SOLAR RDR 1550-12

DEVELOPMENT OF BERYLLIUM HONEYCOMB SANDWICH COMPOSITE FOR STRUCTURAL AND OTHER RELATED APPLICATIONS

by

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and
L. A. GRANT

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SOLAR DIVISION OF INTERNATIONAL HARVESTER COMPANY

SAN DIEGO, CALIFORNIA 92112

RDR 1550-12

FINAL REPORT

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1 July 1967 through 27 February 1972

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GEORGE C. MARSHALL SPACE FLIGHT CENTER

SCIENCE AND ENGINEERING, ASTRONAUTICS LABORATORY

HUNTSVILLE, ALABAMA

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FOREWORD

This is the final report on NASA Contract NAS8-21215 and covers the work performed during the period 1 July 1967 through 27 February 1972. The Solar Research Project Number is 6-2794-7 and the report number is RDR 1550-12.

The contract was initiated by the National Aeronautics and Space Administration, Marshall Space Flight Center with the Solar Division of International Harvester Company, for the Development of Beryllium Honeycomb Sandwich Composites for Structural and other Related Applications. The technical direction is supplied by Mr. F. P. LaIacona of the NASA, Science and Engineering, Astronautics Laboratory, Huntsville, Alabama.

Mr. L. A. Grant, Research Engineer, Solar Research Laboratories was the Principal Investigator and was assisted by J. W. Vogan, Senior Research Engineer. Technical Director was Mr. G. D. Cremer, Chief of the Manufacturing Technology Laboratory. Messrs. L. F. Kamper, D. C. Stenger and R. L. Neher contributed in the processing, metallurgy testing, and fabrication development areas. They were assisted by Messrs. D. D. Wesson, W. A. Shoemaker, J. Marotta, E. B. Mack and N. I. Seebeth. Mr. P. V. Nerger was the Contracts Administrator and Dr. A. G. Metcalfe, the Principal Consultant.

PUBLICATION REVIEW

G. D. Cremer
Chief - Manufacturing Technology Laboratory

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Director of Research

ABSTRACT

Phases I, II, III, IV and V were completed during this three year effort. The following accomplishments constitute the subject of this report.

PHASE I (Development)

Automatic micro-resistance welded beryllium core fabrication methods and processes were developed. A study of diffusion bonding techniques was also made.

A total of 22 braze alloy systems were investigated with one braze alloy selected for the scale-up work.

Braze systems were developed on 2-inch square panels.

PHASE II (Subsize Scale-up)

Scale-up tests on 6-inch square panels were made to determine braze alloy load rates, radiograph inspection techniques, and refining the development techniques of Phase I.

Eight, 6-inch square panels of both 3 mil and 6 mil core were fabricated and sectioned into test specimens.

Mechanical tests of edgewise compression, flatwise tension, flatwise compression, and block shear were conducted. Encouraging results were obtained and reported.

Two, 12-inch square panels were fabricated as a scale-up development.

Two, 18-inch square panels were fabricated; one was delivered to NASA.

Quality assurance standards were developed and reported.

Alternate foil loading and horizontal brazing techniques were verified to reduce assembly time and increase quality.

PHASE III (Full Size Scale-Up)

Two, 1 x 2 foot panels were fabricated as preliminary test panels.

One of the above panels was creep formed into a 10 foot radius.

Two, 10 square foot full scale panels were fabricated.

Mechanical tests of edgewise compression, flatwise tension, flatwise compression and block shear were conducted.

PHASE IV

One panel from Phase III was creep formed to a 10 foot radius of curvature and two additional panels were fabricated. These two fabricated panels were brazed in the curved position with beryllium U-channel edge attachments. All of these panels were full scale, 10 ft^2 in size.

PHASE V

Vibration tests were performed on one panel and results reported. A second was to be tested from RT to 600°F in axial compression, hoop tension and bi-axial stress conditions to design limits. The panel was damaged during strain gage instrumenting and scrapped. Results of tests are reported. The third panel was shipped to NASA.

TABLE OF CONTENTS

Section		Page
1	INTRODUCTION	1
2	PROGRAM PLAN	3
3	MATERIAL - TASKS 4 AND 12	9
	3.1 Materials Received	9
	3.2 Mechanical Properties	12
4	TECHNICAL DISCUSSION - PHASE I DEVELOPMENT	17
	4.1 Design Study - Task 2	17
	4.2 Honeycomb Core Development - Task 5	18
	4.2.1 Ingot Foil Cutting	19
	4.2.2 Ingot Foil Corrugating	20
	4.2.3 Microresistance Tack Welding (MRT)	21
	4.2.4 Automatic Core Machine Modification	22
	4.3 Diffusion Bonding - Task 6a	24
	4.4 Braze Joining Study - Task 6b	
	4.4.1 First-Stage Screening	26
	4.4.2 Second-Stage Screening	32
	4.5 Subscale Testing - Task 7	35
	4.6 Scale-Up Evaluation	40
5	TECHNICAL DISCUSSION - PHASE II	45
	5.1 Scale-Up Panels - Task 8	45
	5.1.1 Six-Inch Square Panels	45
	5.1.2 Twelve-Inch Square Panels	45
	5.1.3 Eight-Inch Square Panels	48
	5.2 Mechanical Testing - Task 9	50

TABLE OF CONTENTS (Cont'd)

Section		Page
6	TECHNICAL DISCUSSION - PHASE III	57
	6.1 Scale-Up Preparations - Task 13	57
	6.1.1 Core Machine Refinement	57
	6.1.2 Alternate Brazing/Loading Techniques	60
	6.2 Preliminary Test Panels (2 ft^2) - Task 14	64
	6.3 Creep Forming Demonstration - Task 15	70
	6.4 Full-Scale Panels (10 ft^2) - Task 16	
	6.5 Mechanical Testing - Task 17	75
	6.5.1 Edgewise Compression Tests	75
	6.5.2 Flatwise Tension Tests	81
	6.5.3 Flatwise Compression Tests	83
	6.5.4 Block Shear Tests	85
7	TECHNICAL DISCUSSION - PHASE IV	87
	7.1 Material Inspection (Task 22)	87
	7.2 Core Fabrication (Task 23)	89
	7.3 Facility Modifications (Task 24)	89
	7.4 Channel Fabrication (Task 25)	89
	7.5 Panel Fabrication	92
	7.5.1 Test of Curved Component Fabrication and Brazing	92
	7.5.2 Panel Assembly	92
	7.6 Modifying Existing Panel (Task 27)	98
	7.7 Creep Forming (Task 28)	98
	7.7.1 Modification of Existing Panel	98
	7.7.2 Detail Parts for Panels B and C	98
	7.8 Braze Two (2) Panels (Task 26)	100

TABLE OF CONTENTS (Cont'd)

Section		Page
8	TECHNICAL DISCUSSION - PHASE V	103
	8.1 Vibration Testing (Panel A)	103
	8.2 Spare (Panel B)	108
	8.3 Axial Compression, Hoop Tension and Bi-Axial Tests (Panel C)	108
	8.4 Discussion of Results (Task 37)	109
9	QUALITY ASSURANCE - TASKS 3, 11 AND 21	115
	9.1 Material	115
	9.2 Core Fabrication	115
	9.3 Braze Filler Metal	116
	9.4 Braze Cycle	116
	9.5 Radiograph Inspection	118
	9.6 Metallurgy and Mechanical Testing	118
10	CONCLUSION	119

ILLUSTRATIONS

Figure		Page
1A	Task Flow for Beryllium Honeycomb Sandwich Development (Phase I and II)	4
1B	Task Flow for Beryllium Honeycomb Sandwich Development (Phase III)	5
1C	Task Flow for Beryllium Honeycomb Sandwich Development (Phases IV and V)	6
2	Schedule	8
3	Beryllium Ingot Foil Material Furnished by NASA/ ORNL Y-12	11
4	Cross Section of 0.006-Inch Beryllium Ingot Foil; Surface Conditions	14
5	Beryllium Ingot Foil Tester	15
6	Beryllium Ingot Foil Tensile Specimens; After Test	16
7	Power Shear for Cutting Beryllium Ingot Foil	19
8	Warm-Node Forming Tests of 0.006-Inch Beryllium Foil	21
9	Microresistance Tack Welding Tests of Beryllium Foil	23
10	Automatic Core Machine, As Used in Phase II	23
11	Diffusion Bonded Test Specimens and Bonder	25
12	Braze Alloy Test Apparatus	27
13	Unicell Braze Alloy Flow Specimens: Brazed at 1450°F for 10 Minutes	28
14	Braze Metallurgy of Five Selected Braze Alloys (Sheet 1 of 2)	29
14	Braze Metallurgy of Five Selected Braze Alloys (Sheet 2 of 2)	30

ILLUSTRATIONS (Cont'd)

Figure		Page
15	Mechanical Property Test Equipment and Typical Specimens	33
16	Machine-Made Honeycomb Core and Typical Subscale Test Specimens	36
17	Time - Temperature - Pressure Braze Cycle	37
18	Solar's Atmosphere Control Panel	38
19	Subscale Mandrel System	39
20	Braze Load/Rate Test Specimen No. 17-10	40
21	Radiograph of Braze Load/Rate Test Specimen No. 17-11	41
22	Beryllium Honeycomb Sandwich Brazed with Ag Cu Sn	43
23	Automatic Resistance Spot Welded Beryllium Core Blanket	46
24	Assorted Core Blankets and Braze Panels	46
25	Fabricating and Inspecting Beryllium Honeycomb Core	47
26	Radiograph of First 6-Inch by 6-Inch Production Panel (Specimen No. 22-12)	47
27	Twelve-Inch Square Beryllium Honeycomb Panel	48
28	Creep Deformed Core of Panel No. 22-20	49
29	Fixtured Beryllium Honeycomb Panel in Brazing Furnace	50
30	Eighteen-Inch Square Panel, As-Brazed	51
31	Eighteen-Inch Square Panel, As-Trimmed	51
32	Masrock Platen Press Brazing Facility	58
33	Core Samples and Inspection Techniques	59
34	Refined Automatic Core Machine	59
35	Typical Screening Specimens - Foil Loading/Horizontally Brazed	61

ILLUSTRATIONS (Cont'd)

Figure		Page
36	Beryllium Honeycomb-Foiled Loaded/Horizontally Brazed	62
37	6" x 6" Beryllium Test Panel	63
38	First 2 Ft^2 Panel - As Brazed (Flat Within 0.005 Inch TIR)	65
39	Photomicrographs of First 2 Ft^2 Panel As Brazed	66
40	Typical Radiograph of Brazed Beryllium Panels	67
41	Third 2 Ft^2 Panel - As Brazed (Flat Within 0.002" TIR)	69
42	Fixturing for Creep Forming Demonstration	70
43	Photomicrographs of First 2 Ft^2 Panel After Creep Forming	71
44	Curved Beryllium Honeycomb Panel (10 Ft. R)	72
45	As-Welded Beryllium Honeycomb Core Blanket	74
46	First 10 Square Foot Brazed Panel	75
47	Second 10 Square Foot Brazed Panel	76
48	Typical Beryllium Honeycomb Test Specimens	77
49	Edgewise Compression Room Temperature Test Set-Up	78
50	Typical Fractured Edgewise Compression Specimens	78
51	Stress versus Temperature, Edgewise Compression Tests	81
52	Typical Tested Flatwise Tension Specimens (2 inch x 2 inch)	82
53	Flatwise Compression Test Set-Up	83
54	Typical Flatwise Compression Failed Specimens	84
55	Test Set-Up for Block Shear Tests	85
56	Typical Core Shear Failed Specimens	86
57	Large Beryllium Sheets (.030 x 36 x 96")	88
58	Large Beryllium Core Blankets	90

ILLUSTRATIONS (Cont'd)

Figure		Page
59	36" x 96" Beryllium Sheet - After Sawing	90
60	Precision Hot-Formed Beryllium U-Channels and Blanks	91
61	Completed Edge Close-Out U-Channels (Curved and Straight)	91
62	Hot Formed Curved Beryllium U-Channels	93
63	Curved Beryllium Honeycomb Core	93
64	Curved Components for Beryllium Panel	94
65	Curved and Brazed Beryllium Honeycomb Sandwich	95
66	Beryllium Panel Components (1/2" x 1/2" x 1/2" x 48")	96
67	Panel "A" As Creep Formed (10 Ft. R)	99
68	Curved Beryllium Panel Details - Before Braze	100
69	Panel "B" As Brazed	101
70	Panel "C" As Brazed	102
71	Three Large (10 ft^2) Brazed Beryllium Honeycomb Sandwich	102
72	Panel Testing Flow Plan (Task 30)	104
73	Panel Fixturing for Vibration Testing	105
74	Vibration Testing of Beryllium Panel	105
75	Trimmed Panel "B" as Shipped to NASA (30" x 42")	108
76	Axial Compression, Hoop Tension Set-Up in Testing Facility (Side View)	111
77	Axial Compression, Hoop Tension Set-Up in Testing Facility (End View)	112
78	Panel C (Concave Side) after Fracture Outlined with Marking Tape	113
79	Panel C (Convex Side) after Fracture Outlined with Marking Tape	114
80	Intermediate Core Surface Inspection Trace	117
81	Final Core Surface Inspection Trace	117

TABLES

Table		Page
I	Beryllium Inventory	10
II	Mechanical Properties of Beryllium Ingot Foil in Various Conditions	13
III	Properties of CRS Beryllium	16
IV	Beryllium Honeycomb Braze Alloy Selection	31
V	Mechanical Property Evaluation (Second-Stage Screen Tests)	34
VI	Beryllium Honeycomb Sandwich Weights	42
VII	Phase II Test Matrix	52
VIII	Mechanical Test Properties of Brazed Beryllium Honeycomb Sandwich Panels (Phase II)	54
IX	Mechanical Test Properties of Brazed Beryllium Honeycomb Sandwich Panels (Phase III)	79
X	Vibration (Sinusoidal) Tests Brazed Beryllium Honeycomb Panel A (10 Ft^2)	106
XI	Steady State Vibration Levels for Typical Aerospace/Space Shuttle Components	107

1

INTRODUCTION

Structural beryllium honeycomb sandwich composites have a wide application potential in the Aerospace fields. Beryllium's unique properties carefully developed into an efficient metallurgically bonded sandwich structure, will allow a major step to be taken in minimum weight applications.

The basis of this development is beryllium Ingot Foil produced by the Oak Ridge National Laboratory (ORNL Y-12). NASA has selected this material to be used in the development of honeycomb sandwich core. They have supplied the necessary foil sheet stock for the development phases and the required material for the scale-up phases.

Development of practical optimum joining methods and processes involved in the fabrication of structural sandwich composites was evaluated during the first year of this program. Mechanical test specimens were cut from 6-inch square panels and tested. Scale-up techniques were applied to 12-inch and 18-inch square panels.

The technology learned from this first year development was applied to larger beryllium honeycomb structures. Improved fabrication techniques were tested on 12 inch by 24 inch test panels prior to fabricating two panels with 10 square feet of surface areas each. Additional mechanical test data was obtained from one of these panels.

The Second Annual Report (Solar RDR 1550-8) describes the work accomplished during both the first year's efforts (Phases I and II) and the second year's efforts (Phase III). More detailed discussion of the first year's efforts are reported in the First Annual Report (Solar RDR 1550-4).

This, the final report covers all of the above past efforts in addition to the third year efforts (Phases IV and V). This included the fabrication of 10 $ft.^2$ curved (10 ft. R) brazed beryllium honeycomb panels and testing of these full size panels.

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PROGRAM PLAN

The program plan in Figure 1 displays the flow of the major development tasks. Three of these tasks supported the program in all phases and were continuing efforts:

- Literature survey
- Design study
- Quality assurance and control.

The literature survey was implemented by Mr. F. P. LaIacona (the principal NASA representative on this development contract) who supplied much of the data and many of the reports. Additional literature searches were made of the AIAA, DOD, DMIC, and others through the Solar library. Although little of the technical information obtained from the literature related directly to this program, the general information was of interest. The one reference which contributed specifically to this program originated at Solar, "Brazing Beryllium By Capillary Flow", Air Force Contract AF33(615)-2853 (MAMP) and its relationship is discussed in Section 4.4 of this report.

The design study was essentially completed in the initial phases of the program. However, both a designer and a stress analyst followed the development throughout the program and became more acquainted with this new material of construction and made valuable inputs from their disciplines.

The quality assurance and control functions were very important to this development. To become a practical material composite for aerospace applications, structural reliability is required. Therefore, it was a goal of the design task to establish preliminary specifications on the material and processes involved in fabricating beryllium honeycomb sandwich structures to meet these requirements.

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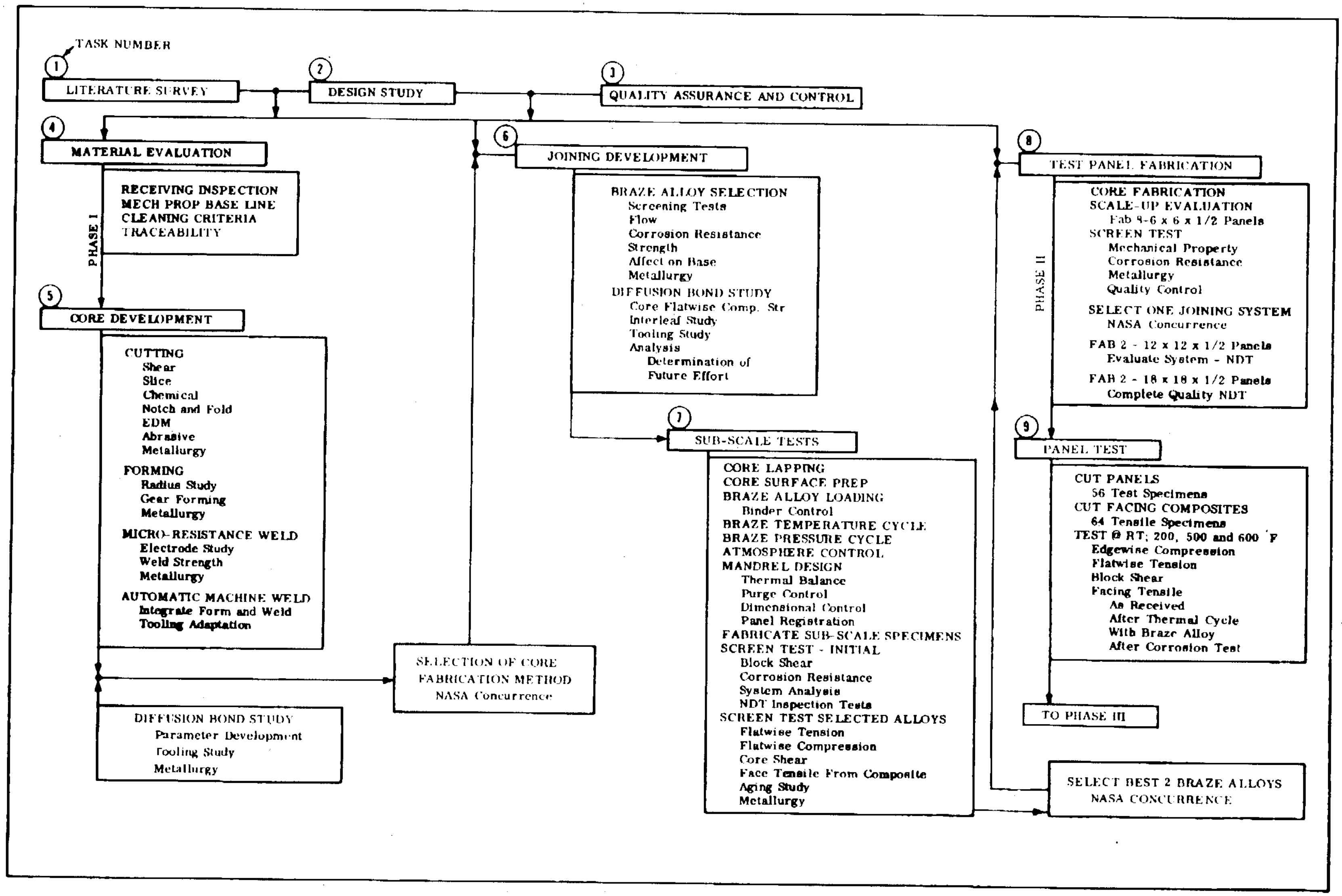


FIGURE 1A. TASK FLOW FOR BERYLLIUM HONEYCOMB SANDWICH DEVELOPMENT (PHASE I AND II)

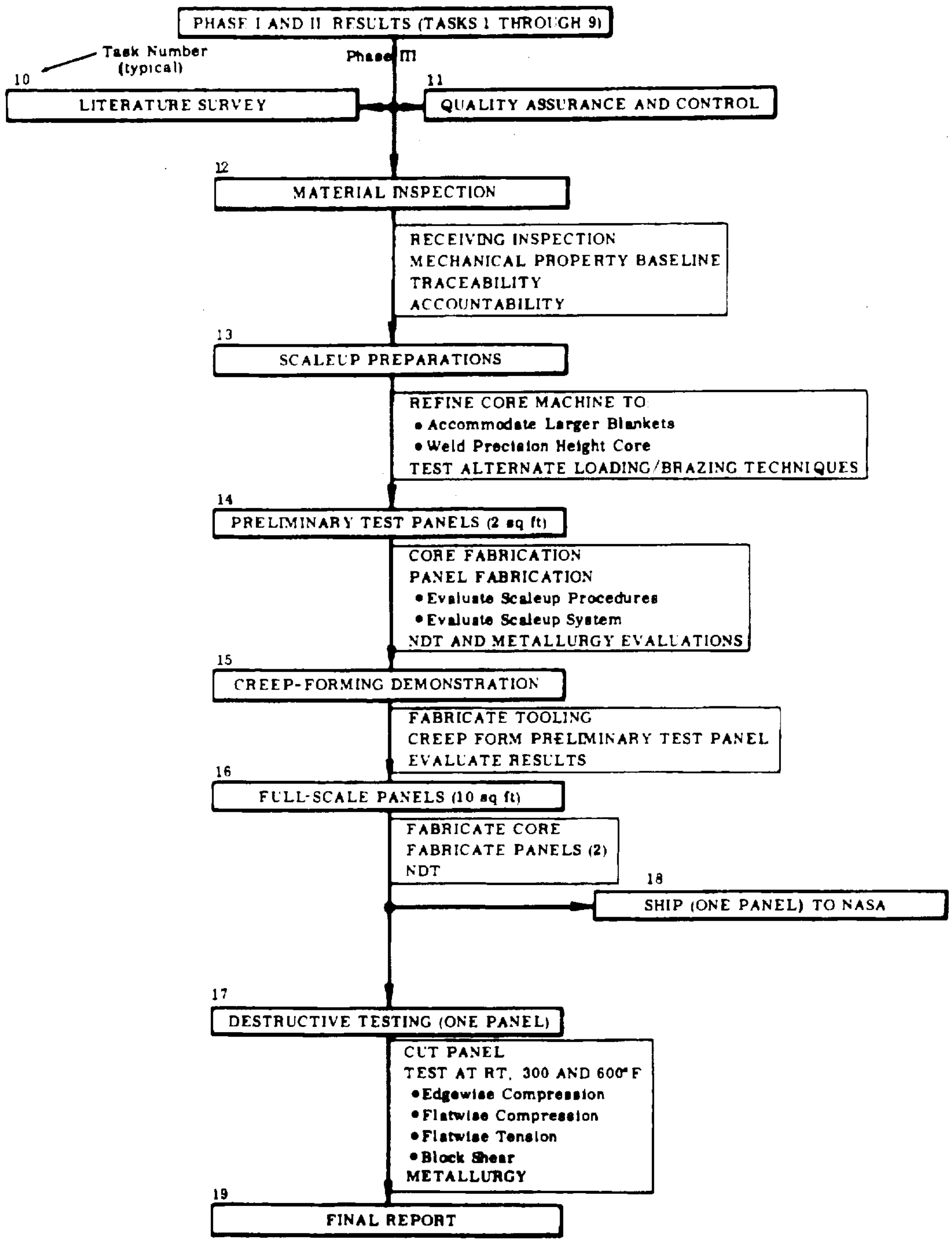


FIGURE 1B. TASK FLOW FOR BERYLLIUM HONEYCOMB SANDWICH DEVELOPMENT (PHASE III)

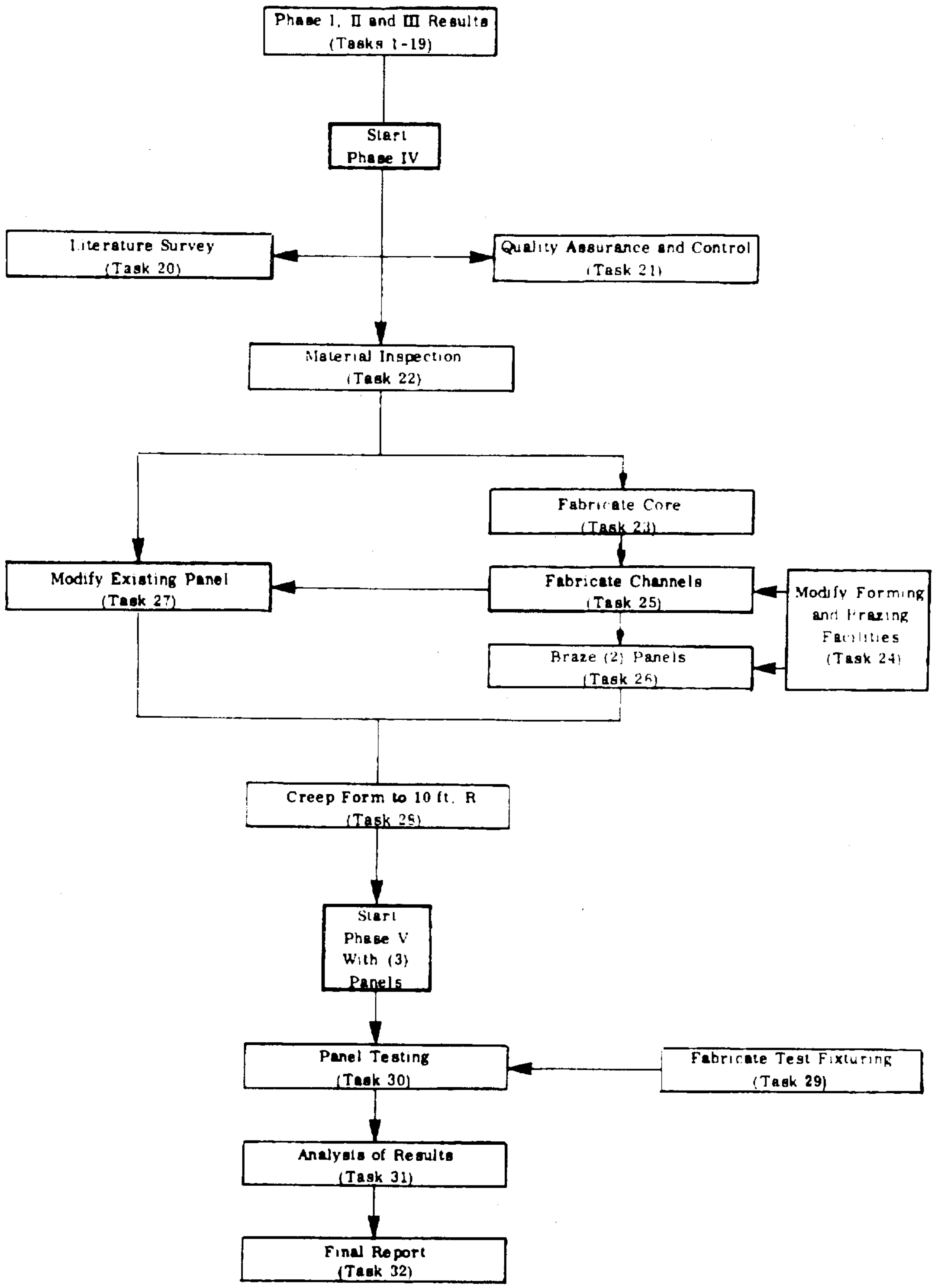


FIGURE 1C. TASK FLOW FOR BERYLLIUM HONEYCOMB SANDWICH DEVELOPMENT (PHASES IV AND V)

The other tasks were divided into a five-phase program. Phase I included:

- Material evaluation
- Honeycomb core
- Joining development
- Subscale tests.

The data established in Phase I was further concentrated and scaled up to large panel fabrication in Phase II of the contract. Scale-up involved steps in panel size from 6 inches by 6 inches (from which test specimens were cut) to 18 inches by 18 inches. The testing task obtained mechanical data of the beryllium honeycomb sandwich structure at temperatures up to 600°F.

Phase III involved refining the core machine and brazing procedures to make core and panel production more efficient and reliable. These procedures were verified on two 2-square foot panels prior to fabricating two full-scale 10-square foot panels. Tests on one of these panels obtained additional mechanical data of the beryllium honeycomb structures at temperatures up to 600°F. Also, a demonstration of creep forming a brazed panel into a 10-foot radius was performed.

Phase IV was the fabrication of two (2) additional large (10 ft^2) panels with beryllium U-channel edge close-out. These were brazed in the curved condition (10 ft. R). Also, the creep forming of a flat panel from Phase III was performed.

Phase V was the vibration and hoop tension/axial compression tests on the 10 ft^2 curved panels.

Schedules followed for all five phases are shown in Figure 2.

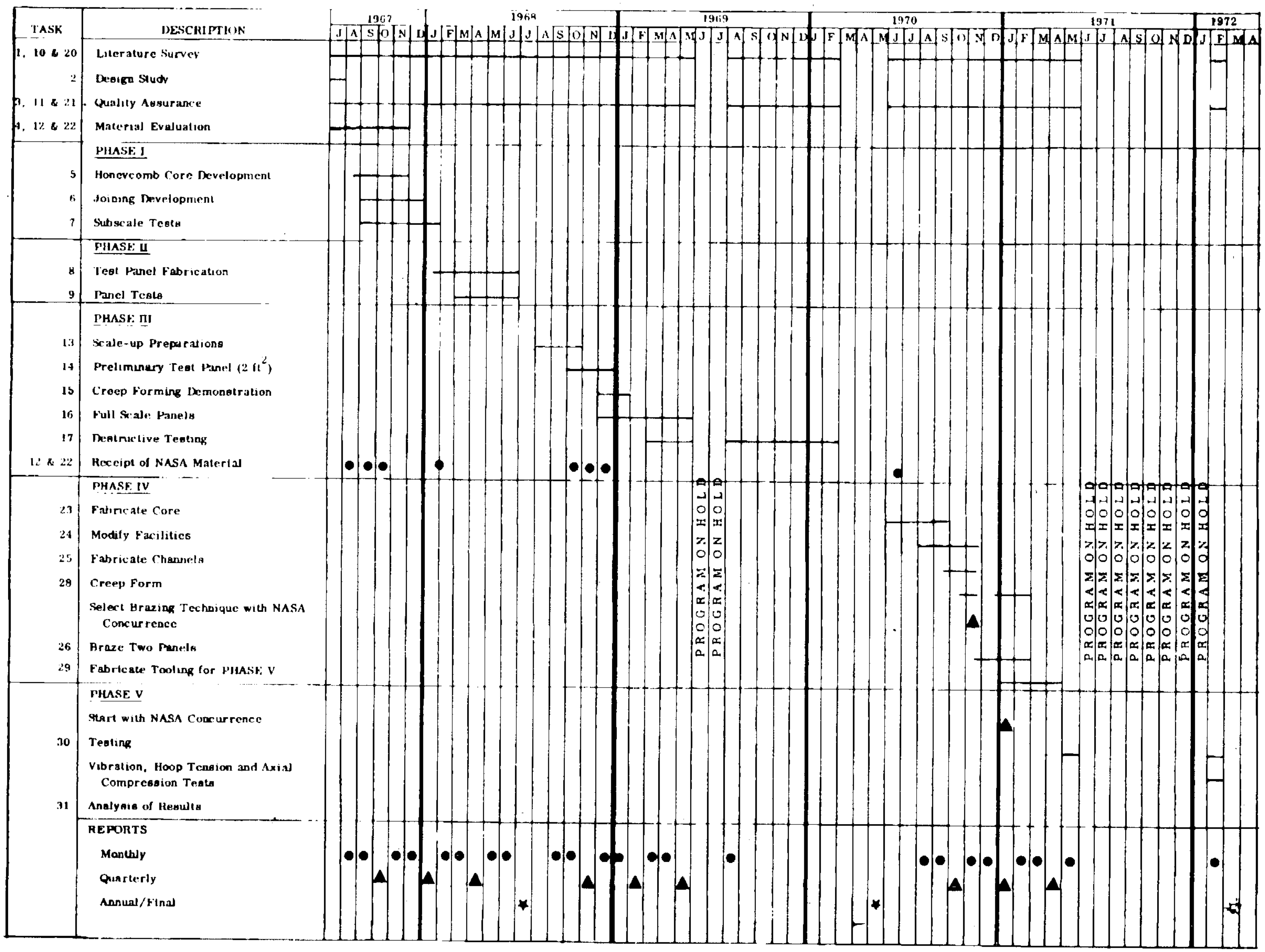


FIGURE 2. SCHEDULE

3

MATERIAL - TASKS 4 AND 12

Messrs. F. P. LaIacona (NASA) and Solar representatives visited Oak Ridge National Laboratory (Y-12) on 7 August 1967 to discuss the ORNL Y-12 developed Ingot Foil beryllium material. A most informative meeting was held with Messrs. Ludwig, Hulsey, Mitchel, Turner, Estes, and Myhre. The process of making the Ingot Foil was discussed in detail along with its properties and problems. It was apparent that the ORNL Y-12 technical group have done an outstanding job in the pioneering development of large ($\approx 14\ ft^2$) beryllium sheet materials and processes.

3.1 MATERIALS RECEIVED

The foil materials received from ORNL Y-12 and the facing materials for all phases of the contract are itemized in Table I. A typical shipment is shown in Figure 3 along with one of Solar's incoming inspection operations.

The material code number identifies the experimental material to the ORNL Y-12 group and the chemistry and characteristic data of these foils were obtained from them. The code number on the cross rolled sheet (CRS) is the Brush sheet number which ties the material to the certifications supplied by the Brush Beryllium Company.

TABLE I

BERYLLIUM INVENTORY

INGOT FOIL

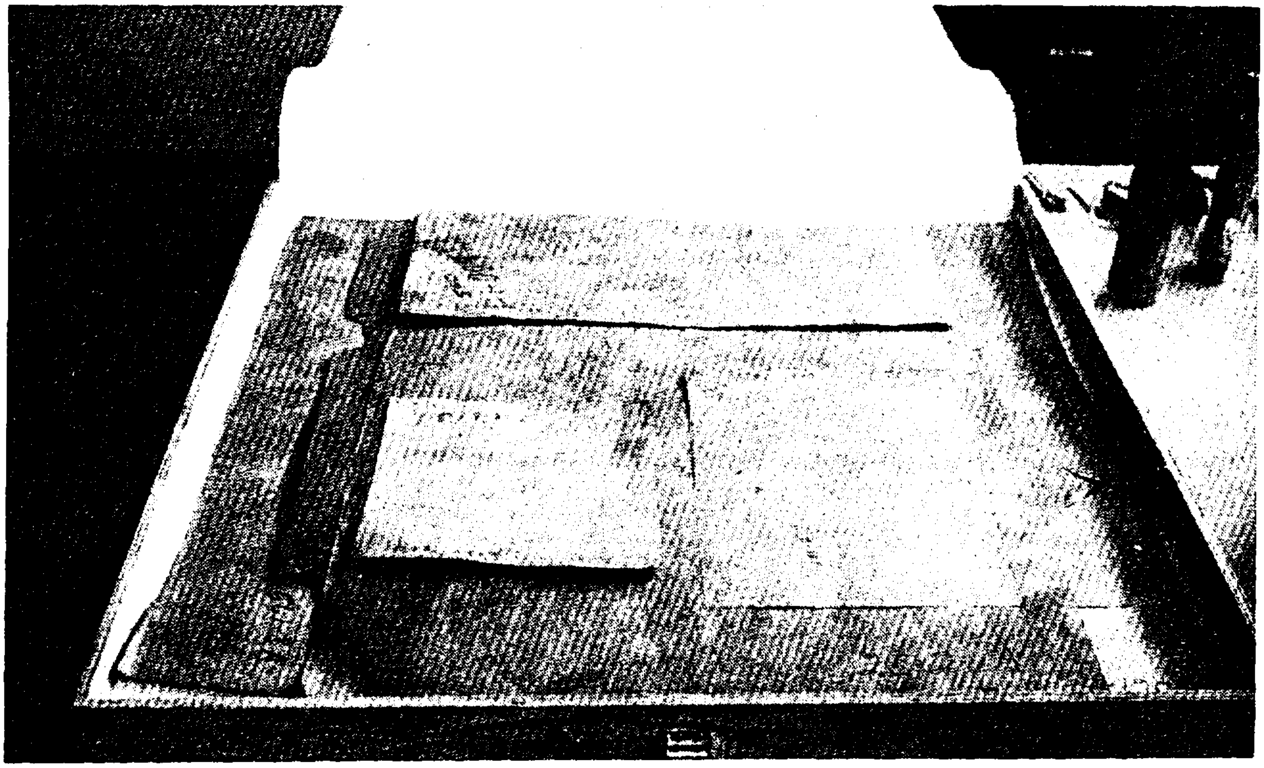
Code No.	Nominal Gage (inches)	Approximate Dimension (inches)	Used For
600-1-1	0.003	11.5 x 29	Preliminary Testing
669-2-2-2	0.003	33 x 35	Preliminary Testing
610-2-2-2	0.006	23.5 x 25	Preliminary Testing
736-2	0.006	42 x 45.5	Preliminary Testing
625-1-2	0.006	39 x 40	Phase I Panels
625-1-3	0.006	43 x 43	Phase I Panels
669-2-2-1	0.003	34.5 x 35	Phase I Panels
691-2-2	0.006	37.5 x 51	Phase II Panels
687-2-2	0.006	34.5 x 36	Phase II Panels
613-2-1 1	0.004	36.5 x 37	Phase II Panels
713-2-1-2	0.003	37 x 37	Phase II Panels
713-2-2	0.003	37 x 37	Phase II Panels
736-2-2	0.006	24 x 11.5	Phase II Panels
606-2-7	0.006	13 x 18.5	Phase III Panels
561-3A	0.006	41 x 42	Phase III Panels
736-2-3	0.007	40 x 49.5	Phase III Panels
723-2-1	0.0065	39 x 40	Phase III Panels
723 2-2	0.0058	40 x 40	Phase III Panels
736-1-1	0053	40 x 40	Phase III Panels
748-2	.005	39 x 42	Phase III Panels

INGOT FOIL

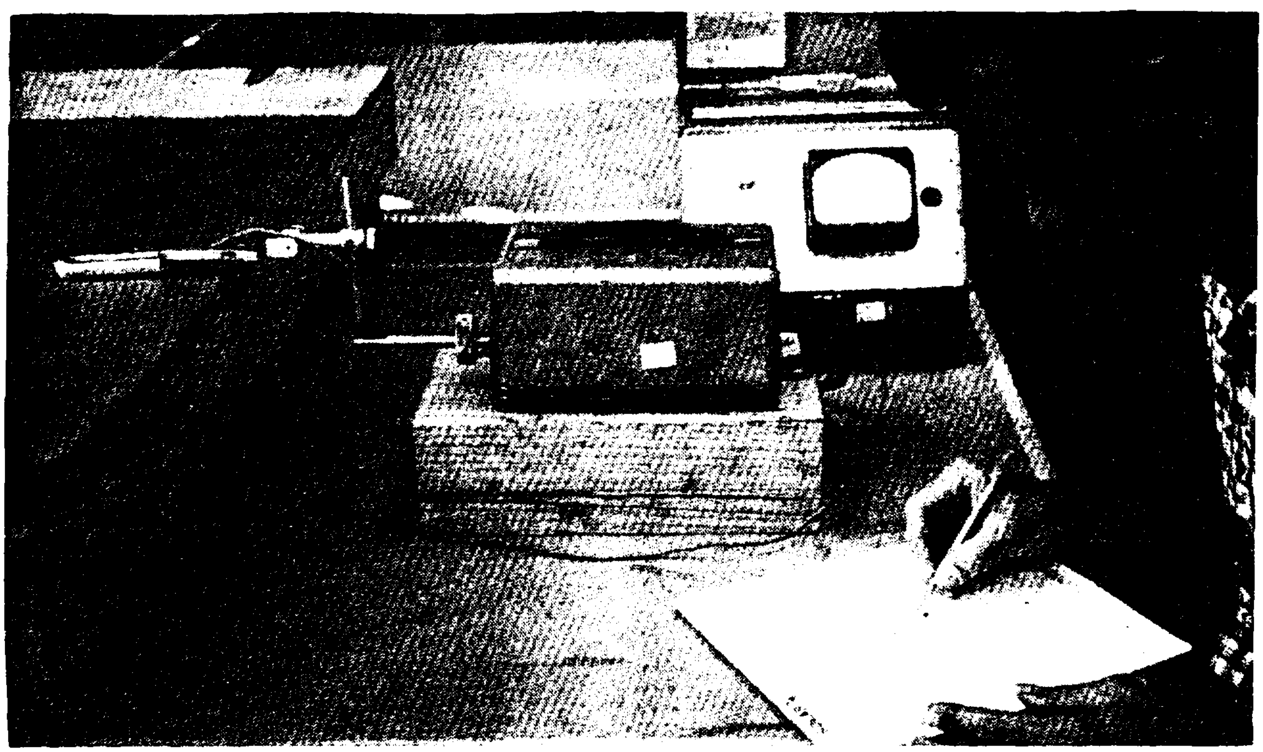
Code No.	Nominal Gage (inches)	Approximate Dimension (inches)	Used For
642-1-1	.006	38 x 39	Phase III Panels
642-1-2	.006	39 x 39	Phase III Panels
642-1-4	.005	38 x 38	Phase III Panels
719-4-1	.005	38 x 39	Phase III Panels
748-4-1	.006	38 x 39	Phase III Panels
748-4-2	.006	39 x 41	Phase III Panels
11-65-4-1-2	.006	37 x 39	Phase III Panels
11-65-20-1-1	.007	39 x 40	Phase III Panels
11-65-20-1-3	.007	37 x 39	Phase III Panels
722-1	.009	40 x 38	Phase III Panels
11 65 4 1 1	.007	41 x 39	Phase III Panels
625-2-1A	0.003	30 x 30	Phase IV
579-3-5	0.003	13 x 13	Phase IV
713-2-2-1	0.003	36 x 37	Phase IV
610-2-2-3	0.006	23 x 24.5	Phase IV
662-3	0.0085	36 x 36	Phase IV
723-2-3	0.006	39 x 40	Phase IV
642 1 3	.007	42 x 40	Phase IV
699-4	.009	40 x 39	Phase IV
11-65-4-1-4	.009	41 x 39	Phase IV
11-65-30-1	.008	42 x 41	Phase IV
11-65-4-1-3	.007	41 x 37	Phase IV

CROSSROLLED SHEET

Code No.	Nominal Gage (inches)	Approximate Dimension (inches)	Used For
1508 B3	0.020	18 x 18	Phase I Tests
1508 A1	0.020	18 x 18	Phase I Panels
1370 B1	0.020	18 x 18	Phase II Panels
1370 B2	0.020	18 x 18	Phase II Panels
1139 A1	0.020	18 x 18	Phase II Panels
1439 A2	0.020	18 x 18	Phase II Panels
1508 C1	0.020	18 x 18	Phase II Panels
1508 C2	0.020	18 x 18	Phase II Panels
1508 A2	0.020	18 x 18	Phase II Panels
1508 A3	0.020	18 x 18	Phase II Panels
1508 B1	0.020	18 x 18	Phase II Panels
1508 B2	0.020	18 x 18	Phase II Panels
HR51 2	.020	25 x 25	Phase III Panels
HR135-2	.020	25 x 25	Phase III Panels
HR134-3	.020	25 x 25	Phase III Panels
1377	.022	36 x 41	Phase III Panels
1369A	.022	36 x 45	Phase III Panels
1377A	.022	36 x 47	Phase III Panels
1369	.022	36 x 18	Phase III Panels
1354	.030	36 x 96	Phase IV Panels
1356	.030	36 x 96	Phase IV Panels



A. As-received beryllium Ingot Foil



B. Profilometer inspection of Ingot Foil shipment

FIGURE 3. BERYLLIUM INGOT FOIL MATERIAL FURNISHED BY NASA/ORNL Y-12

3.2 MECHANICAL PROPERTIES

The Ingot Foil furnished by ORNL Y-12 had a rough surface which was reported by them as being inherent to the development process and is admittedly a problem area. Much work was performed by the developers in an attempt to correct this condition, however, without significant success.

The rough surface condition was evaluated by Solar. RMS values of about 200 microinches on surface conditions and up to 40 percent thickness variation was common. Several disadvantages were noted due to this condition:

- The surface notches would limit forming node radii.
- The roughness would create unreliable MRT (microresistance tack welding) conditions.
- The thickness variations would decrease uniformity of core compressive strength.
- The rough surface disrupts capillary flow of the braze alloy.

A cursory mechanical property evaluation was conducted (Table II) to measure the effects of various methods to improve the surface finish. The methods tested were hand polishing and microrolling. The as-received surface condition relative to that of the microroll process is shown in Figure 4. Testing was accomplished on a thin gage testing facility developed by Solar on USAF Contract AF33(615)-1709. The equipment is capable of accurate mechanical testing of foils between 0.001 and 0.015 inch under inert atmosphere or vacuum at temperatures between -320 and 5000°F.

The tensile specimen, fabricated by chemical milling, was 0.375 inch wide at the grips, 10 inches long, with a 2.25-inch gage length 0.250 inch wide. The testing operation and equipment is shown in Figure 5.

Problems in determining the true load bearing area were not accurately resolved. After evaluating measuring techniques with various micrometer tips, it was decided to take thickness measurements every 1/8-inch along the gage section with a 0.250-inch ball micrometer. Precise width and gage length measurements were made on an optical comparator at 20 power magnification. Due to the thickness variation, properties were reported (Table II) for both average and minimum areas.

TABLE II

MECHANICAL PROPERTIES OF BERYLLIUM INGOT FOIL IN VARIOUS CONDITIONS

Condition	Number of Specimens	Nominal Thickness (in.)	Thickness Variation (in.)	Average Area			Minimum Area		
				UTS (ksi)	YS 0.2% Offset (ksi)	Elongation (% in 2 in. gage)	UTS (ksi)	YS 0.2% Offset (ksi)	Elongation (% in 2 in. gage)
As-Received	4	0.006	0.0050/0.0080	28.8	20.5	1.5	32.2	24.5	1.5
Microrolled, Stress Relieved	2	0.005	0.0045/0.0062	26.4	19.7	1.0	30.5	22.5	1.0
Microrolled, Stress Relieved, and Etched 0.001 Inch/Side	2	0.003	0.0026/0.0043	20.8	18.7	0.63	25.6	23.3	0.65
Sanded, Etched 0.001 Inch/Side	2	0.003	0.0032/0.0038	25.5	23.0	0.35	27.1	25.1	0.35
Microrolled, Etched 0.001 Inch/Side	2	0.004	0.0030/0.0043	29.6	----	0.05	34.2	----	0.05

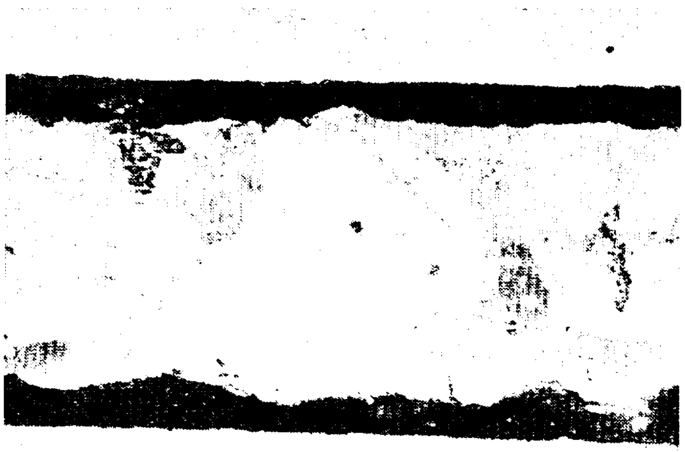
Properties were obtained after various mechanical, chemical, and thermal processing accomplished to obtain a smoother surface condition. The material's sensitivity to these processes is significant and is shown in Table II by a gradual decrease in properties, particularly elongation.

An equal number of the test specimens shown in Figure 6 were taken at 90 degrees to each other to test for anisotropy in the sheet plane. No significant differences were noted in strength and elongation.

The 12 cross rolled beryllium sheets used for facings listed in Table I were procured from the Brush Beryllium Company for use in Phase I and a portion of Phase II of study. The material is standard QMV SR200D beryllium purchased to Solar's beryllium specification ES 9-226A. The chemical analyses and mechanical properties of these materials are shown in Table III.

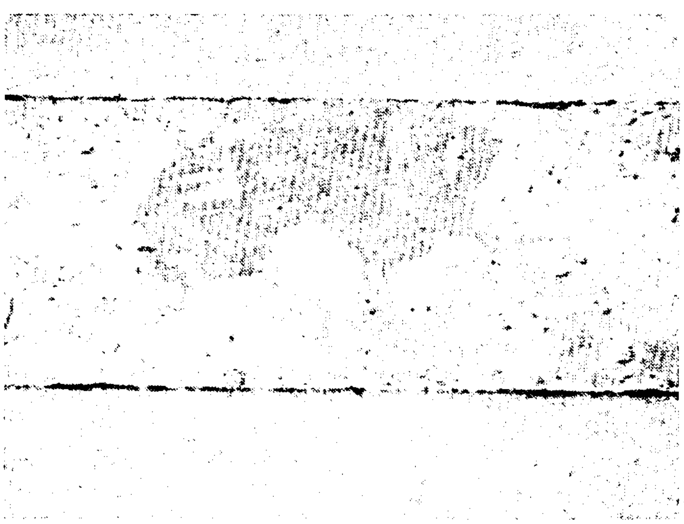
The wrought beryllium for Phase III facing sheets listed in Table I were supplied by NASA. These were cut from 0.020 by 36 by 96 inch sheets. Sizes up to 42 by 120 inches are currently available commercially. Such material makes practicable production of large honeycomb sandwich panels for advanced technology applications.

Note: Metal adjacent to beryllium foil used for support in the mounting process.



A. As-received

Magnification: 250 X



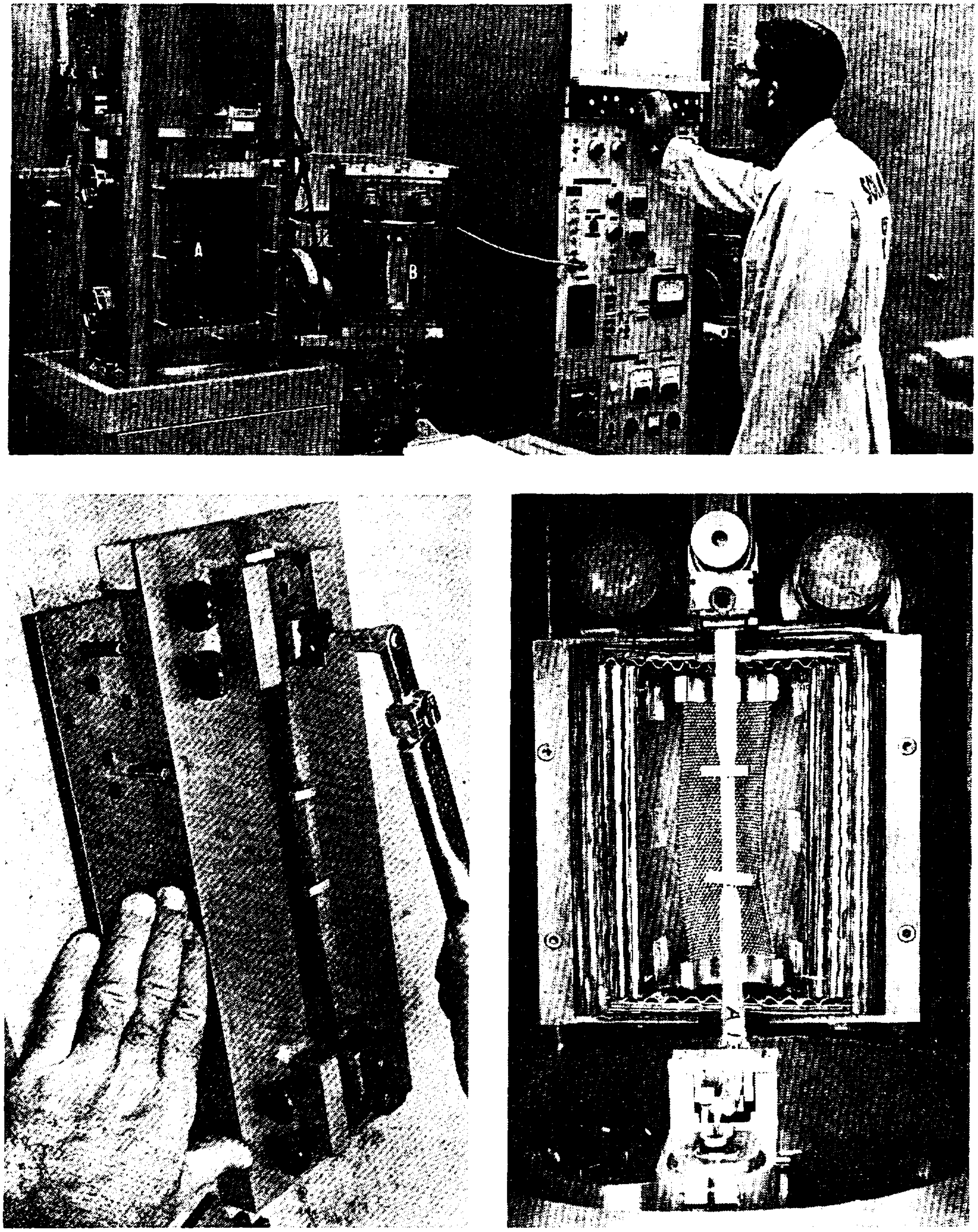
B. Microrolled

Magnification: 250 X

C. Fired in argon for 30 minutes at 1400 F and microrolled

Magnification: 250 X

FIGURE 4. CROSS SECTION OF 0.006-INCH BERYLLIUM INGOT FOIL; Surface Conditions



A. Specimen Alignment Fixture

B. Specimen Setup

FIGURE 5. BERYLLIUM INGOT FOIL TESTER

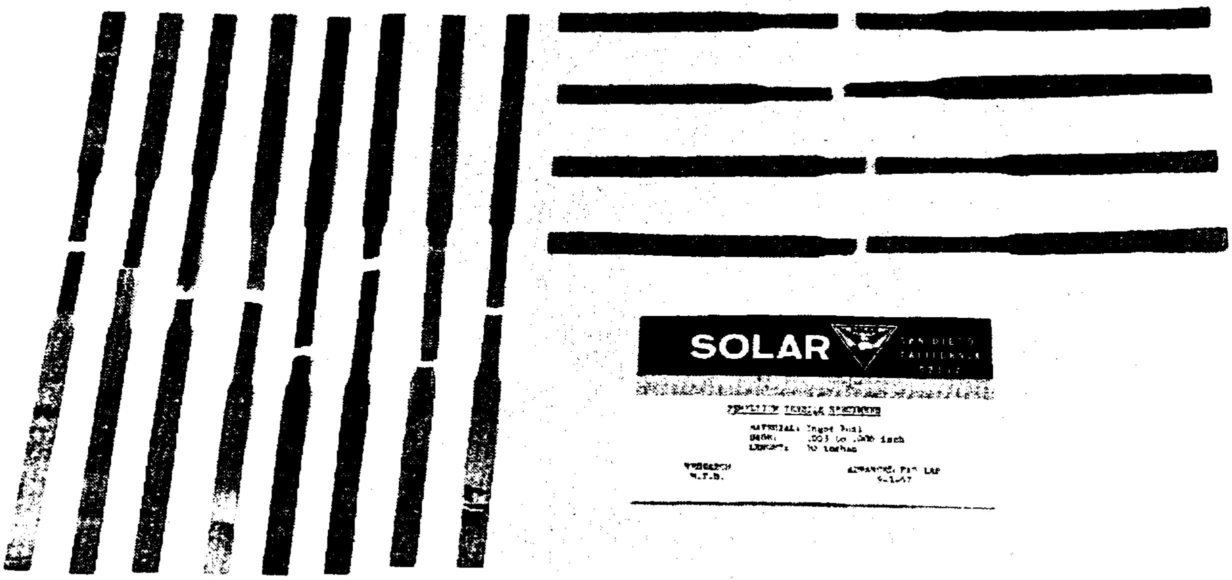


FIGURE 6. BERYLLIUM INGOT FOIL TENSILE SPECIMENS; After Test

TABLE III

PROPERTIES OF CRS BERYLLIUM

Lot No.	Sheet No. (Reference)	Chemical Analysis (%) Be	BeO	Fe	Si	Al	Mg	C	Test Direction	UTS (psi x 10^3)	YS (psi x 10^3)	Elongation (% 1 in.)
4331	1370 B1	98.4	1.5	0.12	0.02	0.07	0.06	0.14	L	87.6	63.7	15.0
	1370 B2								T	82.8	60.6	11.0
4477	1439 A1	98.1	1.8	0.13	0.03	0.06	0.07	0.12	L	86.9	67.0	21.0
	1439 A2								T	82.3	67.9	18.0
4885	1508 A1								L	86.0	58.7	28.5
	1508 A2	99.2	1.1	0.08	0.03	0.05	0.04	0.08	T	83.4	60.6	29.0
	1508 A3											
	1508 B1								L	84.3	60.5	29.0
	1508 B2								T	82.4	58.4	16.0
	1508 B3											
	1508 C1								L	86.2	58.7	33.0
	1508 C2								T	79.6	55.4	26.0

4.2.1 Ingot Foil Cutting

Several cutting methods were investigated to obtain ribbons for core fabrication. These methods were: shearing, slicing, machine notch and brake, chemical, EDM (Electrical Discharge Machining) and abrasive cutoff. A detailed description of each of these methods were presented in the first annual report, RDR 1550-4. The methods selected are discussed in the following paragraphs.

Ribbon cutting of 0.003- to 0.006-inch beryllium Ingot Foil up to 48 inches in length can be satisfactorily performed by shearing methods and was used throughout the program. Shearing of the ribbons to within ± 0.005 inch has been standardized. It should be noted that extreme care was taken to maintain sharp, nick-free, cutting edges. Two blades were used throughout this program on exchange basis to maintain the required precision. The total facility was committed to shearing of Ingot Foil only. This facility is shown in Figure 7.

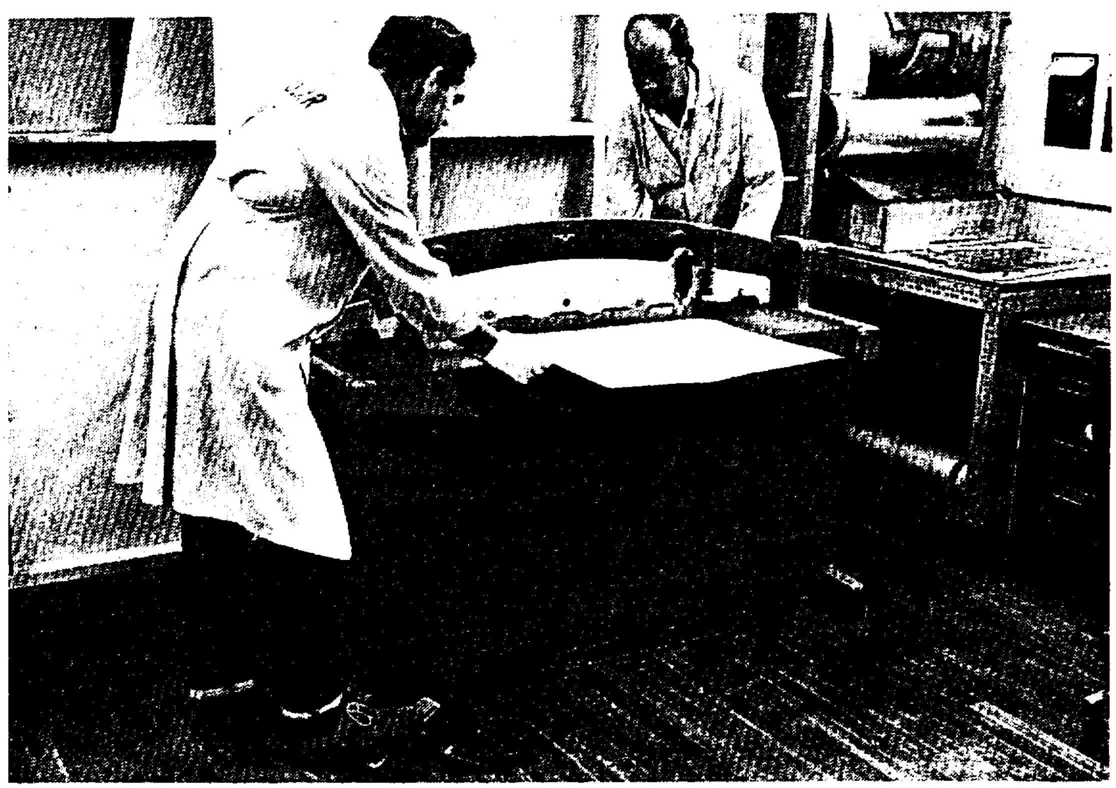


FIGURE 7. POWER SHEAR FOR CUTTING BERYLLIUM INGOT FOIL

Smaller specimens (such as tensile specimens) were accurately cut by a chemical etching process using vinyl masking tape and 50 percent concentrate HCl etchant, or by the EDM method. (The EDM method later proved particularly adept to cutting brazed beryllium panels.)

4.2.2 Ingot Foil Corrugating

Many forming tests were conducted on 1/2-inch beryllium Ingot Foil ribbons. The initial test series employed Solar's existing gear forming tools designed for 1/4-inch square cell honeycomb core at room temperature to 550°F.

The literature survey revealed that vast improvements are possible in forming the Ingot Foil beryllium at temperatures of 500°F. Room temperature forming of 0.006-inch foil requires a bend radii of over 6t, while a 1t bend is reported possible at 500°F.

Room temperature forming tests over standard honeycomb core ribbon gears show that in the as-received condition, microcracks can be observed in approximately 70 percent of the 5t bends.

Forming under the same conditions as described for the room temperature tests were duplicated at 500 to 550°F with heated gear rolls. Figure 8 shows the equipment and some of the node form test pieces which were varied in bend radii by gear gap adjustment. At 500°F, the frequency of microcracks was between 4 and 20 percent of the bends. Additional refinements made in the 500°F forming range have shown much improvement and has lowered the microcrack frequency to less than 5 percent with the same 5t bend condition.

The data developed on this program does not support the literature in the room temperature ratios, but does show significant improvements by forming in the 500°F range. The standard 1/4-inch cell node requires a 3 to 5t bend. This cell shape, more correctly termed "squarecell", presents the minimum practical nodal area and approaches the literature supported optimum cell for high strength/weight ratio.

The method of crack observation may be the large difference between literature data and observed data. It is extremely difficult to observe microcracks by macro-optical techniques; Solar observed (as did ORNL) that lighting methods are all important. With the rough foil surface, it takes highly skilled technicians to make proper observations and attempts were made to develop penetrant techniques to assure that the visual observations are correct; however, no reliable technique was developed.

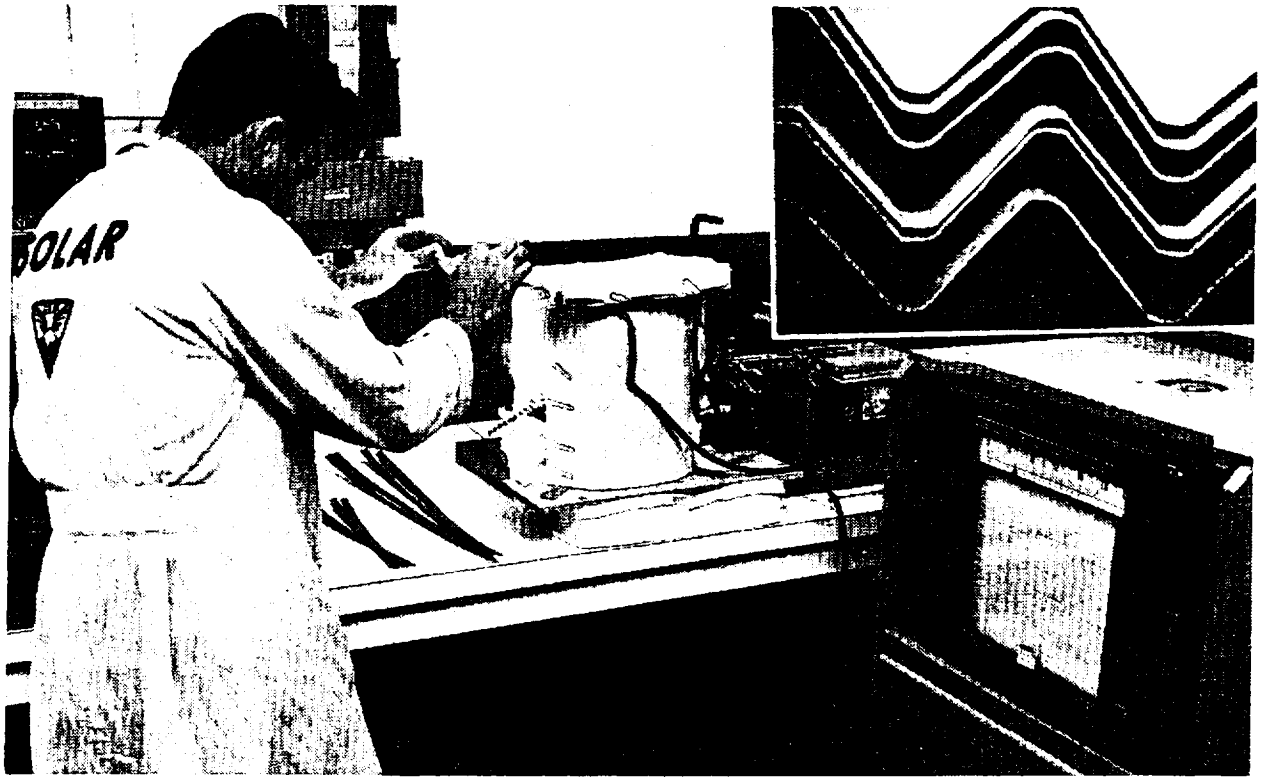


FIGURE 8. WARM-NODE FORMING TESTS OF 0.006-INCH BERYLLIUM FOIL

4.2.3 Microresistance Tack Welding (MRT)

The primary core fabrication method developed for this program is MRT. The goal established for this method was to produce core which will provide reliable handling strength for core surfacing and assembly. The full strength of the node will be developed by the brazing process. Preliminary tests showed that two microresistance tack welds per node will supply the core strength needed for the handling operations.

The secondary core fabrication method is diffusion bonding. This concurrent development will be described in a subsequent paragraph.

Both core fabrication methods are designed for minimum degradation to the beryllium Ingot Foil. In the preferred MRT-brazed node system, the advantages are:

- Fast and economical core fabrication
- The process lends itself to automation
- Two microresistance tack welds have minimum effect on core properties

- The brazing process joins nodes and core to facings in one operation
- Inspection processes are simplified.

Resistance welding schedules were developed to satisfactorily weld the as-received Ingot Foil honeycomb core. Over 100 different tests were evaluated on three different power sources:

- 10 KVA, Seedorf- Model 5705M
- 8.8 KVA, Vacuum Tube Products Model VTF-222
- 160 watt-seconds, Unitek Corp., Weldmatic Model 1034.

Very good results were obtained with the 10 KVA Seedorf power source. The parameters established with this piece of equipment, when coupled to the automatic core machine, produced good results. These tests (Fig. 9) indicated that a 3-pound force on small finger-type electrodes produce sufficient pressure to overcome most of the foil irregularities and make reliable electrical contact. The higher voltages (in the range 10 to 15 volts) and short times (2 cycles) produced the best joints.

It appears that the MRT parameters for rough surface foil welding require close control over the electrode pressure and electrode shape. The unreliable contact area (e.g., resistance) requires a relatively large electrode area with pressures sufficient to assure nodal contact.

Cleaning of the corrugated ribbon in HF-HNO_3 (2 to 12 percent), followed by ultrasonic cleaning in Turco 4215 was standardized as preparatory to the machine tack welding operation.

4.2.4 Automatic Core Machine Modification

A Solar production honeycomb core machine was modified for the 1/4-inch square cell configuration and assigned to this development program during the early phases. The machine, originally made for commercial manufacture of stainless steel core, required refinement before successfully handling beryllium Ingot Foil. These modification details were reported in the First Annual Report (Solar RDR 1550-4).

The automatic core machine is shown in Figure 10.

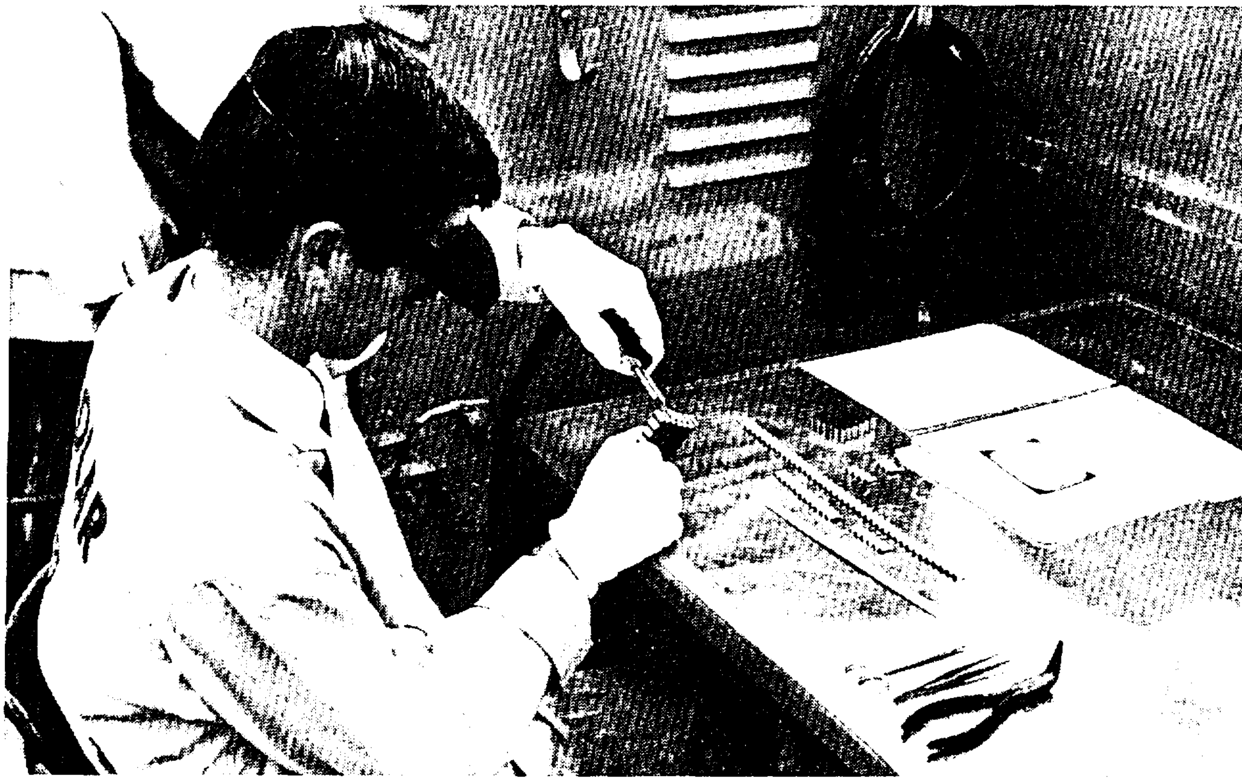


FIGURE 9. MICRORESISTANCE TACK WELDING TESTS OF BERYLLIUM FOIL

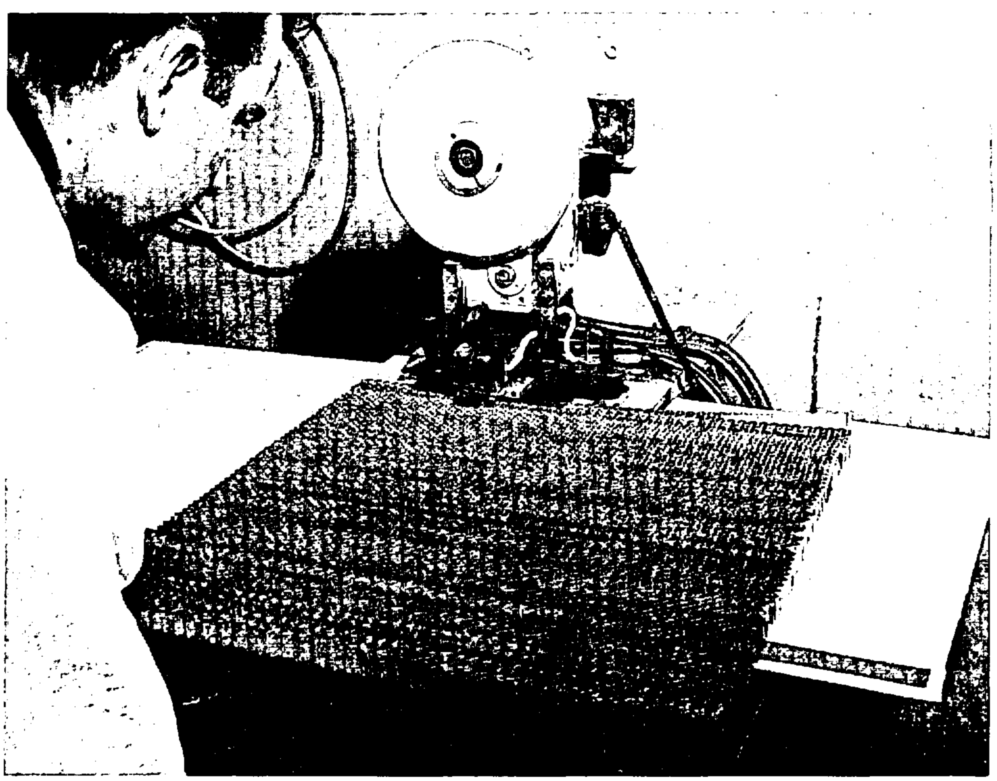


FIGURE 10. AUTOMATIC CORE MACHINE, AS USED IN PHASE II

4.3 DIFFUSION BONDING - TASK 6a

A secondary approach to the core fabrication development was diffusion bonding. A series of tests were conducted to obtain the parameters for diffusion bonding of beryllium Ingot Foil. Figure 11 shows diffusion bonded test specimens and bonder. The First Annual Report gives complete bonding parameters tested and photomicrographs of joints.

The diffusion bonding development study has shown this technique is feasible in joining beryllium. The following summarizes the conclusions reached:

- Metallurgical and mechanical properties are excellent when using 0.001 inch silver interleaf.
- Bonding conditions of 5 ksi, 1400°F, for 30 seconds are good.
- Bonding process conditions appear tolerant to manufacturing variations.
- Heating by electrical resistance through the beryllium stack-up over relatively long current paths results in nonuniform temperature distribution due to thickness stack-up variation and nonuniform current distribution.
- Equipment modification to use self-heated electrodes would be one solution to nonuniform heating problem.
- Roll bonding of the hobe may be another solution to the nonuniform heating problem.
- Bonding in hobe form and post expanding to cellular form at temperature is a satisfactory method of fabricating beryllium honeycomb core.

Although considerable technical progress was made, the diffusion bonding task was terminated and efforts were directed toward the high production, microresistance tack welding method.

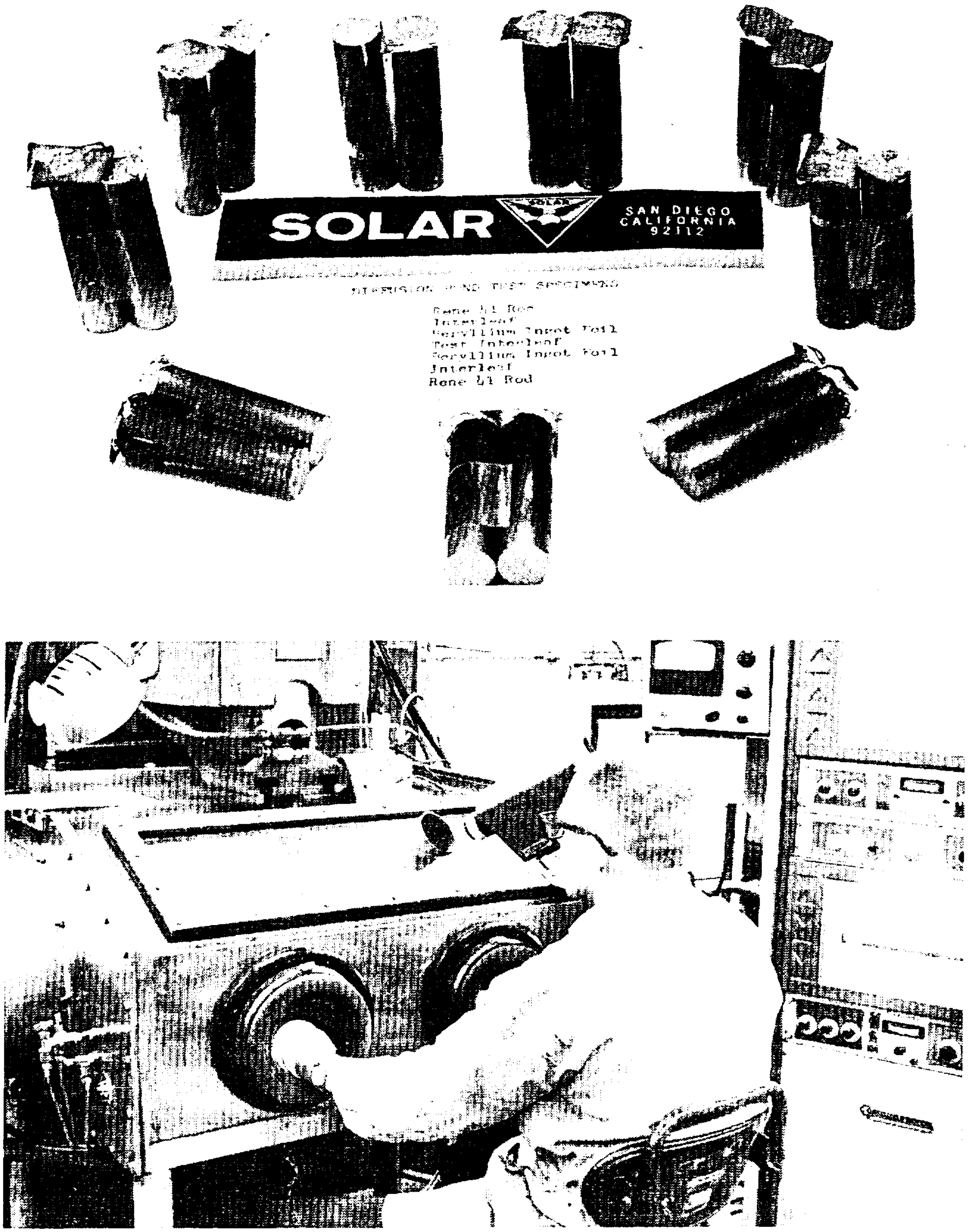


FIGURE 11. DIFFUSION BONDED TEST SPECIMENS AND BONDER

4.4 BRAZE JOINING STUDY - TASK 6b

Twenty-two braze alloy systems, developed by Solar for the Air Force under Contract AF33(615)-2853 (MAMP), Brazing Beryllium by Capillary Flow, were selected for screening. Screening was a two-stage process which covered:

- Flow, wetting, filleting
- Structure
- Corrosion resistance
- Braze temperature
- Production brazing tolerance and scale-up factors
- Mechanical strengths.

4.4.1 First-Stage Screening

The first-stage screening used small, unicell core specimens made by MRT method and brazed to scrap CRS facings. Powdered braze alloy was loaded in the node and fired in a tube furnace in a purified argon atmosphere as shown in Figure 12. The test system was simple, but reproduced many of the factors important to scale-up. These specimens were used to judge the first four parameters. The selection process included:

- Unicell specimens were brazed with the selected braze alloy (Fig. 13); braze tests were performed in small laboratory tube furnace.
- Braze flow (considered to be of prime importance) was evaluated and graded on a 0 to 10 point basis.
- Specimen sections were mounted for metallurgical evaluation of structure, and graded on a 0 to 3 scale. Figure 14 shows selected examples of the 82 specimens examined.
- Sections of all specimens were tested for corrosion resistance in 99 percent relative humidity at 160°F. Visual examinations were made at 30 magnification after 5, 20, and 100 hours. Grading was on a 0 to 3 basis.
- A value grade on a 0 to 4 scale was given each candidate system for items such as erosion tendencies, braze flow temperature, ease of braze alloy manufacture, and visual appearance of the system.

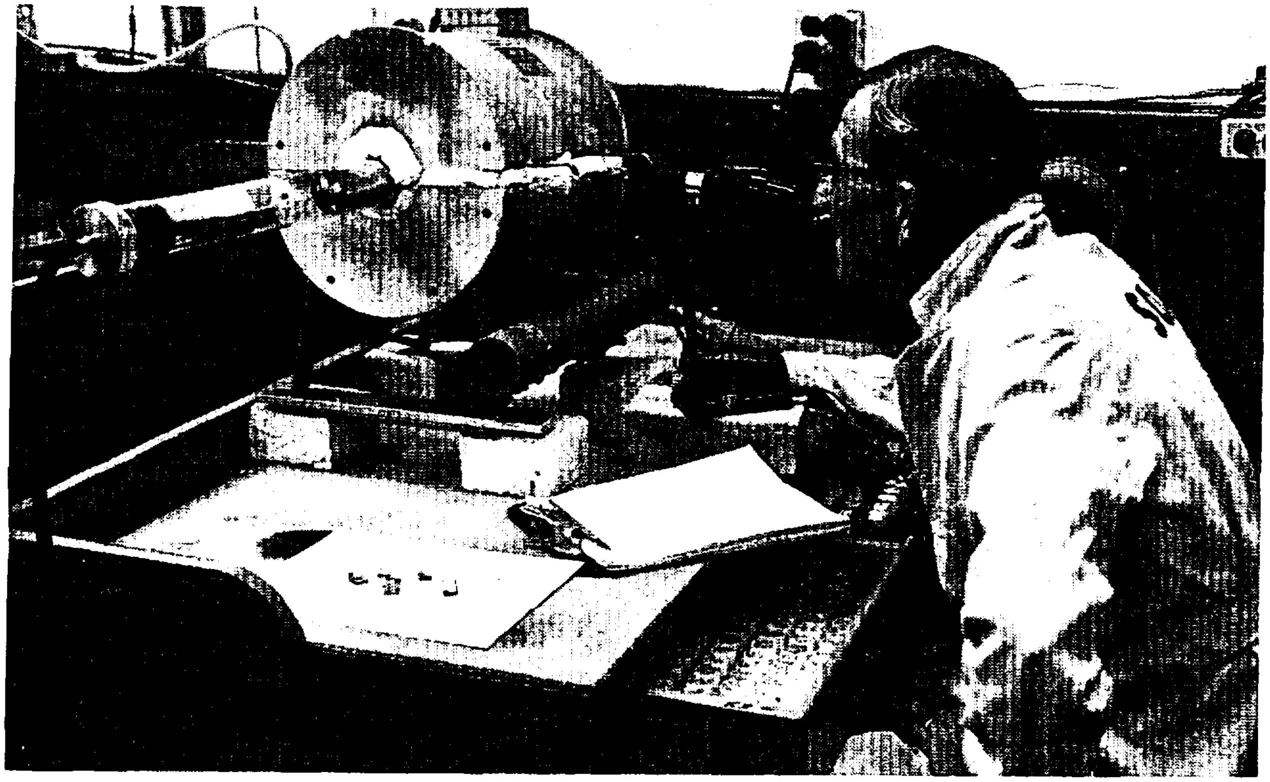
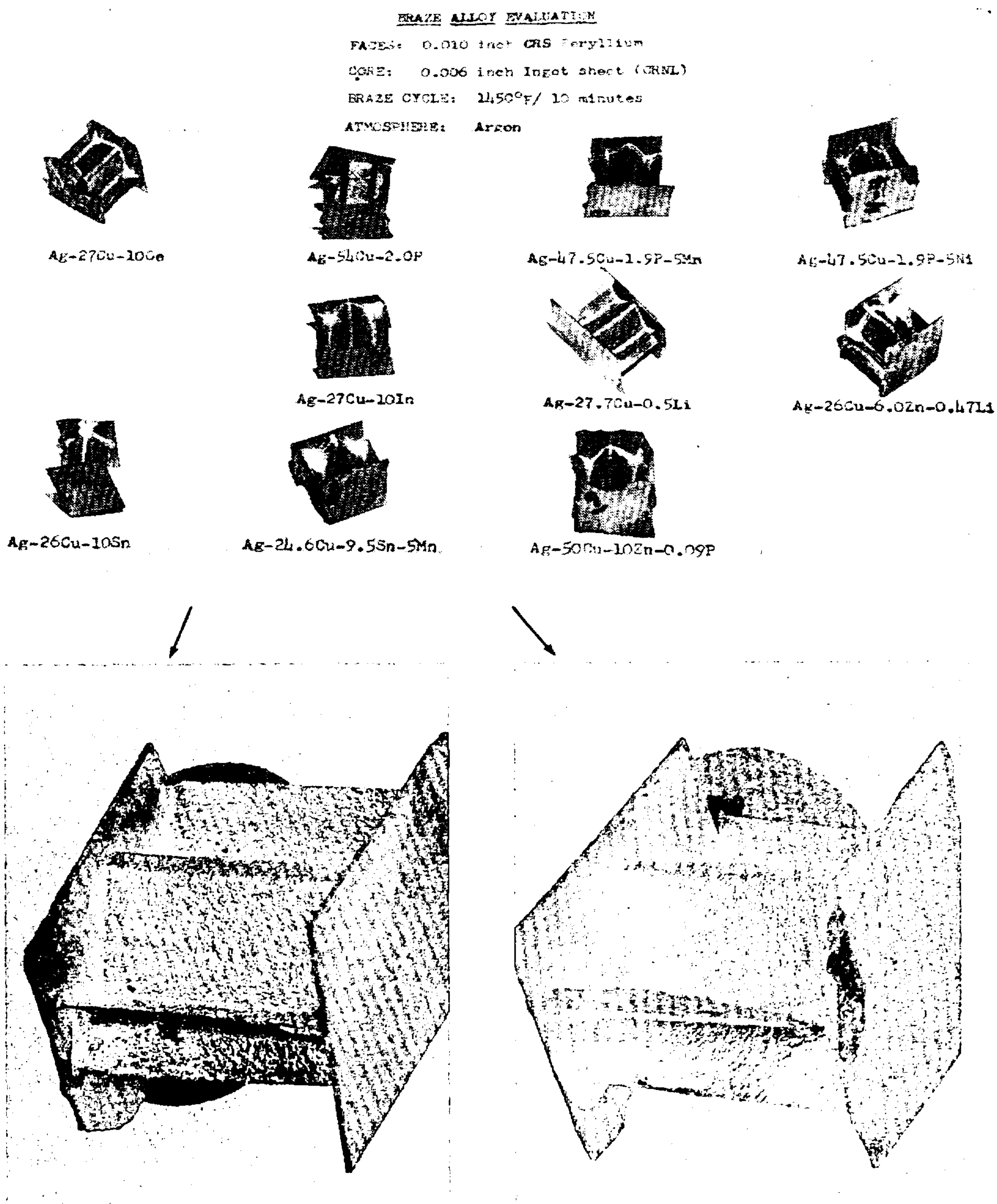


FIGURE 12. BRAZE ALLOY TEST APPARATUS

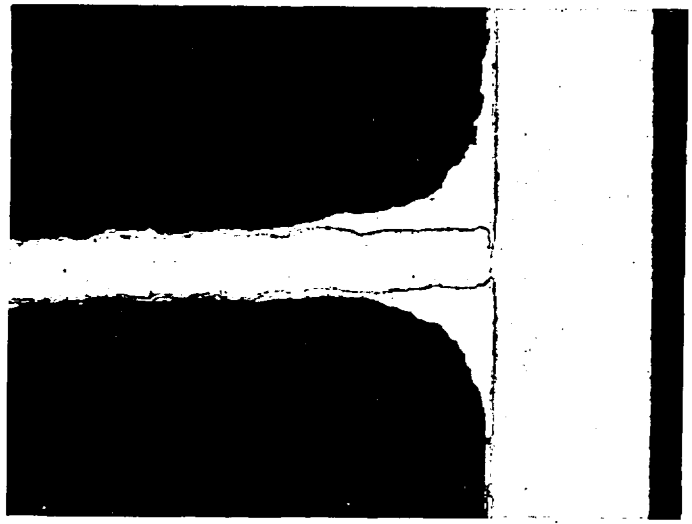
The results of the initial screening are shown in Table IV. From the results of this selection, five braze alloys were chosen for the second-stage screening process which was designed to evaluate the production brazing tolerance, scale-up factors, and mechanical strengths.



Ag, Cu, In Magnification: 3X

Ag, Cu, Mn, Sn Magnification: 3X

FIGURE 13. UNICELL BRAZE ALLOY FLOW SPECIMENS; Brazed at 1450°F for 10 Minutes



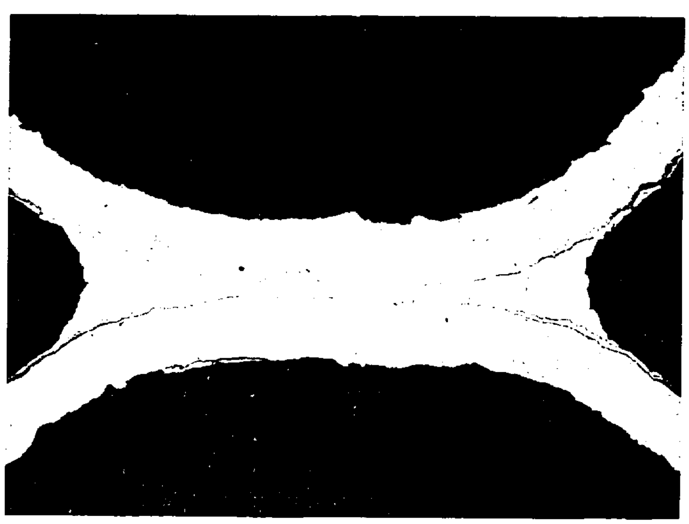
T-JOINT

.020 Be CRS
.006 Be Ingot Foil
BAg-18 Braze Filler

Magnification: 50X

MACRO OF ABOVE

Magnification: 250X

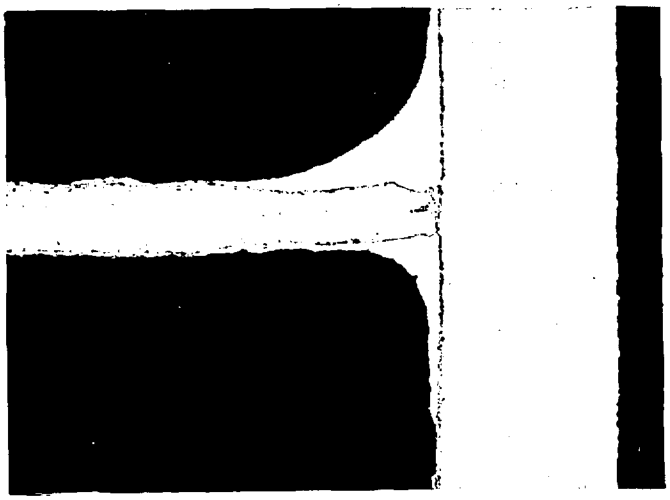


NODE JOINT

Braze Alloy No. 7
(Ag-27Cu-10Sn)

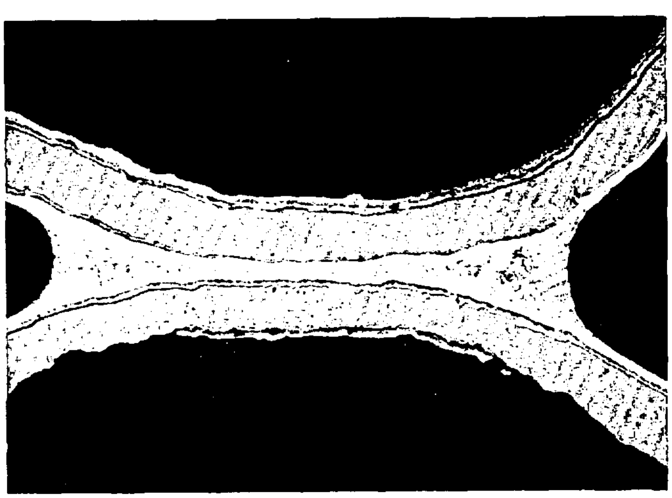
Magnification: 50X

FIGURE 14. BRAZE METALLURGY OF FIVE SELECTED BRAZE ALLOYS
(SHEET 1 OF 2)



Magnification: 50X

Magnification: 250X



Braze Alloy No. 9
(Ag-53Cu-5Zn-0.1P)

Magnification: 50X

FIGURE 14. BRAZE METALLURGY OF FIVE SELECTED BRAZE ALLOYS
(SHEET 2 OF 2)

TABLE IV

BERYLLIUM HONEYCOMB BRAZE ALLOY SELECTION

No.	Composition	Braze Temp. (°F)	Grading System 0-10 Braze Flow	0-3 Corrosion Resistance	0-3 Structure	0-4 Miscellaneous	Total Points	Rank	Comments
1	Ag-27Cu-10Ge	1450	8	2	2	4	16	5	Selected for 2nd stage
2	Ag-54Cu-2P	1450	2	2	1	0	5	22	Erosion
3	AG-47.5Cu-1.9P-5Mn	1450	2	2	2	2	8	21	Marginal
4	Ag-47.5Cu-1.9P-5Ni	1450	2	2	2	2	8	20	Marginal
5	Ag-27Cu-10In	1450	10	2	3	4	19	1	Selected for 2nd stage
6	Ag-27.7Cu-.5Li	1450	4	2	2	2	10	15	Possible
7	Ag-26Cu-10Sn	1450	10	2	3	4	19	2	Selected for 2nd stage
8	Ag-24.6Cu-9.5Sn-5Mn	1450	6	2	2	3	13	10	Possible candidate
9	Ag-50Cu-10Zn-.09P	1450	10	3	3	2	18	3	Selected for 2nd stage
10	Ag-26Cu-6Zn-.5Li	1450	8	2	2	2	14	9	Possible candidate
11-5	Ag-27Cu-10In	1400	4	1	1	3	9	16	Marginal
12-6	Ag-27.7Cu-.5Li	1400	4	2	2	3	11	14	Marginal
13-8	Ag-24.6Cu-9.5Sn-5Mn	1400	2	2	2	3	9	17	Marginal
14-10	Ag-26Cu-6Zn-.5Li	1400	6	1	1	3	11	13	Marginal
15	Ti-30Cu-4Be	1620	10	3	2	0	15	6	Braze temperature to high
16	Ti-39.4Zr-4.5Be-6.7Ni-10Ag	1500	4	2	1	2	9	18	Marginal
17	Ag-59.4Cu-9.5Ge-5Mn-1.9Ti	1450	10	1	3	3	17	4	Selected for 2nd stage
18	Ag-23.6Cu-8.9In-8.8Pd-2Li	1450	8	1	3	2	14	8	Possible candidate
19	Ag-59.4Cu-9.1Ge-9Pd	1450	6	1	1	0	8	19	Erosion
20	Ag-26Cu-9.9Zn-1Li	1450	6	1	2	2	11	12	Marginal
21	Ag-28Cu-.2Li	1450	4	2	2	4	12	11	Possible candidate
22	Ti-47.2Zr-5.6Be	1600	10	3	2	0	15	7	Braze temperature to high

4.4.2 Second-Stage Screening

The five candidate braze systems selected for the second-stage screening were:

- Ag-27Cu-10Ge (Code No. 1)
- Ag-27Cu-10In (Code No. 5)
- Ag-27Cu-10Sn (Code No. 7)
- Ag-50Cu-10Zn-0.09P (Code No. 9)
- Ag-59.4Cu-9.5Ge-5Mn-1.9Ti (Code No. 17)

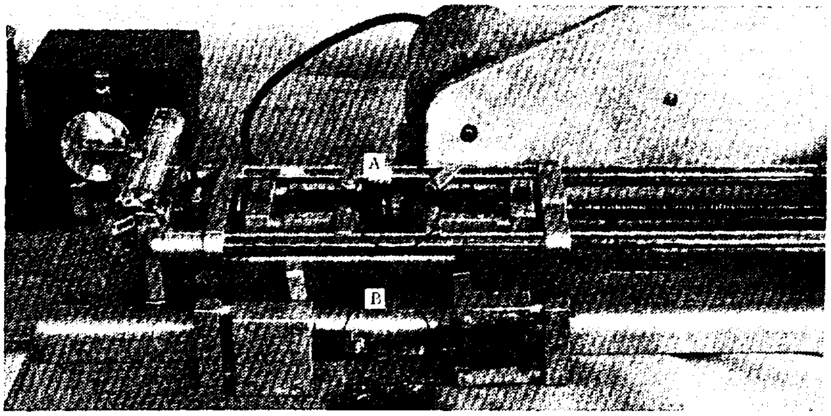
All these alloys were made and comminuted to 30/150 mesh powder. Only one alloy (Code No. 9) did not pass the melt-flow test during braze alloy inspection. This alloy required extensive modification to make it reproducible. The composition was altered to Ag-53Cu-5Zn-0.1P and was subsequently used on subscale testing.

The 2-inch by 2-inch specimens made in the subscale testing phase were tested in flatwise tension, block shear, and flatwise compression. All tests were conducted at room temperature with the setups shown in Figure 15; the results are reported in Table V.

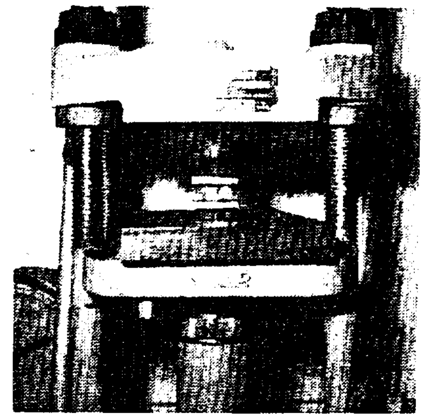
The comparative values in Table V show some of the data for other materials around the same core density as the beryllium Ingot Foil. The values listed for the beryllium core are the preliminary values used in screening the braze alloy systems. Phase II full-scale mechanical testing results are described in subsequent sections.

Code No. 7 braze alloy (Ag-27Cu-10Sn) was the only system tested which produced bonds strong enough to fail the core in both flatwise tensions and block shear; other braze alloys failed to develop full core strength and failed in the joint under the same test conditions. It was therefore concluded that braze alloy Code No. 7 was superior and was used in all of the following phases. It is planned to continue with this alloy for Phase IV as discussed in Section 8 of this report.

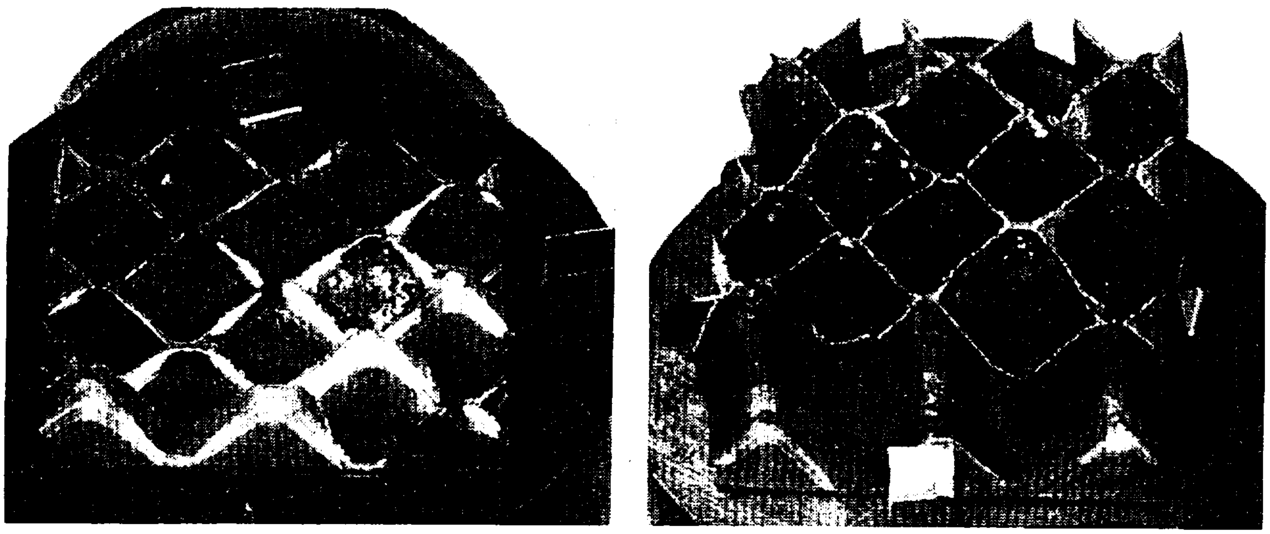
This particular alloy wets and flows well on beryllium surfaces. It has been observed node-capillary flow occurs consistently up to 1/2 inch. In addition, this alloy has the ability to braze bond minute exposed surface irregularity and microcracks.



Tension and Block Shear Test



Flatwise Compression Test



A Flatwise Tension Test Specimens Alloy No. 7 Magnification: 3X
Failed at 760-pound load, 18,000 psi on Foil

B Block Shear Test Specimens Alloy No. 7 Magnification: 3X
Failed at 860 psi, Core Shear

FIGURE 15. MECHANICAL PROPERTY TEST EQUIPMENT AND TYPICAL SPECIMENS

TABLE V

MECHANICAL PROPERTY EVALUATION
(Second-Stage Screen Tests)

NOTE:

Faces: 0.020 CRS Be
Core: 460-1/2 (1/4 square cell, 0.006 inch nominal foil, 1/2 inch thick)
Size: 1 sq in. cut from 2 x 2 specimen

Code No. 1 braze alloy (Ag Cu Ge) not tested (failed in scale up)
Data measurement assumes all Be ingot foil is 0.006 inch
Core density 5.3 lb/ft^3

A. FLATWISE TENSION

Braze Alloy	Specimen Number	Core Tensile Stress (psi)	Tensile Stress On Ribbon Neglecting Braze Reinforcement (psi)	Failure Mode
Code No. 5	6-5-A	330	9700	Joint
Ag-27Cu-10In	6-5-B	240	7500	Joint
Code No. 7	5-7-A	760	18,000	Core Foil
Ag-27Cu-10Sn	5-7-B	540	18,000	Core Foil
Code No. 9	5-9-A	260	6,340	Joint
Ag-53Cu-5Zn-0.1P	5-9-B	200	5,550	Joint
Code No. 17	5-17-A	250	4,410	Joint
Ag-50.4Cu-9.5Ge-5Mn-1.9Ti	5-17-B	420	8,570	Joint

B. BLOCK SHEAR

Braze Alloy	Specimen Number	Ribbon Direction L - Longitudinal W = Width	Core Shear Stress (psi)	Apparent Core Foil Tensile Stress (psi)	Failure Mode
Code No. 5	6-5-C	L	470	10,000	Joint
Code No. 7	6-7-C	L	860	20,000	Core
Code No. 9	5-9-C	L	230	5,750	Joint
Code No. 17	5-17-C	L	200	4,650	Joint

Comparatives

Material	Core Type	Core Density (lb/ft^3)	Ribbon Direction L = Longitudinal W = Width	Core Shear Strength (psi)
3003 Al	420 hex	4.3	L	265
3003 Al	430 hex	6.0	L	450
5056 Al	420 hex	4.3	L	400
5056 Al	320 hex	5.7	L	585
15-7PH	420 sq	7.7	L	380
15-7PH	620 sq	5.1	L	240
15-7PH	440 sq	16.2	L	860
Beryllium (IF)	460 sq	5.3	L	860

C. FLATWISE COMPRESSION

Braze Alloy	Specimen Number	Core Compressive Strength (psi)	Foil Compressive Stress Neglecting Braze Reinforcement (psi)	Failure Mode
Code No. 1	3-1-A	1650	38,400	Core
Ag-27Cu-10Ge	3-1-B	2330	55,000	Core
Code No. 5	6-5-C	2750	63,200	Core
Code No. 7	6-7-A	2060	47,900	Core
	5-7-C	3160	74,200	Core
Code No. 9	5-9-C	3160	74,200	Core
Code No. 17	5-17-C	3840	89,000	Core
	4-17-A	3020	70,300	Core
	4-17-B	2880	67,000	Core
None	-	1370	31,800	Core

Comparatives (Faces Attached To Approximate Service Conditions)

Material	Core Type	Core Density (lb/ft^3)	Core Compressive Strength (psi)
3003 Al	420 hex	4.3	435
3003 Al	430 hex	6.0	745
5056 Al	420 hex	4.3	650
5056 Al	320 hex	5.7	1040
15-7PH	420 sq	7.7	530
15-7PH	620 sq	5.1	235
15-7PH	440 sq	16.2	2200
Beryllium (IF)	460 sq	5.3	3000

4.5 SUBSCALE TESTING - TASK 7

The objective of subscale testing in Phase I was to make the first scale-up step by:

- Establishing core cutting and lapping procedures
- Establishing core cleaning and preparation
- Evaluation of practical braze cycles
- Evaluation of practical pressure cycles
- Establishing braze atmosphere control
- Establishing mandrel design
- Integration of the entire fabrication system and operation sequence
- Providing screening test specimens (Section 3.5.2) for mechanical property evaluation in block shear, flatwise tension, and flatwise compression; and metallurgical evaluation after the practical braze cycle.

Typical sandwich components used in the subscale test program are shown in Figure 16. The core used in this phase was mainly machine made.

Core in the larger blankets (6-inch by 6-inch and 6-inch by 12-inch) were lapped to size by removing 0.005 to 0.013 inch ribbon mismatch. The operation chosen for lapping involved registering the core blanket to a precision aluminum flat plate and freezing in position. This technique provides a firm support for the subsequent handhoning operation. A large flat hone is worked over the surface by hand until all portions of the core face have been surfaced. The operation is repeated on the second side as the final operation. Although the operation is accomplished by hand methods, excellent tolerances (on the order of ±0.002 inch) can readily be obtained on thickness and parallelism.

Several methods of core cleaning have been tested in the subscale series. All have been successful in part; however, the method selected as best for all alloy systems was:

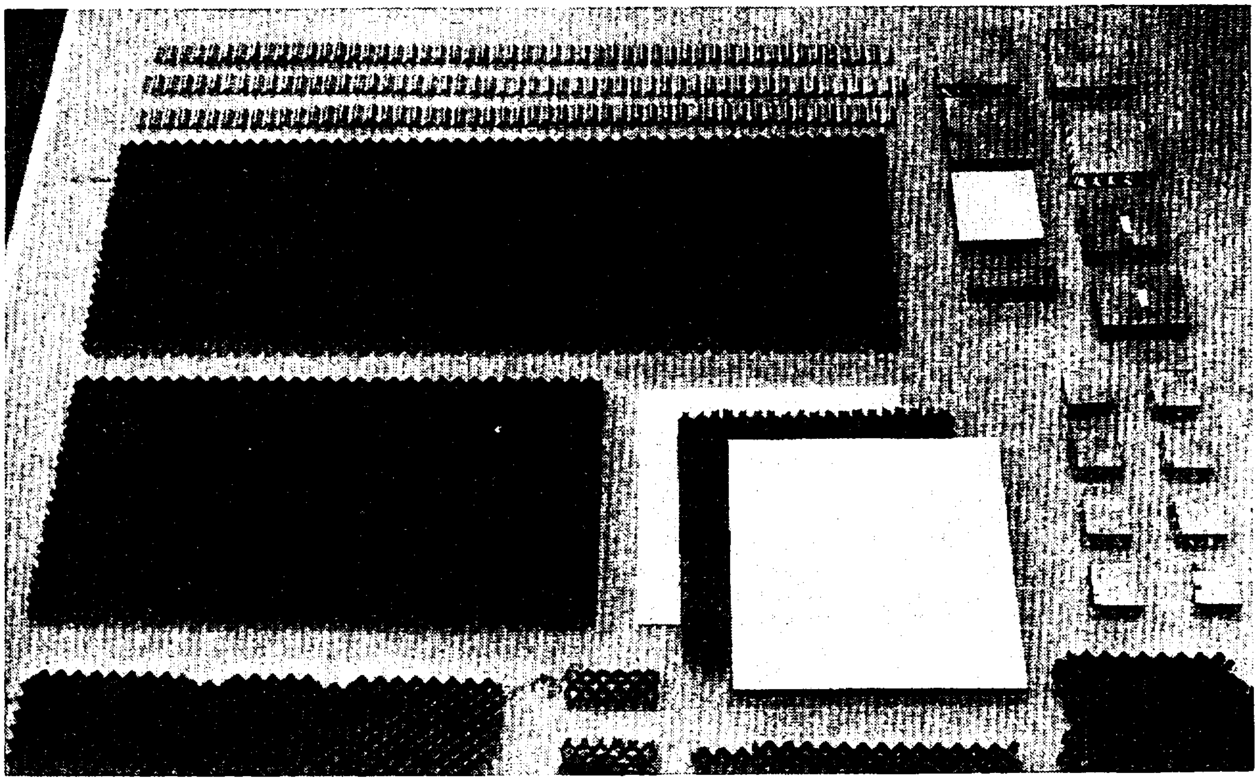


FIGURE 16. MACHINE-MADE HONEYCOMB CORE AND TYPICAL SUBSCALE TEST SPECIMENS

- Light etch in 2HF-15HNO_3 (Vol. %)
- Deionized water rinse
- Ultrasonic clean in Turco 4215
- Deionized water rinse
- Force dry in air oven at 200 to 250°F

All during this phase, parameters of the braze and pressure cycle were evaluated and the system shown in Figure 17 gave the best results. The total cycle was essentially a four-step process consisting of:

- Atmosphere exchange purge (replacement of all air in cells with argon)
- Outgassing purge (removal of moisture and adsorbed surface gases)
- Braze flow cycle (under static atmosphere)
- Cooling cycle (under static and rarified atmosphere)

Atmosphere strip checks were made frequently during the brazing cycle. These checks were fast but sensitive indications of the atmosphere conditions. During the braze cycle, there were many arrest points where decisions were made for continuing the cycle. For example, should the strip check prove negative after the first or second step, the brazing process was aborted or delayed without damage to the assembly. Only after all systems checked positive was the part committed to the total braze flow cycle.

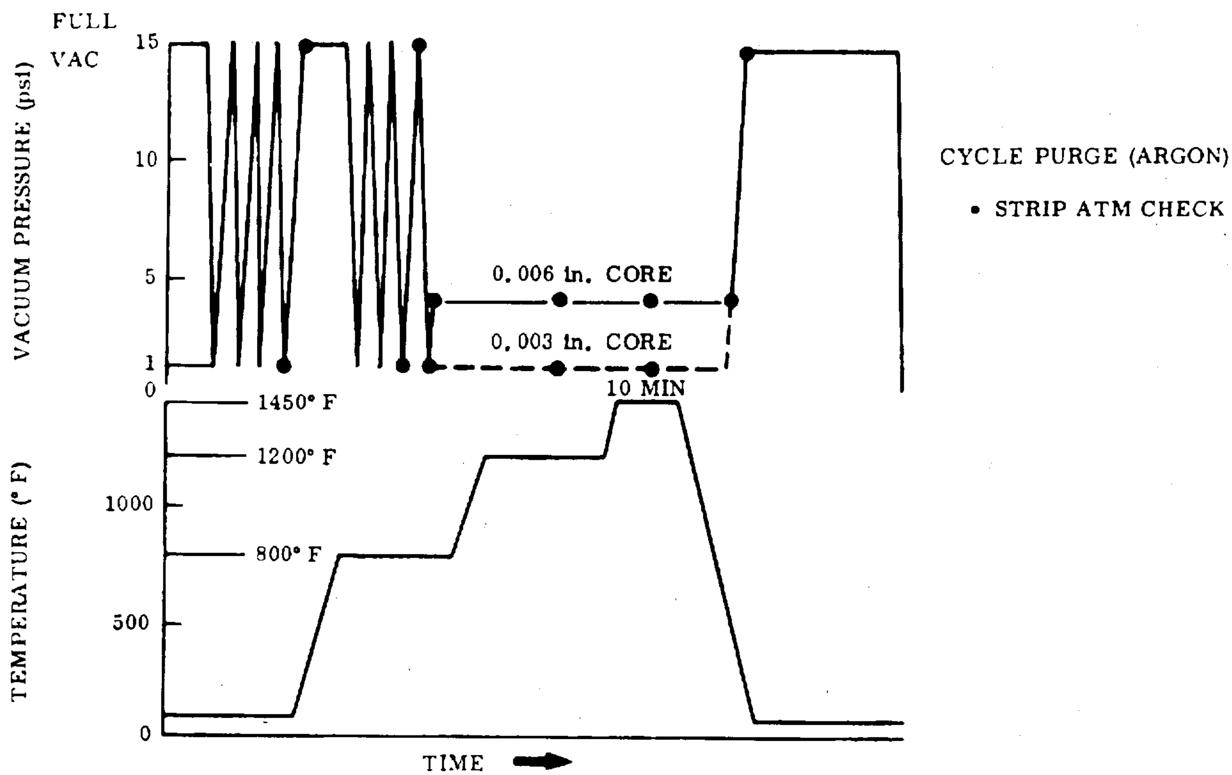


FIGURE 17. TIME - TEMPERATURE - PRESSURE BRAZE CYCLE

The atmosphere control panel (shown in Figure 18) for the braze system incorporated a liquid argon atmosphere supply (boil-off), vacuum pump, both fore line and exhaust line pressure manometers, titanium getter, various control valves, atmosphere strip checker, and an absolute exhaust filter for biological safety.

The mandrel system developed in the subscale test program is shown in Figure 19. Mild steel pans were formed with a lip for "peanut" seal welding and two 3/8-inch inlet and exhaust lines were welded at opposite corners. A thermocouple array was attached to the pan faces to indicate temperature and gradients.

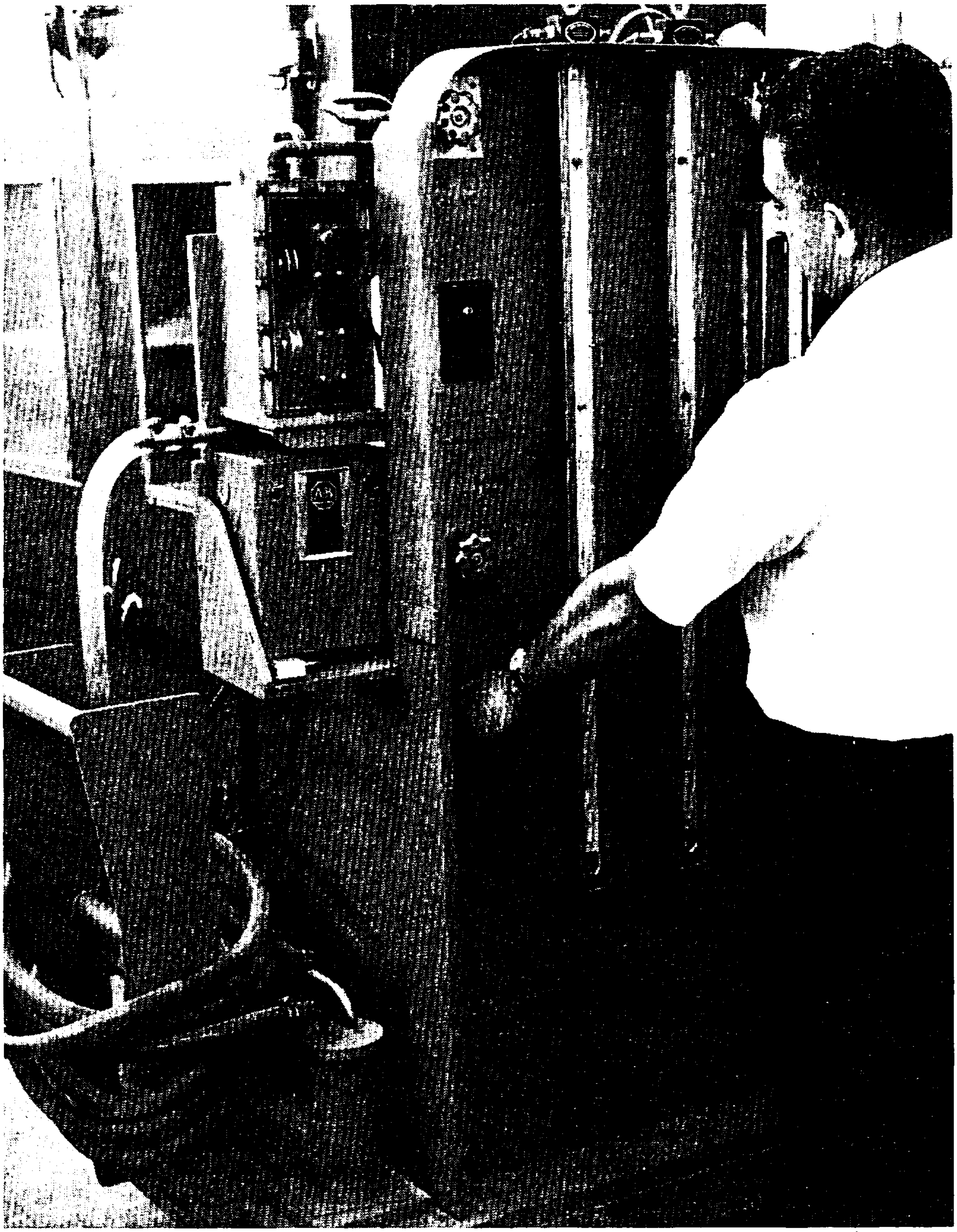


FIGURE 18. SOLAR'S ATMOSPHERE CONTROL PANEL

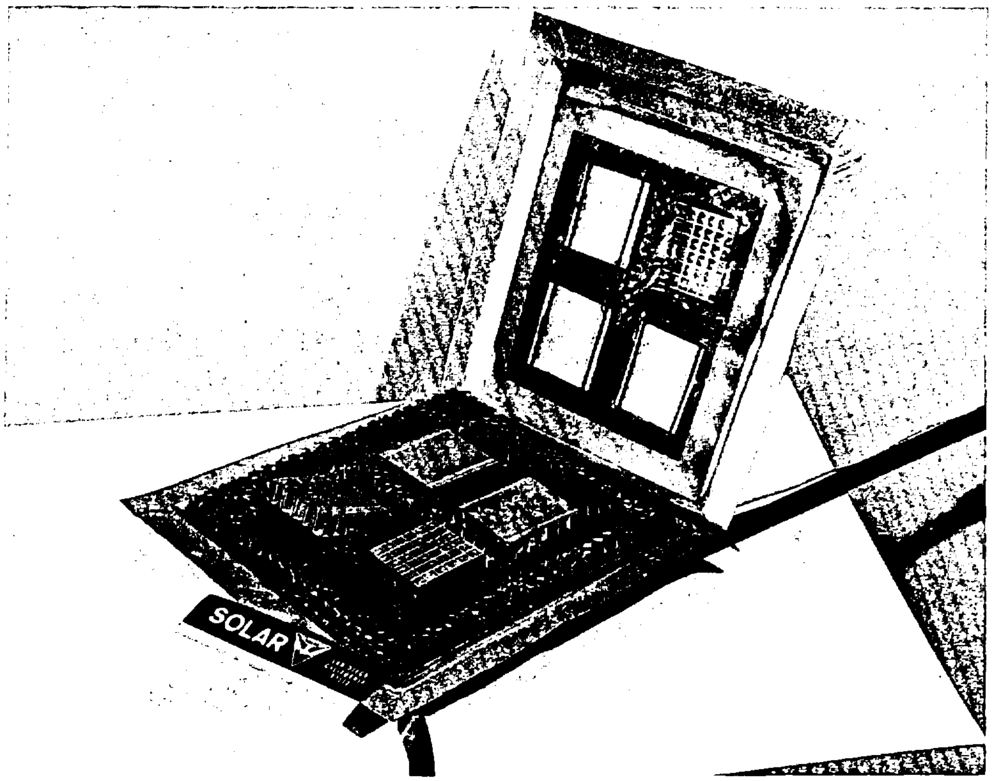


FIGURE 19. SUBSCALE MANDREL SYSTEM

The subscale test panels were 2 inches square by 1/2 inch thick. The ingot foil core was 460 (4/16 inch square cell and 60/10,000 inch foil gage) and the faces 0.020-inch CRS beryllium. These panels were brazed with the five candidate braze alloys in a system which could accommodate an 8-inch by 8-inch panel. The large size mandrel was used to provide a practical base for the scale-up parameters. Titanium core was used as a filler surrounding the test specimens (Fig. 19). Twenty panels were manufactured during this subscale testing phase.

Integration of all assembly and system details was successful. Reliable conditions were established to obtain braze flow over 100 percent of the faying areas of the specimens, including both nodes and face-core joints.

A weight analysis of the initial subscale specimens resulted in a total of 0.82 lb/ft^2 based on an alloy load rate of 100 gm/ft^2 with 1/2-inch thick 460 core and 0.020-inch face sheets.

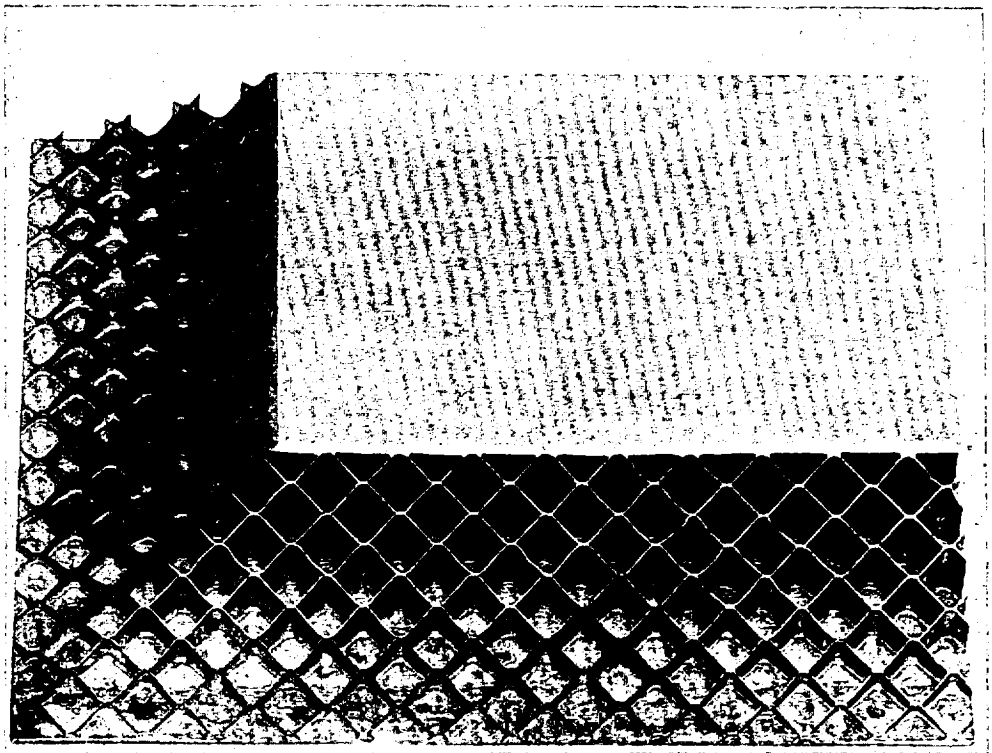


FIGURE 20. BRAZE LOAD/RATE TEST SPECIMEN NO. 17-10

4.6 SCALE-UP EVALUATION

Using the processes developed in Phase I, four, 6-inch by 6-inch panels were brazed to evaluate braze alloy loading rates and scale-up conditions. An arbitrary braze load rate of 100 gm/ft^2 was adopted for all Phase I screening tests on 1/4-inch square cell, 1/2-inch thick sandwich; however, braze load rates of 28 to 100 gm/ft^2 were evaluated during this phase. Typical of the scale-up panels is the one shown in Figure 20; this particular panel incorporated a comparison between foil and wire braze alloy loading. Nondestructive inspection of specimen 17-11 is shown in Figure 21. This panel was all-wire loaded in various sections with a load rate of zero to 84 gm/ft^2. Powder, wire (0.010 and 0.020 inch diameter), and foil were investigated as preplacement braze alloy forms.

Results of the scale-up tests indicated a loading rate of approximately 50 gm/ft^2 as the preferred condition, with the 0.020-inch diameter braze alloy wire showing best results. The single-wire increment into each cell node provided filler metal to feed all capillaries. Powder filler metal was also convenient in this regard except the higher surface area of the powder presented a cleaning problem and the loading process was more variable. Foil was also a convenient method of applying braze alloy; however, it was not efficient as it wets the entire facing area along with the capillaries. Special loading techniques may eliminate this foil-loading inefficiency.

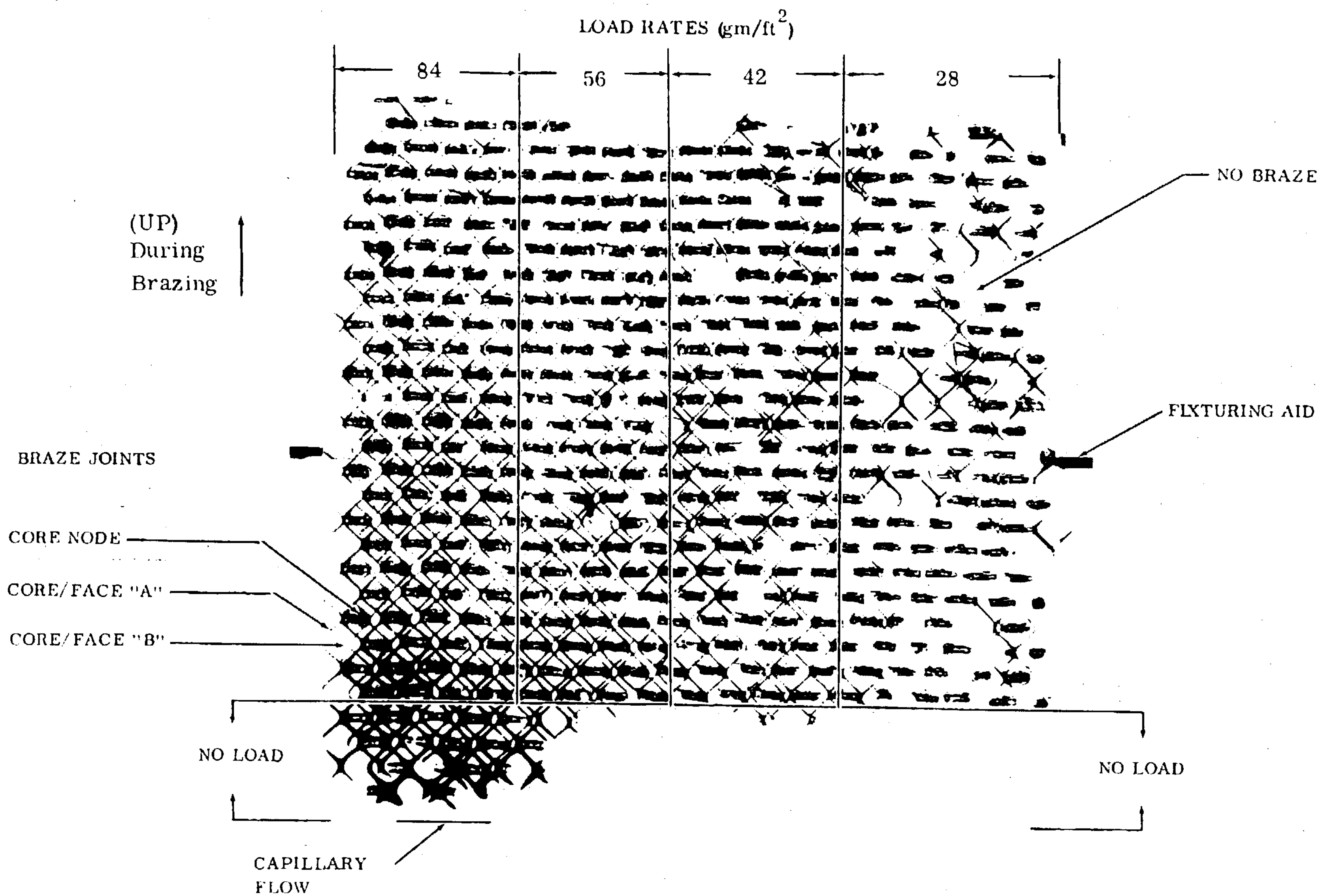


FIGURE 21. RADIOGRAPH OF BRAZE LOAD/RATE TEST SPECIMEN NO. 17-11

The weight breakdown, as determined from these scale-up tests, is shown in Table VI. However, these weights may be lowered by several methods. One method

TABLE VI

BERYLLIUM HONEYCOMB SANDWICH WEIGHTS

Component	Weight (lb/ft^2)	
	4-60-1/2 core[(1)]	4-30-1/2 core[(2)]
Core	0.22	0.11
Faces: 0.020 inch CRS (2)	0.38	0.38
Braze Alloy (at 50 gm/ft^2)	0.11	0.11
Total weight of sandwich with 0.020-inch facings	0.71	0.60

1. 4-60-1/2 = 4/16-inch cell size, 60/10,000-inch foil gage, 1/2-inch thick core

2. 4-30-1/2 = 4/16-inch cell size, 30/10,000-inch foil gage, 1/2-inch thick core

demonstrated was lowering the alloy load rate from 100 gm/ft^2 in the subscale panels to 50 gm/ft^2 in scale-up panels (reduced total from 0.82 lb/ft^2 to 0.71 lb/ft^2 using 4-60-1/2 core). Another method is to lower the facing weight by selective chemical milling the face sheets as shown in Figure 22. A theoretical panel using 0.003-inch facings coupled with demonstrated 4-30-1/2 core and 50 gm/ft^2 alloy loading rate would weigh only 0.28 lb/ft^2. In certain applications, these light-weight panels would be extremely weight-efficient while maintaining useful structural properties.

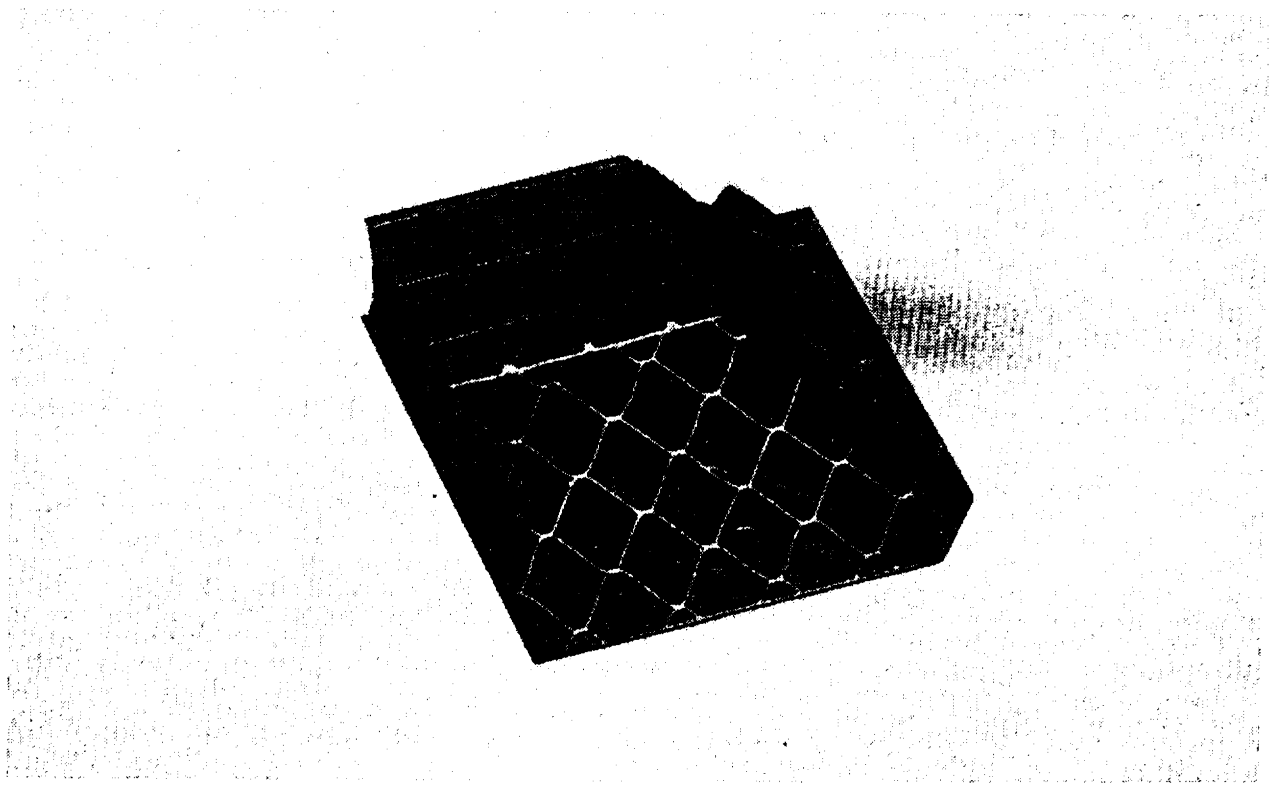


FIGURE 22. BERYLLIUM HONEYCOMB SANDWICH BRAZED WITH Ag Cu Sn

5

TECHNICAL DISCUSSION PHASE II

5.1 SCALE-UP PANELS - TASK 8

This section describes the fabrication of the required 6-inch by 6-inch, 12-inch by 12-inch, and 18-inch by 18-inch brazed beryllium honeycomb panels which were committed to mechanical testing or to delivery to NASA.

A flow diagram for these production panels was established to maintain traceability and assignment of specimen numbers. The diagram shows core and panel sizes, sectioning directions, test assignments, in addition to Ingot Foil and CRS sheet lot control (available in First Annual Report).

Basic procedures previously established were followed throughout this phase of the program, although minor refinements, modifications, and improvements continually updated the processes.

Typical views of the fabricated core and brazed panels are shown in Figures 23 through 25.

5.1.1 Six-Inch Square Panels

A total of eight, 6-inch square panels was fabricated; four of these incorporated 4-30-1/2 core and four incorporated 4-60-1/2 core.

Typical of the high quality of the braze wetting and flow observed on all of these production panels is shown by the radiograph in Figure 26 (this was the first production panel brazed). No problems were encountered during this phase of the program.

5.1.2 Twelve-Inch Square Panels

Two panels were required for mechanical test specimens and scale-up evaluations. Some processing modifications were required for the scale-up tests. These modifications included using paraffin in place of the previously used method of fixturing

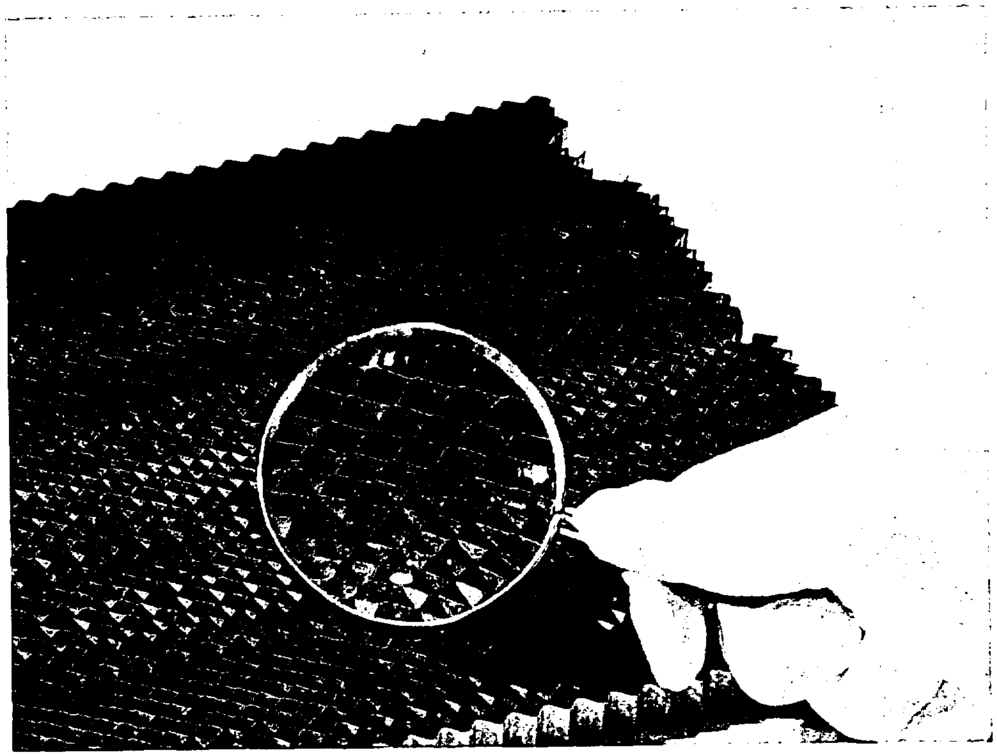


FIGURE 23 AUTOMATIC RESISTANCE SPOT WELDED BERYLLIUM CORE BLANKET

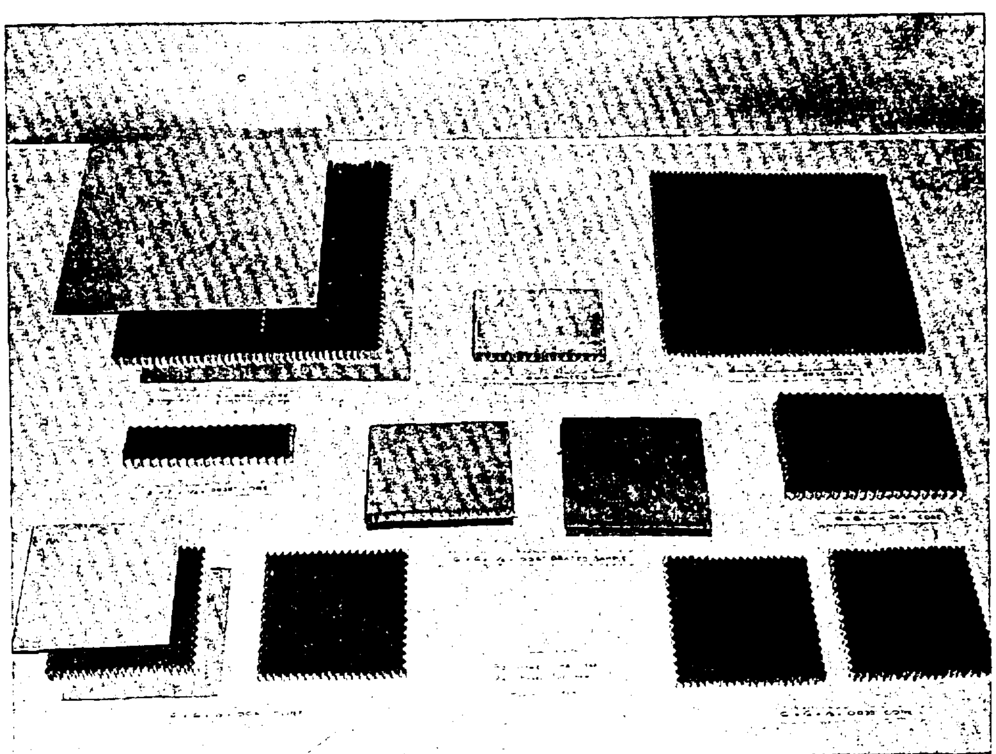


FIGURE 24 ASSORTED CORE BLANKETS AND BRAZE PANELS

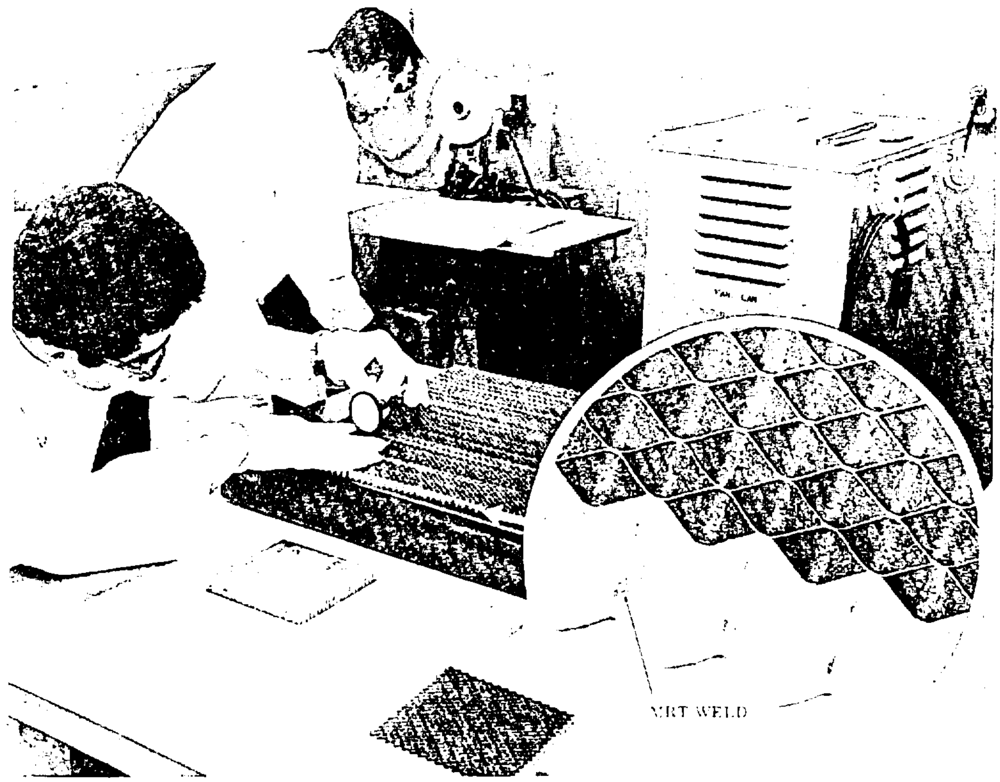


FIGURE 25. FABRICATING AND INSPECTING BERYLLIUM HONEYCOMB CORE

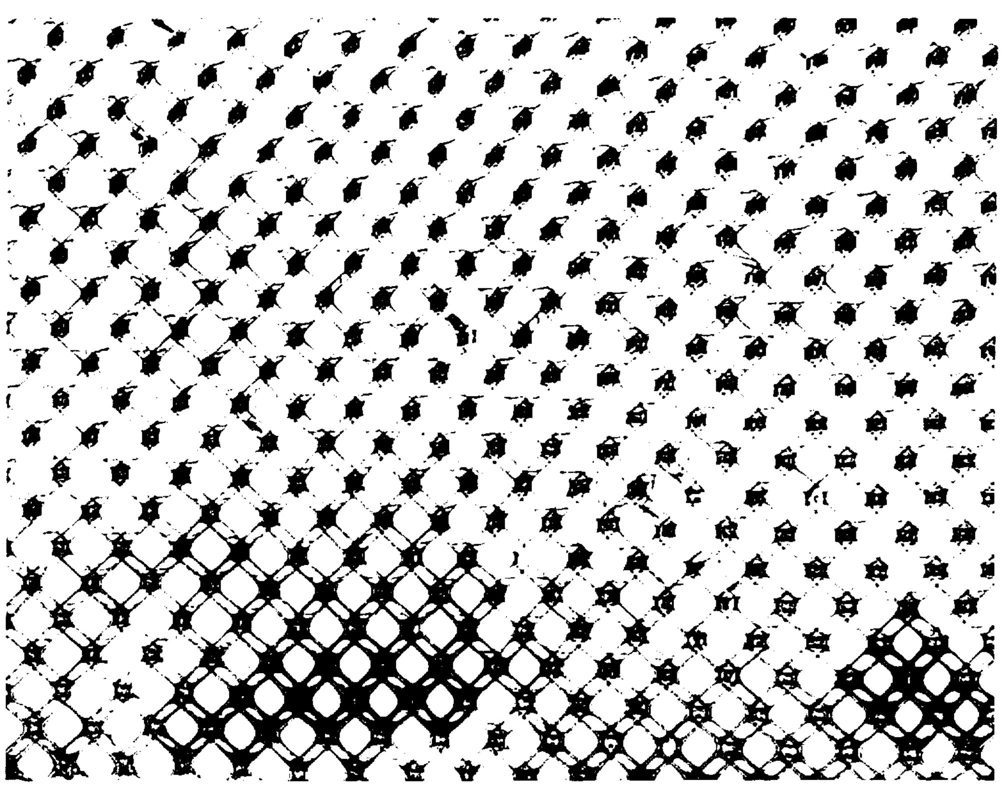


FIGURE 26. RADIOGRAPH OF FIRST 6-INCH BY 6-INCH PRODUCTION PANEL
(Specimen No. 22-12)

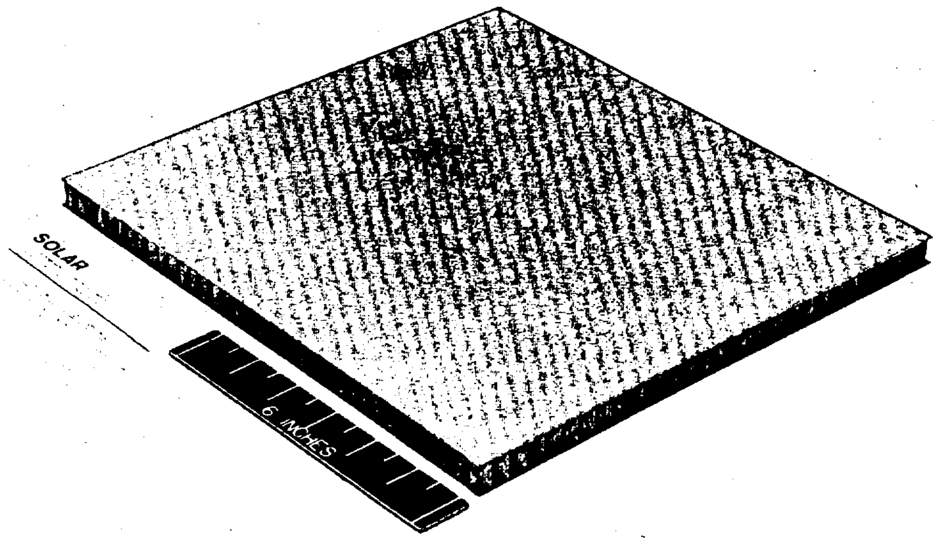


FIGURE 27. TWELVE-INCH SQUARE BERYLLIUM HONEYCOMB PANEL

the core to a reference plate by freezing with deionized water, and increasing furnace size to accommodate larger panels.

Two panels were fabricated for mechanical test specimens and scale-up evaluations. Various problems were encountered and solved with both of these panels.

Incomplete wetting of the first 12-inch square panel (Fig. 27) was eliminated in the second by decreasing both clean lay-up time and the muffle inlet and outlet lines. However, slight core deformation was observed in the second 12-inch square panel (Fig. 28). This was a result of the 3-mil core being subjected to increased time at temperature while pressure (1 psi) remained the same as compared to the small 6-inch^2 panels.

5.1.3 Eight-Inch Square Panels

As a result of the experiences on the two 12-inch square panels, a new furnace facility was reviewed for brazing. This furnace had the required capacity and was equipped with a circulating fan. A calibration run verified the braze cycle could be reduced by 50 percent while losing only 5°F in temperature uniformity. The furnace was modified to accept the muffle inlet and outlet lines.

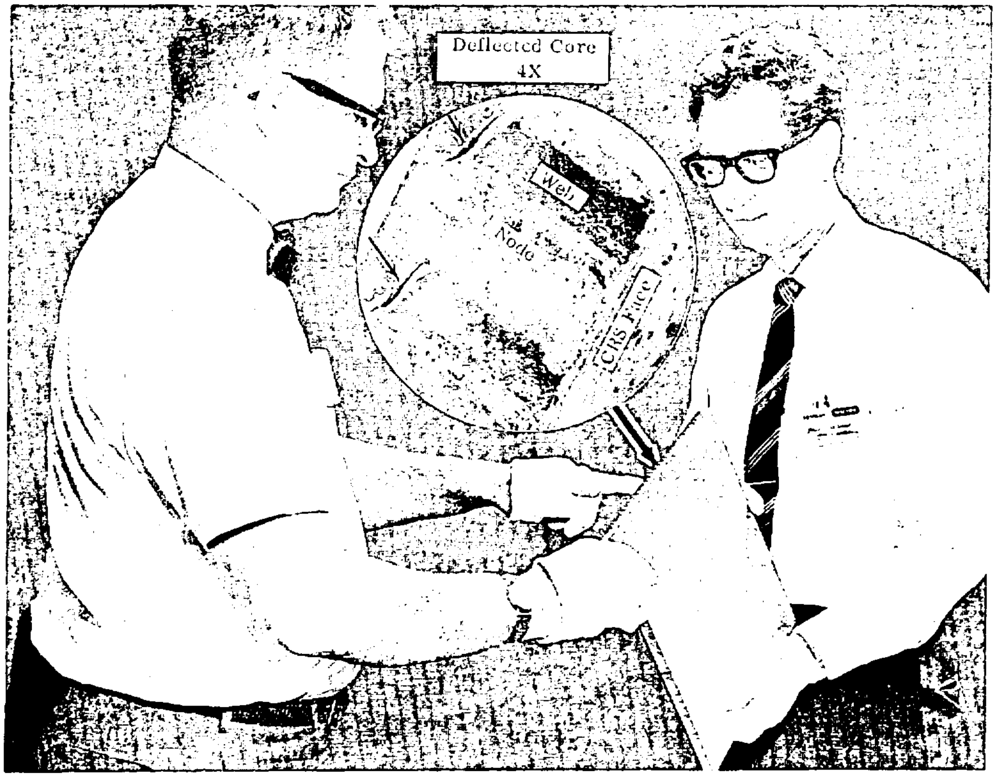


FIGURE 28. CREEP DEFORMED CORE OF PANEL NO. 22-20

First 18-Inch Square Panel

This panel represented a large scale-up from all previous panels. It was fabricated from 4-30-1/2 core (3-mil ribbon). Although complete success was not achieved, important experience was gained.

A slight curve was induced into the panel as a result of one argon tube applying a torque force about its inlet at the muffle flange. In addition to causing some non-brazed areas because of created gaps, this force deflected the panel out-of-flat by approximately 1/4-inch.

The panel was sectioned to compare the X-ray inspection and physical internal braze conditions. Excellent correlation was observed. Good quality was observed in undisturbed areas.

Second 18-Inch Square Panel

All of the technology developed previously was applied to this 18-inch square beryllium honeycomb panel. The core was automatic microresistance welded from 6-mil Ingot Foil ribbon stock and hand surfaced to the required smoothness. Fixturing

FIGURE 29. FIXTURED BERYLLIUM HONEYCOMB PANEL IN BRAZING FURNACE

problems and heating cycles were corrected prior to the actual brazing. The fixtured panel and brazing furnace are shown in Figure 29.

An excellent braze run following previously established parameters was made with good temperature and time control. Visual inspection after brazing showed discoloration of the exposed periphery cells caused by atmosphere contamination; however, X-ray inspection revealed good brazing of the internal cells. (A subsequent trim of the outer edges confirmed this.) Dimensional checks showed excellent precision as the panel was flat and parallel within 0.006-inch. Figures 30 and 31 show the panel in the as-brazed and as-trimmed conditions, respectively.

Shipment of these panels to NASA marked the completion of the first two phases of the program.

5.2 MECHANICAL TESTING - TASK 9

Based on the available beryllium foil supply, it was necessary to fabricate and test production core blankets made from both 3- and 6-mil material. The general test matrix is shown in Table VII.

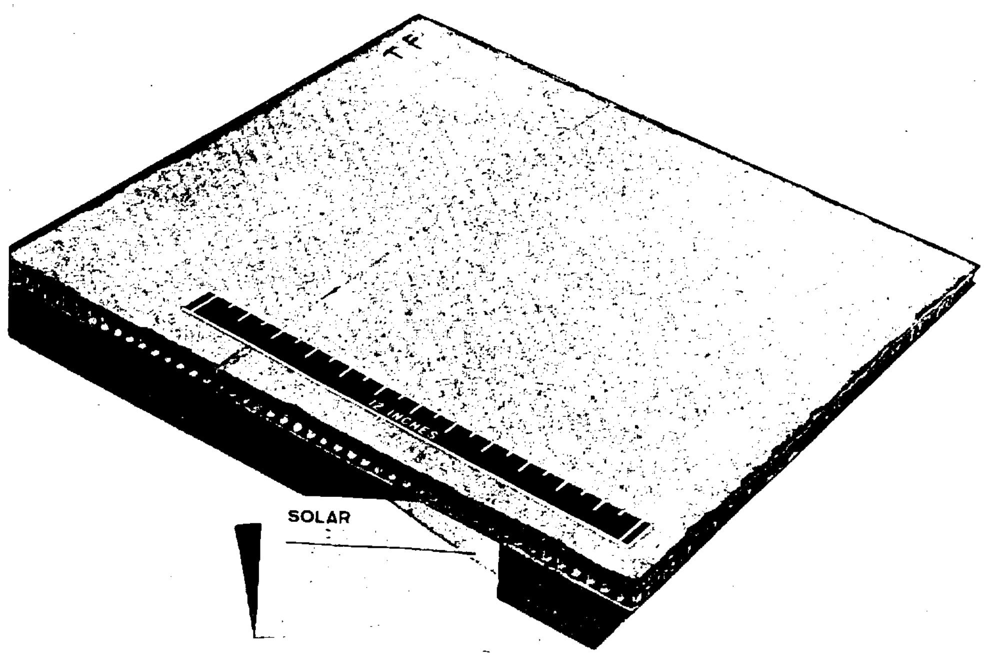


FIGURE 30. EIGHTEEN-INCH SQUARE PANEL, AS-BRAZED

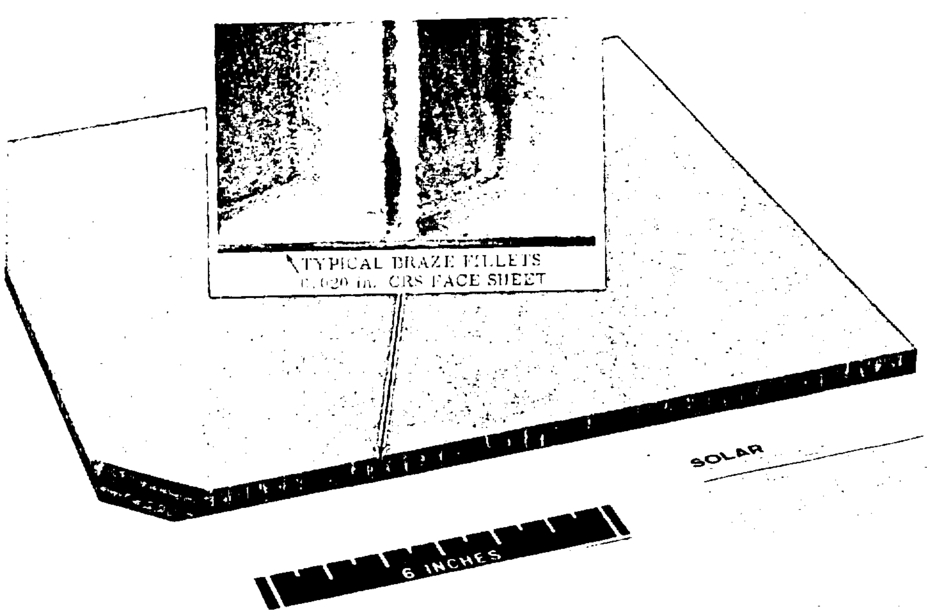


FIGURE 31. EIGHTEEN-INCH SQUARE PANEL, AS-TRIMMED

TABLE VII

PHASE II TEST MATRIX

Type of Test	Temperature (°F)	Number of Specimens			
		0.003 in. Ribbon	0.006 in. Ribbon	Subtotal	Total
Flatwise Compression (1 in. x 1 in.)	RT	2	2	4	14
	300	2	2	4	
	600	2	2	4	
	*	1	1	2	
Flatwise Tension (1 in. x 1 in.)	RT	2	2	4	14
	300	2	2	4	
	600	2	2	4	
	*	1	1	2	
Edgewise Compression (3 in. x 4 in.)	RT (L)	1	1	2	12
	RT (T)	1	1	2	
	600 (L)	2	2	4	
	600 (T)	2	2	4	
Block Shear (2 in. x 3 in.)	RT (L)	2	2	4	32
	RT (T)	2	2	4	
	300 (L)	2	2	4	
	300 (T)	2	2	4	
	600 (L)	2	2	4	
	600 (T)	2	2	4	
	* (L)	2	2	4	
	* (T)	2	2	4	

* Spares to be tested as required.

(L) = Longitudinal Ribbon Direction

(T) = Transverse Ribbon Direction

Tests of edgewise compression, flatwise compression, flatwise tension and block shear were performed. Results are summarized in Table VIII. Actual test set-ups and specimen failures are shown in the First Annual Report.

Additional test results of Phase III are discussed in Section 6.5 of this report.

TABLE VIII

MECHANICAL TEST PROPERTIES OF BRAZED BERYLLIUM HONEYCOMB SANDWICH PANELS (PHASE II)

Type	Specimen No.	Test Temp (°F)	Specimen Size (in.)	Ribbon Direction	Ribbon Gage (in.)	ULT Load (lb)	Average Stress (Calculated) KSI	Average Stress (Calculated) Type	Failure Mode	Notes
Edgewise Compression	22-12A	RT	2.745 x 3.660	T	.006	8450	76.3	Compressive, Faces	Face/Core	
	22-13A	RT	2.810 x 3.460	L	.006	7490	66.5			
	22-16A	RT	2.765 x 3.450	L	.0035	7970	73.3			
	22-17A	RT	2.560 x 3.660	T	.0035	5250	49.6	----------	----------	Strain gage indicated eccentric loading
	22-15B	600	2.770 x 3.25	T	.006	6600	59.0			
	22-12B	600	2.698 x 3.75	T	.006	5170	47.4			
	22-14B	500	2.662 x 3.12	L	.006	5770	55.2			
	22-13B	600	2.830 x 3.50	L	.006	5780	52.0			
	22-17B	600	2.598 x 3.62	T	.0035	4370	43.0			
	22-19B	600	2.920 x 3.50	T	.0035	5400	47.7			
	22-16B	600	2.745 x 3.50	L	.0035	4910	44.7			
	22-18B	600	2.975 x 3.50	L	.0035	5420	48.0	Compressive, Faces	Face/Core	
Flatwise Compression	22-13G	RT	1.025 x 1.015	-	.006	980	0.943/19.6	Core Comp/Ribbon Comp	Core	
	22-15G	RT	1.012 x 0.992	-	.006	1400	1.391/48.4			
	22-16G	RT	1.015 x 0.993	-	.003+	765	0.761/29.4			
	22-19G	RT	1.010 x 0.980	-	.003	405	0.414/27.7			
	22-13H	300	1.040 x 1.020	-	.006	--	--	----------	----------	Machine overload, no test
	22-15H	300	1.040 x 1.040	-	.006	1360	1.265/51.4			
	22-16H	300	1.015 x 1.015	-	.003+	1170	1.140/28.7			
	22-19H	300	1.020 x 1.010	-	.003	400	0.398/28.8			
	22-13I	600	1.015 x 1.000	-	.006	835	0.823/48.8			
	22-15I	600	1.044 x 1.012	-	.006	1150	1.100/50.2			
	22-16I	600	1.016 x 1.005	-	.003+	560	0.550/28.6			
	22-19I	600	1.010 x 1.010	-	.003	195	0.191/28.6	Core Comp/Ribbon Comp	Core	
Flatwise Tension	22-13F	RT	1.008 x 0.995	-	.006	395	0.395/8.25	Core Tensile/Ribbon Tensile	50% Core	5% no braze area
	22-15F	RT	1.022 x 0.990	-	.006	365	0.360/7.50		Core	
	22-16F	RT	1.018 x 1.022	-	.0035	455	0.438/11.65		15% Core	
	22-19F	RT	0.980 x 0.975	-	.0035	290	0.303/10.85		Core	5% no braze area
	22-13K	300	----------	-	.0035	--	----------	----------	----------	Furnace overheat, no test
	22-15K	300	1.030 x 1.006	-	.006	430	0.416/8.65		2% Core	
	22-16E	300	1.017 x 1.005	-	.0035	300	0.292/10.45		Braze	
	22-19E	300	1.040 x 1.018	-	.0035	225	0.212/7.58		80% Core	
	22-130	600	1.015 x 1.010	-	.006	460	0.449/9.35		Core	
	22-15D	600	1.035 x 0.970	-	.006	570	0.569/11.80		Epoxy	No specimen failure
	22-16J	600	1.020 x 1.002	-	.0035	250	0.245/8.75		20% Core	
	22-19D	600	1.040 x 1.000	-	.0035	102	0.098/3.50	Core Tensile/Ribbon Tensile	Core	

TABLE VIII (CONT)

MECHANICAL TEST PROPERTIES OF BERYLLIUM HONEYCOMB SANDWICH PANELS (PHASE II)

Type	Specimen No.	Test Temp (°F)	Specimen Size (in.)	Ribbon Direction	Ribbon Gage (in.)	ULT Load (lb)	Average Stress (Calculated) KSI	Average Stress (Calculated) Type	Failure Mode	Notes
Block Shear	22-12C	RT	2.680 x 2.000	L	.006	1540	0.287	Sandwich Shear	Braze	
	22-12D	RT	2.755 x 2.000	L	.006	1720	0.312	↕	Braze	
	22-14C	RT	2.660 x 1.953	T	.006	1105	0.271		Braze	
	22-14D	RT	2.645 x 1.935	T	.006	1560	0.304		Braze	
	22-17C	RT	2.600 x 2.025	L	.0035	1380	0.260		Core/Braze	
	22-17D	RT	2.570 x 2.015	L	.0035	1128	0.218		Braze	
	22-18C	RT	2.920 x 2.005	T	.0035	894	0.153		Core/Braze	
	22-18D	RT	2.960 x 2.010	T	.0035	890	0.150		Braze	
	22-14A	600	3.035 x 2.055	L	.006	1485	0.239		Core/Braze	Cut from spare edgewise compression specimens
	22-15A	600	3.045 x 2.040	T	.006	1655	0.266		Braze	
	22-18A	600	3.025 x 2.035	T	.0035	915	0.149	↕	Core/Braze	
	22-19A	600	3.015 x 2.025	L	.003	480	0.079	Sandwich Shear	Core/Braze	

All specimens -0.020 CRS Be face sheets (nominal)
1/4-inch Solar square cell ingot foil core, 1/2 inch high

NOTE: SEE TABLE IX FOR PHASE III RESULTS.

6

TECHNICAL DISCUSSION
PHASE III

The second year scale-up efforts was Phase III which includes tasks 10 through 19. Figure 1 shows the task flow plan. This section of the report is the technical discussion of the scale-up preparations, preliminary test panels (2 ft^2), creep forming demonstration, fabrication of 10 ft^2 panels and mechanical testing

6.1 SCALE-UP PREPARATIONS - TASK 13

This task consisted of preparing for scale-up operations which ultimately produced two panels each of ten square feet surface area.

The size of the large scale-up panels dictated a slightly modified approach to the brazing conditions previously established in Phases I and II. A precision hydraulic press equipped with "Masrock" heated platens was planned for use as the brazing facility on both the 2 and 10 square foot size panels. This facility (Fig. 32) has a working surface of 38 inches by 54 inches which is flat within 0.002 inch. All scale-up operations were targeted for ultimate use of this facility.

6.1.1 Core Machine Refinement

Solar's automatic resistance core making machine was refined in two ways. First, it was adjusted to weld more precise ribbons into uniform height core. Additional reference plates were added to control the ribbon being welded to the core reference height. Tests were made using stainless steel ribbon. Figure 33 shows a section of this core height uniformity being checked with ink traces. Very encouraging results were obtained. Significant improvement over previous core assemblies was achieved. Preliminary tests showed a core height control of ± 0.001 inch. With additional test settings, it is believed, even closer control is obtainable.

The second refinement was providing additional table work surface to accommodate the larger core blankets. Figure 34 shows the new work table as installed on the refined core machine.

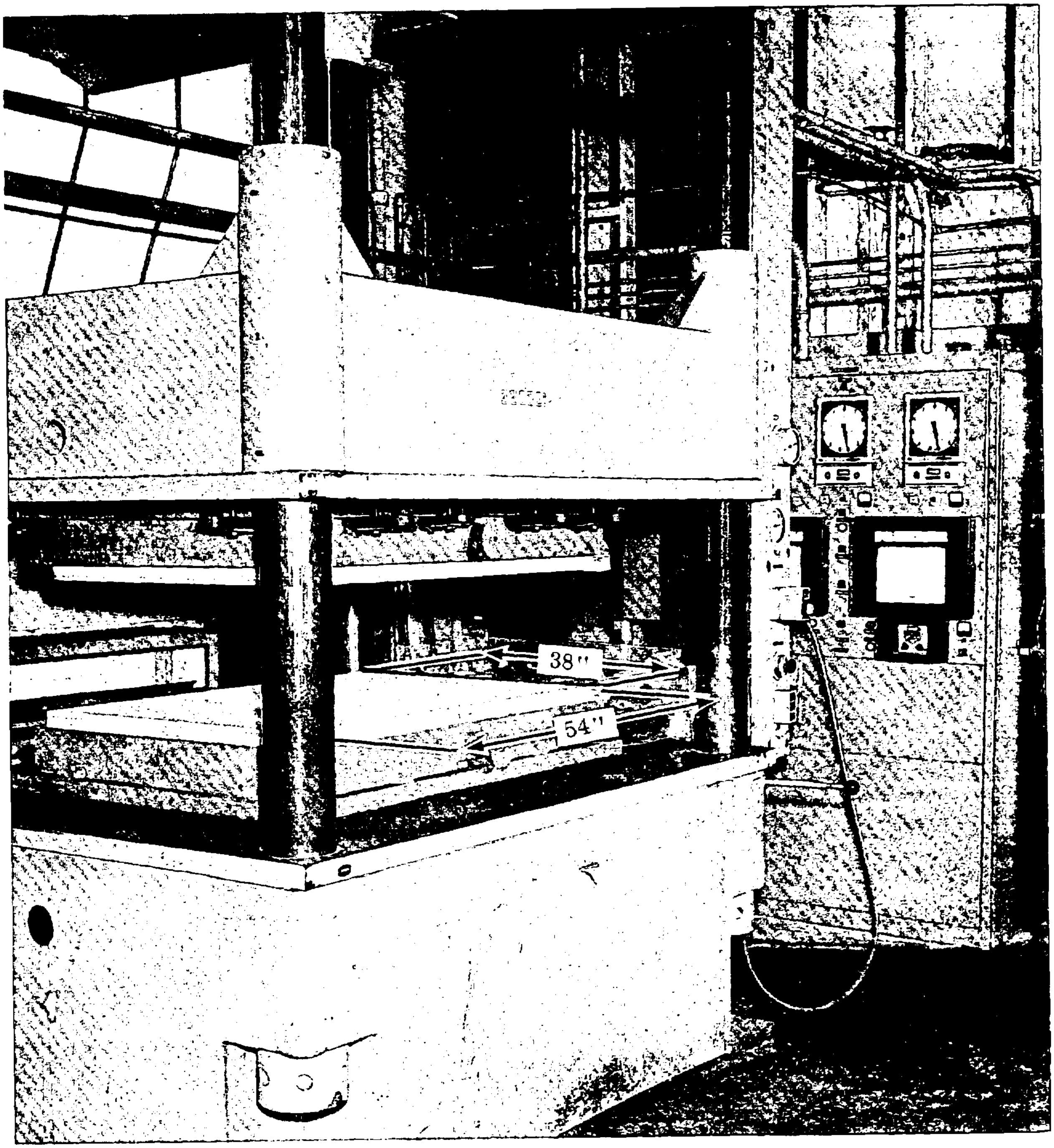


FIGURE 32. MASROCK PLATEN PRESS BRAZING FACILITY

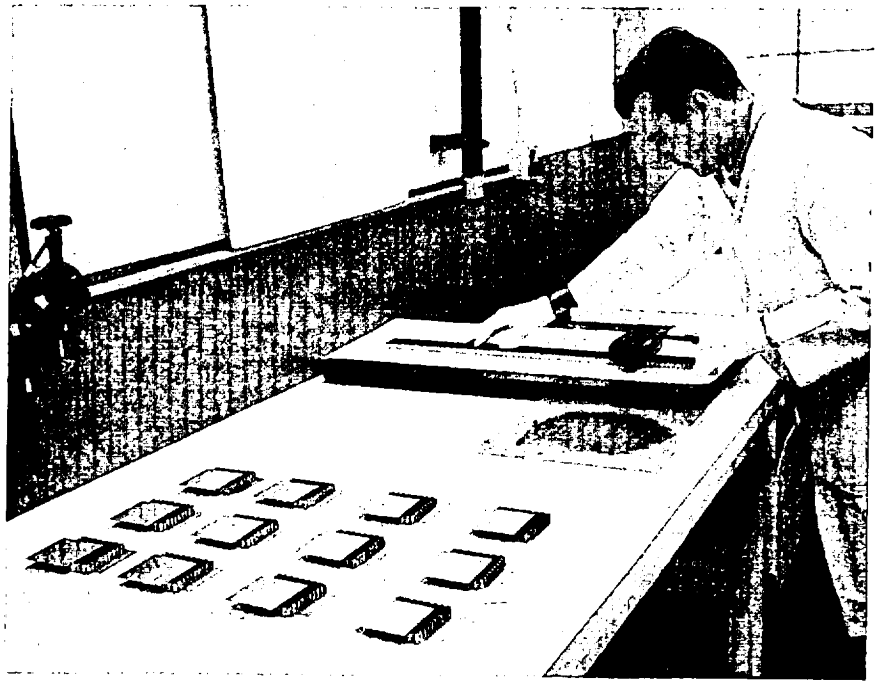


FIGURE 33. CORE SAMPLES AND INSPECTION TECHNIQUES

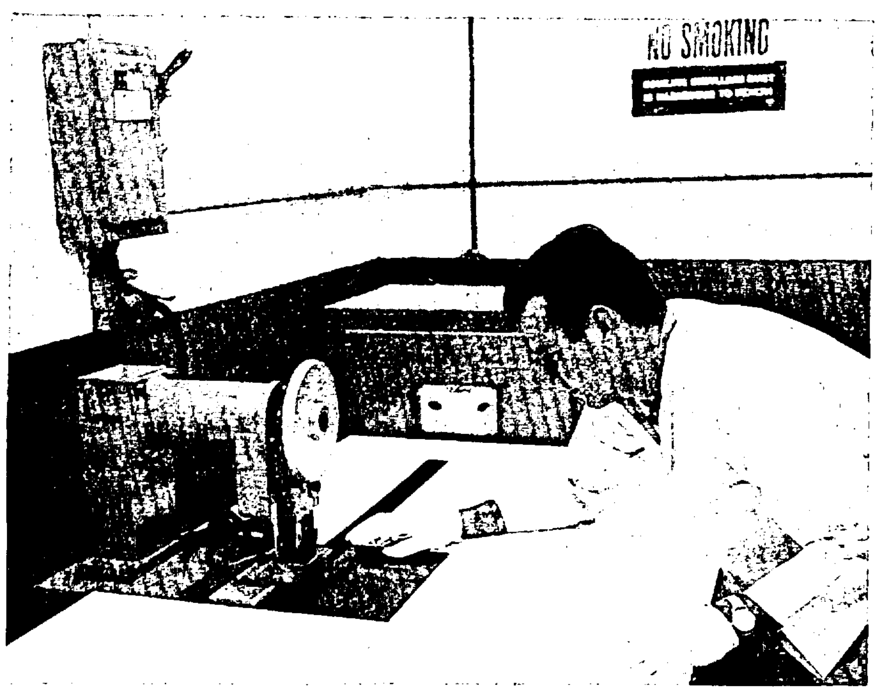


FIGURE 34. REFINED AUTOMATIC CORE MACHINE

6.1.2 Alternate Brazing/Loading Techniques

As a result of brazing in a horizontal position, the incremental node loading technique used in the earlier development phases for vertical brazing required modification. Because of the increased area, a more economical method of loading was also desirable to reduce manhour costs incurred in loading. Means were studied to control filler metal wetting to node and face joints only (excessive wetting of face sheets and core web is undesirable for weight considerations).

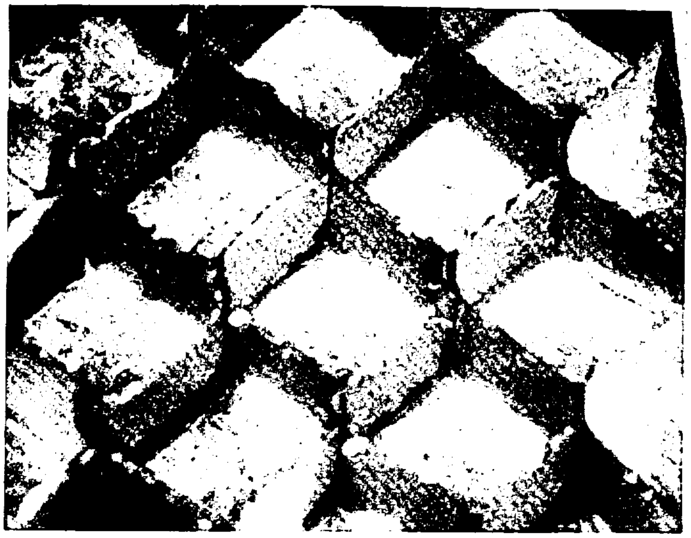
Previously fabricated core samples were cut into 1 inch by 1 inch and 1 inch by 2 inch samples and fitted with 0.020 inch CRS beryllium facing sheets. These small size specimens were selected for ease of brazing in a tube furnace. They served as screening tests for various techniques of loading for horizontal brazing.

A dozen specimens were brazed employing various loading techniques utilizing 1-mil thick braze alloy foil (Ag-Cu-Sn). Techniques included various degrees and types of dimpling, perforating, corrugating and combinations of these. Node and face joints were compared to previous Phase II incremental node loading results and the excessive wetting of the face compared to a standard foil loaded specimen. Figure 35 shows some of these specimens.

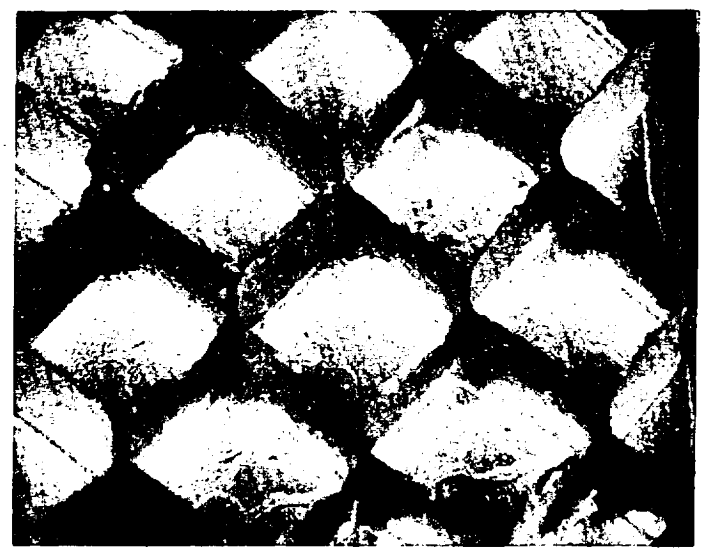
Two types of perforated braze foil gave excellent core-to-face joints with only slight excessive face sheet wetting. Approximately 50 to 80 percent of capillary node flow was observed. Results are shown in Figure 36.

These techniques of perforating the braze alloy foil which gave excellent core-to-face joints with only slightly excessive face sheet wetting were verified on a 6 inch by 6 inch sample. This specimen had 0.020 inch CRS face sheets and "as welded" Ingot Foil core and was furnace brazed in a horizontal position. Both X-ray and visual inspection after sectioning in the plane of the sandwich showed promising results. All core-to-face joints were 100 percent brazed and node to joints were 50 to 100 percent brazed depending on the specific test area. Figure 37 shows this panel after sectioning for visual inspection.

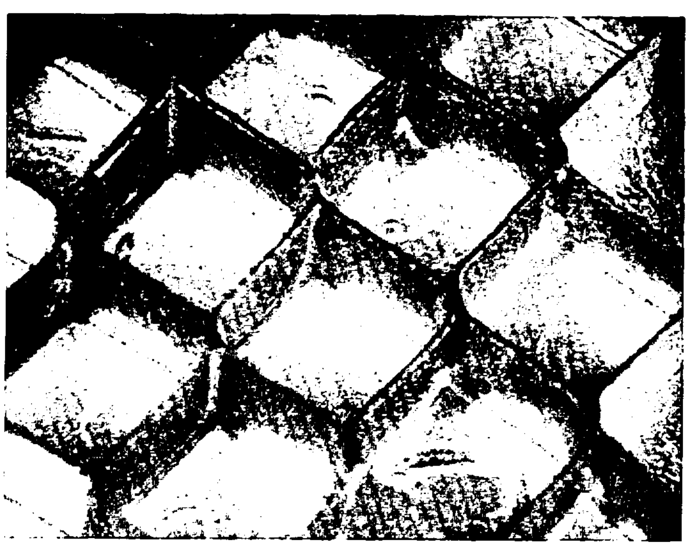
A second 6 inch by 6 inch sample similar to the one above was fabricated to verify the heater platen braze technique. A small 9 inch by 12 inch "Glasrock" platen was used to demonstrate the process, while the large facility was being repaired. This panel confirmed the above metallurgical results. However, the limited platen size was not adequate to provide uniform heating. Several smaller 3 inch by 3 inch specimens verified the platen approach and no problems were anticipated using the large facility on full size panels if a minimum 2 inch wide heating zone outside the panel is maintained.



TEST 1A
7X
EXCESSIVE FACE SHEET
WETTING. NO CAPILLARY
NODE FLOW

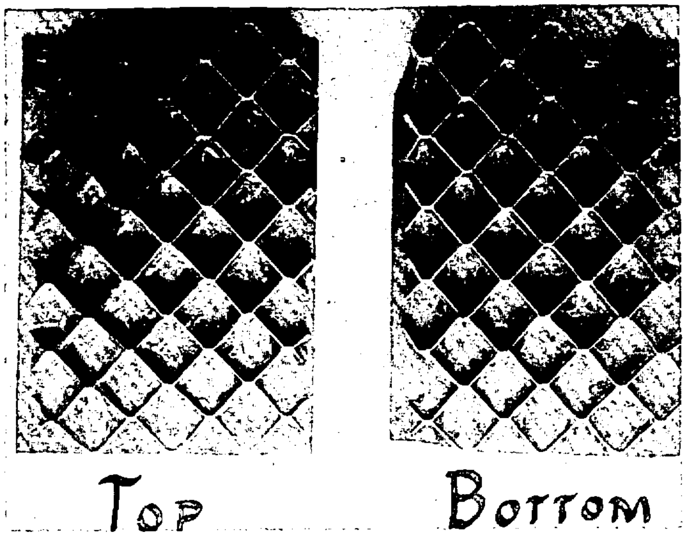


TEST 1B
7X
LIGHT FACE SHEET WETTING
LIMITED CAPILLARY NODE FLOW

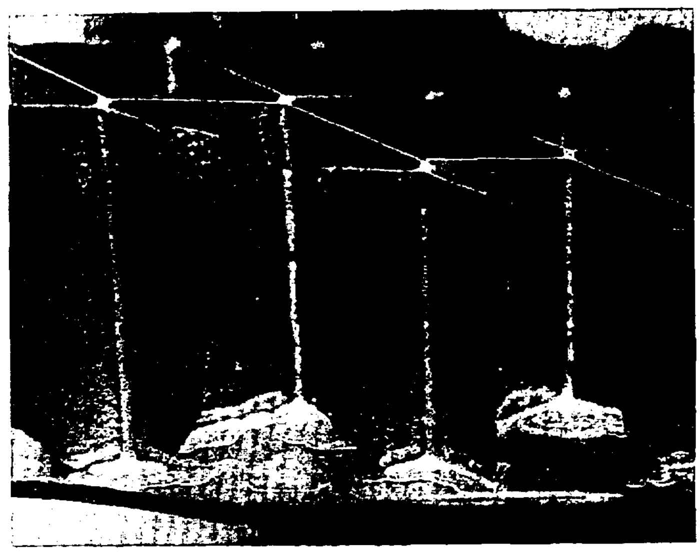


TEST 1D
7X
LIGHT FACE SHEET WETTING
80% CAPILLARY NODE FLOW

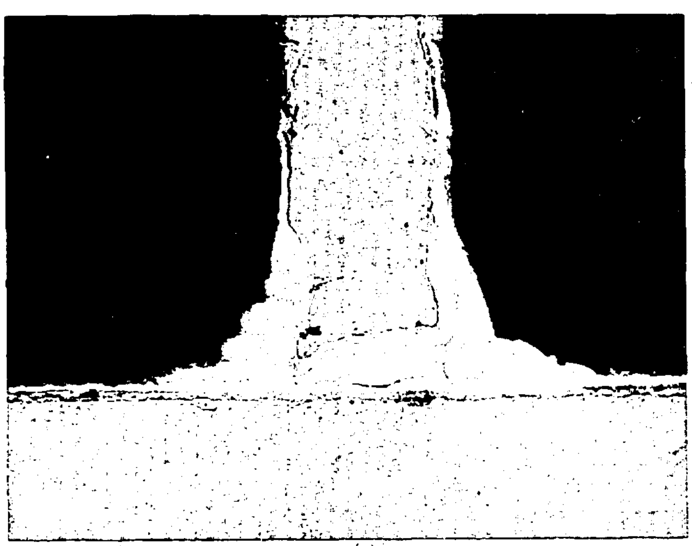
FIGURE 35. TYPICAL SCREENING SPECIMENS - FOIL LOADING/HORIZONTALLY BRAZED



SPECIMEN 10A
TOP AND BOTTOM FACE SHEETS
BOTH EXHIBITED CONTROLLED
FACE SHEET WETTING.
(APPROX. 1X)



CAPILLARY NODE FLOW
APPROACHED 100%
(APPROX. 4X)



TYPICAL "T"-JOINT
.006" INGOT FOIL
.020" CRS FACE SHEET
MOUNT 1034 (150X)

FIGURE 36. BERYLLIUM HONEYCOMB-FOIL LOADED/HORIZONTALLY BRAZED.

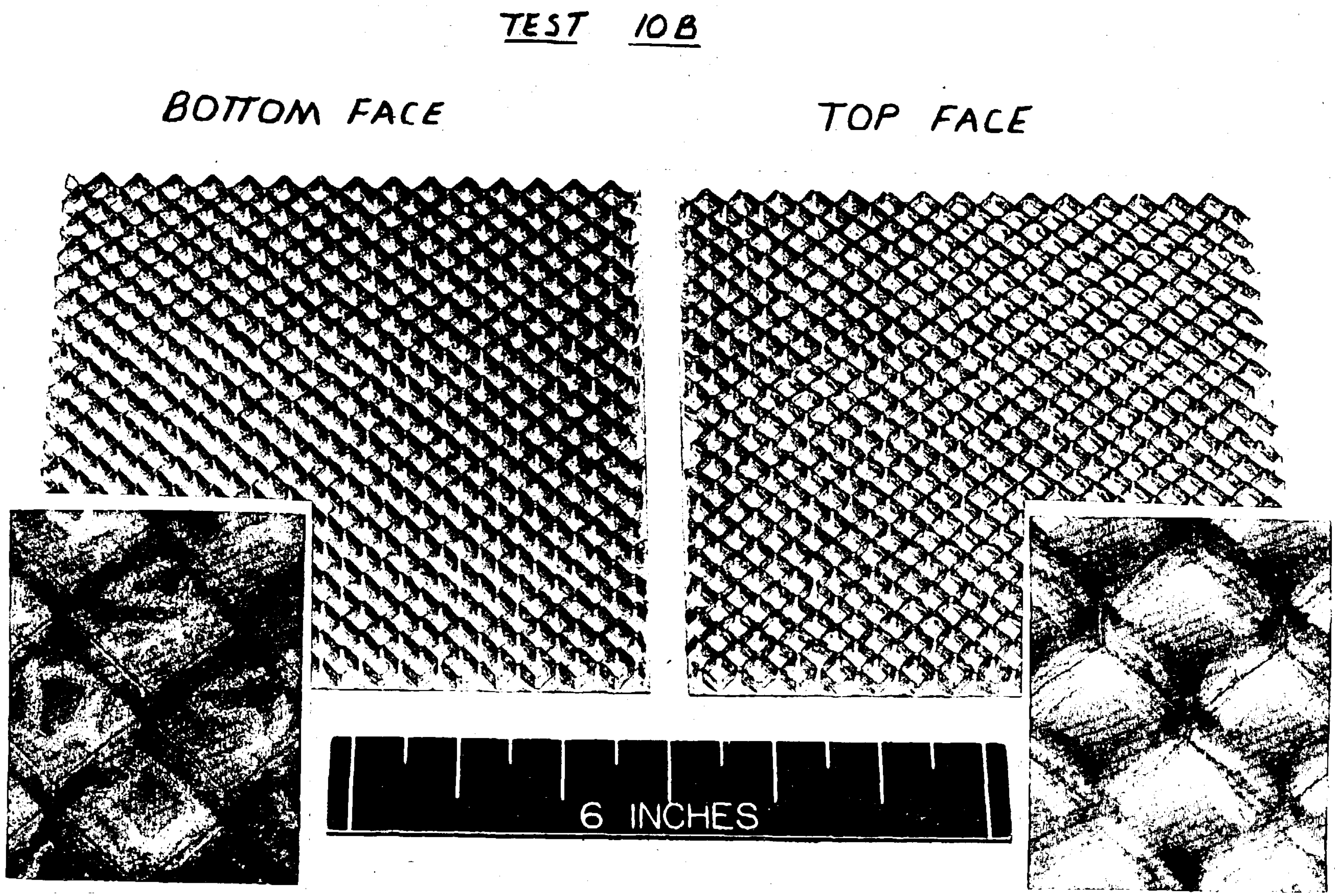


FIGURE 37. 6" x 6" BERYLLIUM TEST PANEL

6.2 PRELIMINARY TEST PANELS (2 ft^2) - TASK 14

The required 12 inch by 24 inch test panel core blankets were made from six-mil Ingot Foil stock which was sheared into ribbons by processes defined in Phase I. The sheared ribbons were then precision ground to be uniform in width within $\pm$ 0.0002 inch. Next, these uniform width (1/2 inch wide) ribbons were corrugated by processes established in Phases I and II. These precision components were then automatic resistance tack welded into honeycomb core on Solar's machine. The core was welded to a uniform height blanket which required no additional surfacing prior to brazing. Face sheets were cut-to-fit from 0.020 inch CRS beryllium sheets.

The first panel was successfully brazed in the horizontal position by heated platens and incorporated foil loading. Thus, a major step in improving the quality and producibility was achieved. Figure 38 shows this panel.

Excellent quality braze joints were produced as verified by both X-ray and metallurgical photomicrographs. The X-rays indicated 100 percent web-to-face brazing and 75 percent overall capillary-node flow. Photomicrographs indicate micro-fillets and sound joints as shown in Figure 39.

Dimensional analysis after brazing indicated the panel was flat within 0.005 inch TIR with a thickness uniformity of 0.003 inch. One area of the panel exhibited a few shallow ripples approximately 4 inches long by 0.002 inch high in the CRS face sheet. They resulted from a slight fixturing interference.

The second panel was also a success. Although brazing after final cleaning and lay-up was delayed over three weeks while the platen brazing facility was undergoing extensive repairs, the braze quality was excellent. Thus, production panels could be processed to the fixtured point and stored prior to brazing several in a row with one braze facility. The X-ray examinations show 100 percent web-to-face brazing and 99 percent capillary-node flow (Fig. 40). Metallurgical sections indicated similar results as the first 2 ft^2 panel. Minor fixturing problems still existed, but were resolved on a third 2 ft^2 panel.

The third test panel brazed was of similar size (2 ft^2) and braze quality. All of the minor fixturing problems were completely eliminated. After braze, inspections showed the panel to be 100 percent brazed (both web-to-face and capillary-node joints), flat within 0.002 inch TIR and no face or honeycomb core deformation was evident. This superb panel is shown in Figure 41.

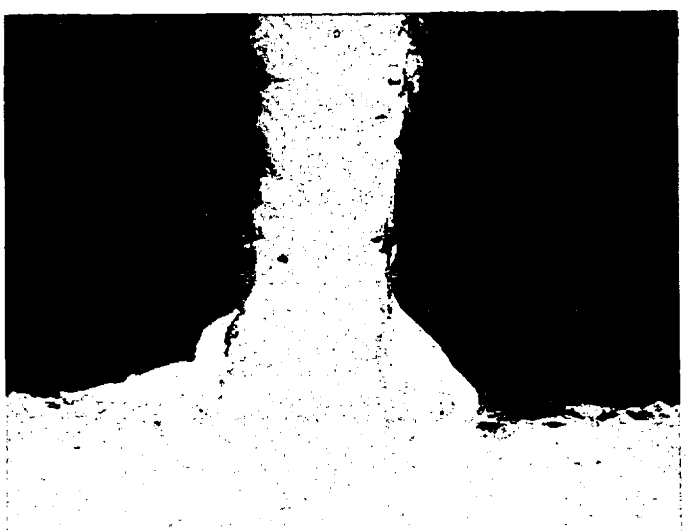
FIGURE 38. FIRST 2 FT^2 PANEL - AS BRAZED (FLAT WITHIN 0.005 INCH TIR)

Typical Top T-Joint

Material:
Core - 0.006" Be Ingot Foil
Face - 0.020" Be CRS
Braze Alloy - Ag-Cu-Sn Foil

Mount No. 1087

Magnification: 150X



Typical Bottom T-Joint

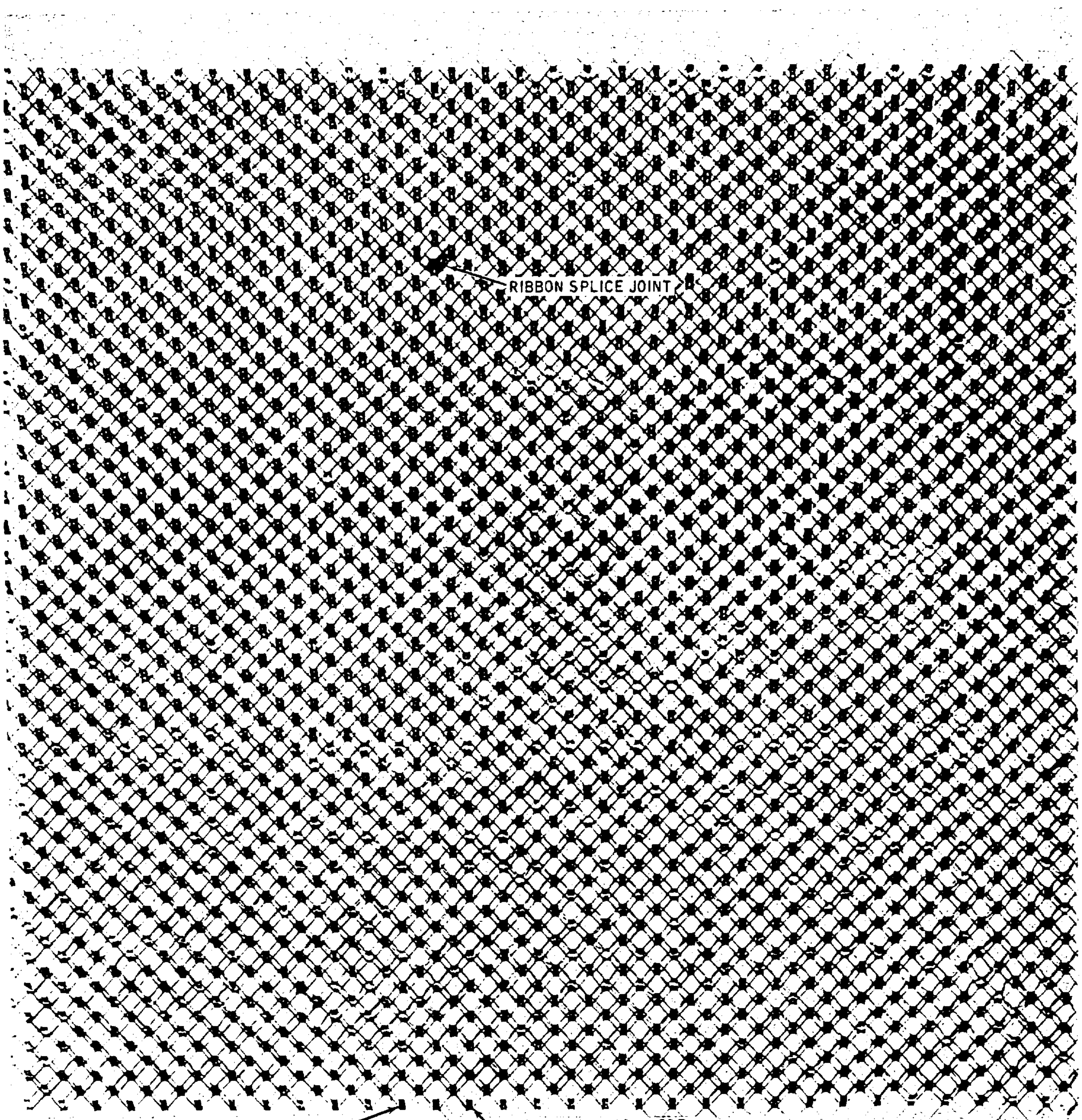
Material:
Core - 0.006" Be Ingot Foil
Face - 0.020" Be CRS
Braze Alloy - Ag-Cu-Sn Foil

Mount No. 1089

Magnification: 150X

FIGURE 39. PHOTOMICROGRAPHS OF FIRST 2 FT^2 PANEL AS BRAZED

FOLDOUT FRAME



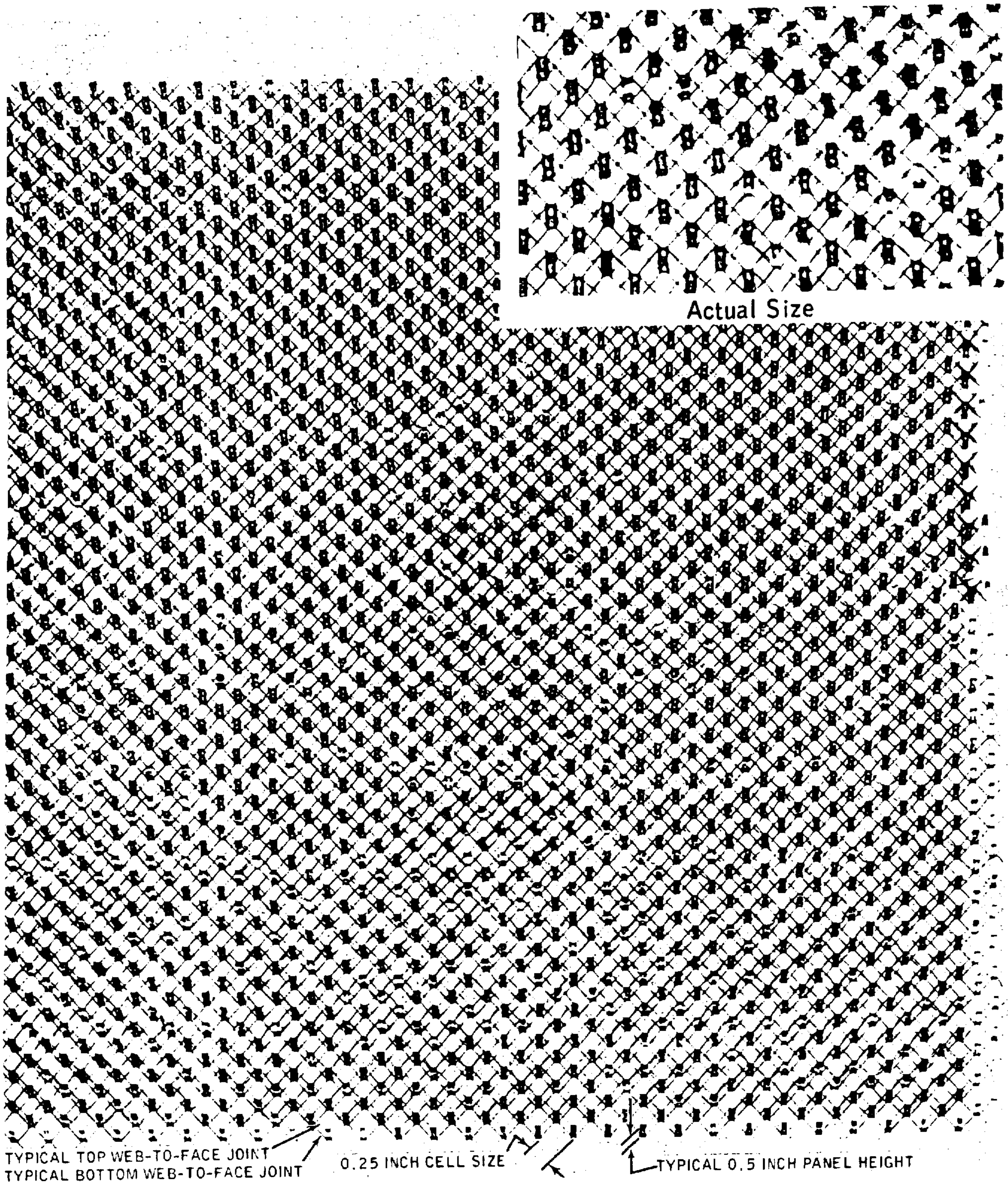


FIGURE 40. TYPICAL RADIOGRAPH OF BRAZED BERYLLIUM PANELS

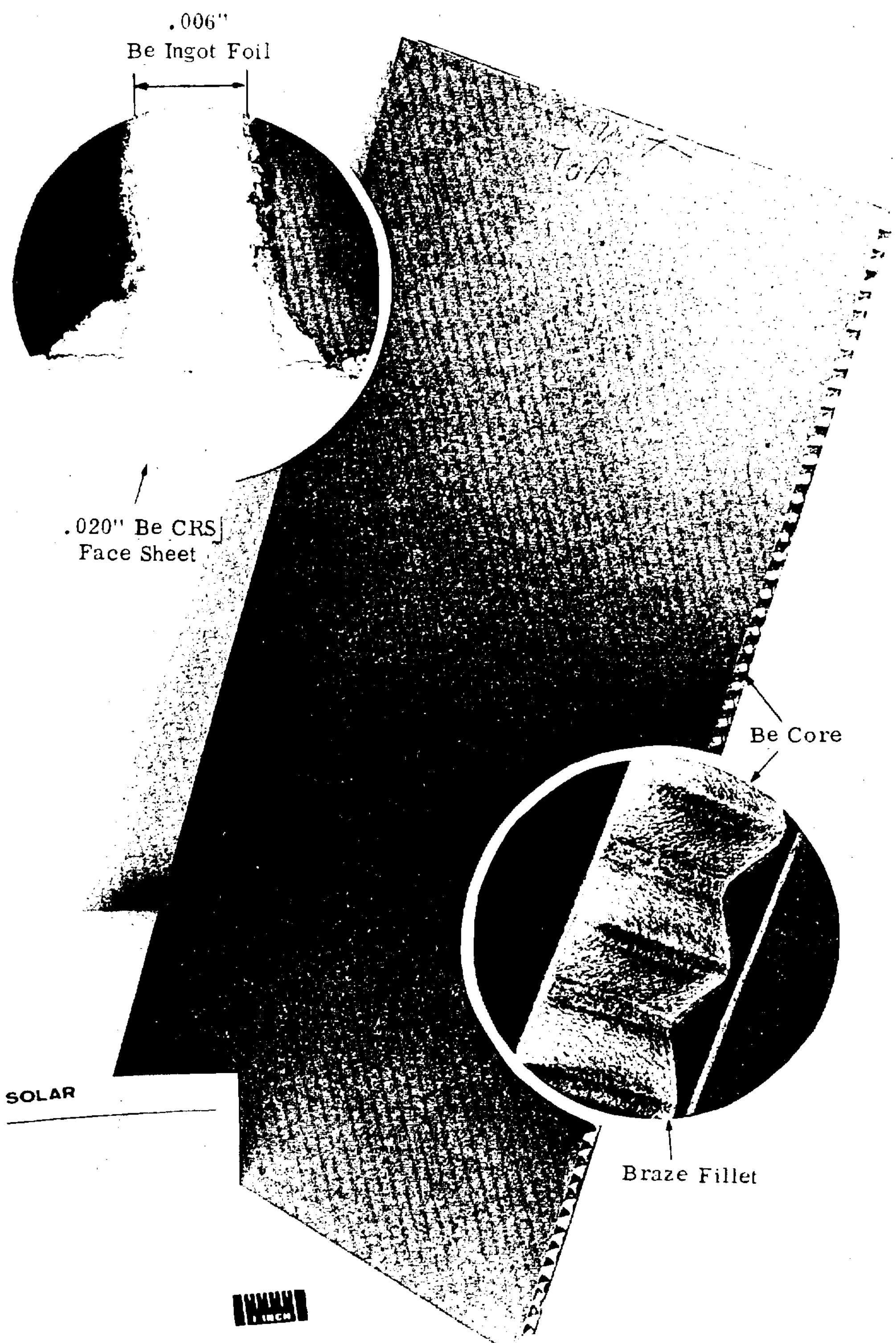


FIGURE 41. THIRD 2 FT^2 PANEL - AS BRAZED
(FLAT WITHIN 0.002" TIR)

6.3 CREEP FORMING DEMONSTRATION - TASK 15

The first 1 by 2 foot brazed panel described in Section 6.2 was used for this demonstration to show feasibility for making cylindrically curved, all beryllium, honeycomb panels for space hardware applications by creep forming flat, prebrazed panels.

Creep forming process was done at 1250°F in a simple vacuum bagged die with a 10 ft. radius. Cycle purging prior to the test prevented oxidation at the 1250°F forming temperature. Figure 42 shows the fixtured part.

Dimensions, X-ray and metallurgical analysis after forming indicated this process was feasible for making cylindrically curved, all beryllium, honeycomb panels for space hardware applications by this method. The curved panel conformed to the die within 0.003 inch at room temperature after forming. No change in the metallurgical structure (Fig. 43) or X-ray discrepancies were noted when compared to identical before-forming data. Figure 44 shows the curved panel.

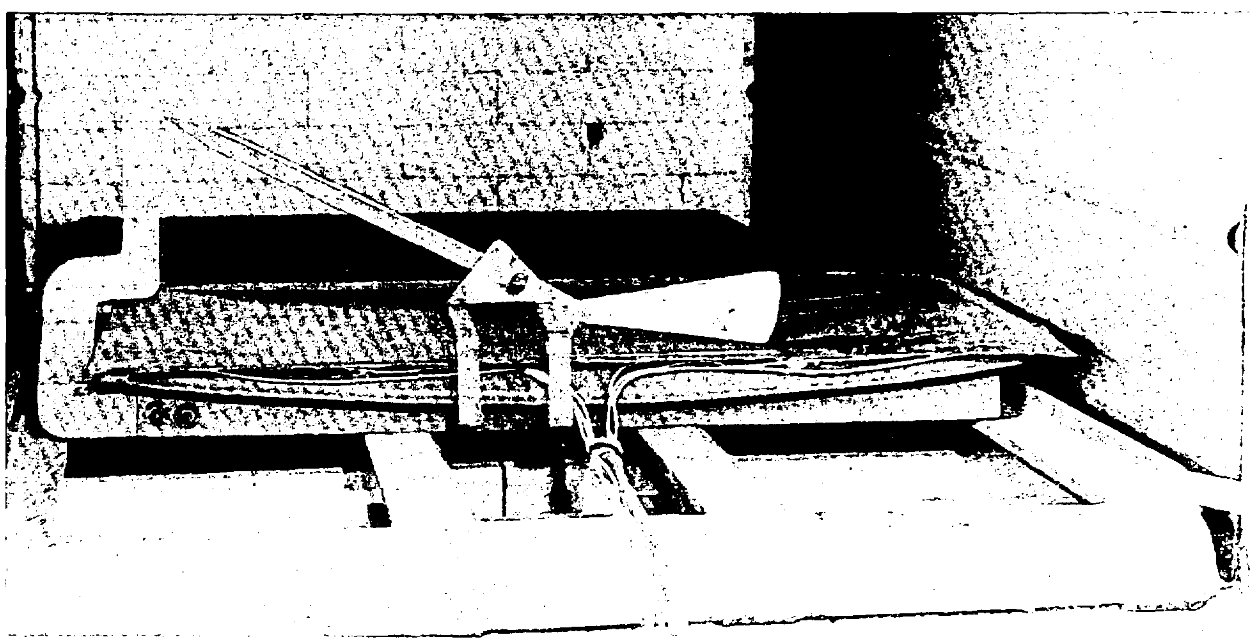
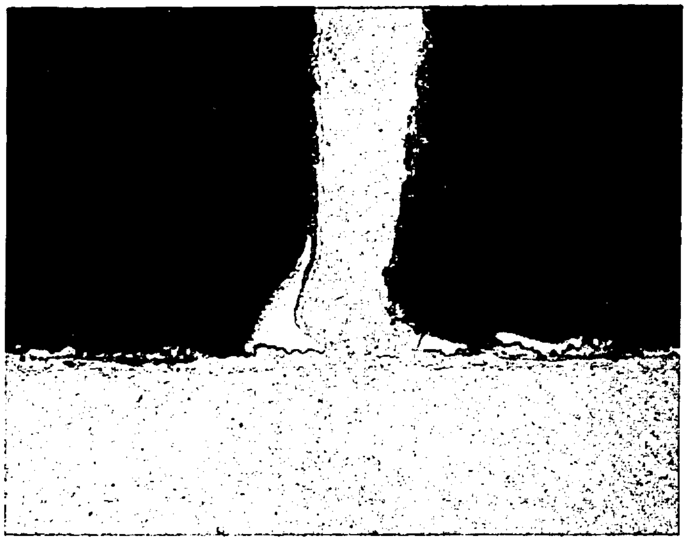


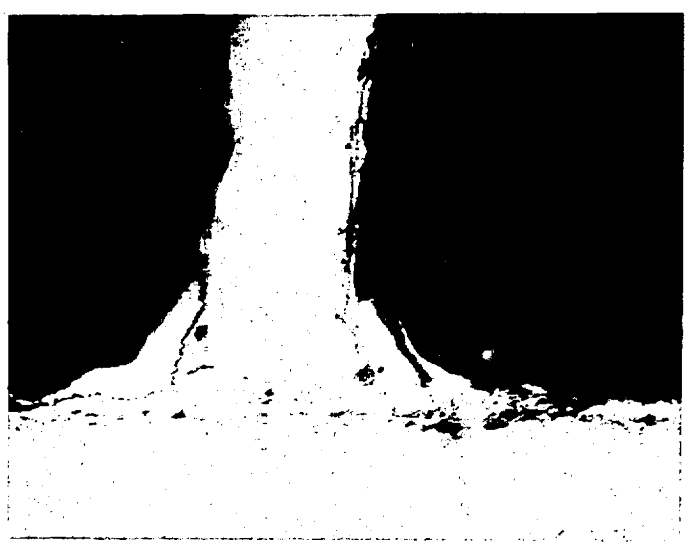
FIGURE 42. FIXTURING FOR CREEP FORMING DEMONSTRATION



Typical Top T-Joint

Mount No. 1100

Magnification: 150X



Typical Bottom T-Joint

Mount No. 1101

Magnification: 150X

FIGURE 43. PHOTOMICROGRAPHS OF FIRST 2 FT^2 PANEL AFTER CREEP FORMING

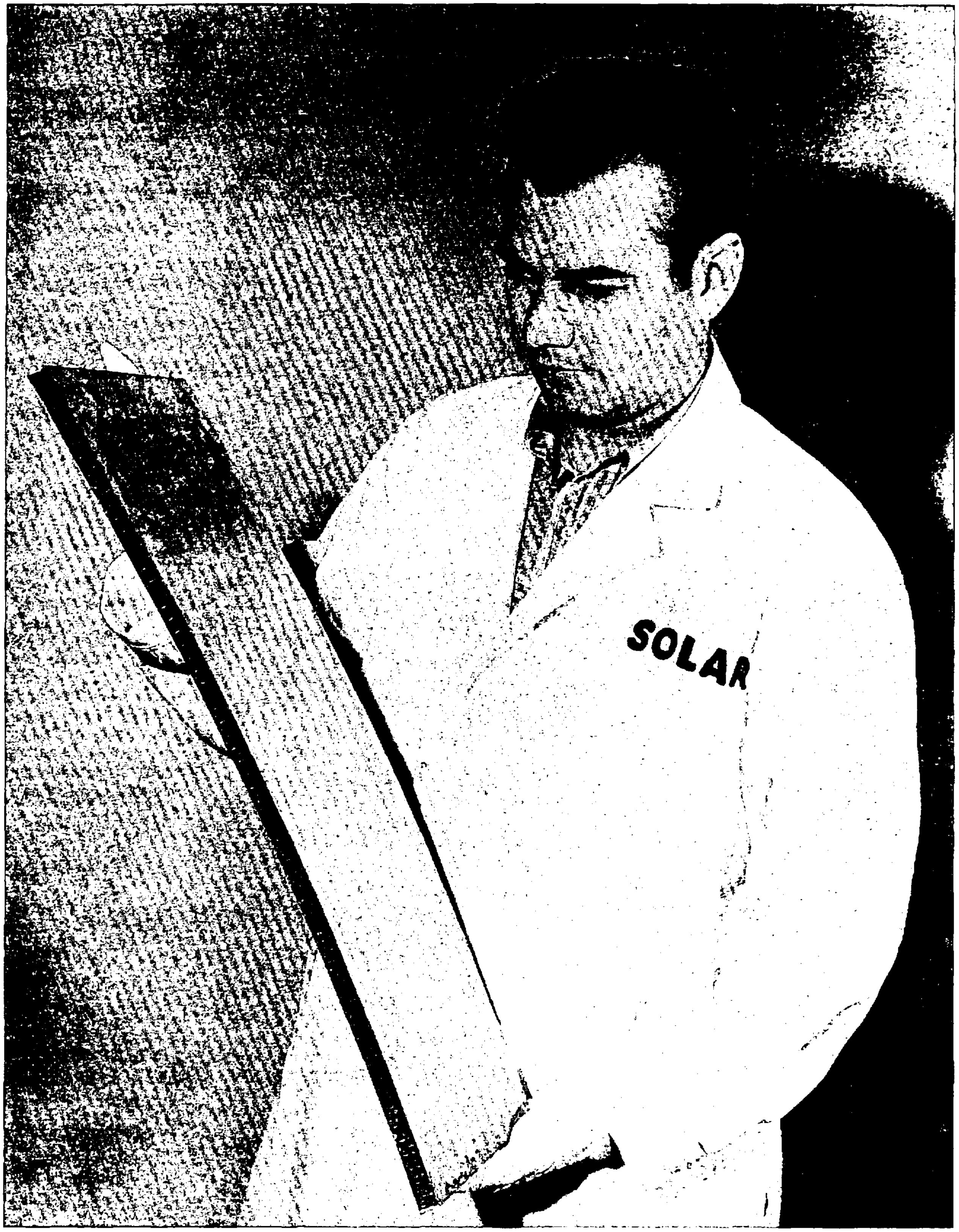


FIGURE 44. CURVED BERYLLIUM HONEYCOMB PANEL (10 FT. R)

6.4 FULL-SCALE PANELS (10 ft^2) - TASK 16

This task consisted of fabricating two 10 square foot panels. The core blanks were made from six-mil Ingot Foil stock which was sheared into ribbons by processes defined in Phase I. As on the 2 square foot test panels, the sheared ribbons were then precision ground to be uniform in width within ± 0.0002 inch. Next, these uniform width (1/2 inch wide) ribbons were corrugated by processes established in Phases I and II. These precision components were then automatic resistance tack welded into honeycomb core on Solar's machine. This uniform height core required no additional surfacing prior to brazing. Figure 45 shows one of these large core blankets in this "as-welded" condition. These exhibited remarkable stiffness.

Face sheets were cut into 32 x 41 and 47 inch faces from large 0.020 inch by 36 inch by 96 inch CRS beryllium sheets. These components were readied for brazing by previously established cleaning procedures.

The panels were brazed with the AgCuSn braze alloy foil and in the horizontal position. Figure 32 shows the brazing facility used.

The first scale panel was successfully brazed. Post brazing inspection by X-ray indicated excellent braze quality and flow. A dimensional analysis showed the panel to be flat within 0.010 inch TIR over the 10 square feet surface area. This panel is shown in Figure 46 with one 9 by 9 inch area removed.

The second 10 square foot panel was slightly larger (32 by 47 inches versus 32 by 41 inches) than the first. It was brazed in the identical manner as the first, but wrinkling of both face sheets occurred. The pattern of wrinkling of the as-brazed panel is shown in Figure 47. The cause of this wrinkling was attributed to the non-uniform cooling of the periphery resulting from the increased panel size and equal decrease of edge insulation.

Both X-rays and visual examination indicated excellent wetting and braze flow. Dimensional checks indicate parallelism was maintained through the wrinkles and it is basically a structurally sound panel.

Originally this panel was scheduled to be sent to NASA, but has been reassigned to the third year's efforts (Phases IV and V).

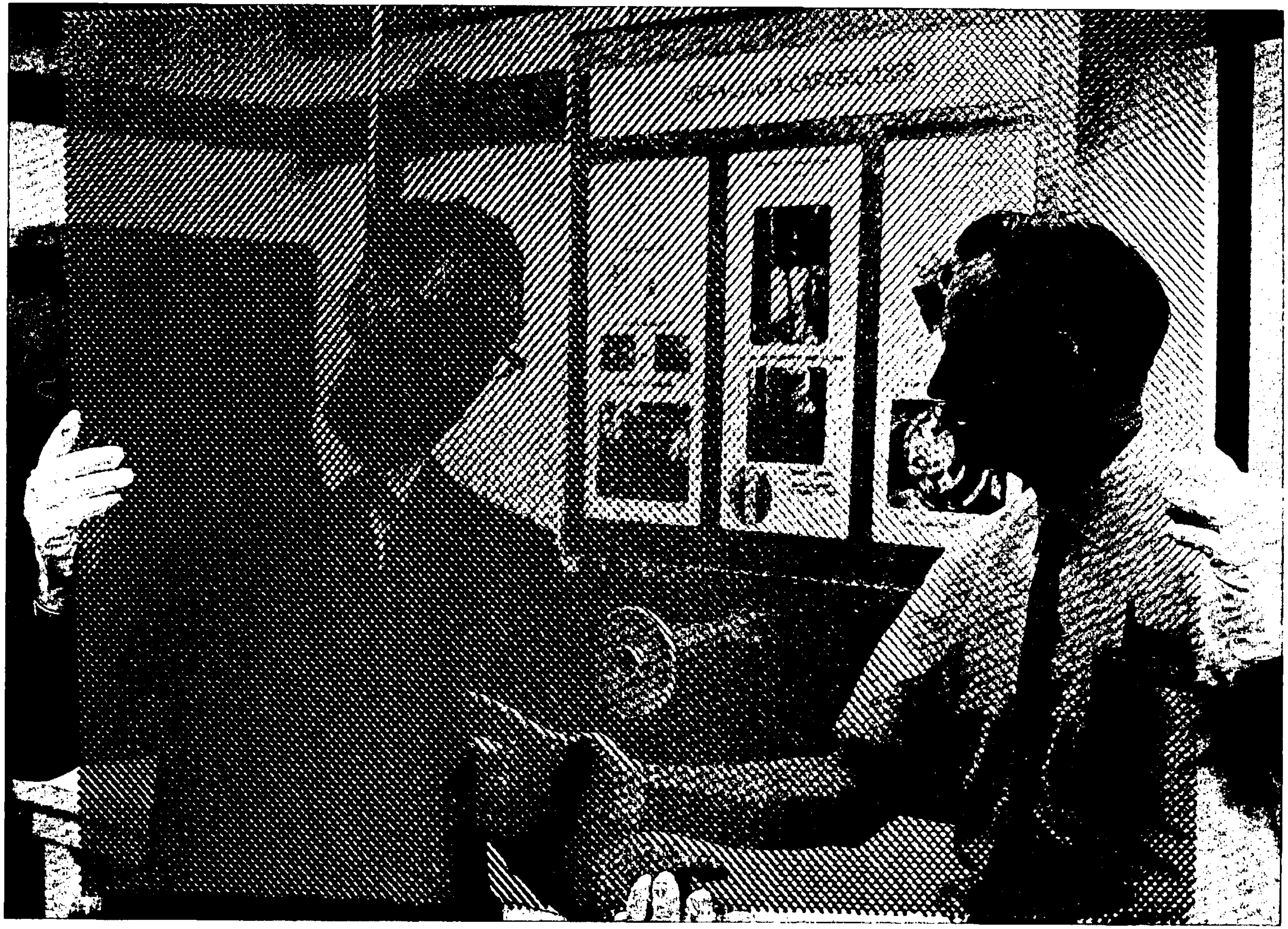


FIGURE 45. AS-WELDED BERYLLIUM HONEYCOMB CORE BLANKET

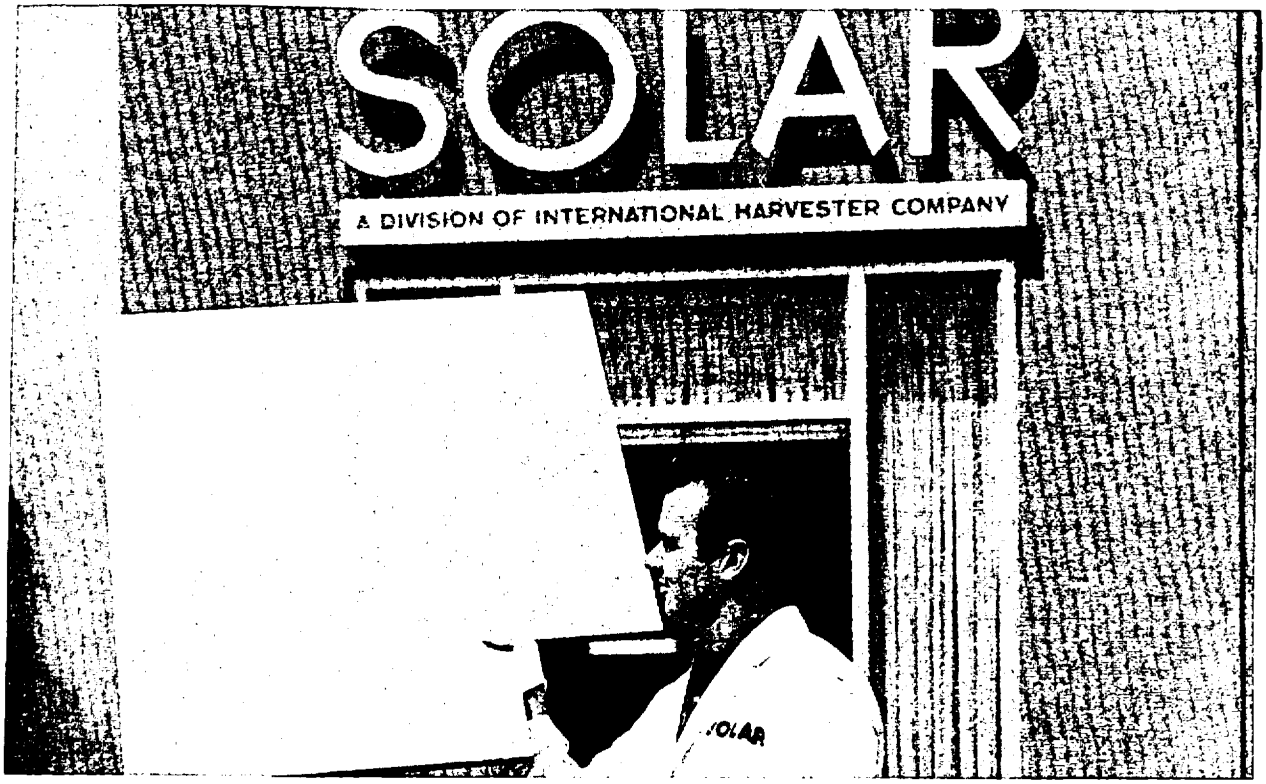


FIGURE 46. FIRST 10 SQUARE FOOT BRAZED PANEL

6.5 MECHANICAL TESTING - TASK 17

The first 10 square foot panel brazed (shown in Figure 46) was sectioned into mechanical test specimens as shown in Figure 48. Tests of flatwise compression, flatwise tension, edgewise compression and block shear were performed at RT, 300°F and 600°F and are reported in the following paragraphs. Although not included in the original scope-of-work, beam bending test specimens were cut from the panel as an extra task and are available for testing.

6.5.1 Edgewise Compression Tests

Edgewise compression tests were conducted to provide a basis for judging the load carrying capacity of the beryllium sandwich in terms of facing stresses as compared to the standard tensile yield stress of the facing material. Since general instability failures resulting from long columns in any design are accurately predicted by stress analysis, considerations of local instability in short columns becomes a prime interest (Section 8 of this report discusses anticipated work related to long column stability). Thus, this test was based on short columns per MIL-STD-401A (Sandwich Constructions and Core Materials; General Test Methods).

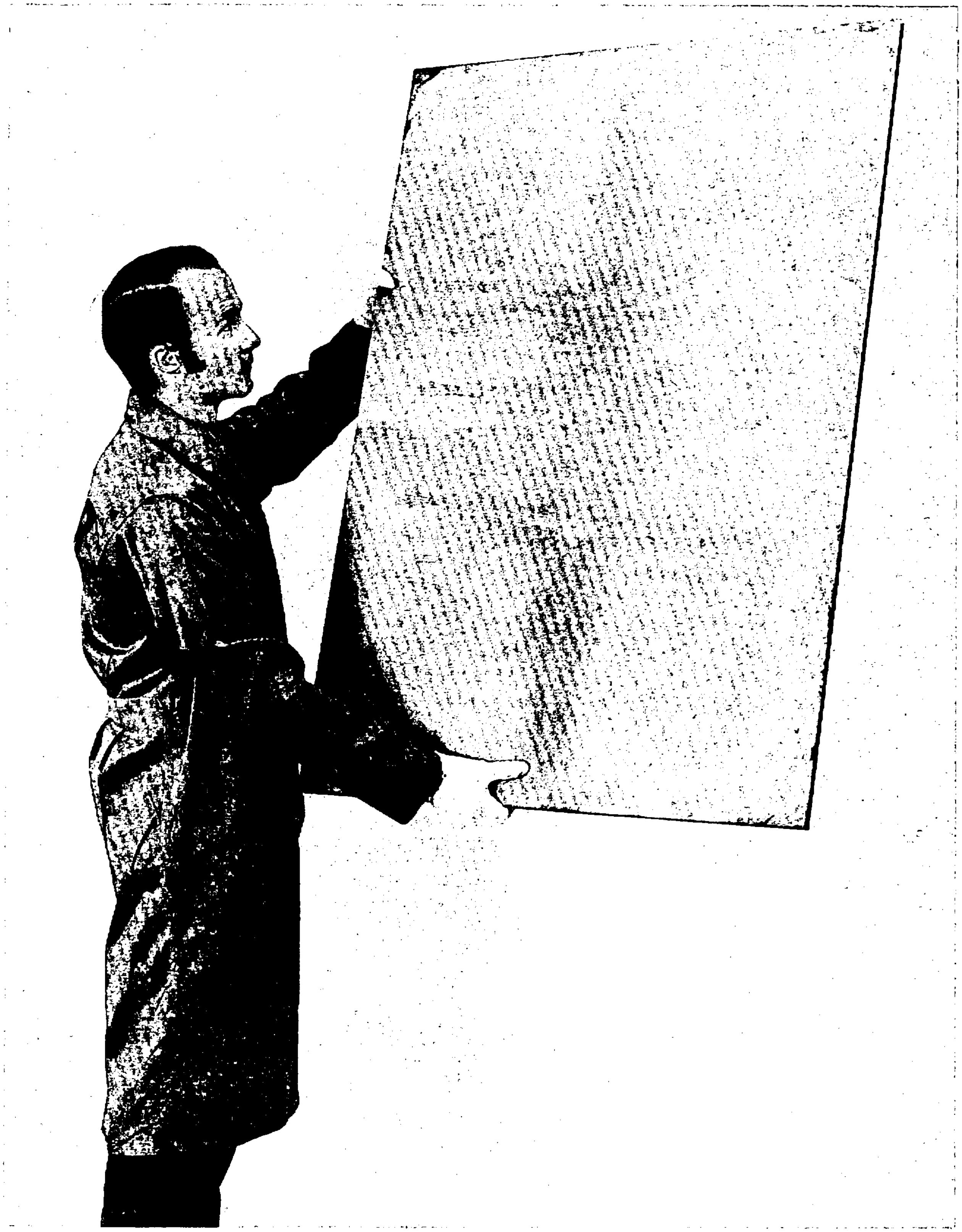


FIGURE 47. SECOND 10 SQUARE FOOT BRAZED PANEL

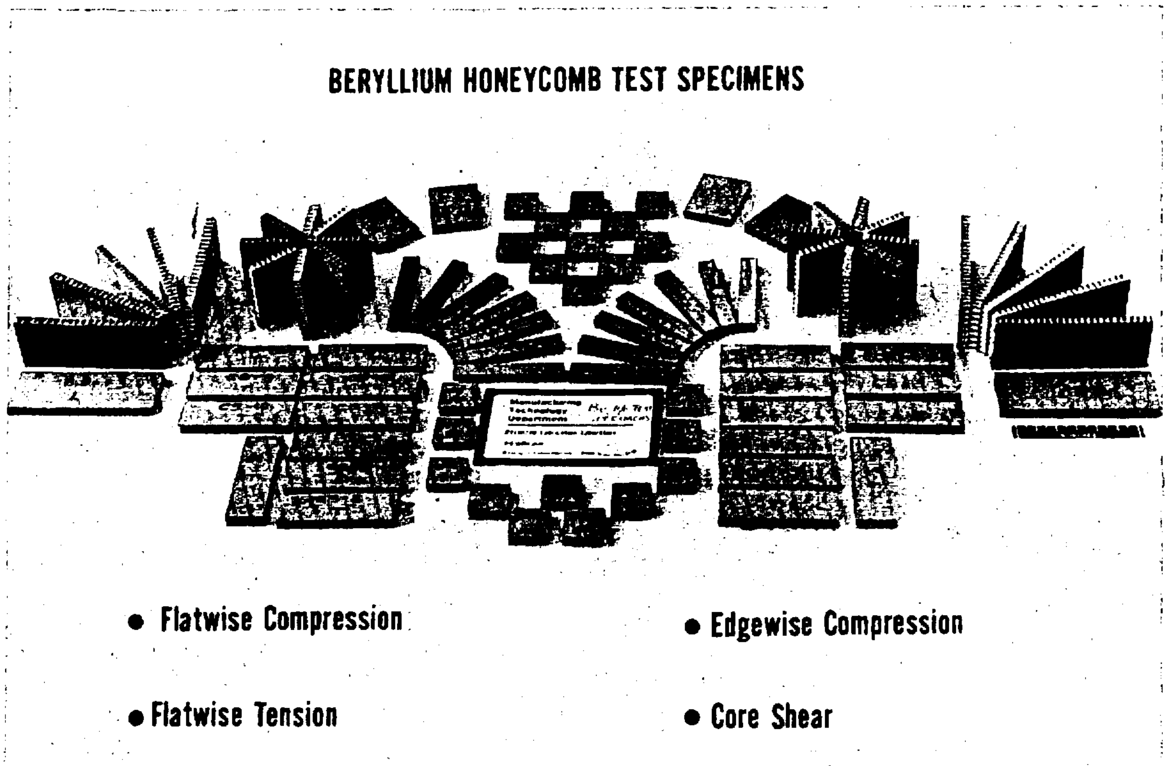


FIGURE 48. TYPICAL BERYLLIUM HONEYCOMB TEST SPECIMENS

Specimens of approximately 3 inches by 4 inches were prepared for testing by grinding the load bearing ends parallel (within 0.0005 inch) to each other and perpendicular to their length. The open core along the two loaded ends was filled with support material (epoxy for the room temperature tests and castable Glasrock for the elevated temperature tests) for edge stabilization.

Fixturing in the Instron tensile test machine is shown in Figure 49. A cross head rate of 0.002 inch/minute was used. Both longitudinal and transverse ribbon directions were tested with no significant differences. Also a comparison between the 3 inch and 4 inch column lengths were made with little changes in values.

Typical fractured specimens are shown in Figure 50. The highly encouraging and significant results of this critical test are shown in Table IX. Average values of the computed compressive stress developed in the two 0.020 inch CRS beryllium face sheets ranged from 79.8 to 91.2 ksi at room temperature, 77.0 to 80.8 ksi at 300°F and 60.2 to 72.0 ksi at 600°F. In all cases, these values were well above the proportional limit of the CRS beryllium face sheet materials (approximately 35 ksi at room temperature), indicating all failures occurred after plastic deformation, as originally designed (Section 4.1). Deformation before failure was recorded up to 0.240 inch indicating this brazed composite honeycomb sandwich is more ductile

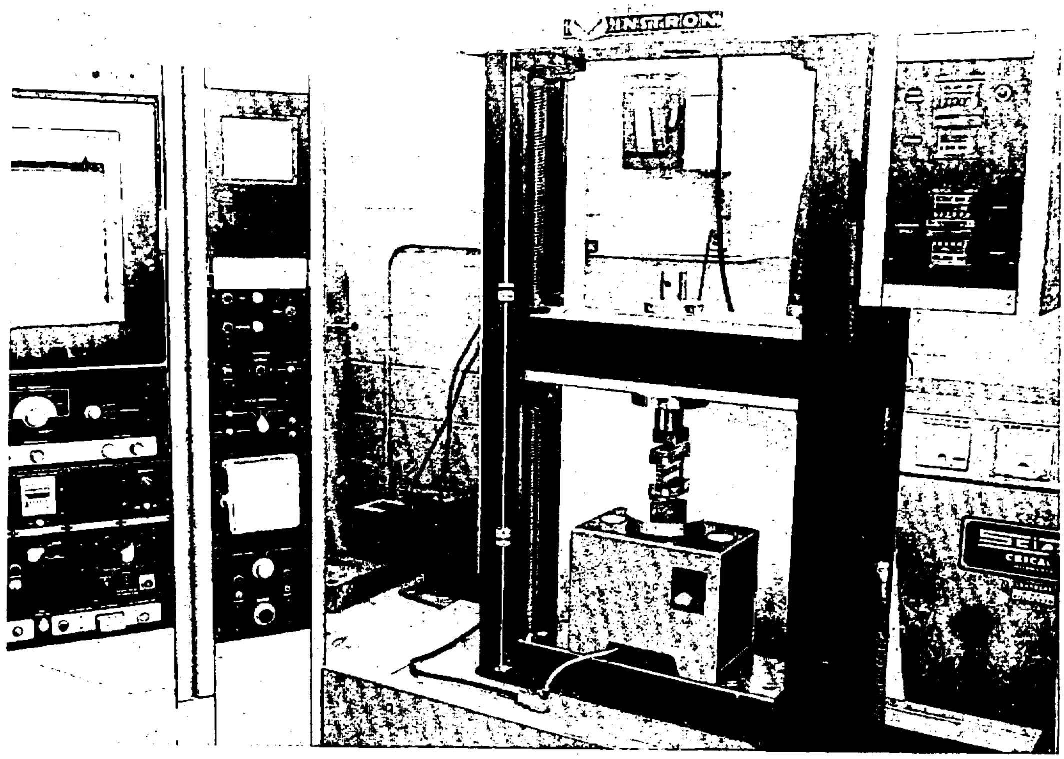


FIGURE 49. EDGEWISE COMPRESSION ROOM TEMPERATURE TEST SET-UP

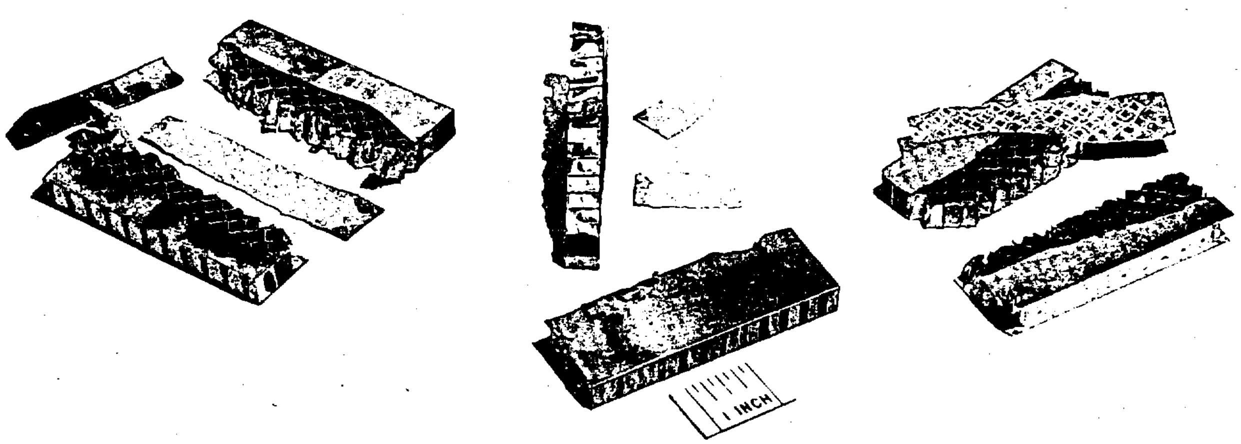


FIGURE 50. TYPICAL FRACTURED EDGEWISE COMPRESSION SPECIMENS

TABLE IX

MECHANICAL TEST PROPERTIES OF BRAZED BERYLLIUM HONEYCOMB SANDWICH PANELS (PHASE III)

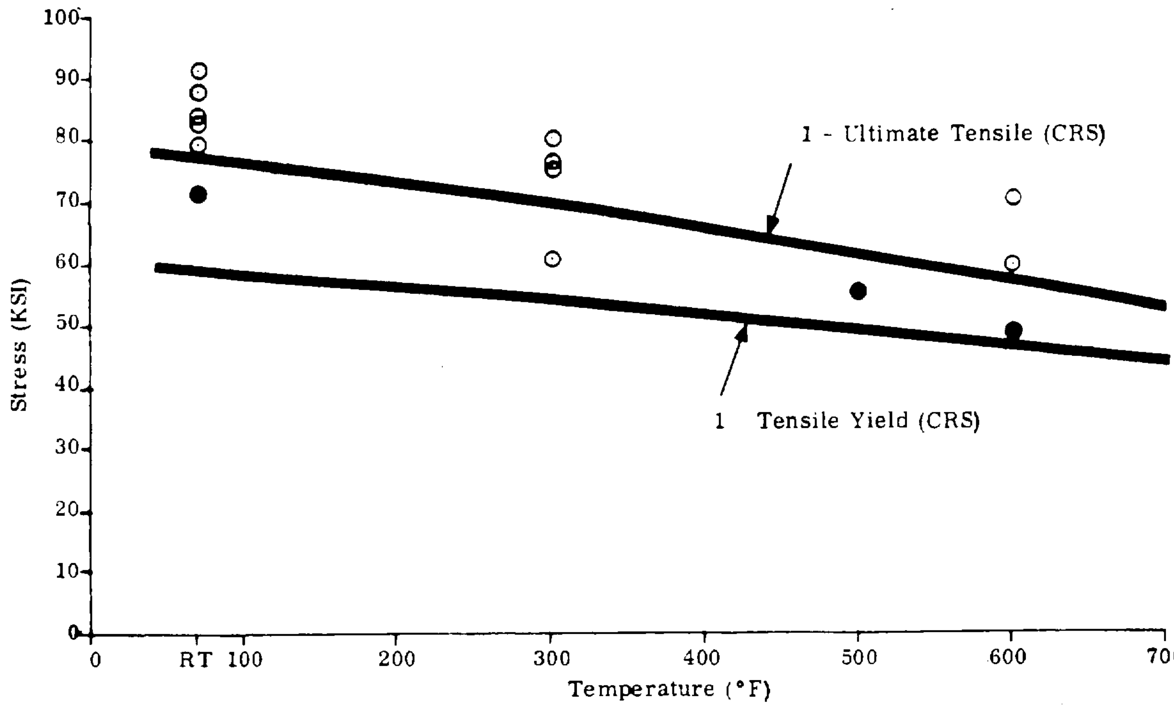
Type	Specimen No.	Test Temp (°F)	Specimen Size (in.)	Ribbon Direction	Gage (in.)	ULT Load (lb)	Average Stress (Calculated) KSI	Average Stress (Calculated) Type	Failure Mode	Notes
Edgewise Compression	ECL4	RT	2.951 x 3.993	T	.006	13430	81.0	Compressive, Faces	Face/Core	
	ECL9	RT	2.922 x 3.995	L	.006	10240	87.8			Tested in long direction.
	ECL10	RT	2.906 x 4.068	T	.006	13650	84.2			
	ECT3	RT	2.927 x 4.002	L	.006	9600	60.0			Edge notch noted.
	ECT5	RT	3.019 x 3.900	T	.006	11050	91.2			Tested in long direction.
	ECT9	RT	3.005 x 4.069	L	.006	13000	79.8			
	ECL1	300	2.916 x 3.941	T	.006	9800	62.2			
	ECL7	300	2.968 x 4.100	T	.006	13200	80.8			
	ECL8	300	2.926 x 4.003	T	.006	12400	77.0			
	ECT10	300	3.020 x 3.998	L	.006	12200	76.3			
	ECT2	300	2.968 x 4.012	L	.006	9800	61.0			Eccentric load, spec. failed on one side only.
	ECT6	300	2.865 x 4.001	L	.006	8500	53.0			Concentrated point load due to particle in fixture.
	ECL2	600	2.945 x 3.530	T	.006	6400	45.4			Eccentric load, spec. failed on one side only.
	ECT4	600	2.895 x 3.425	L	.006	5800	42.3			Fixture out of flat.
	ECT7	600	3.020 x 3.975	L	.006	6800	43.0			Fixture out of flat.
	ECL6	600	2.970 x 3.947	T	.006	9500	60.2			Fixture reground.
	ECL5	600	2.815 x 4.100	T	.006	11700		Compressive, Faces	Face/Core	Fixture reground.
	ECT1	600	---	L	.006	---	----	---	---	No test - specimen damaged in processing.
Flatwise Compression	FC1	RT	1.995 x 2.000	-	.006	4450	1.111/23.6	Core Comp/Ribbon Comp	Core	
	FC2	RT	1.985 x 2.000	-	.006	4400	1.100/23.4			
	FC7	RT	1.970 x 2.065	-	.006	4900	1.225/26.0			
	FC3	300	1.950 x 1.975	-	.006	3780	0.980/20.8			
	FC4	300	1.925 x 1.980	-	.006	3600	0.950/20.2			
	FC8	300	2.016 x 2.031	-	.006	3770	0.920/19.5			
	FC5	600	1.967 x 1.976	-	.006	2770	0.730/15.2			
	FC6	600	2.060 x 1.979	-	.006	3400	0.835/17.8			
	FC9	600	1.990 x 1.930	-	.006	2140	0.555/11.7	Core Comp/Ribbon Comp	Core	
Flatwise Tension	FT1	RT	1.959 x 1.965	-	.006	2426	0.564/13.4	Core Tensile/Ribbon Tensile	Core	
	FT7	RT	1.960 x 1.926	-	.006	2475	0.618/13.9			
	FT10	RT	1.940 x 2.068	-	.006	2750	0.687/14.6			
	FT3	300	1.975 x 1.946	-	.006	2415	0.628/13.4		Core	
	FT6	300	1.960 x 1.935	-	.006	2680	0.705/15.0		95% Core	
	FT8	300	1.980 x 1.950	-	.006	2635	0.680/14.5		Core	
	FT4	600	1.986 x 1.986	-	.006	2185	0.606/12.9		Core	
	FT5	600	2.015 x 2.010	-	.006	1200	0.296/6.3		Core	
	FT9	600	1.950 x 1.985	-	.006	1285	0.305/7.1	Core Tensile/Ribbon Tensile	80% Core	

TABLE IX (Cont)

MECHANICAL TEST PROPERTIES OF BRAZED BERYLLIUM HONEYCOMB SANDWICH PANELS (PHASE III)

Type	Specimen No.	Test Temp (°F)	Specimen Size (in.)	Ribbon Direction	Ribbon Gage (in.)	ULT Load (lb)	Average Stress (Calculated) KSI	Average Stress (Calculated) Type	Failure Mode	Notes
Block Shear	CSL4	RT		L	.006			Sandwich Shear		No test, specimen damaged in processing.
	CSL5	RT	2.055 x 6.050	L	.006	3305	0.267		Face/Core	With peel component.
	CSL10	RT	1.959 x 6.000	L	.006	1990	0.166			
	CST1	RT	1.995 x 6.025	T	.006	3080	0.256			
	CST4	RT	2.067 x 6.095	T	.006	2330	0.194			
	CST7	RT	1.950 x 6.025	T	.006	2860	0.238		Face/Core	
	CSL2	300	2.110 x 5.940	L	.006	2210	0.184		Bond/Fail	
									Face/Crack	
	CSL3	300	2.015 x 6.002	L	.006	2660	0.219		Face/Core	With peel component.
	CSL8	300	1.935 x 5.997	L	.006	4410	0.382		Core Shear	Pure shear.
	CST2	300	1.925 x 6.050	T	.006	4365	0.375			
	CST5	300	1.975 x 6.045	T	.006	5020	0.422			
	CST8	300	1.975 x 5.995	T	.006	4525	0.384			
	CSL1	600	2.025 x 6.020	L	.006	4355	0.356			
	CSL6	600	2.020 x 6.066	L	.006	4370	0.357			- Bond failure at 2000 lbs.
	CSL9	600	1.937 x 6.011	L	.006	3000	0.259		Core Shear	Pure shear.
	CST3	600	1.950 x 6.050	T	.006	2090	0.174		Face/Core	With peel component.
	CST6	600	1.995 x 6.036	T	.006	3750	0.310		Core Shear	Pure shear.
	CST9	600	1.950 x 6.070	T	.006	3580	0.304	Sandwich Shear	Core Shear	Pure shear.

than beryllium is generally believed to be. As shown in Figure 51, most of the data points were above the typical commercial 0.2 percent offset yield. Last year's results are also shown on this curve.



1) Typical Commercial Curves
2) Avg. Compressive Stress Computed for Two, 0.020 Inch CRS Face Sheets
● Averages of last year's results (4 at RT, 1 at 500°F, 7 at 600°F)
○ This year's results (invalid data points from Table IX excluded).

FIGURE 51. STRESS VERSUS TEMPERATURE, EDGEWISE COMPRESSION TESTS

Eccentric loading was observed on a few of the later specimens to be tested and values reported in Table IX are excluded from above valid values. An analysis of the fixturing indicated some plastic deformation had occurred in the fixture from previous tests. This condition was corrected to obtain valid results on the remaining specimens.

6.5.2 Flatwise Tension Tests

Flatwise tension tests were conducted at room temperature, 300°F and 600°F to determine the effective strength of the core-face sheet joints in tension, with the load applied normal to the sandwich facing.

Two-inch by two-inch square specimens were used with loading blocks bonded to the facings of each test specimen. For both the room temperature and 300°F tests, 55 percent Shell Epon Resin No. 828 in conjunction with 45 percent General Mills Versamid No. 125 was used. However, at 600°F, the only bonding system which proved effective was Sablon 1000; a Solar-developed, high-temperature Polyimide system. The test set-up included a standard tensile test machine (Baldwin) coupled with self-aligning fixture, tube furnace, furnace controls and specimen thermocouple readout device (Mini-Mite).

All elevated temperature specimens were allowed to stabilize for 10 minutes at temperature before testing. A constant load rate of approximately 50 pounds per minute was applied until failure. Typical fractured test specimens are shown in Figure 52.

The results obtained from the flatwise tension tests are listed in Table IX. The results are considerably higher and more consistant than previous results obtained (Table VIII) in Phase II for smaller, one inch square specimens. The calculated tensile stress in the ribbon material averaged 13.9 ksi at room temperature, 14.3 ksi at 300°F, and 8.7 ksi at 600°F.

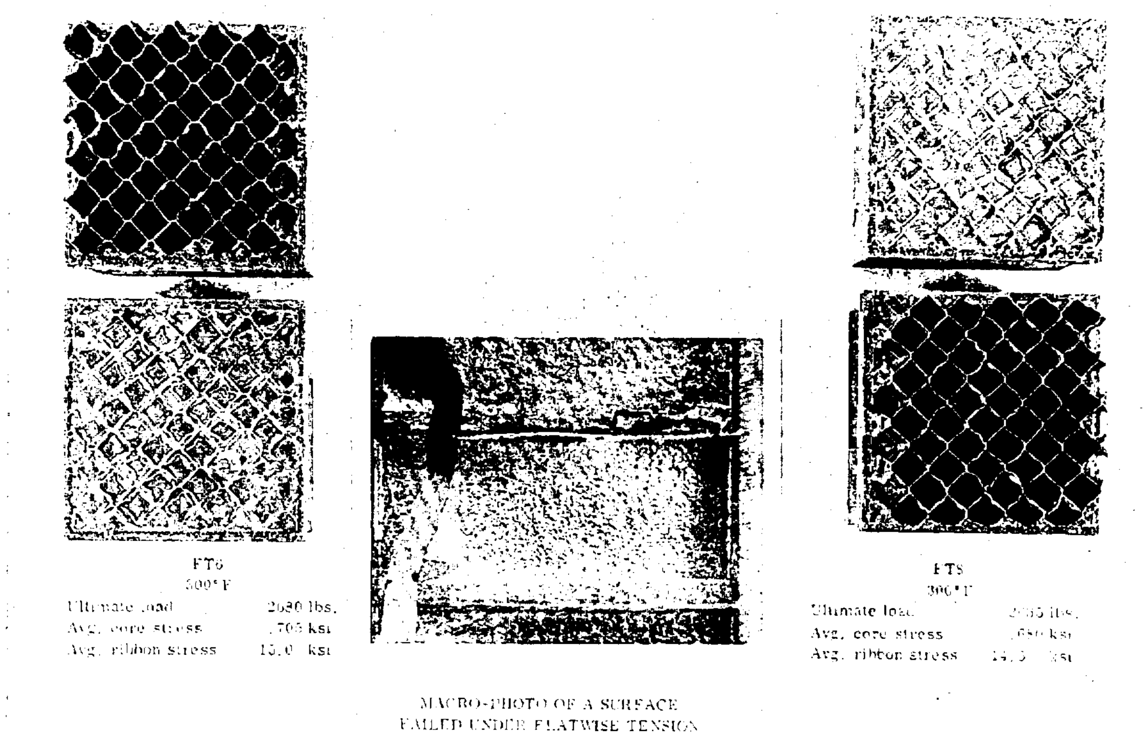


FIGURE 52. TYPICAL TESTED FLATWISE TENSION SPECIMENS (2 INCH x 2 INCH)

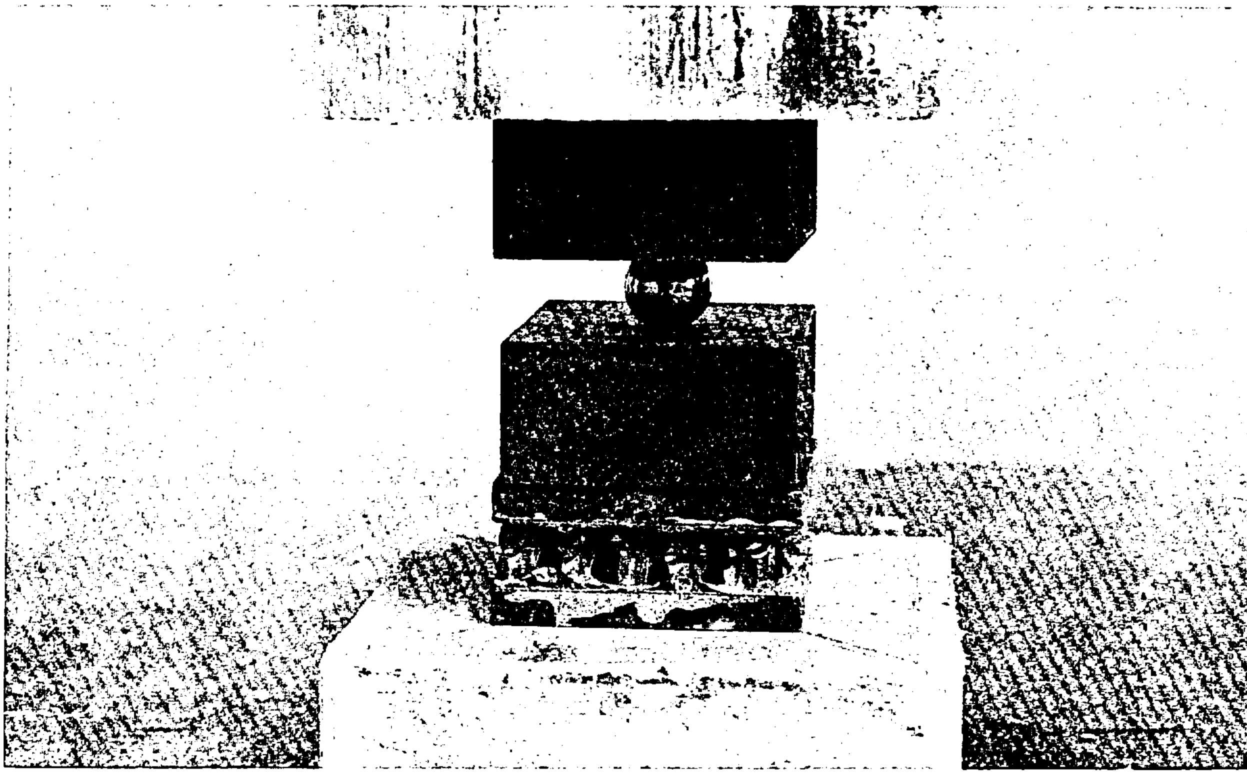


FIGURE 53. FLATWISE COMPRESSION TEST SET-UP

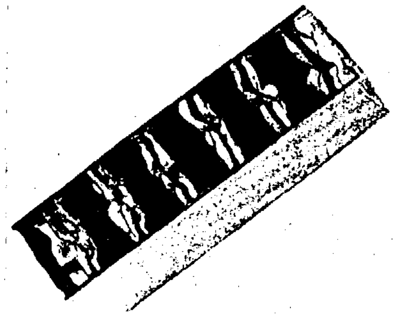
6.5.3 Flatwise Compression Tests

Flatwise compression tests were conducted at room temperature, 300°F, and 600°F to determine the core strength in compression, with load applied normal to the sandwich facing.

Similar specimens (2 inches square) and bonding adhesives were used as previously described in the flatwise tension tests. To assure alignment, the specimens were bonded to 2 inch square steel plates.

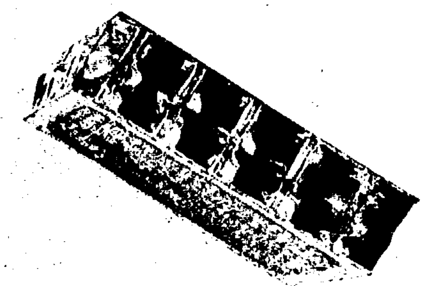
The test set-up is shown in Figure 53. For the elevated temperature tests, a small furnace complete with controls, and with thermocouples attached to the specimens, were added to the fixturing shown. All elevated temperature specimens were stabilized for 10 minutes at temperature before testing. A constant load rate of approximately 50 pounds per minute was applied until failure; a typical fractured specimen (2 inch square reference plates removed) is shown in Figure 54.

The results obtained from the flatwise compression tests are listed in Table IX. The calculated compressive stress in the ribbon material ranged from 24.3 ksi at room temperature, 20.1 ksi at 300°F and 14.9 ksi at 600°F.



FC7
RT

Ultimate load	4900 lbs.
Avg. core stress	1.225 ksi
Avg. ribbon stress	26.0 ksi



FC6
600° F

Ultimate load	3400 lbs.
Avg. core stress	.835 ksi
Avg. ribbon stress	17.8 ksi

FC4
300° F

Ultimate load	3600 lbs.
Avg. core stress	.950 ksi
Avg. ribbon stress	20.2 ksi

FIGURE 54. TYPICAL FLATWISE COMPRESSION FAILED SPECIMENS

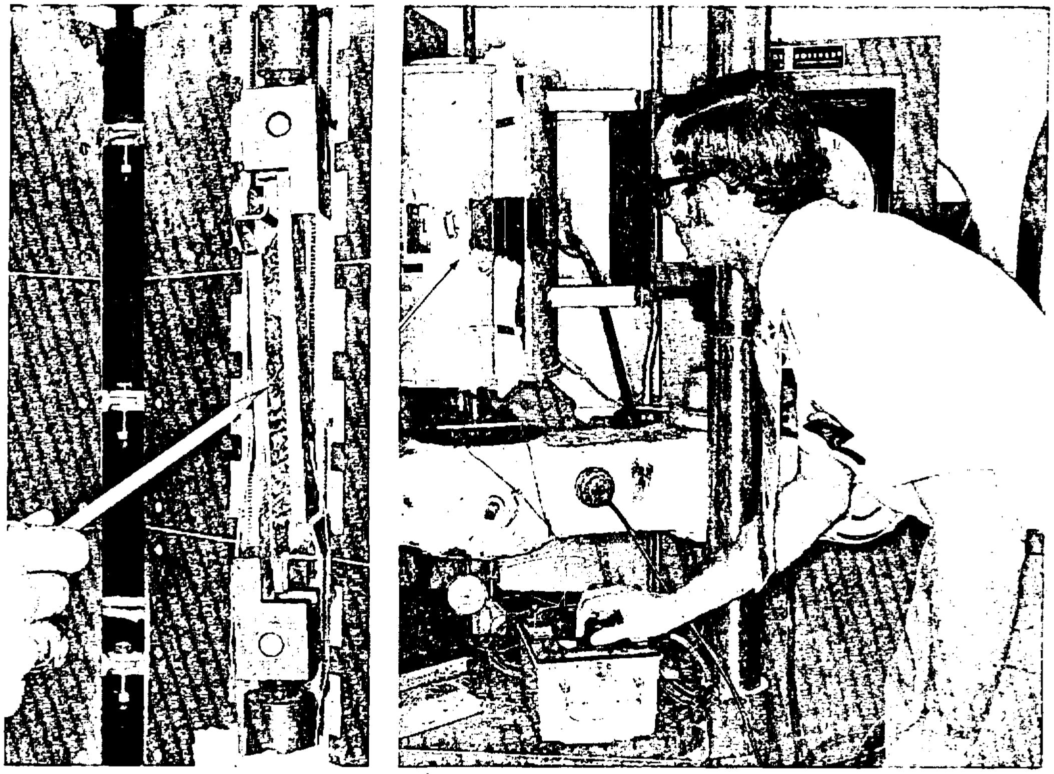


FIGURE 55. TEST SET-UP FOR BLOCK SHEAR TESTS

6.5.4 Block Shear Tests

Block shear tests were conducted to determine shear properties of the brazed beryllium sandwich-core construction.

Two-inch by six-inch specimens were used rather than the previously 3-inch long specimens. The bonding procedures used to attach the specimens to the fixtures were the same as those used during the flatwise tension tests.

The specimens were fixtured as shown in Figure 55. Standard universal testing equipment was used with tube furnace and controls for the elevated temperature tests. All elevated temperature specimens were stabilized for 10 minutes at temperature before testing. A constant load rate of approximately 50 pounds per minute was applied until failure; typical failures are shown in Figure 56.

The results obtained from the block shear tests are listed in Table IX.

Tests were conducted both with and without a peel-component on the face sheets. Results were very encouraging with the "pure" shear specimens as shown in Table IX and Figure 56.

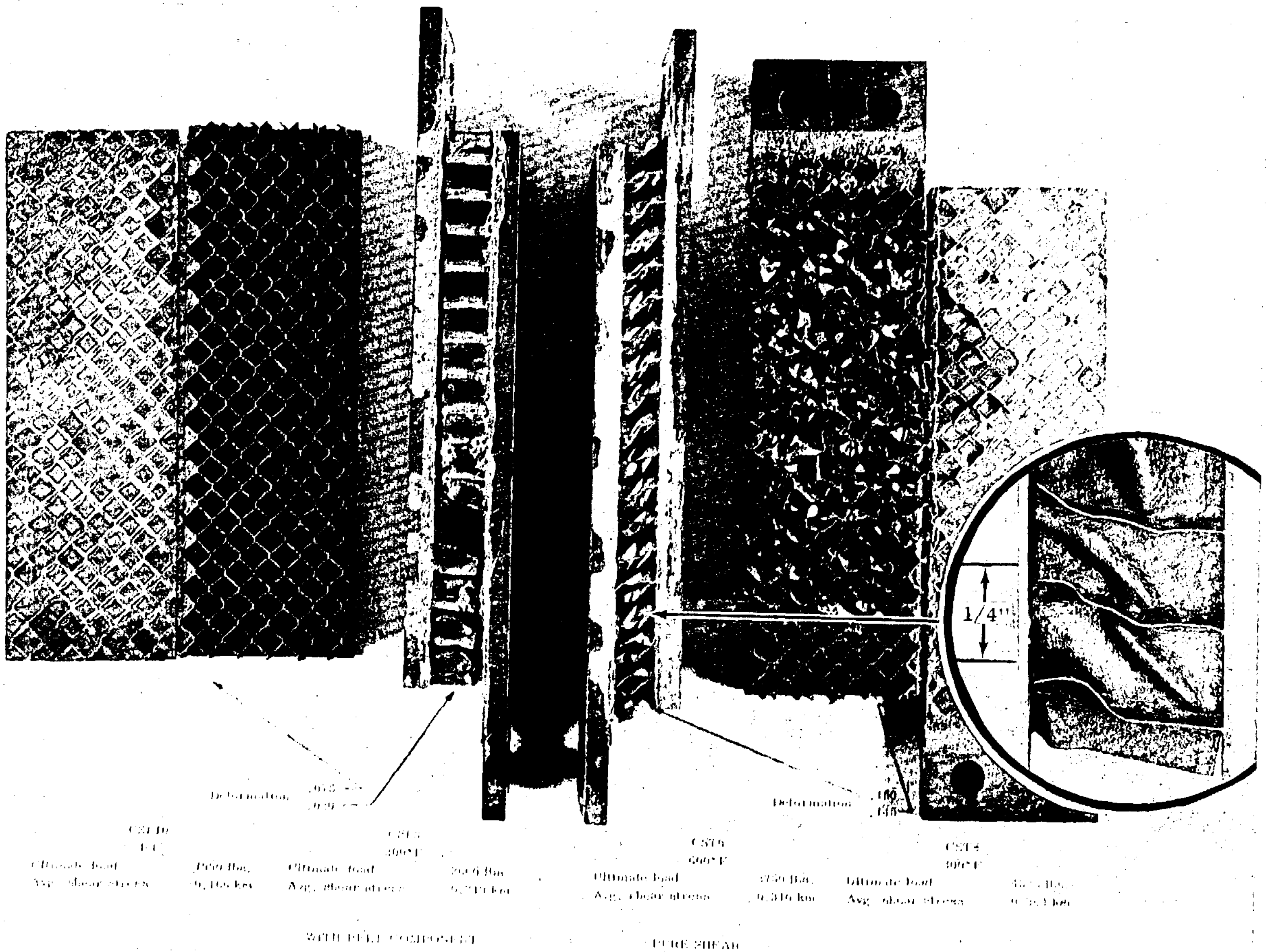


FIGURE 56. TYPICAL CORE SHEAR FAILED SPECIMENS

7

TECHNICAL DISCUSSION - PHASE IV

The third year efforts were divided into two phases (IV and V). This section discusses Phase IV, the modification of one (1) and fabrication of two (2) large 10 ft^2 brazed all beryllium honeycomb panels. These panels were arbitrary called A, B and C, respectively.

7.1 MATERIAL INSPECTION (Task 22)

The ingot foil residual from the previous year's effort was reassigned to Phase IV. The total beryllium inventory was shown previously in Table I (Section 3) and reflects this new assignment of materials.

New cross rolled sheet materials for the face sheets of the Phase IV panels were received and also added to Table I (Section 3). These two (2) sheets measured .030" x 36" x 96" (Fig. 57) and are currently commercially available materials. Large beryllium sheets of this size and availability make possible the practicable production of large honeycomb sandwich panels for advanced technology applications. However, the original requirements for the face sheets were for .020" nominal thickness. The .030" nominal thickness of these sheets represents a 50 percent increase in thickness. This added thickness was evaluated as to the effect on the program.

A joint decision between NASA and Solar to use these sheets as is has been made for the following reasons:

1) Additional funding (~$2000) is not available to cover the etching costs to produce 0.020" material.
2) Added risk involved in etching these large sheets.
3) Replacement .020" thick material not available at NASA.
4) Mechanical testing based on design limit load stresses of facing materials.
5) Relative comparison could be made to previous testing of .020" thick faces.

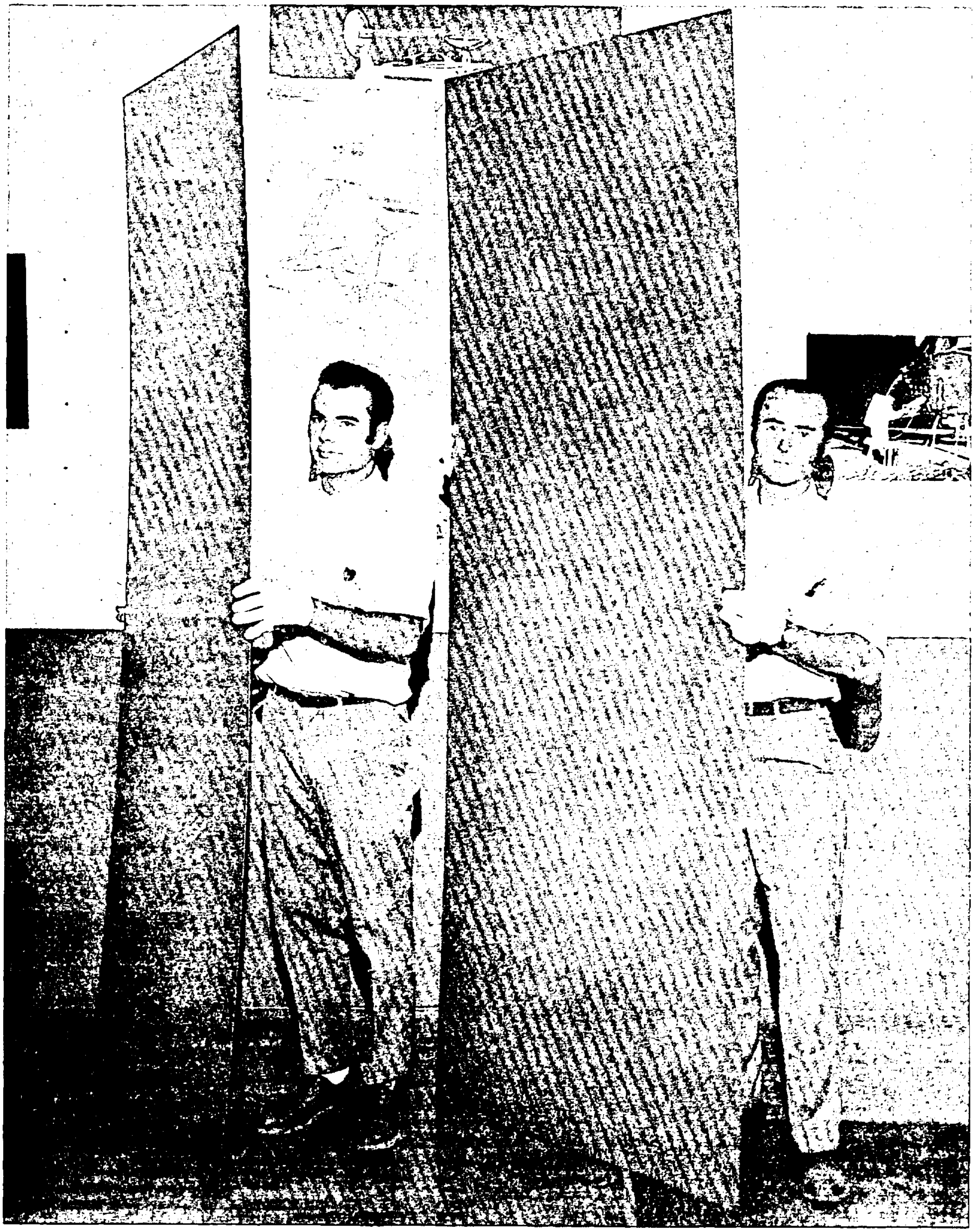


FIGURE 57. LARGE BERYLLIUM SHEETS (.030 x 36 x 96")

7.2 CORE FABRICATION (Task 23)

All the ingot foil materials required to fabricate the core were previously sheared into ribbons, ground to the precision uniform height and corrugated. Procedures previously established were followed and no problems occurred.

Welding of the corrugated stock into core was completed. The welding went smoothly after the power source was overhauled and repaired as reported in Section 7.3. Figure 58 shows the two (2) large core blankets which were resistance welded on Solar's automatic core machine. These each measure 31" x 46" with a precision (as welded) .500" height. Approximately 80 square feet of .006" beryllium ingot foil material was used to produce these two core blankets. Solar's standard 1/4" square cell was used to match the previously fabricated panels.

7.3 FACILITY MODIFICATIONS (Task 24)

Solar's automatic core machine was cleaned and checked for welding efficiency. A pneumatic system was added to control and maintain a constant electrode pressure.

It was elected to use Solar's large circulating furnace for creep forming of Panel A and components for Panels B and C. Brazing of Panels B and C was elected to be performed in the curved condition. This was selected over the ceramic tooling for increased temperature uniformity and control. This concept was verified in Section 7.5.1 of this report.

7.4 CHANNEL FABRICATION (Task 25)

Edge support channels were fabricated from beryllium sheet. Channel blanks and face sheets were layed out on the large .030" x 36" x 96" CRS beryllium sheets (Fig. 58). Cutting of the components from these sheets was accomplished using Solar's precision abrasive saw. This facility is capable of producing straight cuts in beryllium over 9 feet long.

One of the .030" x 36" x 96" beryllium sheets is shown in Figure 59 after sawing into channel blanks and face sheet details. The 48" long channel blanks were straight within .001" to .004" "as-cut".

The channel blanks were precision hot formed into U-channels with a tight 2t bend radius. These stress-relieved components and detail blanks are shown in Figure 60. The short (32" length) channels will be used straight, as formed, for end close-outs. The longer (48") channels were formed to a 10 ft radius used for edge close-outs. Figure 61 shows some of the completed channels used for edge close-outs (both straight and curved).

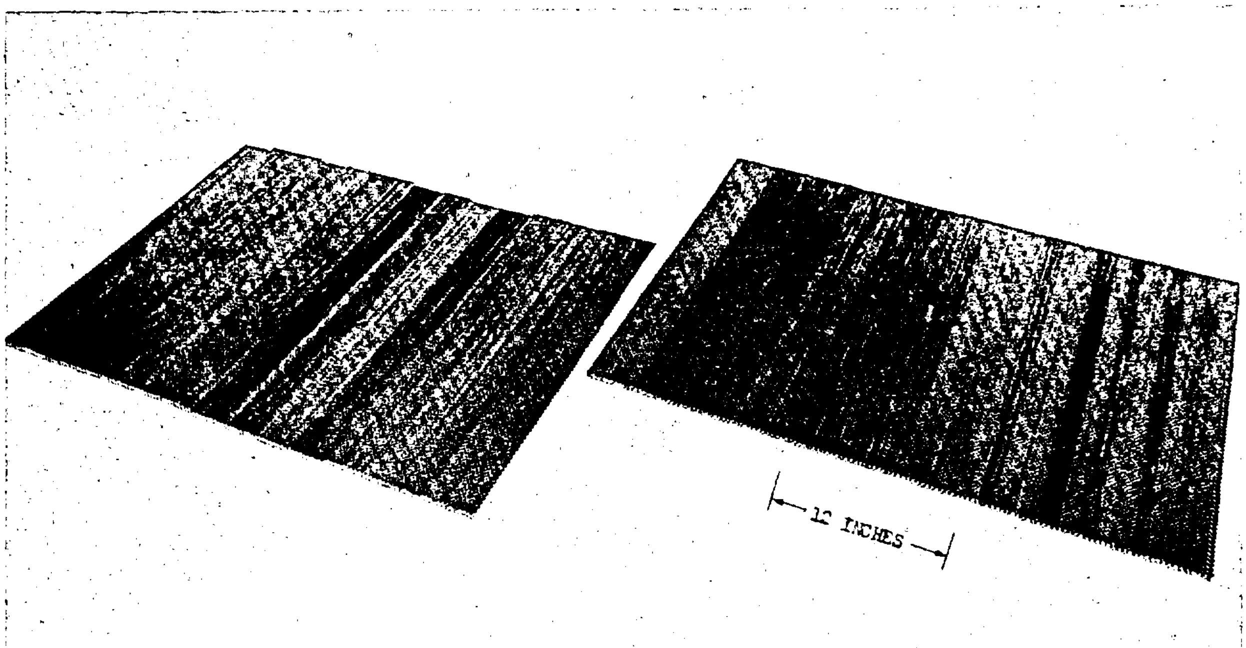


FIGURE 58. LARGE BERYLLIUM CORE BLANKETS

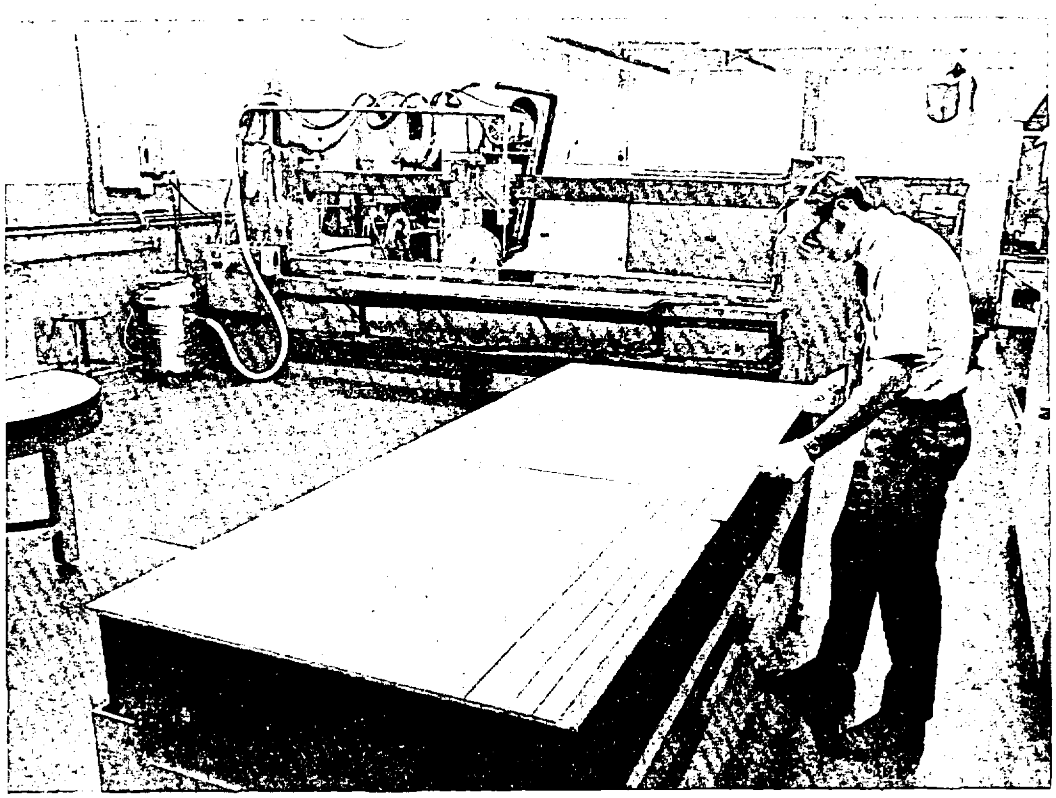


FIGURE 59. 36" x 96" BERYLLIUM SHEET - AFTER SAWING

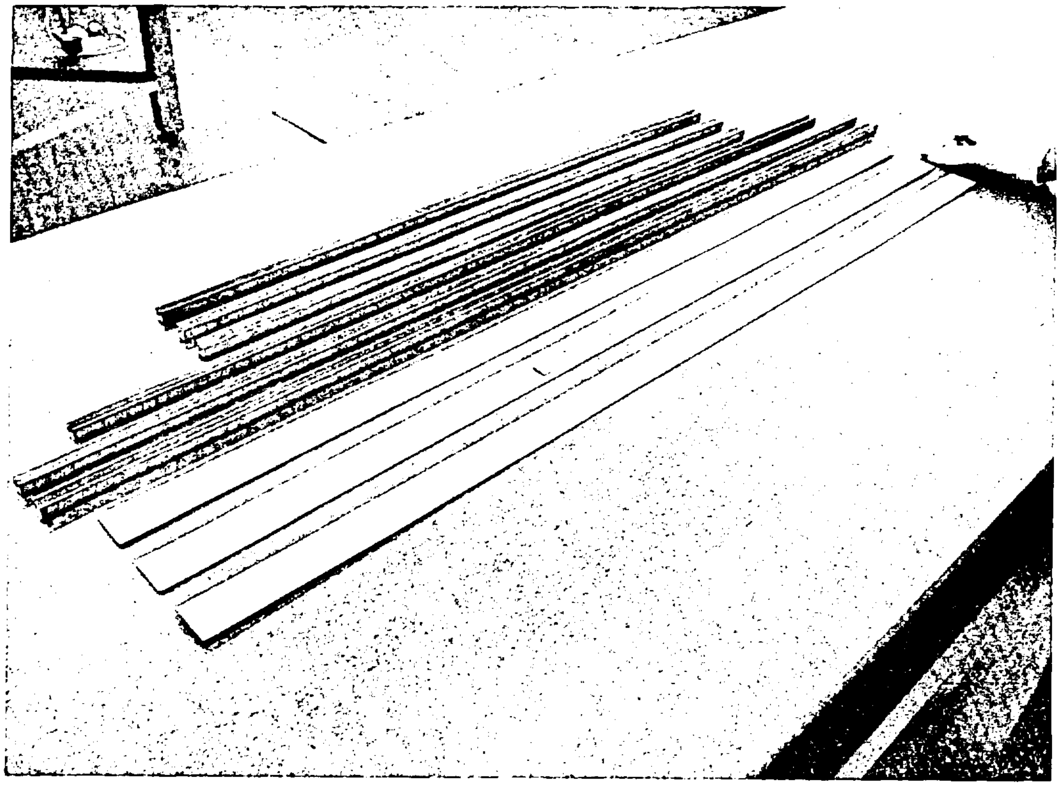


FIGURE 60. PRECISION HOT-FORMED BERYLLIUM U-CHANNELS AND BLANKS

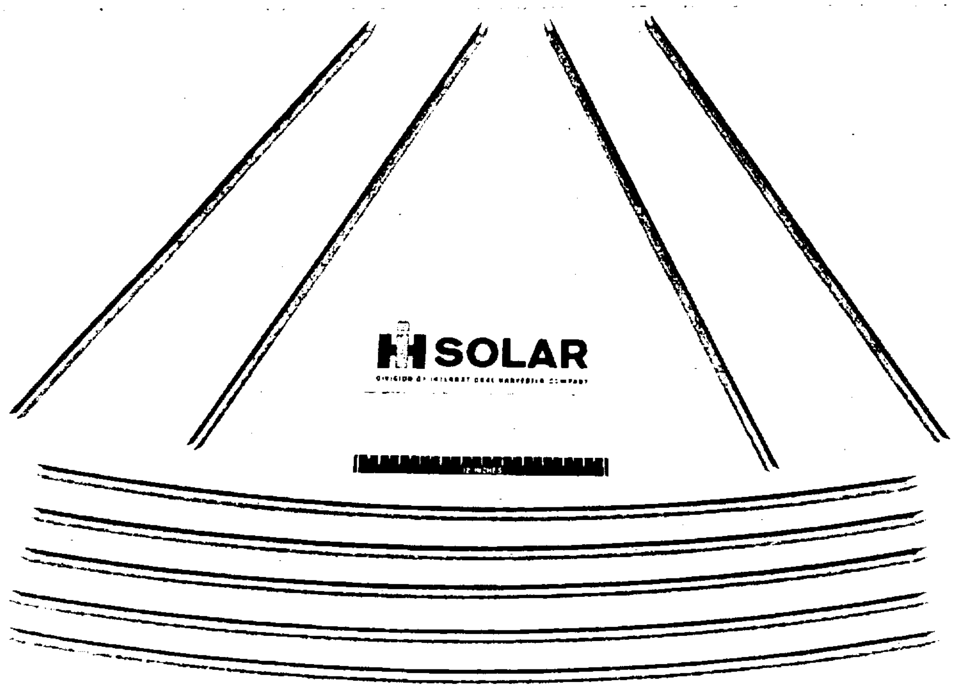


FIGURE 61. COMPLETED EDGE CLOSE-OUT U-CHANNELS (CURVED AND STRAIGHT

7.5 PANEL FABRICATION

7.5.1 Test of Curved Component Fabrication and Brazing

A test was performed to evaluate the potentials of preforming the panel components (core, faces and channels) for brazing into the final, 10 ft radius, configuration. Based on Solar's past technology in the field of beryllium, it was known that the channels and faces could be readily formed into the required 10 ft radius. Figure 62 shows some previously fabricated U-channels which demonstrated this capability.

The core contouring presented the only unknown obstacle in preforming of panel components. Several pieces of beryllium Ingot Foil were hot formed to an approximate one foot radius. Results indicated "as welded" core had sufficient strength to be formed over this much tighter (1 ft. R vs 10 ft. R) radius. Figure 63 shows some of these formed core samples. Test results showed the welded core could be formed with the ribbon in either the "L" or "T" direction.

Based on the above encouraging results, components for a 3" x 12" panel were formed to a 4 ft. radius of curvature in one operation. These components, shown in Figure 64 were then combined with two (2) three inch long U-channels and assembled for brazing.

Standard cleaning and loading procedures were followed and the assembly was brazed at 1460°F. Excellent braze flow and fillets were observed on the as-brazed panel as shown in Figure 65. These results were confirmed by radiographs. The structure remained stable throughout the braze cycle and conformed to the 48 inch radius of curvature.

The above results indicated it would be practical to build both Panels B and C in this manner.

7.5.2 Panel Assembly

As discussed in the preceding section, the face sheets were cut to size along with cutting of channel blanks. Figure 66 shows some of the components that were used to fabricate the brazed Panels B and C.

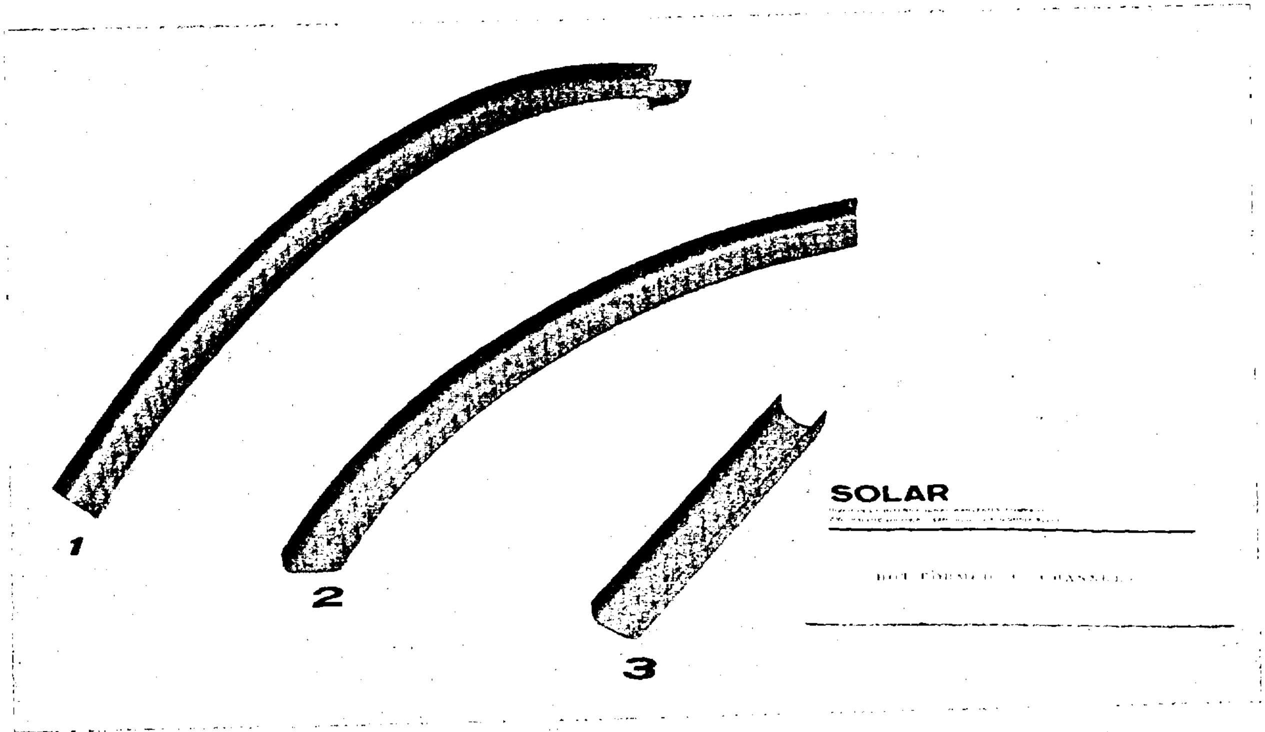


FIGURE 62. HOT FORMED CURVED BERYLLIUM U-CHANNELS

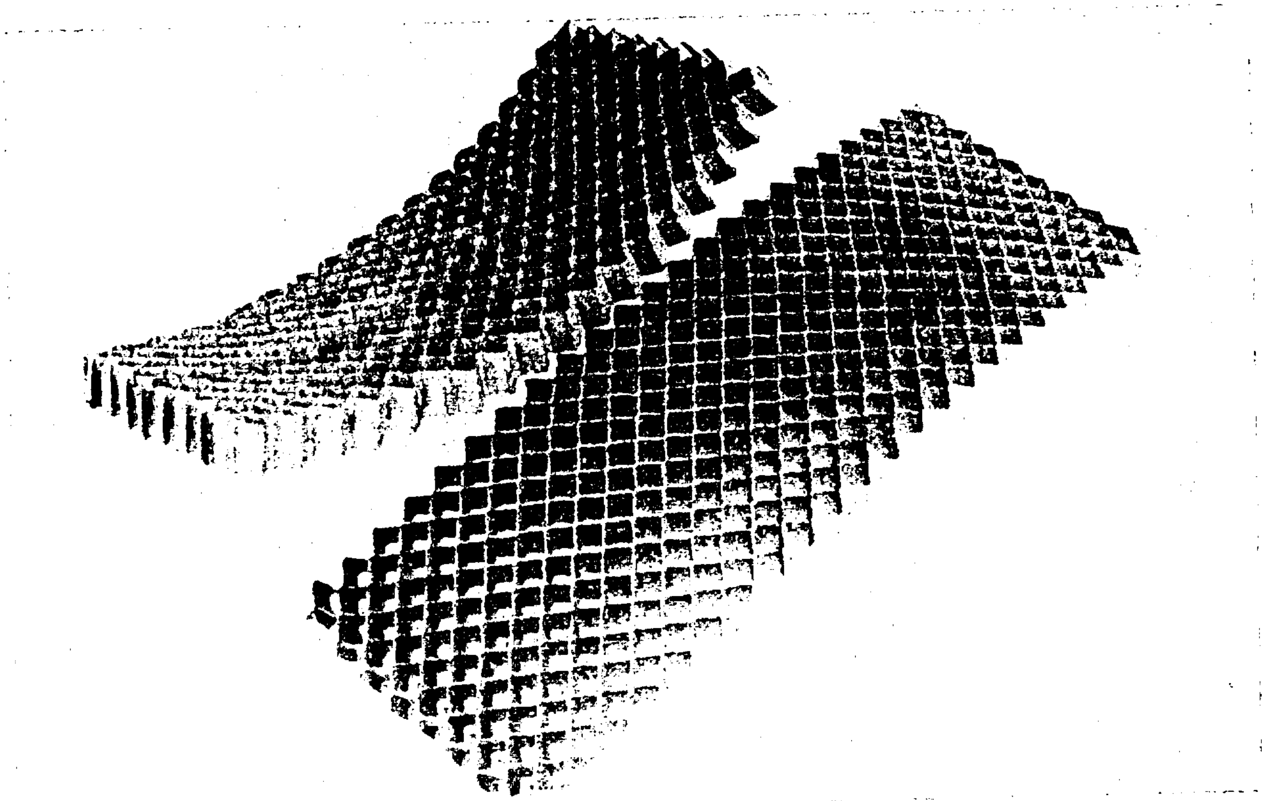


FIGURE 63. CURVED BERYLLIUM HONEYCOMB CORE

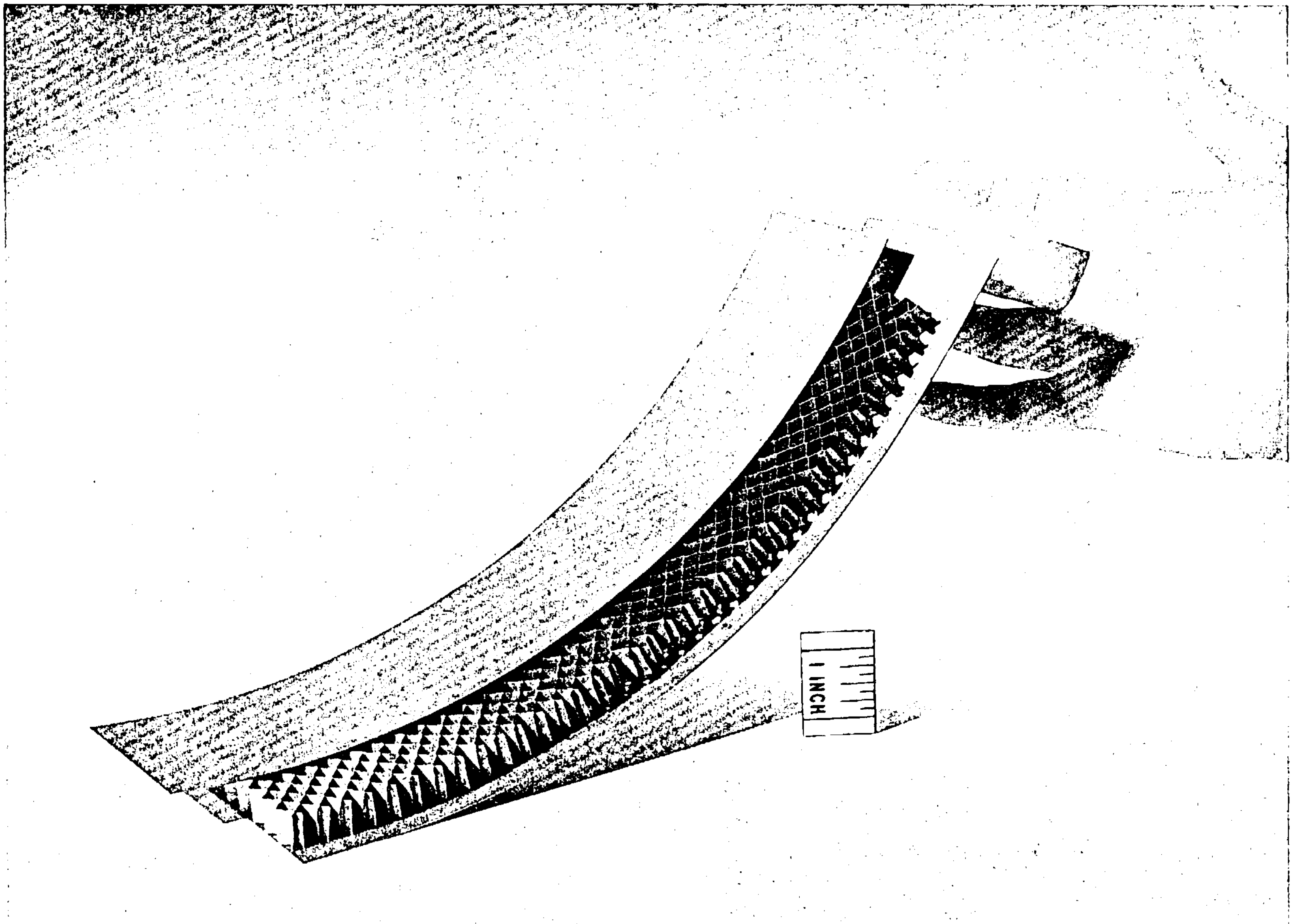


FIGURE 64. CURVED COMPONENTS FOR BERYLLIUM PANEL

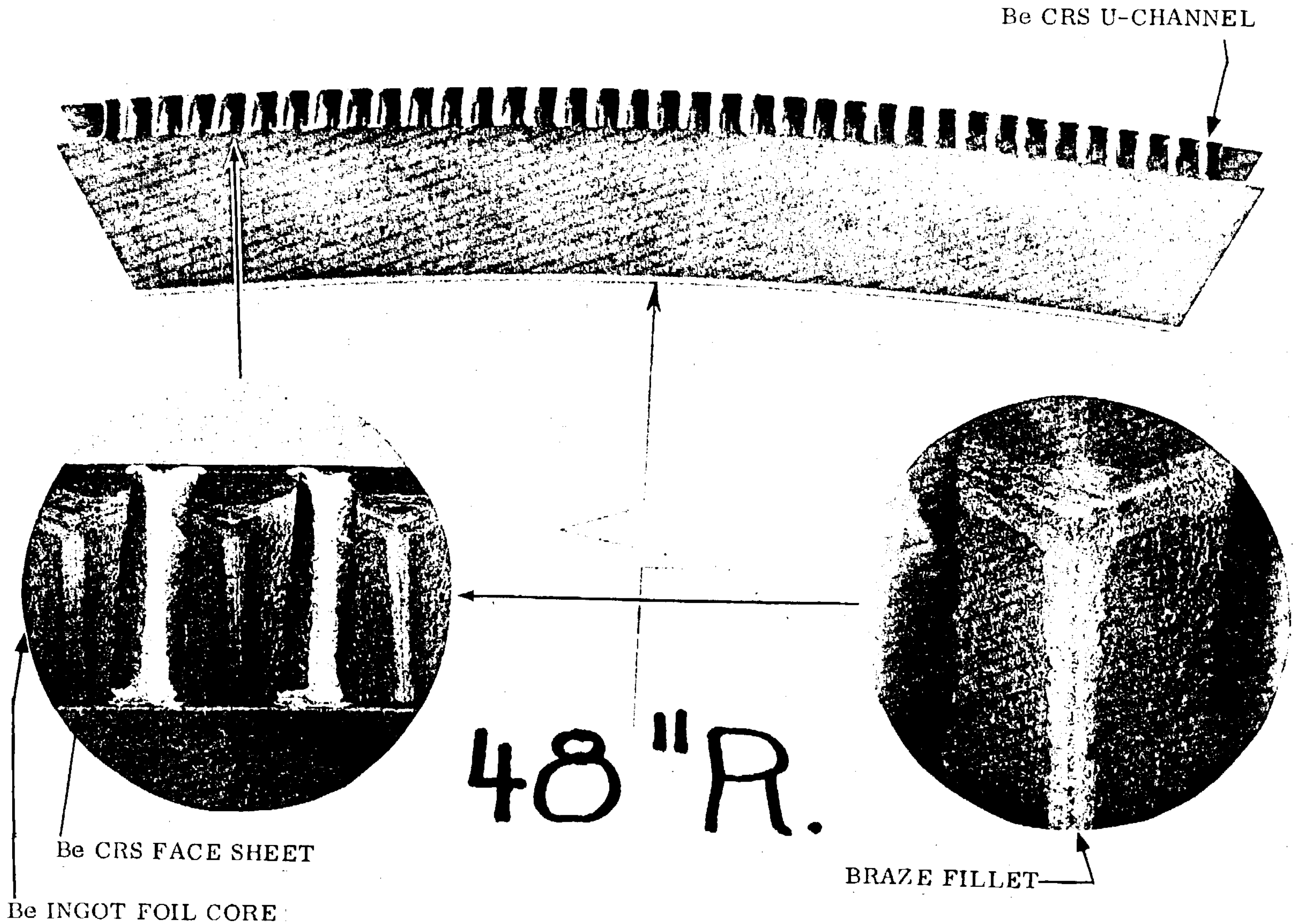


FIGURE 65. CURVED AND BRAZED BERYLLIUM HONEYCOMB SANDWICH

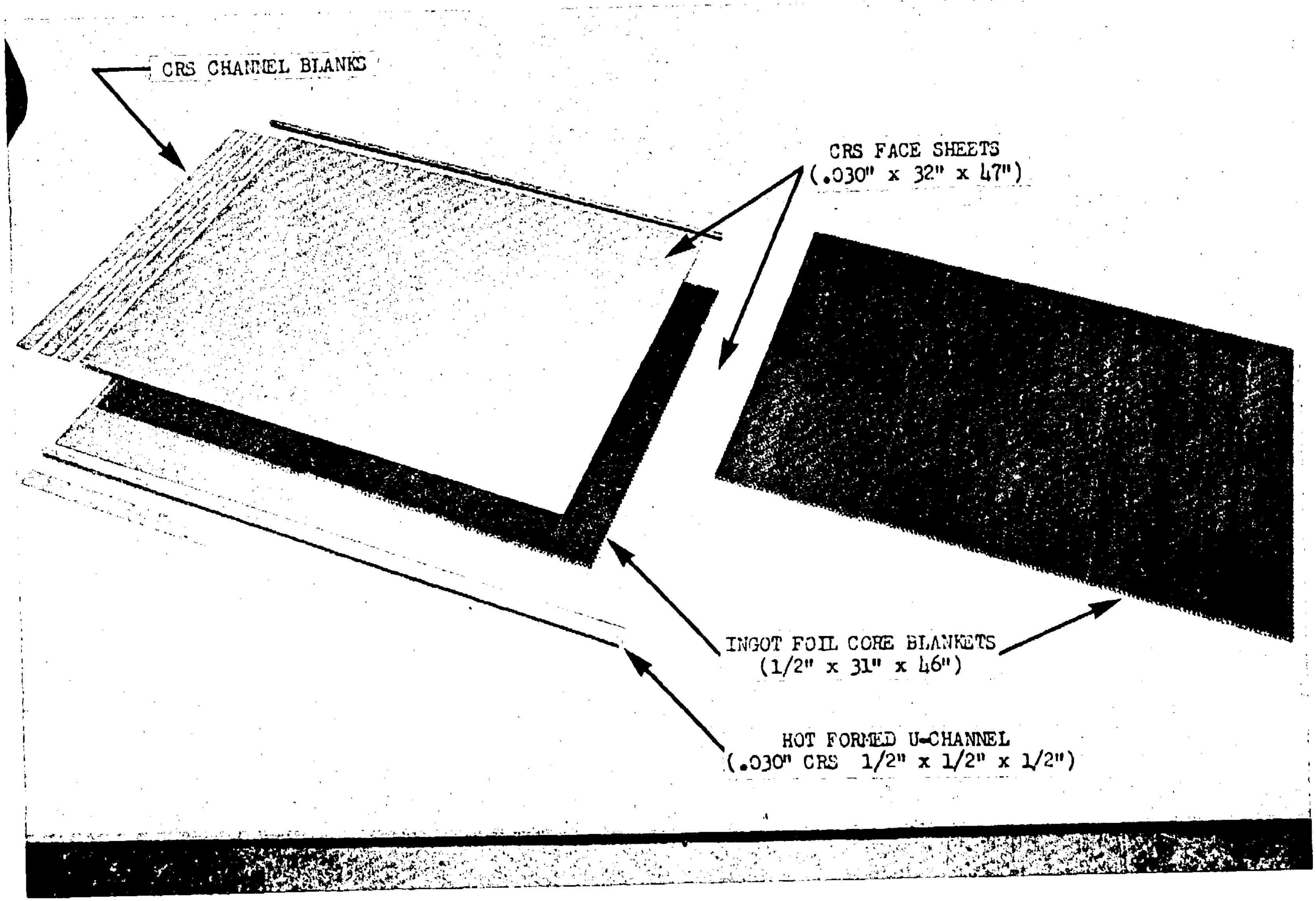


FIGURE 66. BERYLLIUM PANEL COMPONENTS (1/2" x 1/2" x 1/2" x 48")

By utilizing the novel approach the following may be feasible:

- Beryllium core sized precisely to fit facings and desired panel contour.

- Beryllium components are stress free after creep forming at 1300°F. Being dimensionally very stable in this condition they permit easy re-assembly and insure reliable braze fit-up.

- By incorporating edge members, inserts, lap strips, high density core, etc., into the preliminary lay-up, (but not the brazing material) then creep-forming, a high precision assembly of individual components is possible at low cost.

- To insure precision component matching, it appears desirable to utilize core several thousandths of an inch or so thicker than say edge channels or inserts. During creep forming, core would then be sized down to meet the more massive component. Channels, "Z" sections, etc., may require support filler bars.

- Close tolerance machining of individual beryllium components as is usually required, may now be relaxed. Tolerance stack-up problems are minimized as the new method allows dimensional accommodation in the creep forming operation.

7.6 MODIFYING EXISTING PANEL (Task 27)

This task was combined with Task 28 and discussed in the following paragraphs.

7.7 CREEP FORMING (Task 28)

7.7.1 Modification of Existing Panel

The previously brazed flat panel (A) was creep formed to the 10 ft radius of curvature. This was accomplished at a controlled 1250°F temperature by gentle vacuum pressure into a female die.

At room temperature, the panel matched the forming fixture closely after the cycle was completed. However, the face sheet wrinkles responded only slightly to an added bend/stretch form action. This added stretch was included in the creep forming operation in an attempt to remove some of the shallow wrinkles existing on the faces of the as-brazed panel as previously reported (RDR 1550-8). Figure 67 shows this panel as creep formed.

The integrity of the panel appeared sound under X-ray examination and the panel was trimmed to the required 32" x 44" test size. Edge pieces confirmed the brazing of the internal core and face sheets as viewed by X-rays.

Because of the face sheet wrinkling, the edge close-outs Be U-channel cannot be adhesive bonded along the non-uniform edges. Therefore, vibration testing of this panel (Section 8) was without the edge close-outs in place.

7.7.2 Detail Parts for Panels B and C

Core blankets and face sheets (previously fabricated) were creep formed into the 10 ft. radius of curvature in two (2) forming runs. Each forming run comprised of two (2) face sheets and one (1) core blanket. These components were kept as "matched" sets of details for Panels B and C, respectively.

Results were excellent and all details conformed to the 10 ft. radius in the stress free condition after creep forming at 1300°F. Figure 68 shows these details prior to braze assembly. Being dimensionally very stable in this condition they will permit easy reassembly and insure reliable braze fit-up.

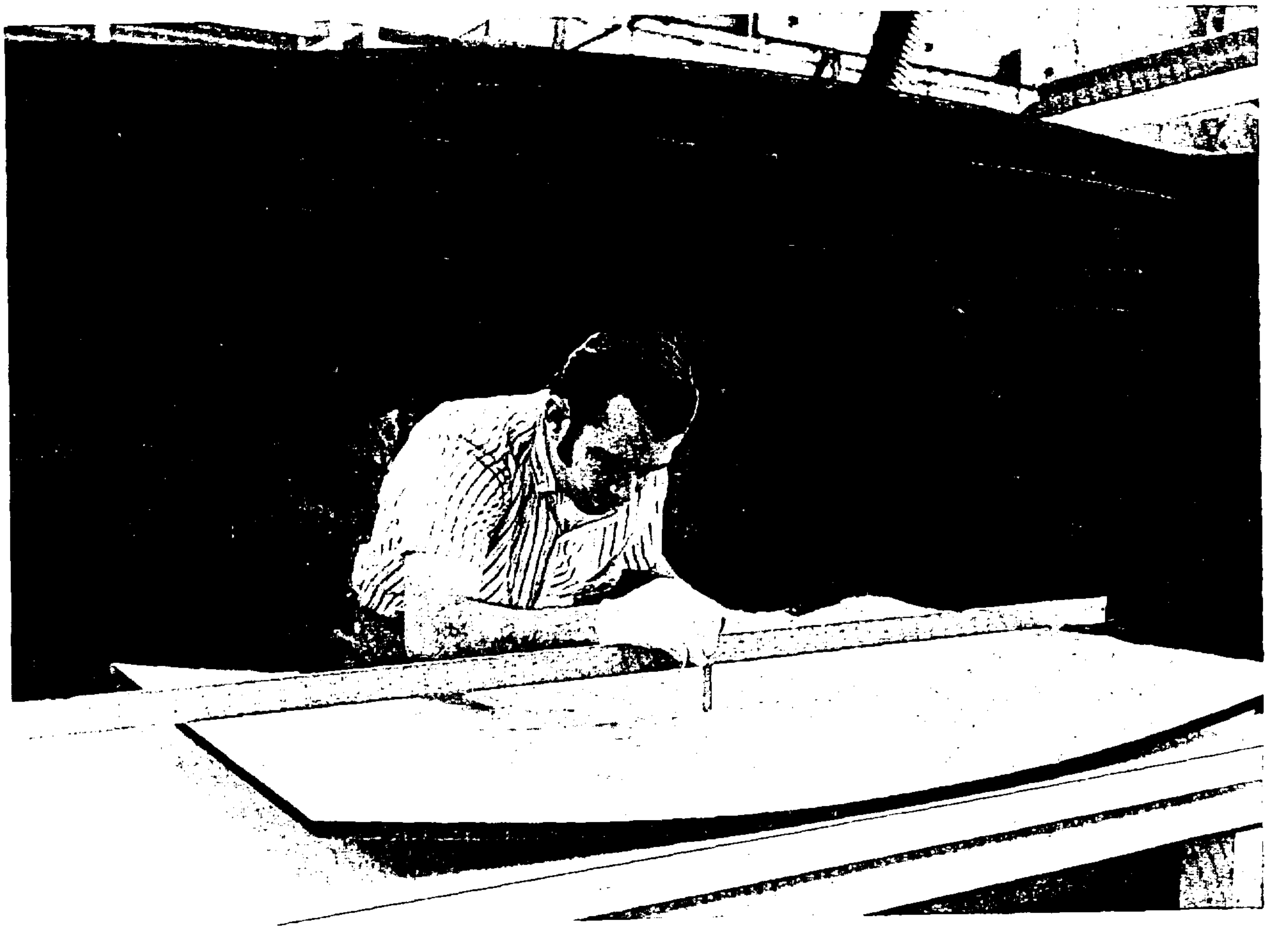


FIGURE 67. PANEL "A" AS CREEP FORMED (10 ft. R)

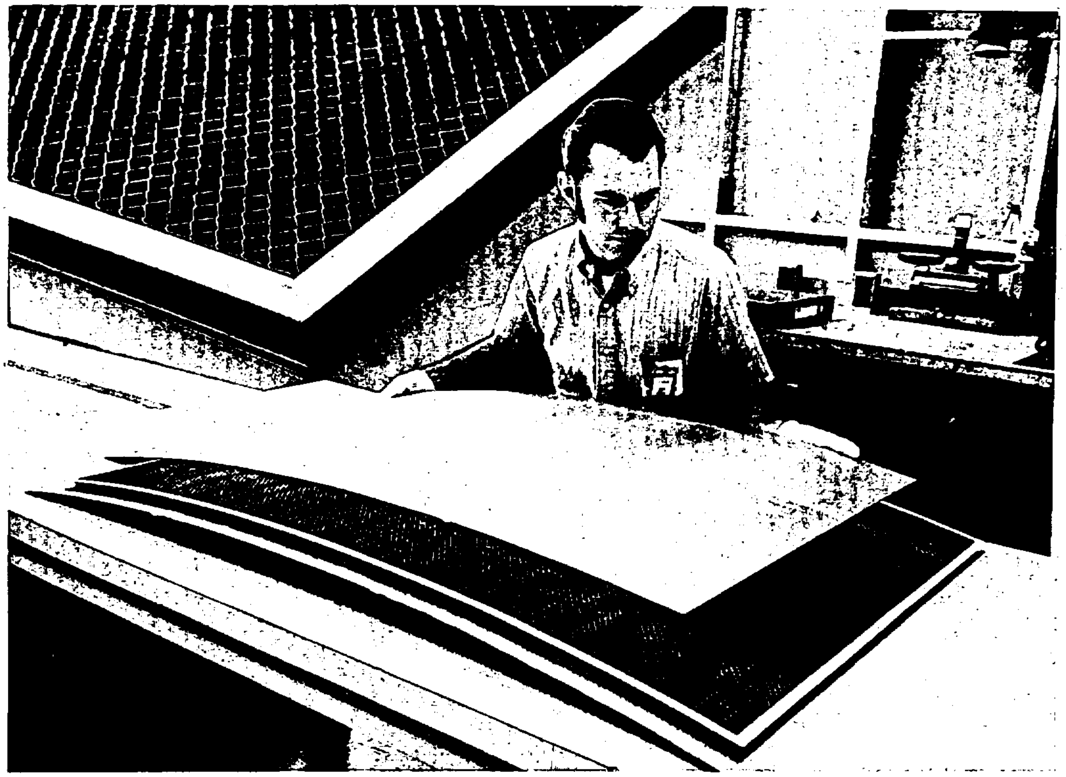


FIGURE 68. CURVED BERYLLIUM PANEL DETAILS - BEFORE BRAZE

7.8 BRAZE TWO (2) PANELS (Task 26)

The fabricated beryllium panel details were brazed to produce Panels B and C. The details for each panel included the following:

2 - curved (10 ft. R) .030" x 30" x 43" Be CRS face sheets

1 - curved (10 ft. R) 1/2" x 29" x 42" Be Honeycomb Core blanket

2 - straight edge close-out Be U-channels, .030" x 1/2" x 1/2" x 1/2" x 30" long

2 - curved (10 ft. R) edge close-out Be U-channels, .030" x 1/2" x 1/2" x 1/2" x 43" long.

All details were chemically cleaned per processes previously established (Solar RDR 1550-8) and loaded with braze alloy filler material (BAg-18). Brazing was accomplished in a circulating furnace at 1460°F under controlled heating and cooling rates.

After brazing the panels were physically, radiographically and dimensionally inspected. Good wetting and flow was observed at the visible periphery. Previously reported edge distortions in Panel B had some edge distortions which were corrected by rebuilding the brazing fixture to allow for additional edge insulation which permitted heating through the face sheets only prior to brazing Panel C.

X-ray film inspection showed the face sheet/edge closeout channel faying surfaces braze increased from 50 percent in Panel B to 80 percent in Panel C. These films also showed excellent core-to-face sheet joints which were brazed over 97 percent in Panel C as compared to 95 percent in Panel B. The twist of approximately 0.40" for Panel B was reduced to 0.16" in Panel C.

The overall results were considered to be very good for these first attempts at such large, complex beryllium structures. Figures 69 and 70 show panels B and C "as brazed". Figure 71 shows all three large (10 ft^2) all beryllium brazed honeycomb sandwich structures. This completes Phase IV.

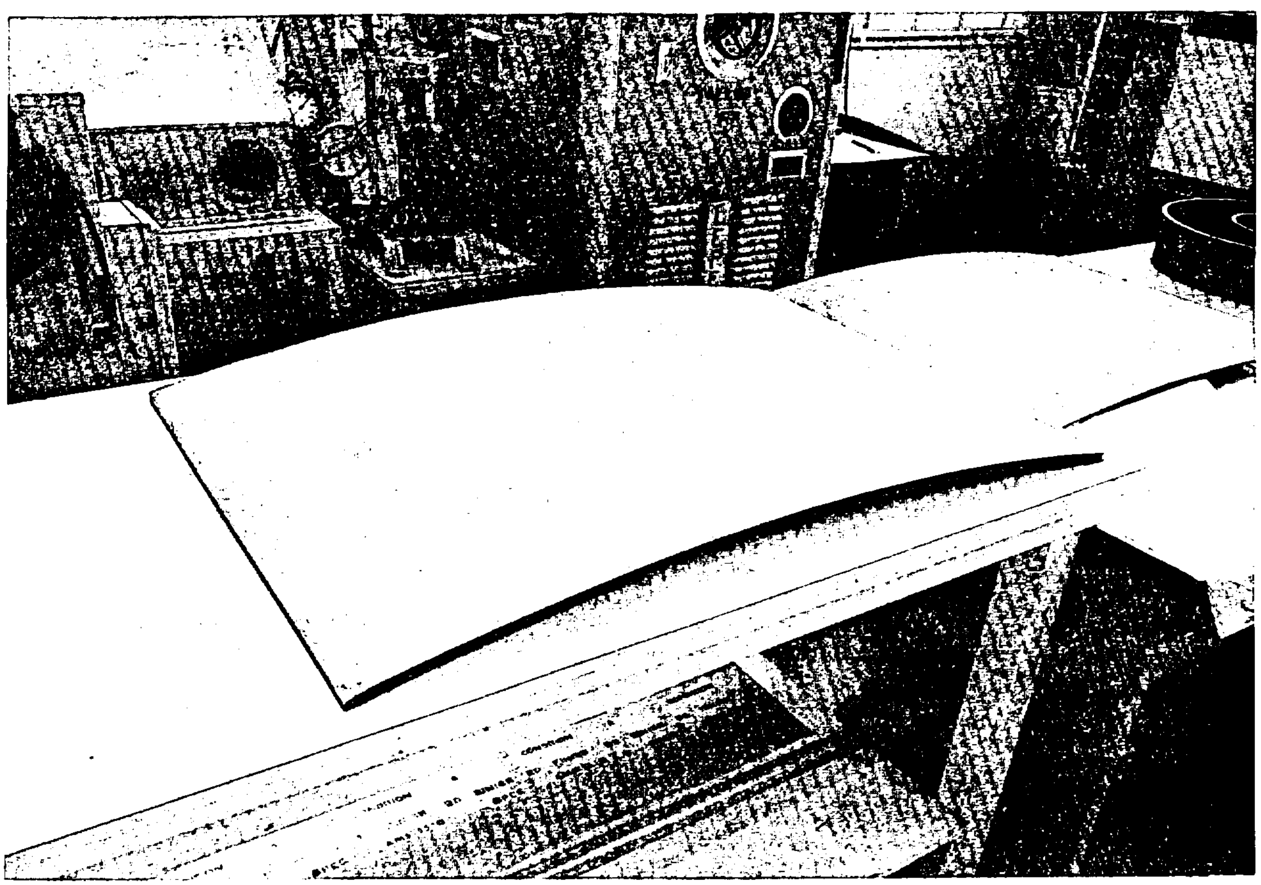


FIGURE 69. PANEL "B" AS BRAZED

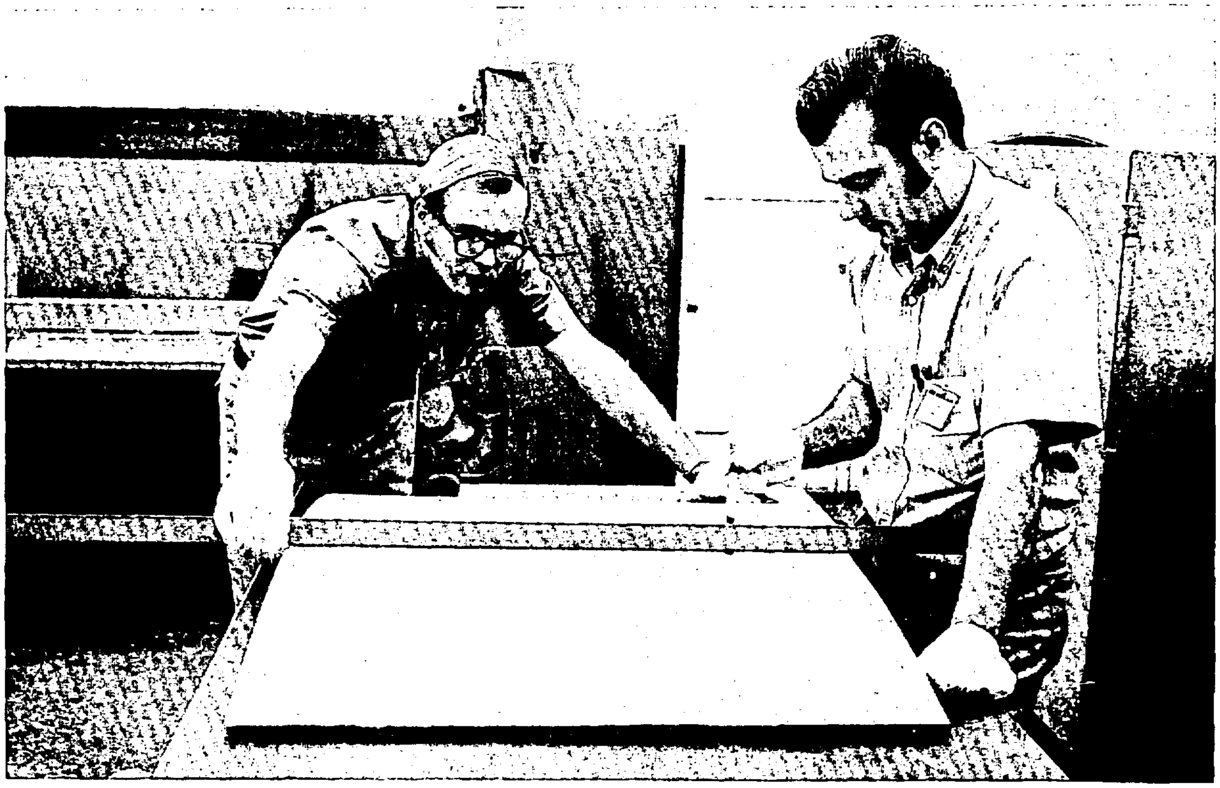


FIGURE 70. PANEL "C" AS BRAZED

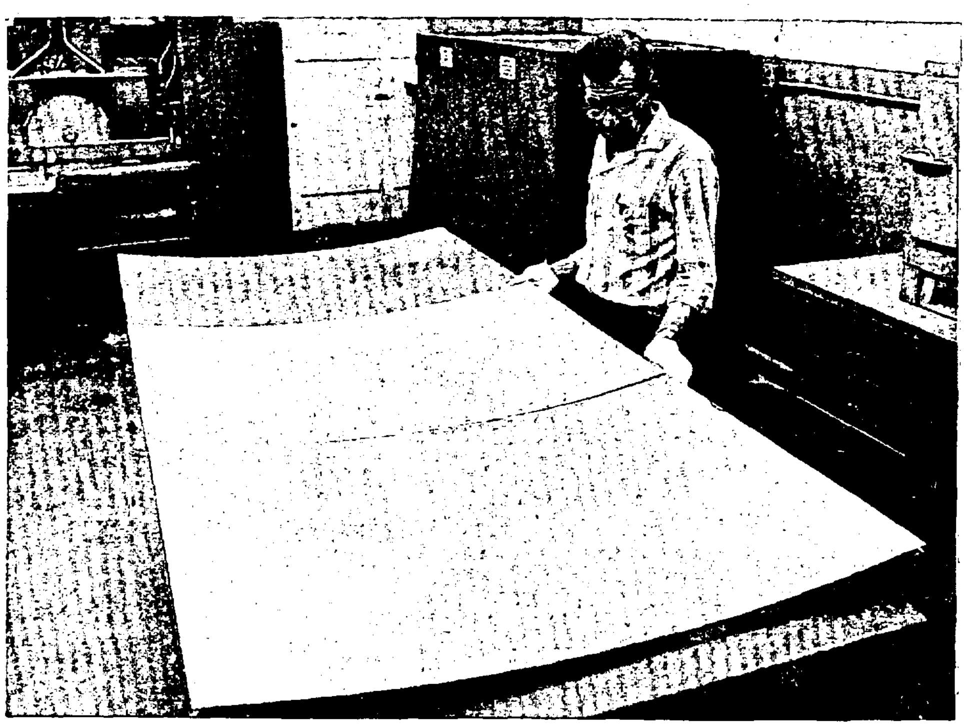


FIGURE 71. THREE LARGE (10 ft^2) BRAZED BERYLLIUM HONEYCOMB SANDWICH PANELS

8

TECHNICAL DISCUSSION - PHASE V

8.0 FULL SCALE PANEL TESTING (Task 30)

The panel testing flow plan is shown in Figure 72. Panel A was one of the two original large (10 ft^2) panels (Section 6) which was brazed in the flat condition and creep formed (Section 7) to the 10 ft radius of curvature. Panels B and C were brazed (Section 7) in the curved condition with beryllium U-channel edge close-outs. Vibration tests, axial compression, hoop tension, biaxial tests and results are discussed in this section.

8.1 VIBRATION TESTING (PANEL A)

The test panel was mounted in a cantilever position with the supported end attached to a solid wall plate and vibrations introduced at the opposite unsupported end as shown in Figure 73. Both ends of the panel had a 2-1/2" wide x .026 beryllium doubler adhesively bonded in place. The fixed end was potted with Epon 828 and Versimid 125 into a mild steel fixture and bolted to the reference wall. The cantilever end was likewise potted into an aluminum fixture with a yoke pinned to the shaker. Vibratory motion was perpendicular to the panel centerline.

The test equipment included Tektronix Storage Oscilloscope, Type 564, Hewlett-Packard Electronic Counter, Model 521C, Endevco Dyna-Monitor, Model 2704, Chadwich-Helmulth Slip-Sync, Model 105A, Strobex Power Supply, Model 126A and Calidyne Shaker System, 1500 force/pounds, Model 174, as shown in Figure 74.

The test panel was scanned for resonance over a frequency range of 20 to 2000 cps along the x-x axis. The resonance survey was conducted at a vibratory input of 2g.

The amplitude of excitation was modulated at each resonance point applying only sufficient energy to determine the frequency of resonance. The resonant frequencies found during the resonance survey are shown in Table X.

Two (2) SR-4 Epoxy foil general purpose strain gages, type FAE-12-1259 and two (2) Endevco Accelerometers, Model 2215, were installed on the panel as also shown in Figure 74. The accelerometers were attached to the panel with dental cement and the strain gages were bonded with M-200 bond adhesive.

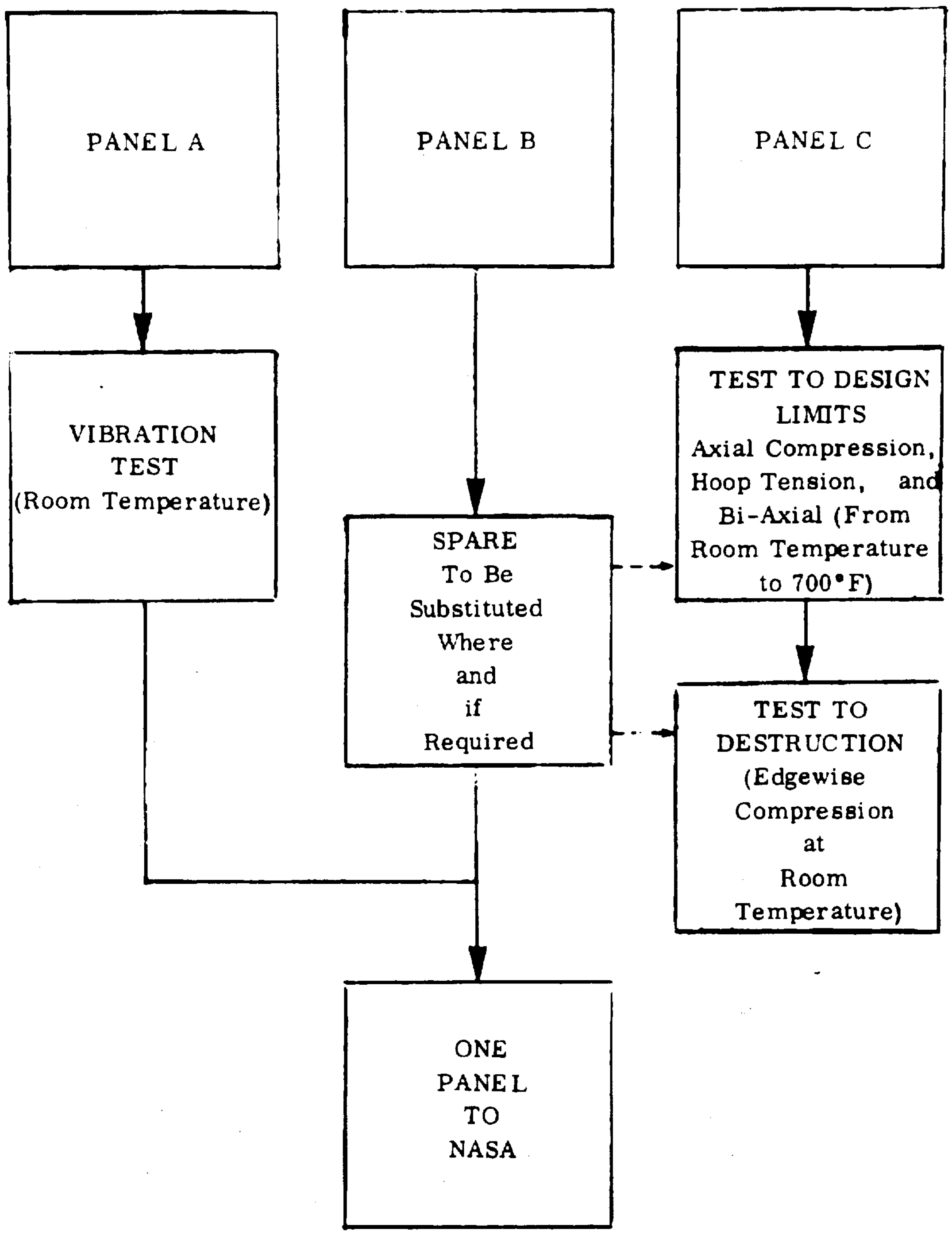


FIGURE 72. PANEL TESTING FLOW PLAN (Task 30)

FIGURE 73. PANEL FIXTURING FOR VIBRATION TESTING

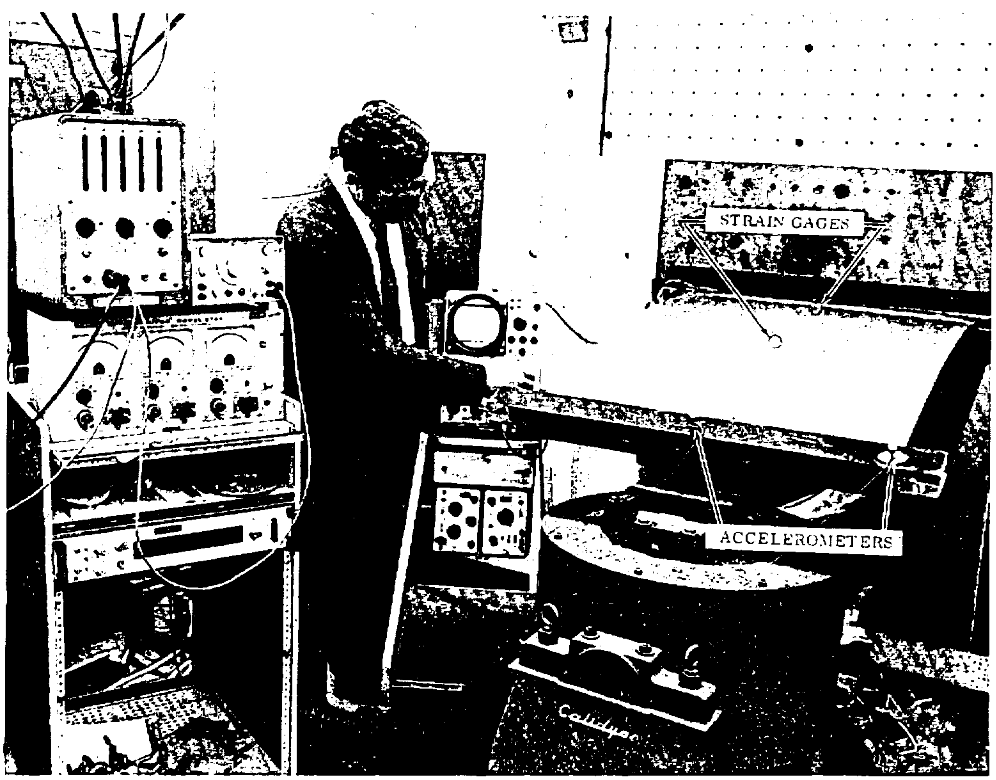


FIGURE 74. VIBRATION TESTING OF BERYLLIUM PANEL

TABLE X

VIBRATION (SINUSOIDAL) TESTS BRAZED BERYLLIUM HONEYCOMB PANEL "A" (10 FT^2)

Date	Time	Freq. (Hz)	Vibration Intensity Accel. #1 Input (g)	Vibration Intensity Accel. #2 Hwde. (g)	Remarks and Observations
	Resonance Scan x-x axis - 20 to 2000 cps:				
2/17/2	1100		2.0	---	No indication res. 20-100 cps.
		123	1.0	1.0	General res. more pronounced front Panel section w/node fixed end.
		278	0.2	2.0	Slight to moderate resonance back and right edge panel.
		*358	2.0	10.0	Good torsional res. - mod. res. moving end and right side (band 340-380 cps with peak at 358 cps). *Considered most severe.
		997	4.0	2.0	Meter indication - internal structure.
		1777	7.5	2.0	Slight system resonance.
	1120	2013	5.0	1.0	Meter indication - end res. sweep.
	Recheck of most severe resonance:				
		123	1.5	2.5	General resonance
2/17/2	1125	358	2.0	10.0	Good general res. with nodes center and outer edge (isolated locations)
		Elapsed Time: 25 Minutes			
2/17/2	Dwell at Resonance:				
	1340	358	2.0	10.0	Start 30 min. endurance
	1355	357	2.5	9.5	
	1410	358	2.5	9.8	End 30 min. endurance test - no visual indication of failure.
2/18/2	(Recheck) Resonance Scan - 20 to 2000 cps:				
	0900	*123	1.0	1.0	
		267/278	.2	2.7	
		*358/361	2.0	9.0	
		537	1.2	1.2	Meter indication - slight res. left side.
		797	2.0	0.5	Meter indication -
		*943/997	2.5	1.0	Peak at 991
		1134	4.0	1.0	
		1390	2.0	6.8	
	0925	1881	6.0	0.5	Total Elapsed Time - 25 Minutes 358 cps, 123 and 999 cps considered most severe resonances.
	Dwell at Resonance:				
2/18/2	1345	123	5.0	8.5	Start 30 min. endurance at 5g input.
	1415	123	5.0	8.0	End 30 min. test - no visual damage.
2/21/2	0845	991	21.0	25.0	Start 30 min. endurance at 25g.
	0915	990	20.0	25.0	End 30 min. test - no visual damage.
	Verification Reading:				
	0916	356	2.0	8.0	Recheck of 358 cps resonance.
	Total Elapsed Time: 2 hr. 20 min.				

The strain gages were installed only for maximum strain indications as a function of the vibratory frequency input to the panel during the resonant frequency scan. Due to the limited funds available, no attempts were made to determine the true strain measurements of panel skins in these tests. The limited strain gage information did demonstrate the excellent damping characteristics of this type of structure.

The three resonant frequencies of 123, 358 and 990 cps were selected as the most severe and which could produce vibration failure.

Resonant dwell tests were conducted at the selected frequencies for a period of thirty (30) minutes each and at the vibratory acceleration level(s) shown in Table X.

Vibratory input levels were monitored with accelerometer(s) mounted on the test panel as shown in Figure 74.

After completion of the vibration test, as outlined in RDP 7016, the vibratory input was increased to a maximum of 25g, at the most severe resonant condition of 358 cps, to simulate transient and steady state vibration levels attained in the testing of previous aerospace/space shuttle components, (Table XI.)

TABLE XI

STEADY STATE VIBRATION LEVELS FOR TYPICAL AEROSPACE/SPACE SHUTTLE COMPONENTS

Frequency Range (cps)	Vibration Intensity Transient	Steady State
20-150	7 g	3.5 g
150-292	.006 DA	.003 DA
292-2000	26 g	13 g

Test data and observations are tabulated in Table X. Total elapsed time (including resonance scan) was 2 hours and 20 minutes.

At the conclusion of all testing the assembly was visually examined for damage resulting from the vibration test.

There was no indication of damage in any portion of the assembly.

8.2 SPARE (PANEL B)

This panel was trimmed to a 27" x 41" size to provide for metallograph edge samples. One of the corners was scarfed to show the honeycomb construction After trimming the panel was ultrasonic cleaned and oven dried.

An edge frame of 1/8" thick plexiglass was added to keep the panel dry, provide for visual examination of the construction and allow normal handling. The panel is shown in Figure 75 as shipped to NASA.

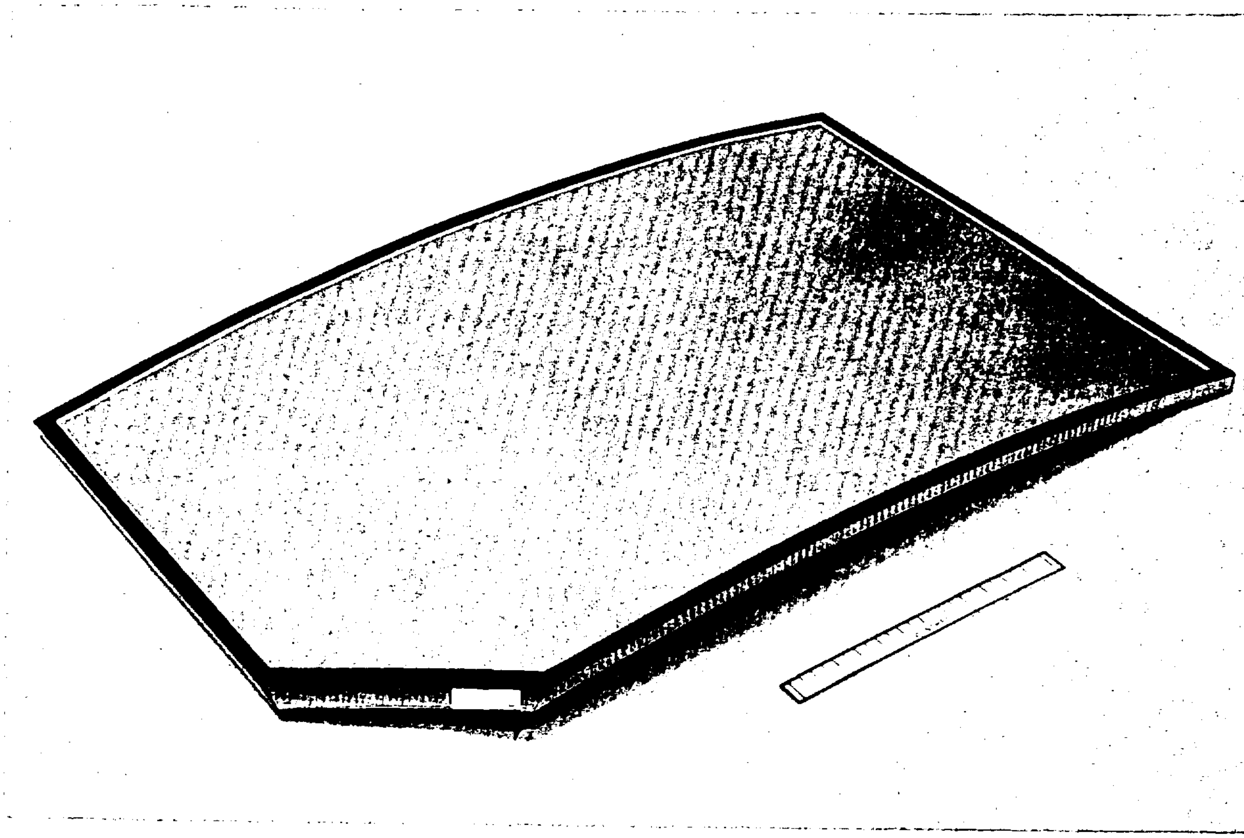


FIGURE 75. TRIMMED PANEL "B" AS SHIPPED TO NASA (30" x 42")

8.3 AXIAL COMPRESSION, HOOP TENSION AND BI-AXIAL TESTS (PANEL C)

A fracture in panel C, during the strain gage instrumentation bonding cure cycle, necessitated cancellation of this portion of testing. The following describes the tasks completed up to the time of fracture.

Axial compression end fixtures were fabricated and bonded to the Be H/C panel with steel lap strips. The hoop tension whiffle-tree was made to react the hoop tension forces generated from the pneumatic loading device. Bonding of both axial compression and hoop tension lap strips (shear area 2" x 30" on the ends and 2" x 43" on the sides) was achieved by utilizing a Solar high temperature polyimide adhesive. The polyimide was cured 30 minutes at 300°F, followed by one hour at 600°F in a recirculating furnace. The curved ceramic reaction structure, pneumatic loading device, whiffle-tree support structure, axial compression end fixtures and the test panel were set up in the Dake press testing facility as shown in Figures 76 and 77.

Thermal electric blankets were obtained with a 6 watts/in^2 rating from Briscoe Mfg. Co. for the elevated temperature testing. These were also utilized to cure the high-temperature strain gages. Four double and five triple direction SR-4 Baldwin Lima-Hamilton strain gages were bonded to the panel as shown in Figure 76. The cure cycle was as follows:

1. Heat to 250-300°F for 1 hour with 30 psi clamping load on the gages.
2. Remove clamps and hold 1 hour at 300°F; heat to 400°F and hold 2 hours.
3. Heat to 600°F and hold 2 hours.

During the 600° cure cycle, the heating rate exceeded the automatic proportioning response of the control instrument, and the panel temperature reached 700°F. The low thermal mass of the beryllium skin and core, coupled with the heat sink properties of the massive steel test fixturing created severe thermal gradients in the assembly. In a repeated cure cycle test, using additional thermocouples to determine temperature variations, it was found that gradients of more than 100°F existed in the beryllium facings; and a gradient of more than 240°F existed between the beryllium facings and the massive steel fixturing. During the initial strain gauge cure cycle a sharp, loud noise was heard during the 600°F portion of the cure cycle. After completion of the cure cycle it was observed that both panel facings had cracked. The crack patterns extended from approximately the midpoint of the curved edge, out to the shorter sides of both sides of the sandwich. Figures 78 and 79 show the crack pattern on both sides of the panel by means of marking tape.

Further testing was discontinued and the panel put in storage to await final disposition.

8.4 DISCUSSION OF RESULTS (TASK 37)

The vibration test portion of the program was successful. The strain gage data showed the panel to have excellent damping characteristics and all of the test requirements were met. (See Table X)

DISCUSSION OF RESULTS (Contd.)

The bi-axial test was not completed due to panel failure during bonding of the strain gauges. Review of the repeated thermal cycle data obtained indicated that the thermal stresses generated by the >240° F gradient between the beryllium facings and massive steel fixturing were sufficient to cause the cracking of the panel. A biaxial thermal stress in the range of 74,000 psi (in the beryllium ($\simeq$ 20,000 psi above σ_{ys} at 600° F) was calculated, from this thermal data. Panel failure is attributed to this cause.

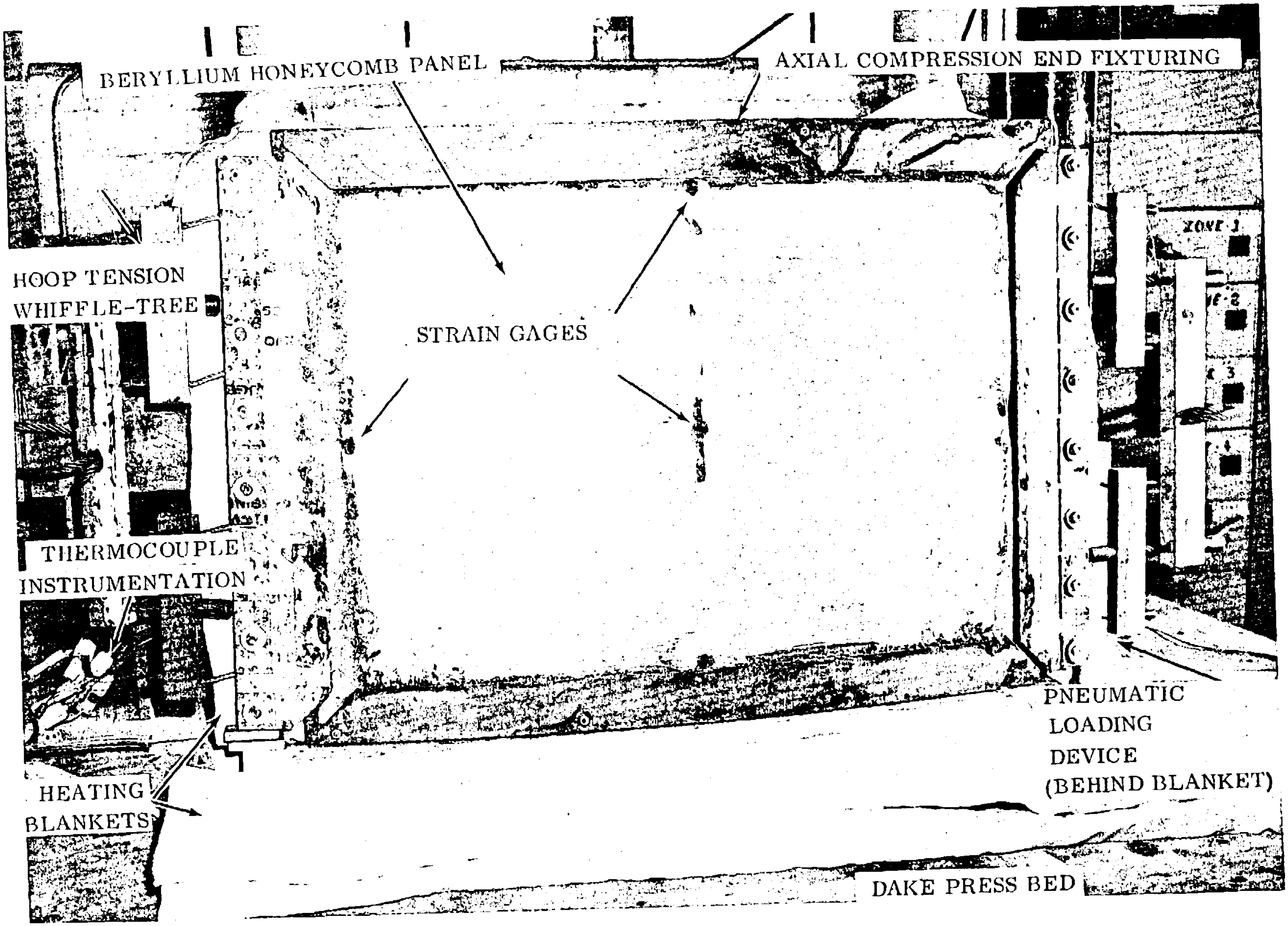


FIGURE 76. AXIAL COMPRESSION, HOOP TENSION SET-UP IN TESTING FACILITY (SIDE VIEW)

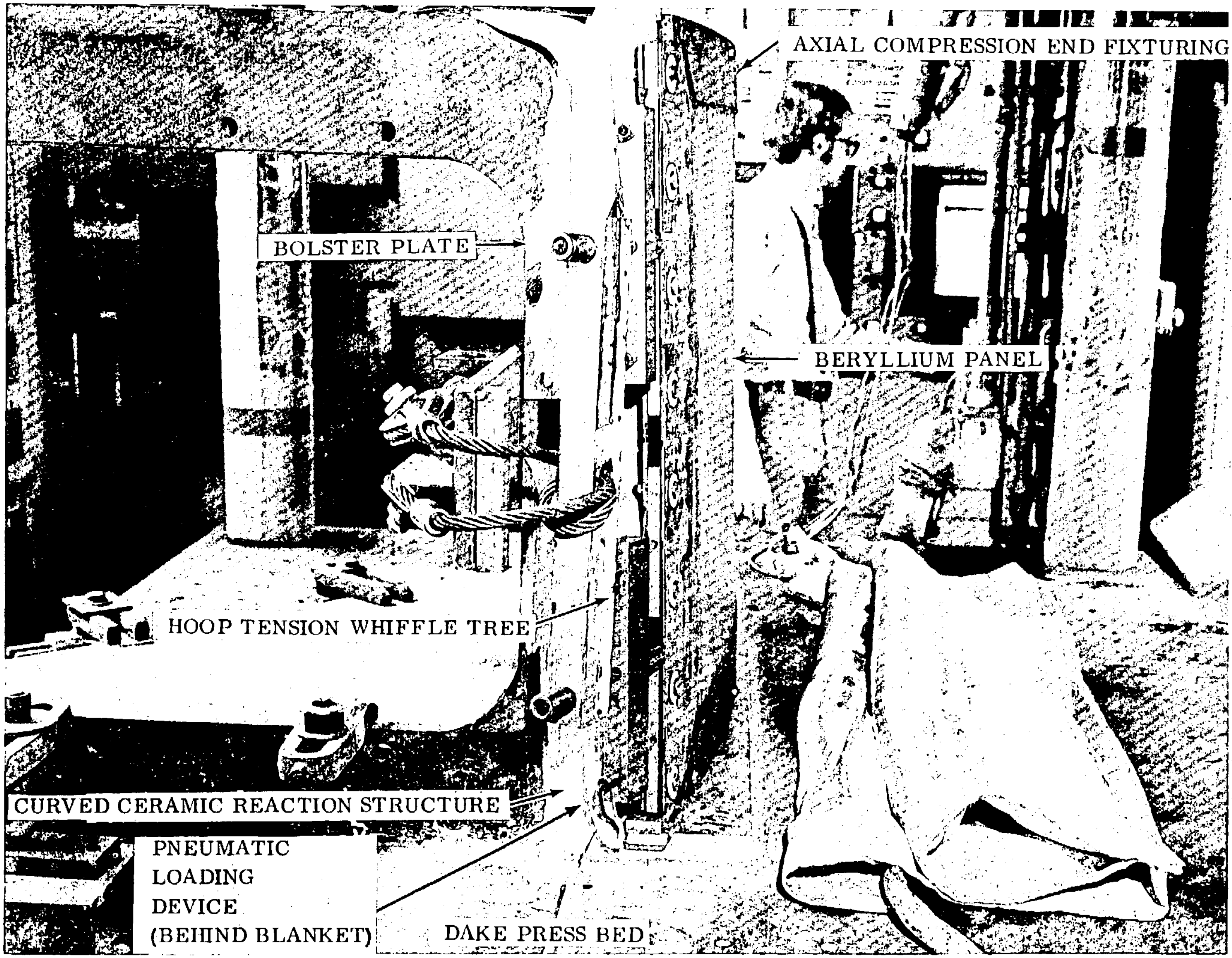


FIGURE 77. AXIAL COMPRESSION, HOOP TENSION SET-UP IN TESTING FACILITY (END VIEW)

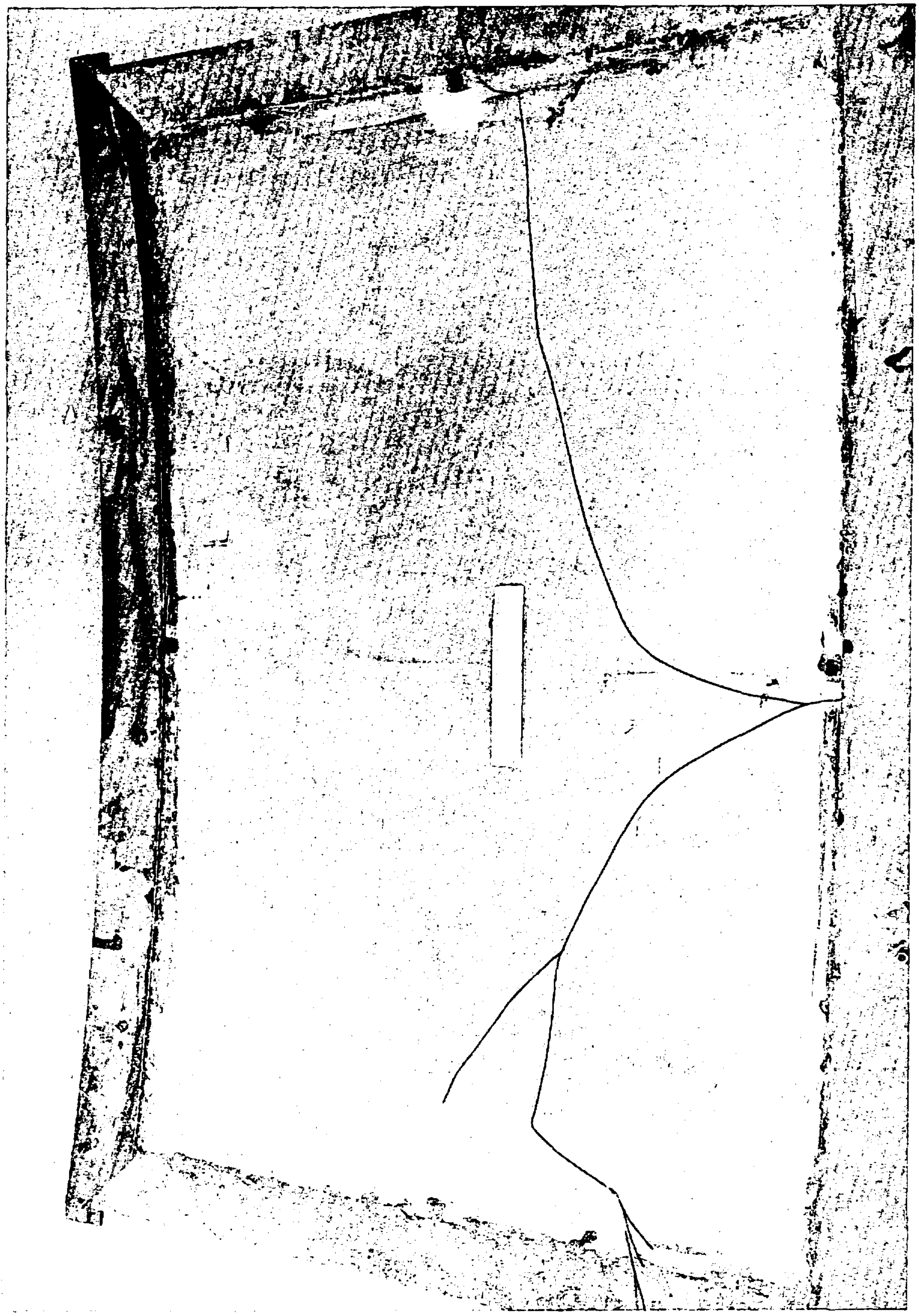


FIGURE 78. PANEL C (CONCAVE SIDE) AFTER FRACTURE OUTLINED WITH MARKING TAPE

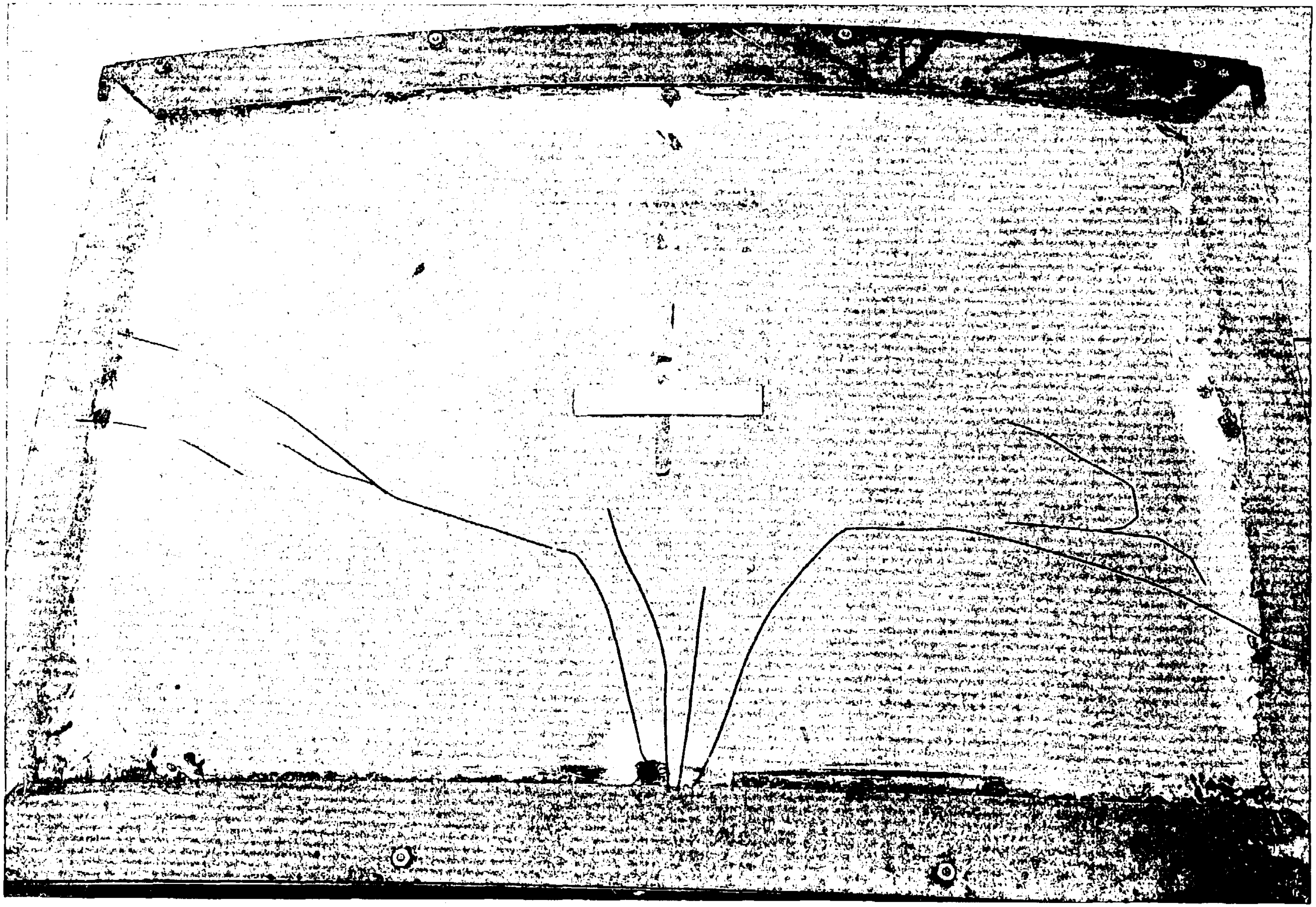


FIGURE 79. PANEL C (CONVEX SIDE) AFTER FRACTURE OUTLINED WITH MARKING TAPE

9

QUALITY ASSURANCE - TASKS 3, 11 AND 21

Quality assurance and quality control functions are vital aspects to a meaningful structure development. To become a practical material composite for aerospace applications, process and fabrication reliability is basic. Preliminary specifications and specific comments on the processes involved in manufacturing the brazed beryllium honeycomb sandwich panels developed on this program are discussed in the following sections. Much of the information presented will apply in part to fabrications of other configurations; however, manufacturing process specifications are foreseen for each individual brazed component or assembly.

9.1 MATERIAL

The basic incoming material inspection operations described in Section 3.2 of this report should be followed. It would be desirable to have improved Ingot Foil surface conditions. RMS values of about 200 microinches on the surface and up to 40 percent thickness variations should be reduced to below approximately 60 and 10, respectively. It was found that the 0.006-inch Ingot Foil ribbon stock was more acceptable for fabrication than the 0.003-inch stock because of better handling and brazing characteristics. The commercially available CRS material was acceptable for facings in all respects and Solar used grade SR-200D during this development work. Manufacturer's specifications are available for CRS material from Brush or Kawecki-Berylco; however, no guaranteed chemical or mechanical properties are presently available for Y-12 Ingot Foil material.

9.2 CORE FABRICATION

Preliminary specifications applicable to the 0.006-inch Ingot Foil ribbon include:

Corrugate:	1/4-inch Solar Square Cell at 525 $\pm$ 25°F
Clean:	HF-HNO_3 (2 to 12 percent) followed by ultrasonic cleaning in Turco 4215.

Automatic Weld

- Two tacks per node
- Seedorf Model 5705M power source settings

  Tap 8 (70 to 80 percent)

  Cycle 4

Dimensional Control (as welded or surfaced)

- Height = ± 0.005-inch overall panel
- Steps = 0.001-inch maximum (ribbon-to-ribbon)
- Flatness = within 0.001-inch at RT with uniform load of 1 psi

The height control (0.005-inch overall) is for surfaced core and would be in the form of a gentle taper in faces. Precision automatic welded core would have a much tighter tolerance on height; basic ribbon height being the controlling factor of steps and flatness requirements.

Solar successfully used a trace method of inspecting the steps from ribbon-to-ribbon. While core was referenced to a flat plate for surfacing, ink was applied to the core edges and a trace made on paper using a full-length steel roller. Typical results are shown in Figures 80 and 81. It was determined experimentally that a "no print" indicated a step of 0.0005 inch or greater.

9.3 BRAZE FILLER METAL

Alloy Code No. 7 had a nominal composition of Ag-27Cu-10Sn; the practical equivalent of this development alloy is AMS Specification No. 4773 (Ag-30Cu-10Sn), and was used for scale-up testing on this program.

A loading rate of 50 gm/ft^2 was found satisfactory for complete node and face brazing.

9.4 BRAZE CYCLE

The standardized brazing cycle is shown in Figure 17. As in all beryllium braze cycles, the temperature uniformity and time at temperature are critical items. Therefore, a maximum spread of 15°F should be maintained from the 1200°F soak temperature until part is cooled below 1000°F.

FIGURE 80. INTERMEDIATE CORE SURFACE INSPECTION TRACE

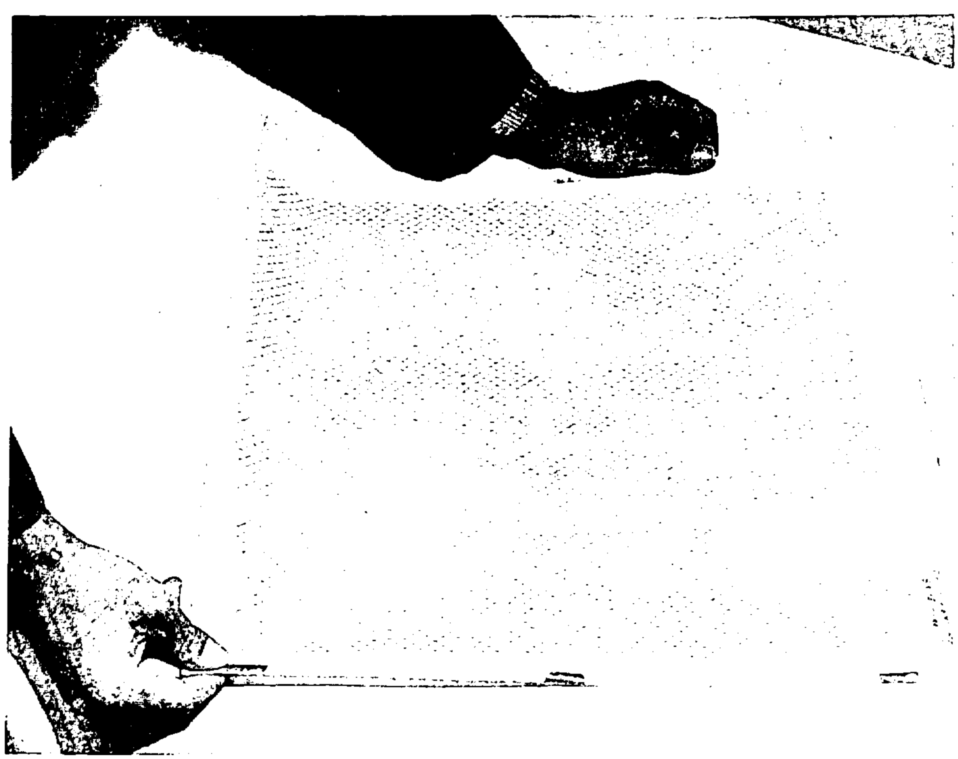


FIGURE 81. FINAL CORE SURFACE INSPECTION TRACE

9.5 RADIOGRAPH INSPECTION

The following X-ray parameters were established:

Power:	25 KV
Time:	2 minutes
Angle:	5 to 10 degrees
Distance:	104 inches TTD
Machine:	Norelco MG No. 150
Film:	Ansco 17.

Typical of the results obtained by radiograph inspection are shown in Figures 26 and 40.

9.6 METALLURGY AND MECHANICAL TESTING

Spare material on panel edges should be reserved for metallurgical samples and used to inspect all aspects of each braze run.

Mechanical testing parameters were established and results obtained for ultimate strength in edgewise compression, core shear, flatwise compression, and flatwise tension. Table IX shows the latest results obtained.

10

CONCLUSIONS

The feasibility of fabricating large beryllium honeycomb panels was demonstrated by this program. Both flat and curved sandwich structures were manufactured using practical, braze bonding techniques. The processes developed prove that metallurgically assembled beryllium honeycomb panels, show decided potential where rigid, lightweight structures are required.

During this program three panels, each 10 square feet in surface area, were fabricated, and radiographically inspected to determine integrity. This examination revealed a 97 percent braze in the final panel.

The first panel was brazed in the flat position and hot creep formed to a curved structure after brazing. The components for the other two panels with "U" channel edge members were hot formed and then brazed to form the curved panel. A higher degree of confidence was attained with the latter method, which consisted of brazing in a muffle with a controlled atmosphere.

It is believed that ceramic dies for forming and brazing would greatly facilitate the fabrication techniques for higher production rates. Ceramic dies would yield a lower thermal gradient in the panel during the braze cycle. This would eliminate the small amount of face sheet wrinkling present in the panels. Hot forming the various panel components (face sheets, core and channels) demonstrated efficient manufacturing techniques for scaling up and producing large numbers of hot formed beryllium components and panels.

To increase producibility, automated braze lay-up procedures could be incorporated into a program which would eliminate the hand lay up associated with developmental programs, such as this one. Excellent edgewise compression, flatwise tension/compression and block shear values up to 600°F were achieved due to the high integrity of the brazed beryllium honeycomb structures.

The beryllium honeycomb panel demonstrated very good vibrational loading characteristics under test with desirable damping characteristics.

Future beryllium honeycomb programs will incorporate the developmental technology, gained in this program, with high production efficiency to produce hardware when lightweight beryllium structures are a necessity.

Improved thermal control systems incorporated into fabrication and test facilities should eliminate most of the problems encountered in this program. The stress developed between the massive test fixturing and the panel would not be encountered in a normal structure where design consideration is given to thermal compatibility between components.