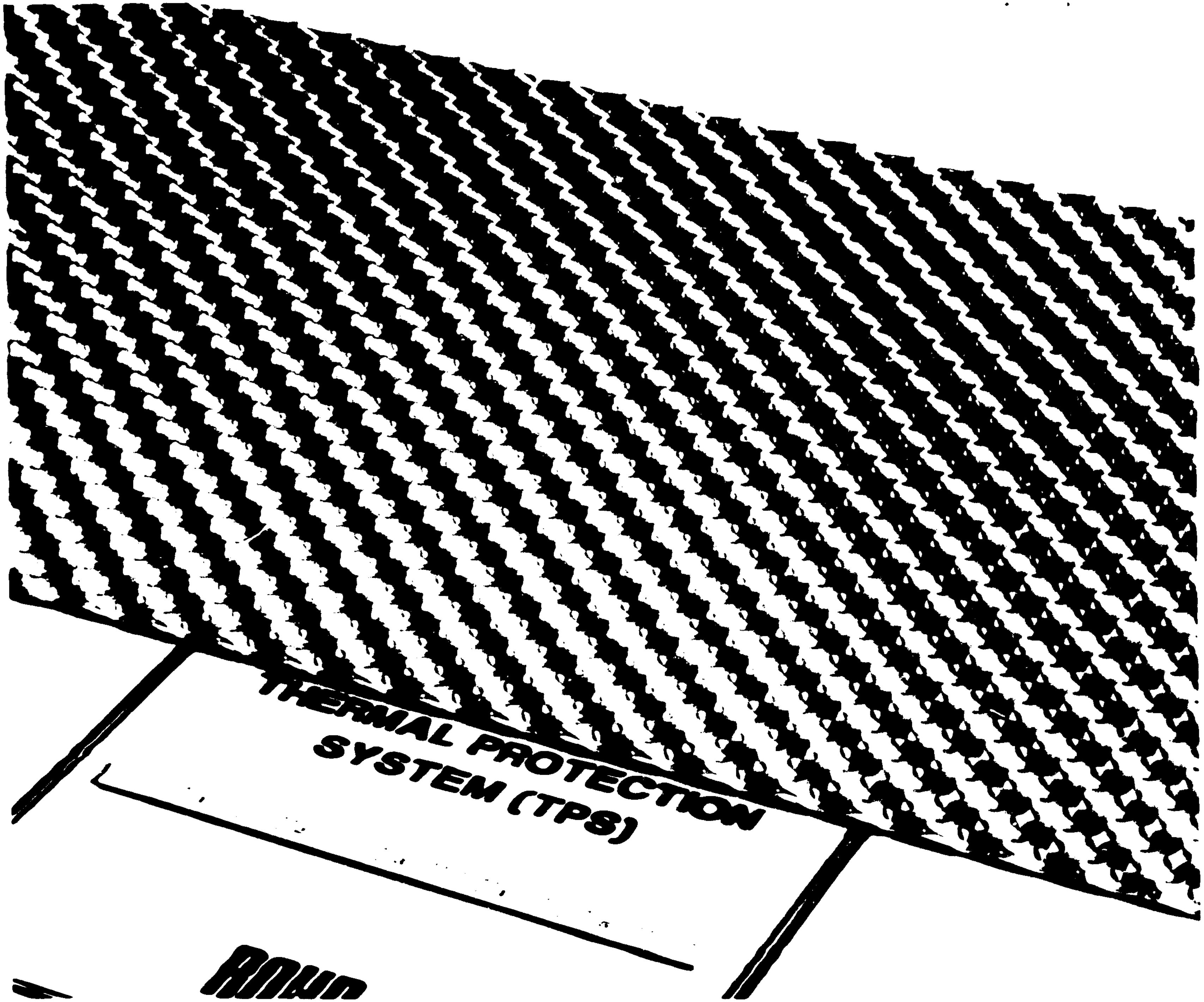


Figure 8. Superplastically Formed Ti-6Al-4V Dimpled Sheet (0.0076 x 30.5 x 61 cm (0.003 x 12 x 24 inches))

Figure 9. Superplastic Form Tool Ready for Loading Into Vacuum Furnace

Figure 10. Dimpled Sheet Prepared for Chem-Blanking

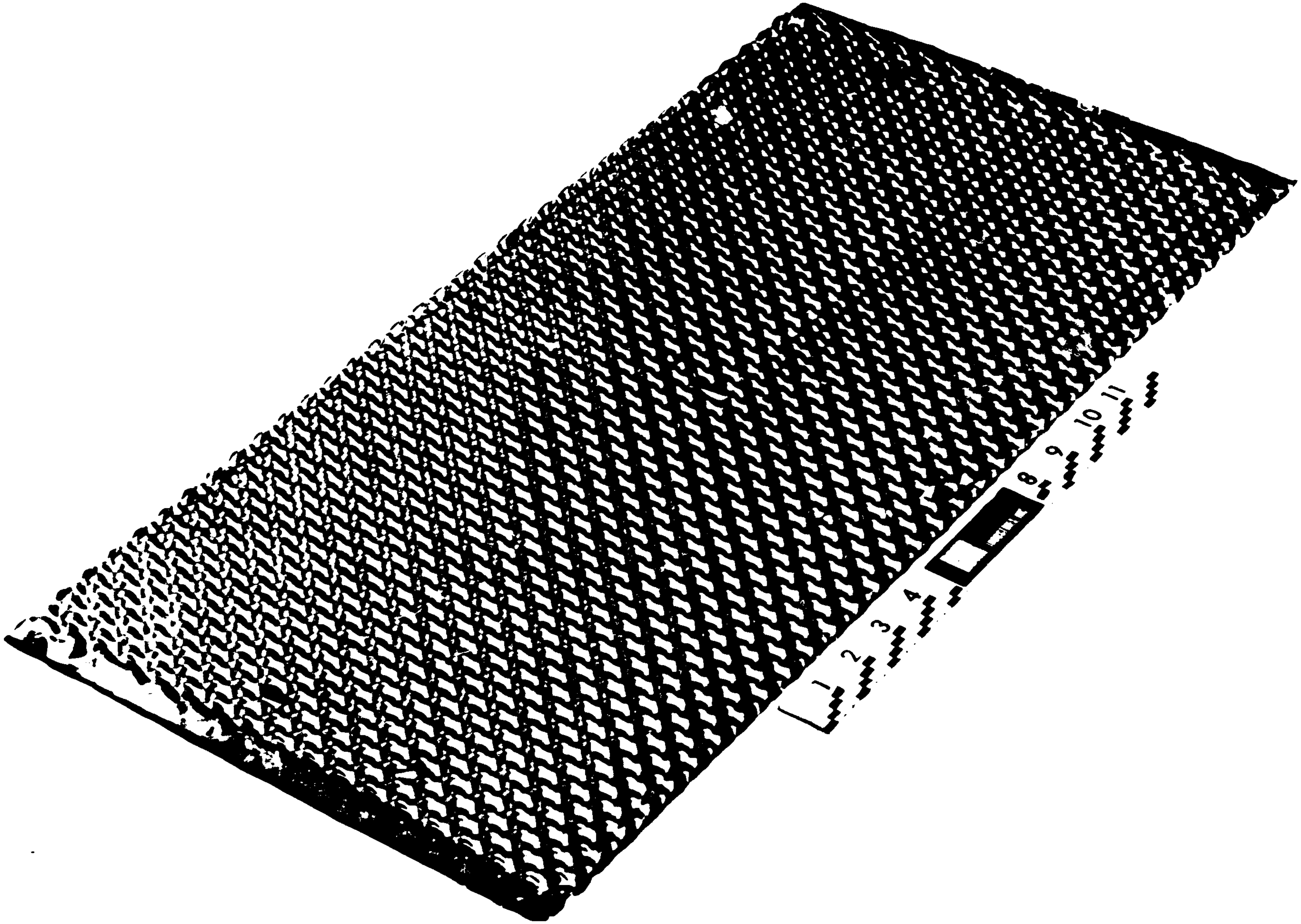


Figure 11. Plated Dimpled Sheet (Only the Node Flats Are Plated, Cutouts Taken for Microexamination)

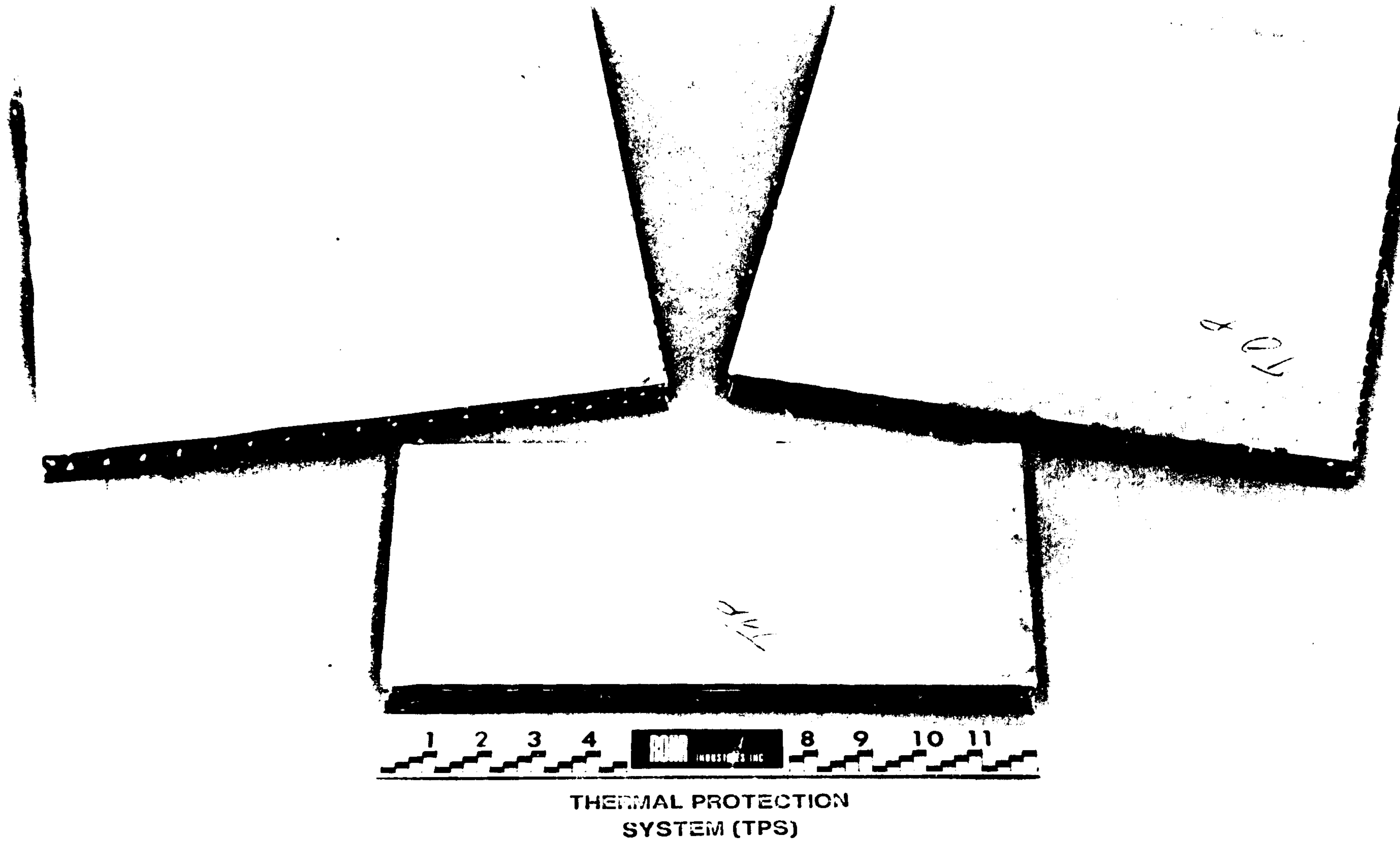


Figure 12. Multiwall Panels LID Bonded for Test Specimens

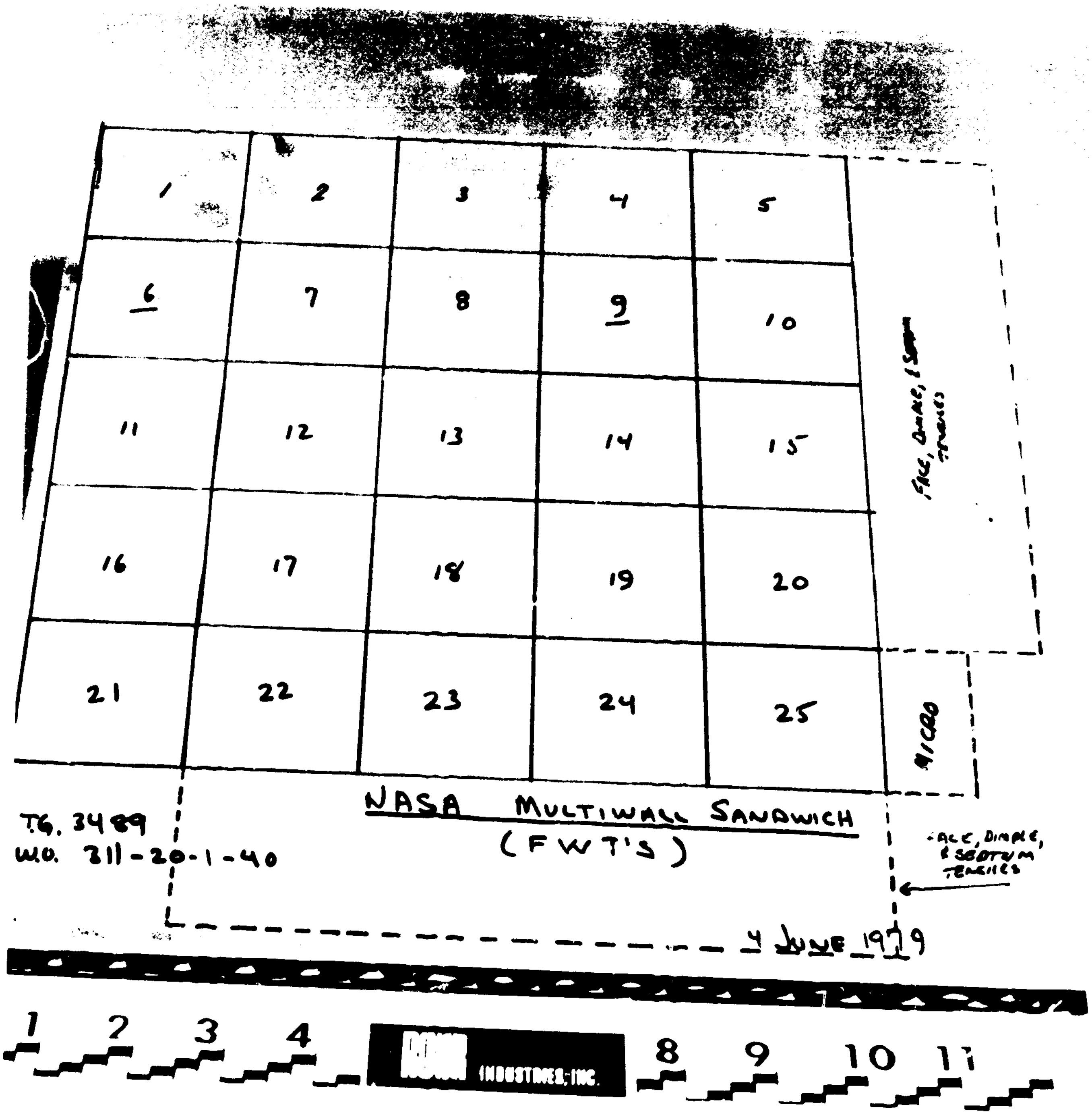


Figure 13. Beam Flexure Test Speciment Layout for Cutting Flatwise Face Tension, Tensile and Micro Specimens

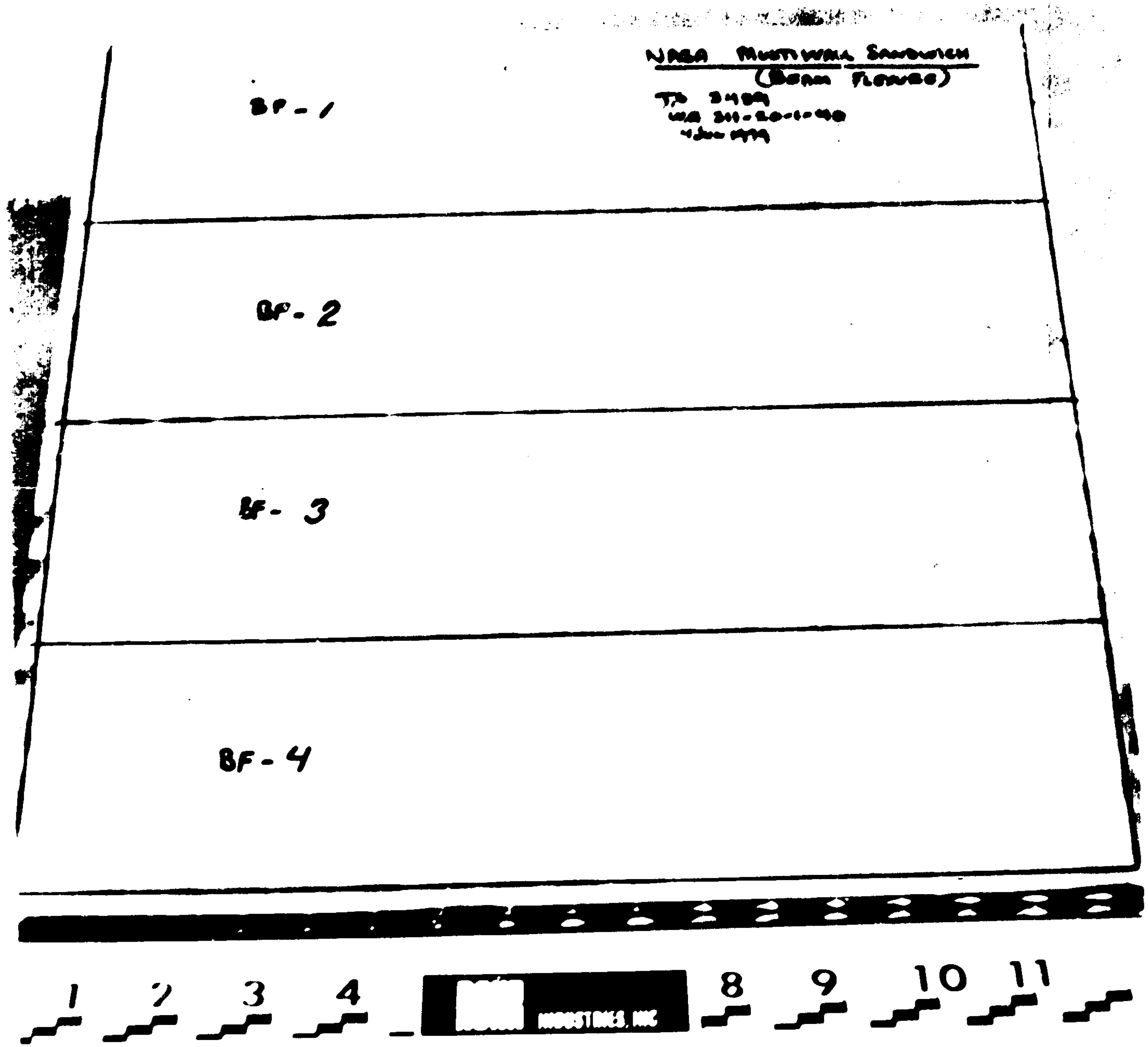


Figure 14. Beam Flexure Test Specimens Layout for Cutting Beam Flexure Test Specimens

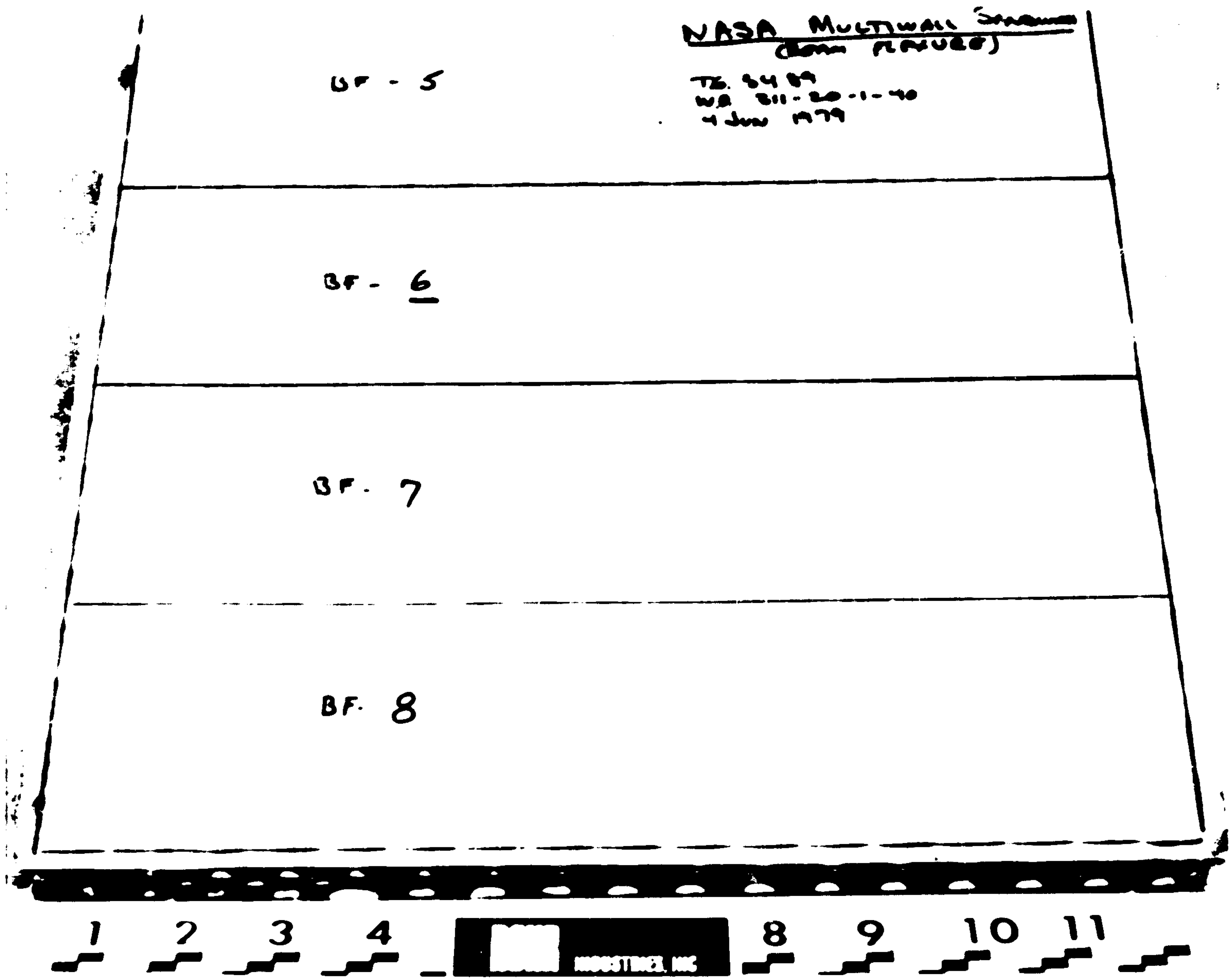


Figure 15. Flatwise Tension Test Specimen Layout for Cutting Beam Flexure Test Specimens

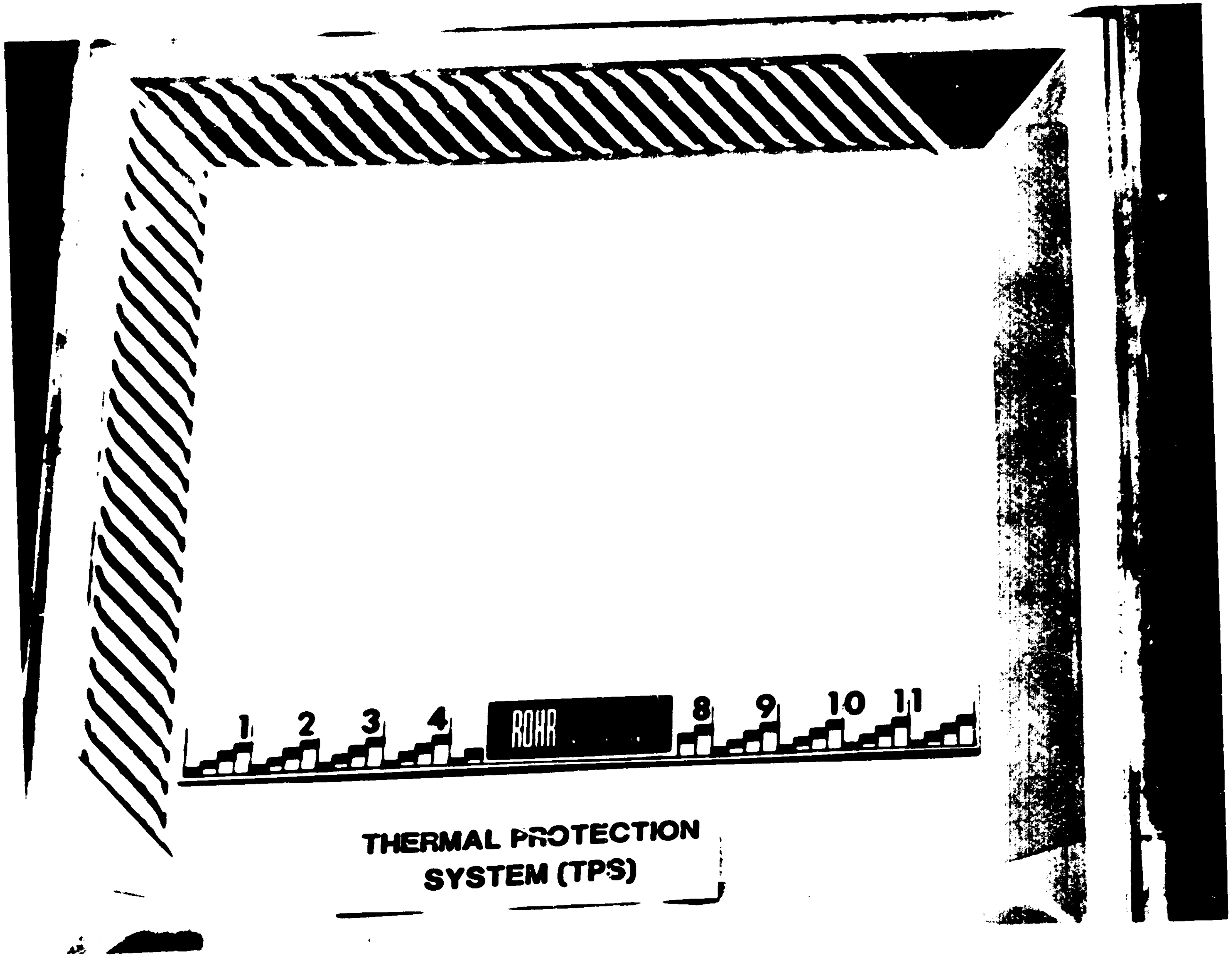


Figure 16. Superplastically Formed Skin - Ready to be Trimmed

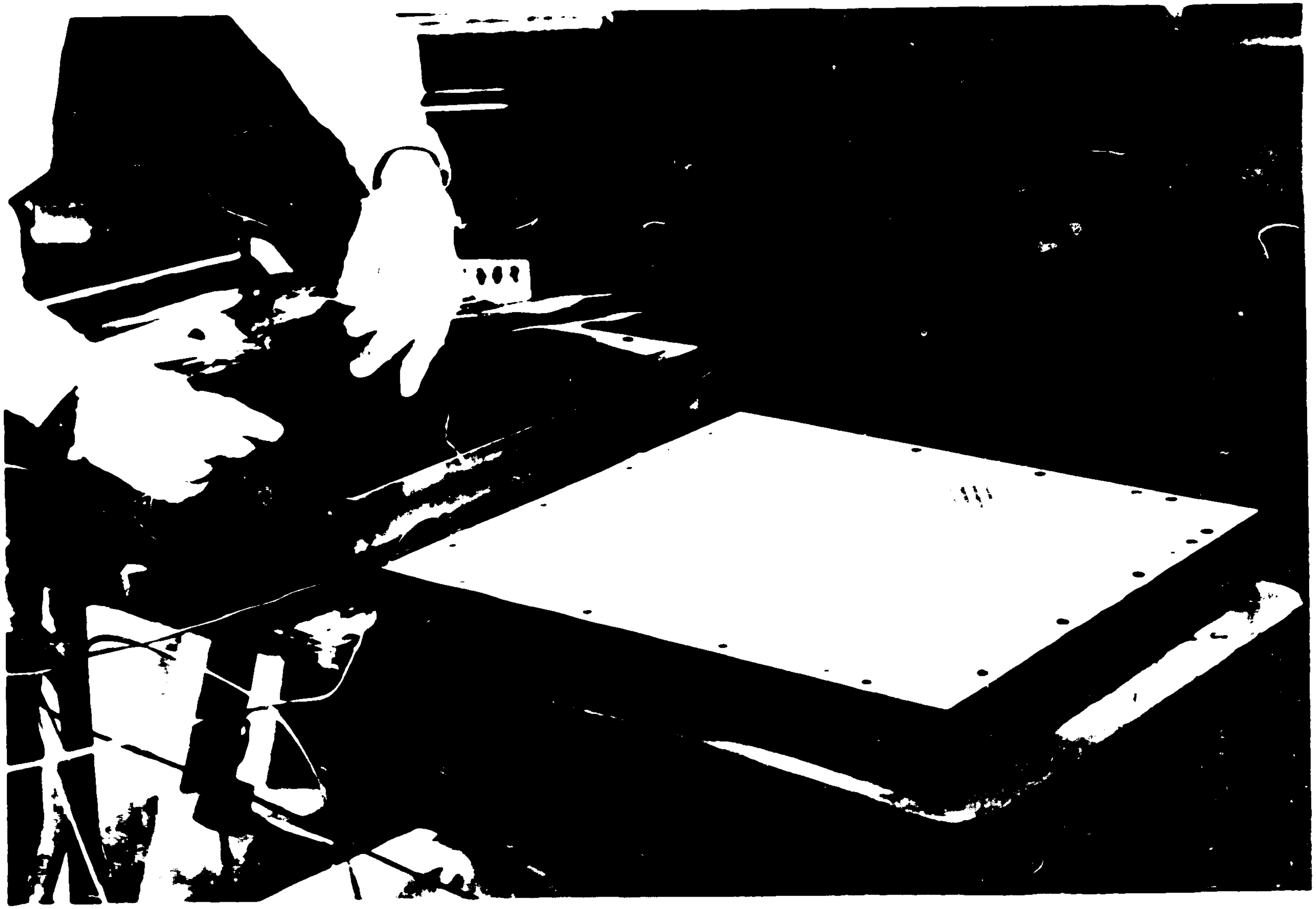


Figure 17. Skin Form Tool - Ti-6Al-4V Sheets Being Installed in Tool for Superplastic Forming Skins (Which Also Close the Panel Sides)

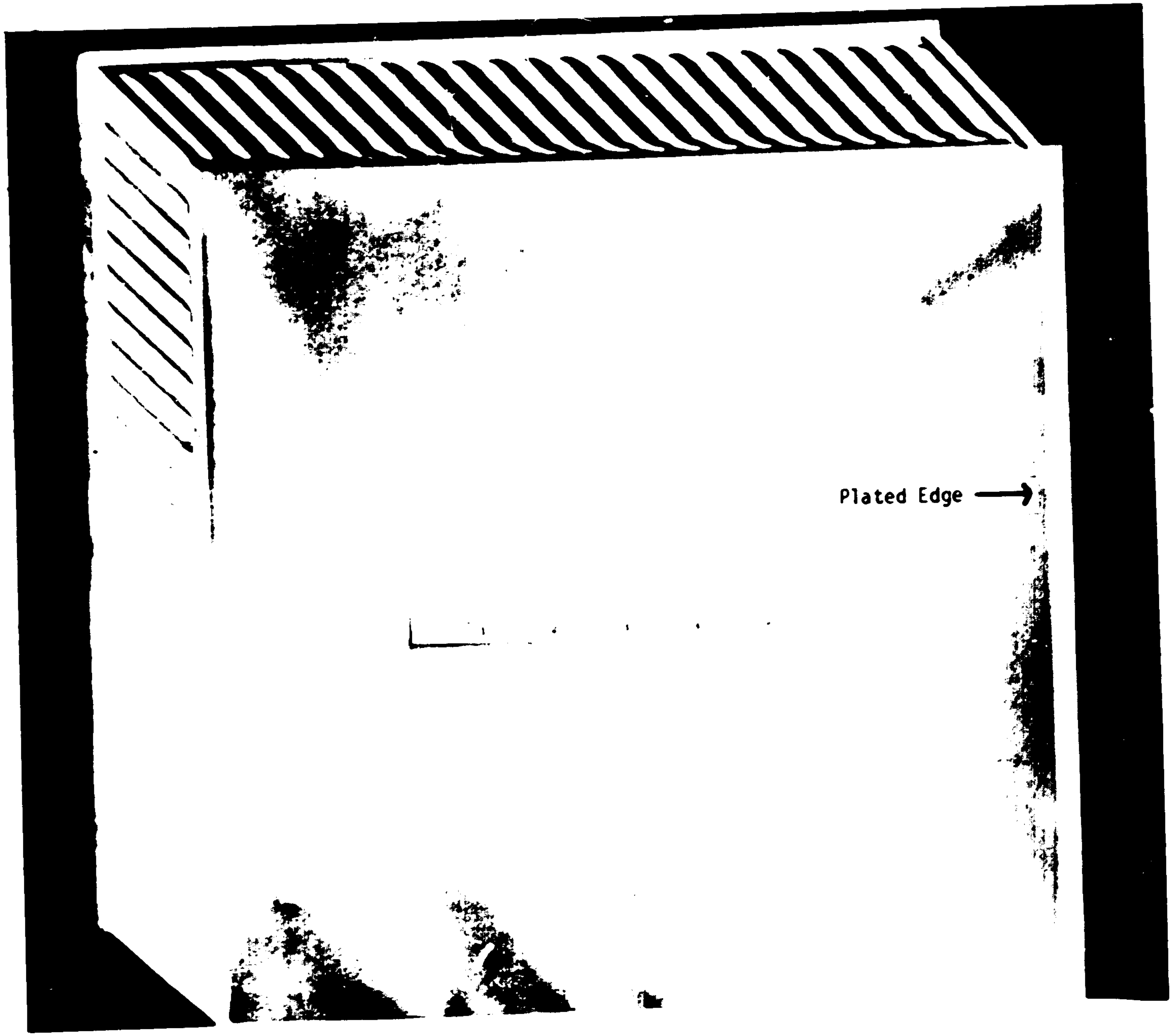


Figure 18. Plated Skin - Skin Has Edge Plated 5.1 mm (0.2-Inch) Wide for LID Bonding to Opposing Skin

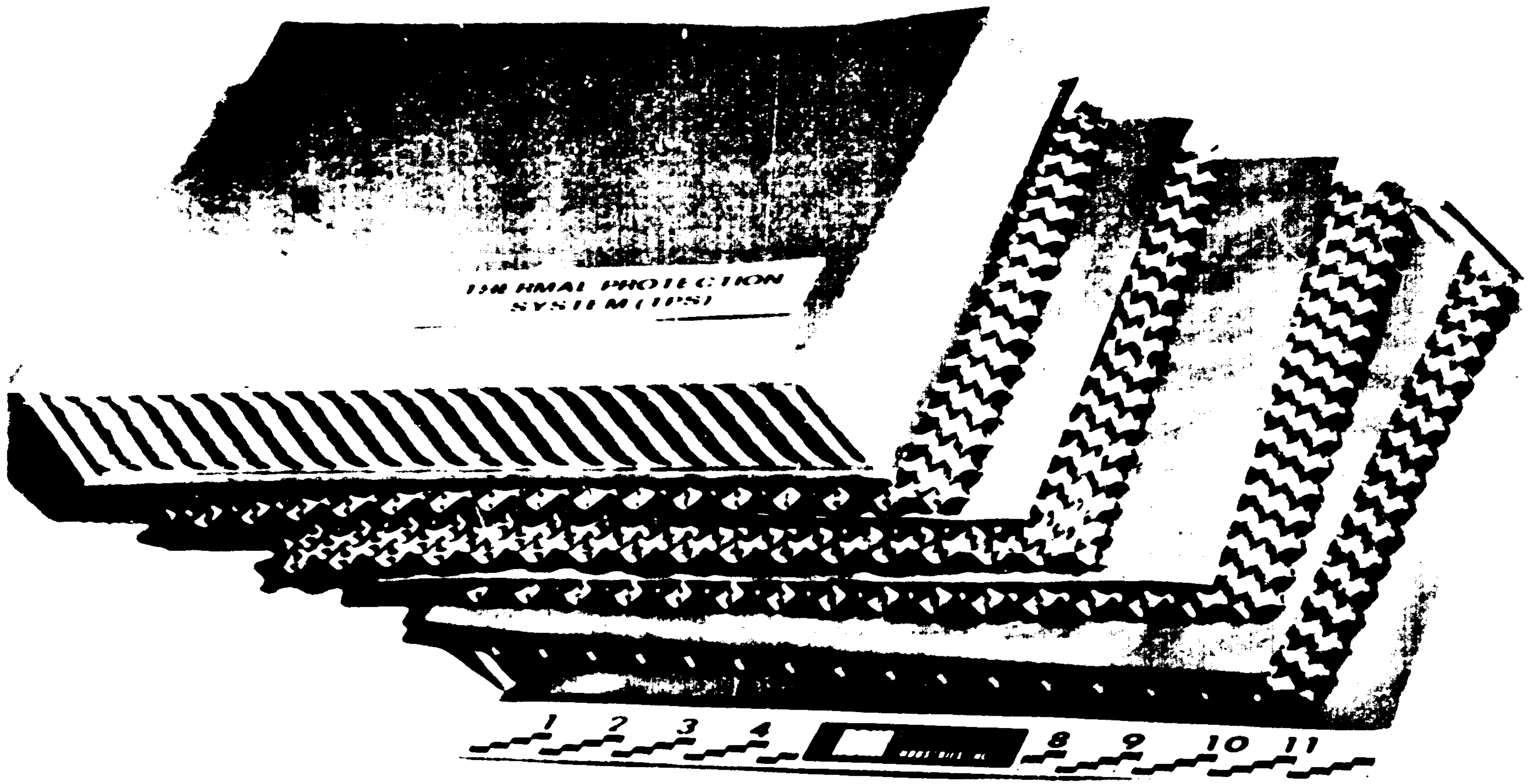


Figure 19. Dimpled Sheets, Septum Sheets and Skins Prepared for Assembly (Ready for Layup and LID Bonding)

Figure 20. Vacuum Tight Panel Test Panel Being Aided for LIP Bonding

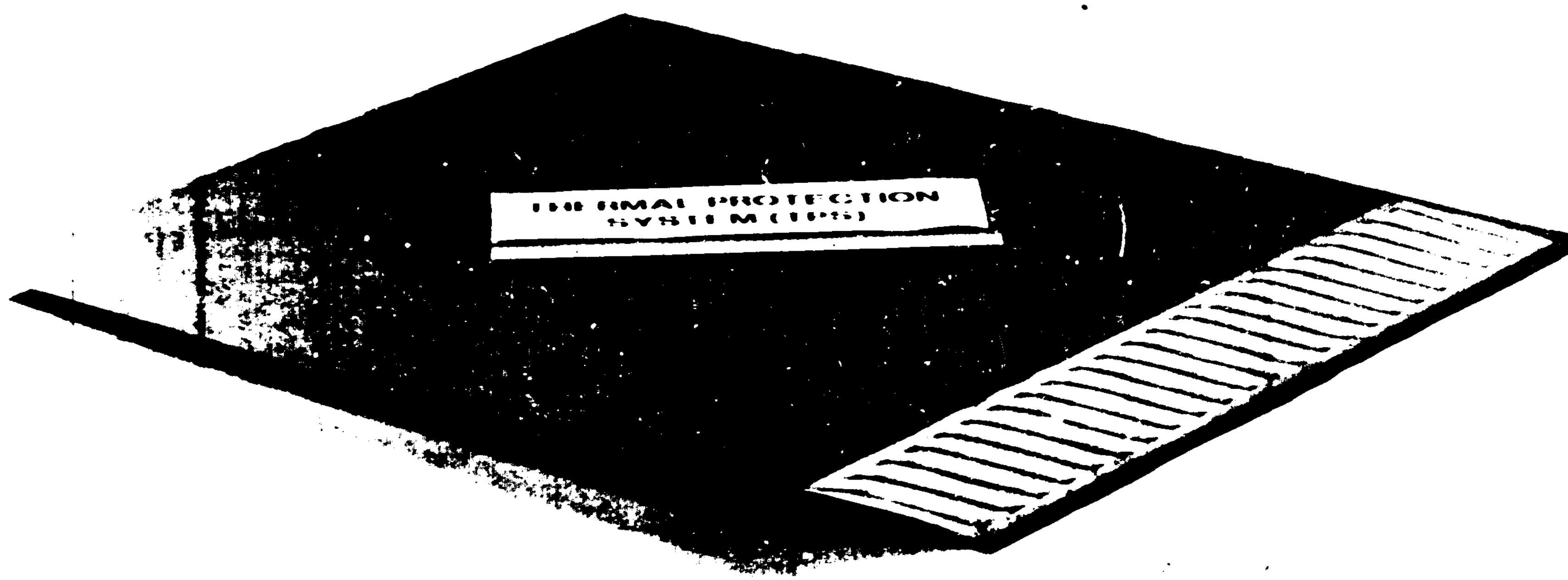
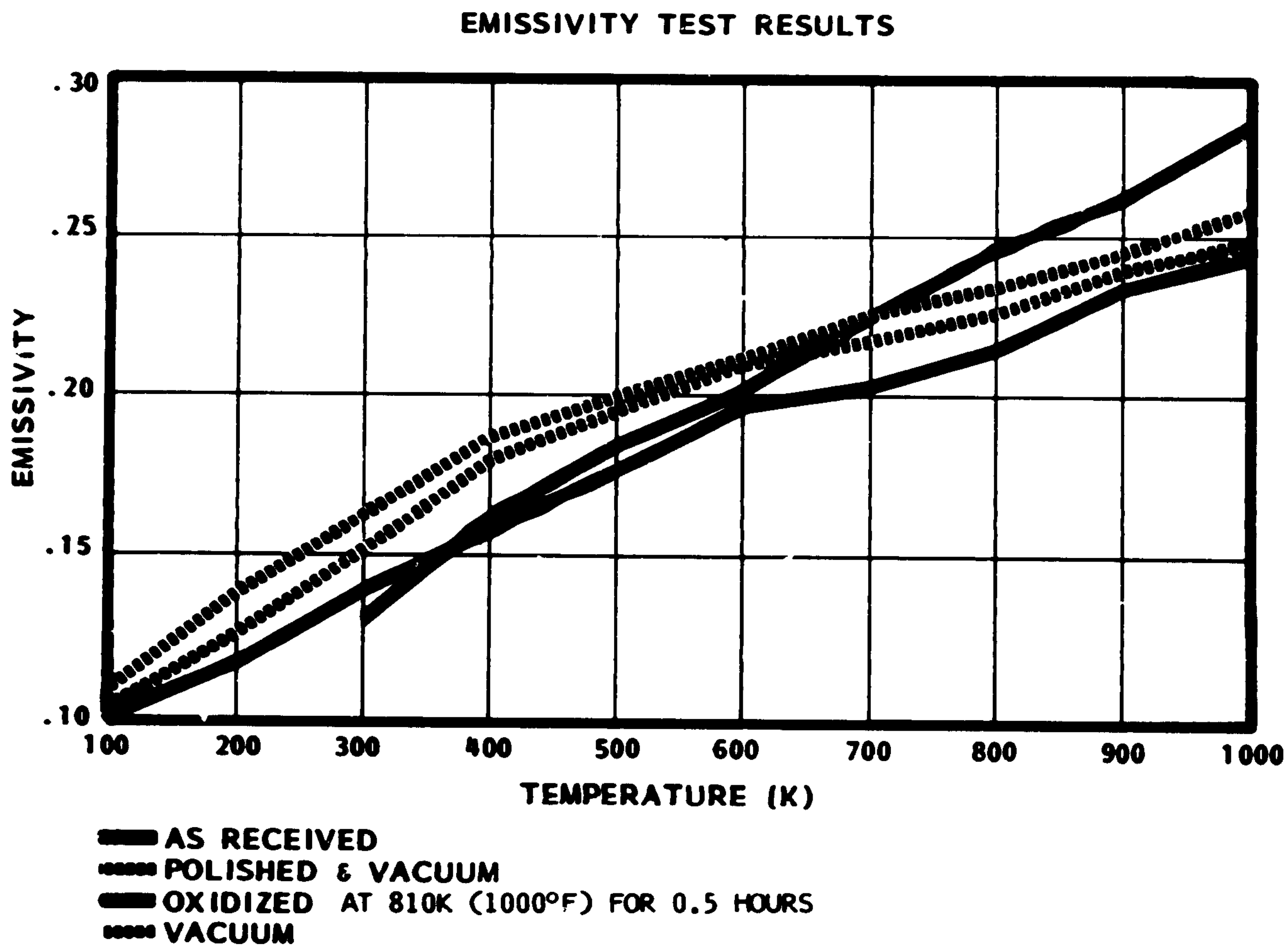


Figure 21. LID Bonded Panel (Vacuum Tight Evaluation)



144044

Figure 22. Emissivity Test Results

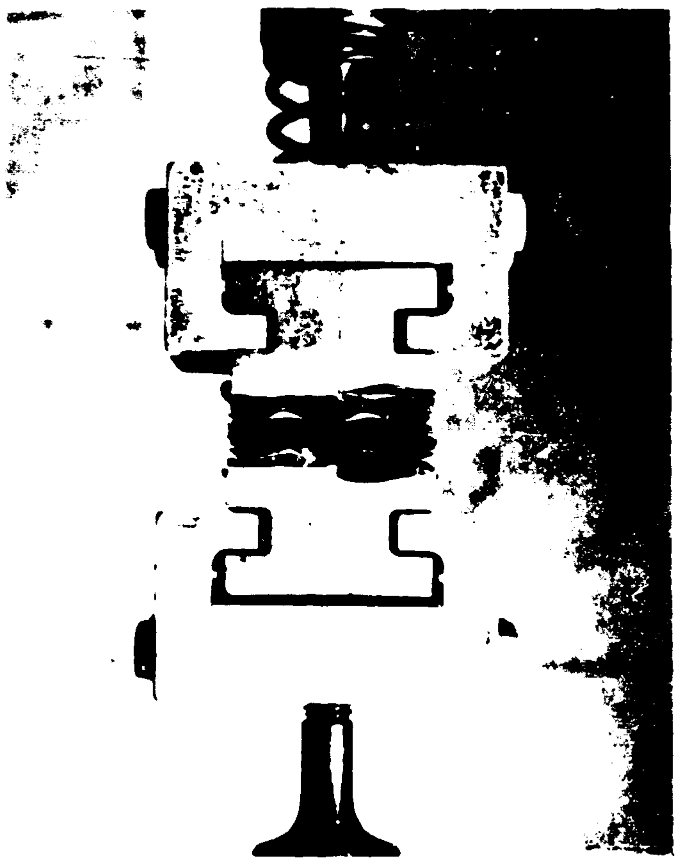


Figure 23. Test Fixture for Flatwise Tension Tests

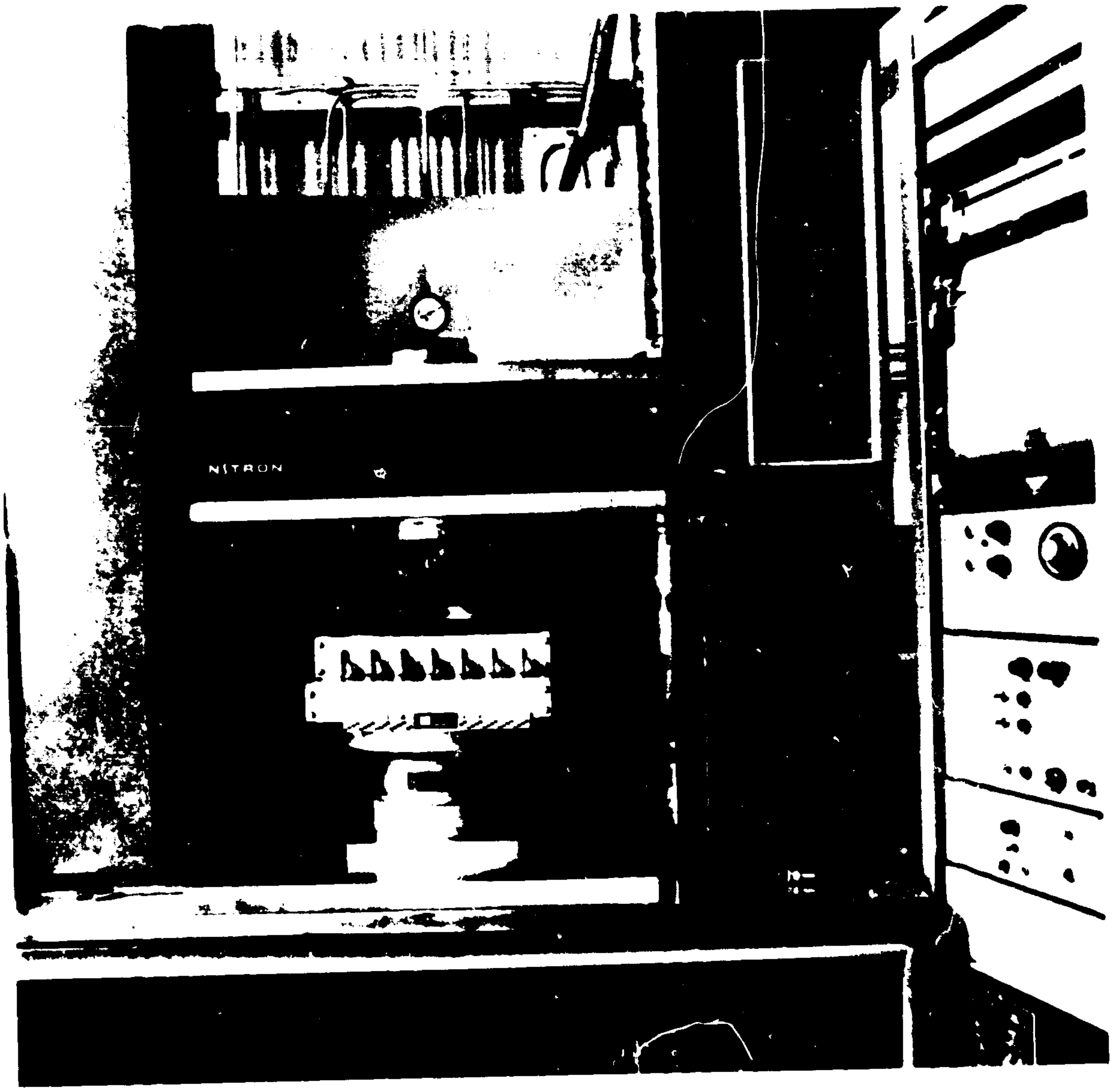
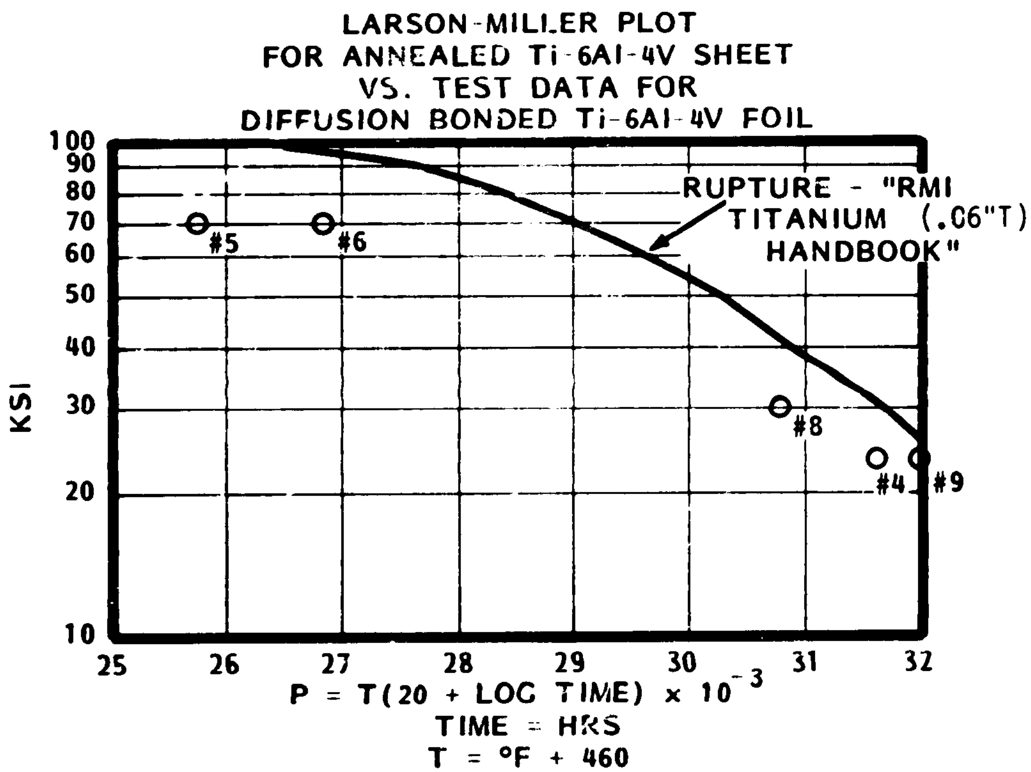


Figure 24. Test Setup for Hot Beam Flexure Tests



144043

Figure 25. Creep Test Results

TABLE I: EMITTANCE TEST DATA

Sample #7910

TEMPERATURE (KELVIN)	EMISSIVITY
50	0.
100	.1002E+00
200	.1176E+00
300	.1365E+00
400	.1548E+00
500	.1721E+00
600	.18[illegible]E+00
700	.2027E+00
800	.2165E+00
900	.2296E+00
1000	.2420E+00
6050	.4518E+00

Sample #7911

TEMPERATURE (KELVIN)	EMISSIVITY
50	0.
100	.1030E+00
200	.1361E+00
300	.1[illegible]E+00
400	.1[illegible]9E+00
500	.1976E+00
600	.2121E+00
700	.2251E+00
800	.2369E+00
900	.247[illegible]E+00
1000	.2581E+00
6050	.4324E+00

Sample #7912

TEMPERATURE (KELVIN)	EMISSIVITY
50	0.
100	.1041E+00
200	.1275E+00
300	.1507E+00
400	.1706E+00
500	.1878E+00
600	.2033E+00
700	.2164E+00
800	.2282E+00
900	.2369E+00
1000	.2487E+00
6050	.4[illegible]2E+00

Sample #7904

TEMPERATURE (KELVIN)	EMISSIVITY
50	0.
100	.1037E+00
200	.1172E+00
300	.1[illegible]69E+00
400	.15[illegible]5E+00
500	.1[illegible]22E+00
600	.2[illegible]E+00
700	.2274E+00
800	.24[illegible]0E+00
900	.2[illegible]E+00
1000	.2853E+00
6050	.5275E+00

Sample #7910 As Received
Sample #7911 Through manufacturing process
Sample #7912 Polished then through manufacturing process
Sample #7904 Oxidized

TABLE 2

FLATWISE TENSION TESTS

SEPARATE LAYERS OF SANDWICH

LAYER 1		LAYER 2		LAYER 3		LAYER 4	
SPECIMEN NO.	FAILING STRESS, KPa (psi)	SPECIMEN NO.	FAILING STRESS, KPa (psi)	SPECIMEN NO.	FAILING STRESS, KPa (psi)	SPECIMEN NO.	FAILING STRESS, KPa (psi)
10-1	150 (22)	15-2	160 (23)	10-3	140 (20)	14-4	300 (44)
11-1	210 (30)	16-2	28 4[(1)]	12-3	190 (27)	15-4	230 (34)
12-1	170 (24)	17-2	130 (19)	13-3	170 (24)	16-4	190 (28)
13-1	300 (44)	23-2	150 (22)	18-3	190 (27)	17-4	170 (24)
18-1	340 (49)	24-2	100 (15)	19-3	300 (43)	22-4	260 (38)
19-1	320 (46)	25-2	97 (14)	20-3	83 (12)	23-4	190 (28)
21-1	180 (26)	22-2	35 (5)[(1)]	21-3	160 (23)	24-4	41 (6)[(1)]
20-1	150 (22)					25-4	270 (39)
Avg.	230 (33)		100 (15)		170 (25)		210 (30)

(1) Microscopic examination of the failed surface indicated a good diffusion bond. Peeling loads from test setup suspected. See write up.

TABLE 3

FLATWISE TENSION TESTS

FULL DEPTH SANDWICH

SPECIMEN NO.	FAILURE LOAD N, (LBS.)	FAILURE STRESS KPa (PSI)	LOCATION OF FAILURE
1	400 (90)	157 (22.7)	Septum 1/Core 2
2	367 (82.5)	143 (20.8)	Septum 1/Core 2
3	351 (79)	137 (19.9)	Septum 2/Core 3
4	371 (83.5)	145 (21.0)	Septum 2/Core 3
5	291 (65.5)	114 (16.5)	Septum 2/Core 3
6	378 (85)	148 (21.5)	Septum 1/Core 2
7	287 (64.5)	112 (16.3)	Septum 1/Core 2
8	222 (50)	88 (12.7)	Septum 1/Core 2
9	267 (60)	104 (15.1)	Septum 1/Core 2
Avg.	326 (73.3)	185 (18.5)	

TABLE 4

BASIC FACE SHEET TENSION TESTS - ROOM TEMPERATURE

	.04 mm (.0015")			.08 mm (.003")			.1 mm (.004")		
Configuration	F_{ty}, Mpa (ksi)	F_{tu}, Mpa (ksi)	e	F_{ty}, Mpa (ksi)	F_{tu}, Mpa (ksi)	e	F_{ty}, Mpa (ksi)	F_{tu}, Mpa (ksi)	e
As Received	1098 (159.3)	1351 (195.9)	3.8	986.0 (143.0)	1193 (173.1)	6.7	952.2 (138.1)	1121 (162.6)	9.3
After LID Thermal Cycle	1028 (149.1)	1082 (157.0)	1.0	910.1 (132.0)	1062 (154.0)	4.7	876.3 (127.1)	996.3 (144.5)	9.0
After LID Bonded and Core Removed	N/P	839.8 (121.8*)	.0*	950.1 (137.8)	950.1 (137.8)	.6	958.4 (139.0*)	1022 (148.2*)	12.9*

All values are an average of (3) except those marked by * which are an average of (5).

TABLE 5

BEAM FLEXURE TESTS

SPECIMEN NO.	MAX. TEMP. RANGE TENS. SIDE, K (°F)	MAX. TEMP. RANGE COMP. SIDE, K (°F)	FAILURE LOAD N, (LBS.)(1)	FAILURE MODE
BF-1	RT	RT	645N (145)	Disbond of .004 (102 μm) face sheet at center of panel due to severe buckling
BF-2	RT	RT	600N (135)	Same as above
BF-3	410-429K (278-312)	679-706K (763-814)	489N (110)	Core shear instability at inner supports
BF-5	412-426K (283-306)	678-706K (760-810)	556N (125)	Same as above
BF-6	411-419K (280-294)	781-811K (946-999)	383N (86)	Same as above
BF-7	408-422K (274-300)	784-809K (951-997)	400N (90)	Same as above
BF-8	422-444K (300-340)	789-809K (960-997)	120N(2) (27)	No failure

(1) This numerical value is also equivalent to the value of the maximum bending moment, N-m (in-lbs).

(2) This is the sustained applied load without failure.

APPENDIX

A

REPORT NO. CASD-RTC-001

P. O. Y21778NR

THERMAL CONDUCTIVITY OF TITANIUM
SANDWICH INSULATION

Prepared by

General Dynamics Convair Division

San Diego, CA

for

Rohr Industries, Inc.
Chula Vista

June, 1979

INTRODUCTION

Thermal conductivity of a titanium foil sandwich panel supplied by Rohr Industries was measured in air at four temperatures from ambient to 800F on a guarded hot plate apparatus. Measurements were made by General Dynamics Convair Divisions' Physical Properties Laboratory.

TEST SPECIMENS

The test specimens consisted of two panels 8" x 8" x approximately .68". They were composed of a multi-layer convoluted titanium foil core with titanium foil face sheets. Edges were open.

TEST METHOD

Measurements were made on a guarded hot plate apparatus custom-built for the measurements. The apparatus is shown schematically in Figure 1. It consists of a pair of identical test panels with a thin guarded heater sandwiched between. The outer face of each panel is in contact with another heater assembly. Both faces of both panels and all four heaters (center, guard and 2 cold-face) are instrumented with thermocouples for temperature measurements. The entire assembly is lightly clamped together and encased in several layers of glass fabric insulation.

Measurements are made by adjusting electrical power to all heaters to establish the desired hot and cold face temperatures. Power to the guard heater is adjusted to establish the same temperature in the center and guard areas of the hot face to prevent lateral heat flow.

When equilibrium has been reached, conductivity is calculated from the center heater power, the center area, the specimen thickness and the temperature difference between the hot and cold faces using:

$$K = \frac{(I \cdot E/2) \cdot t}{A \cdot \Delta T}$$

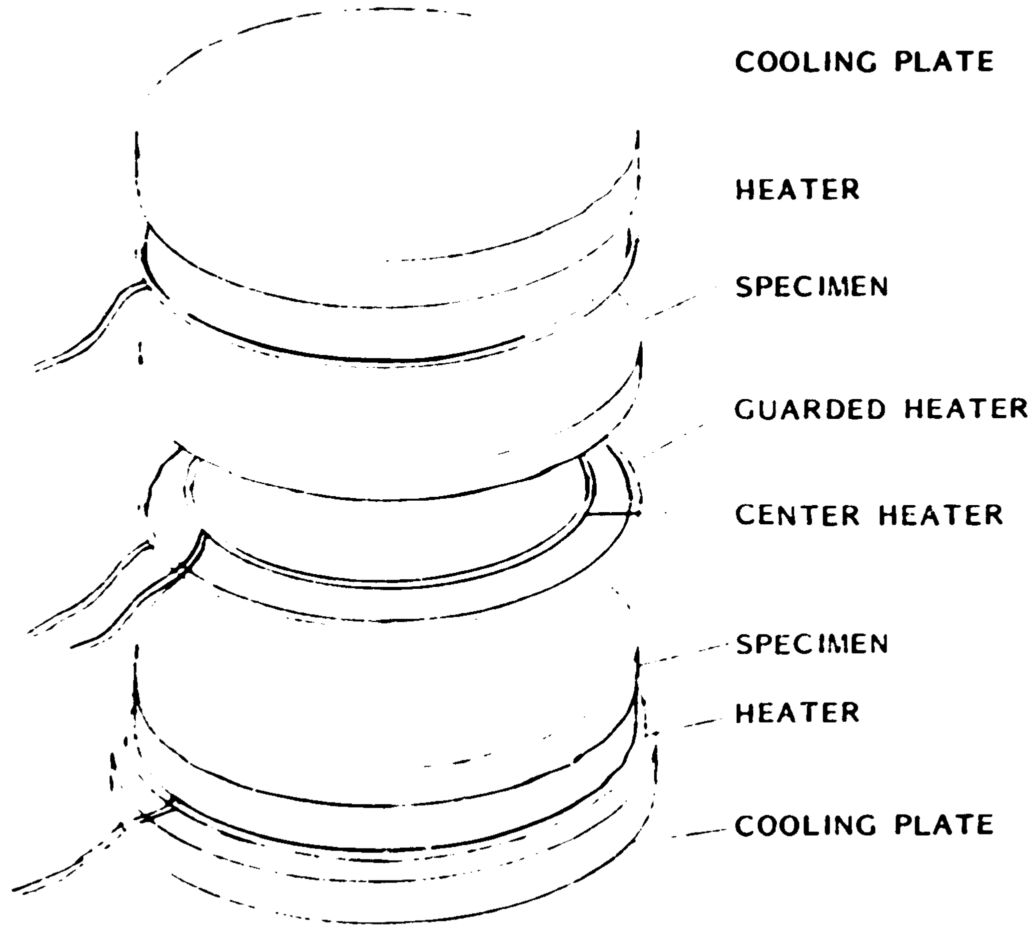
TEST RESULTS

Conductivity values measured are shown in Table 1. They are reportedly higher by approximately 50% than analytical values provided to the requester. Excessive air flow through the specimen was suspected and points were repeated at ambient and 750F with tighter edge insulation and with the stack vertical instead of horizontal. As the date shows, there were no effects significant enough to explain these differences.*

TABLE 1. TEST RESULTS

Mean T (F)	Δ T (F)	K (BTU/HR-FT-F)	Comments
83.3	18.6	.035	Horizontal, loose fiber glass insulation on edges
255.3	24.7	.067	Horizontal, loose fiber glass insulation on edges
500.0	20.0	.100	Horizontal, loose fiber glass insulation on edges
746.0	50.0	.128	Horizontal, loose fiber glass insulation on edges
93.8	14.5	.039	Horizontal, tight dynaquartz insulation on edges
93.2	13.3	.041	Vertical, tight dynaquartz insulation on edges
733.5	32.0	.126	Horizontal, tight dynaquartz insulation on edges
736.0	30.0	.133	Vertical, tight dynaquartz insulation on edges

*Note: Subsequent to the tests by General Dynamics reported in this Appendix, conductivity measurements were made by Rohr Industries on a 305 x 305 mm (12 x 12 inch) panel. Results from these additional tests have been added to the figure in this Appendix. Also shown is an analytical curve calculated from NASA CP-2065.



SCHEMATIC OF GUARDED HOT PLATE
THERMAL CONDUCTIVITY APPARATUS

144068

Mean T (F)	ΔT (F)	K (BTU/HR-FT-F)	Comments
83.3	18.6	.035	Horizontal, loose fiber glass insulation on edges
255.3	24.7	.067	Horizontal, loose fiber glass insulation on edges
500.0	20.0	.100	Horizontal, loose fiber glass insulation on edges
746.0	50.0	.128	Horizontal, loose fiber glass insulation on edges
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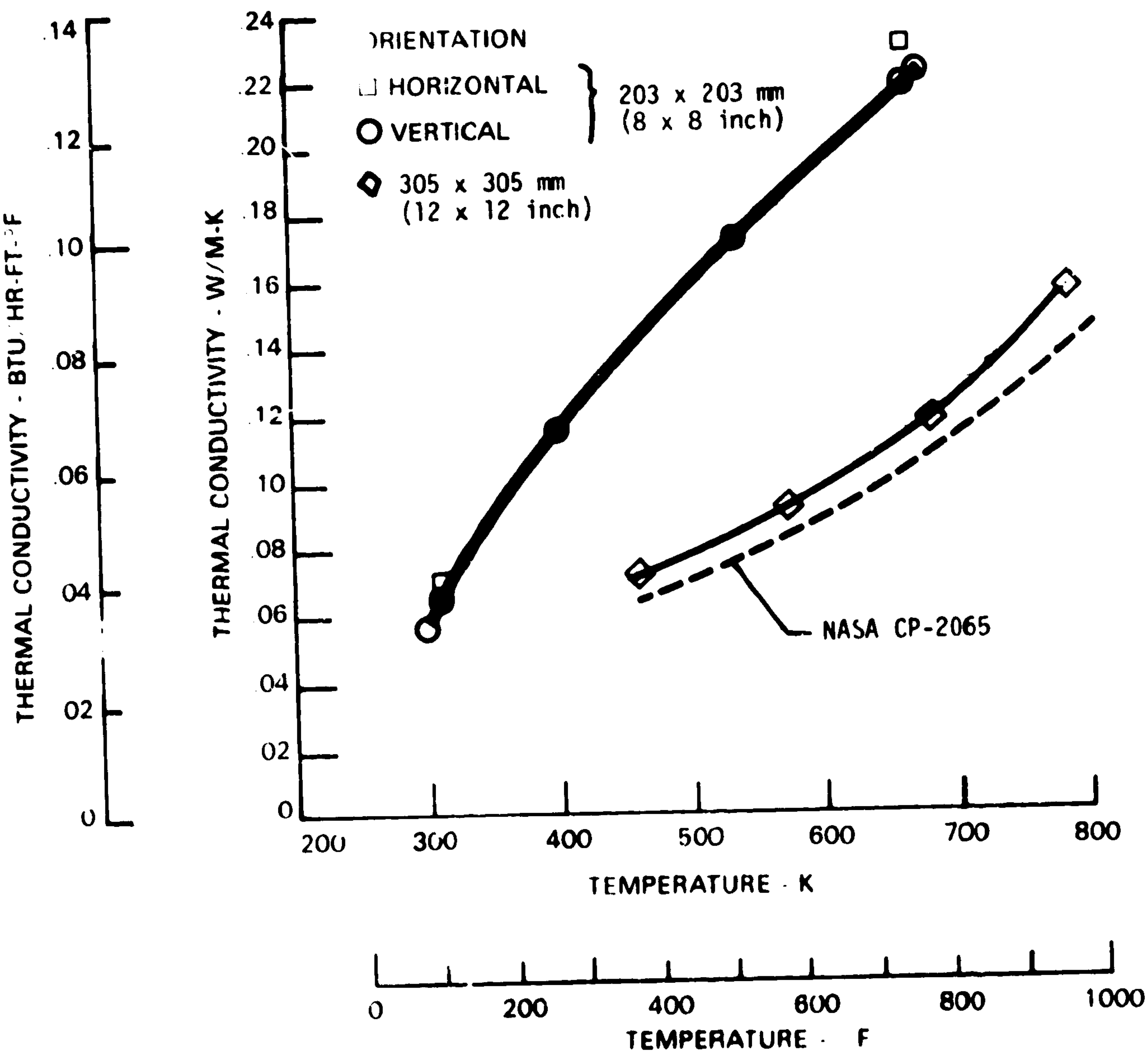
733.5	32.0	.126	Horizontal, tight dynaquartz insulation on edges
736.0	30.0	.133	Vertical, tight dynaquartz insulation on edges



THERMAL CONDUCTIVITY VS. TEMPERATURE