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FABRICATION PROCESS SCALE-UP AND OPTIMIZATION FOR A BORON-ALUMINUM COMPOSITE RADIATOR

LTV Aerospace Corporation
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FINAL REPORT FOR NASA/MSC
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REPORT NO. 00.1579

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REPORT NO. 00.1579

SUBMITTED BY

LTV AEROSPACE CORPORATION
DALLAS, TEXAS

TO

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACE CRAFT CENTER
HOUSTON, TEXAS

Prepared by: K P O'Kelly

Reviewed by: J W Seeger

Approved by:

FOREWORD

This report was prepared by K. P. O'Kelly under NASA Contract NAS9-8260 Exhibit "D". It was administered under Mr. G. M. Ecord, Materials Technology Branch of the Structures and Mechanics Division as Project Monitor.

This report covers work performed during the period from January through November 1972. The program was performed by the Engineering Materials and Processes Group, with Mr. W. G. Worth serving as Program Manager, Mr. K. P. O'Kelly as Project Engineer, and Mr. A. B. Featherston as Fabrication and Test Engineer assisted by Mr. J. Soroka.

Assistance in the metallurgical studies was provided by Mr. J. Meador. Messrs. Tufte, VanWeeldon and Lederer provided radiator design and thermal analyses.

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1.0 INTRODUCTION

Shuttle Orbiter Phase B studies baselined aluminum space radiators located inside the cargo bay doors. Phase C-D concepts have subsequently baselined modular radiator panels mounted to the aft doors and deployed from the forward doors as shown in Figure 1-1. The external surface of the doors is covered with a silicone ablator material varying from 0.5 to 0.8 inch thick at 15 pound/cubic foot. Open, the effective area for radiation is 1436 square feet (1734 square feet of panel). Forward radiators are baselined as back-to-back panels separated with insulation but recent studies have indicated advantages in using single panels which radiate from both sides.

Design simplicity aimed at reducing costs can be realized if the material in the radiators can repeatedly withstand the thermal environment of the external surfaces. Aluminum, the usual radiator material, is not structurally usable at temperatures above 300°F. Preliminary evaluation of boron-aluminum composite (Reference 1) has shown that these materials possess useful strength properties to 800°F, withstand thermal cycling between -250°F and 800°F, and exhibit thermal properties which make the material attractive for space radiator applications.

This program addressed two design approaches to a practical utilization of boron-aluminum for the Shuttle space radiators. Initially, an externally mounted unit was considered an attractive concept. As more firm baseline designs evolved in the transition period beyond Phase B, this program redirected the design effort to include use of boron-aluminum in a sheltered unit. A substitution of boron-aluminum for aluminum panels would not be lighter in the current door-sheltered concept but would be beneficial primarily through elimination of the ablator. Overpressurization of the coolant system during reentry would be eliminated by venting the coolant. In this case the door material would be titanium and/or boron-aluminum. Required thermal protection for the payload during reentry can be provided with a lightweight, easily installed insulation inside the radiator or the door or both.

1.1 SUMMARY

The primary purposes of this program were to scale up laboratory composite material processes, demonstrate the fabricability of a structural and functional composite radiator panel and examine the associated costs. The long-range objective was to incorporate a modular radiator made of boron-aluminum on the space shuttle. To accomplish the foregoing, the contractual effort was divided into tasks as described below:

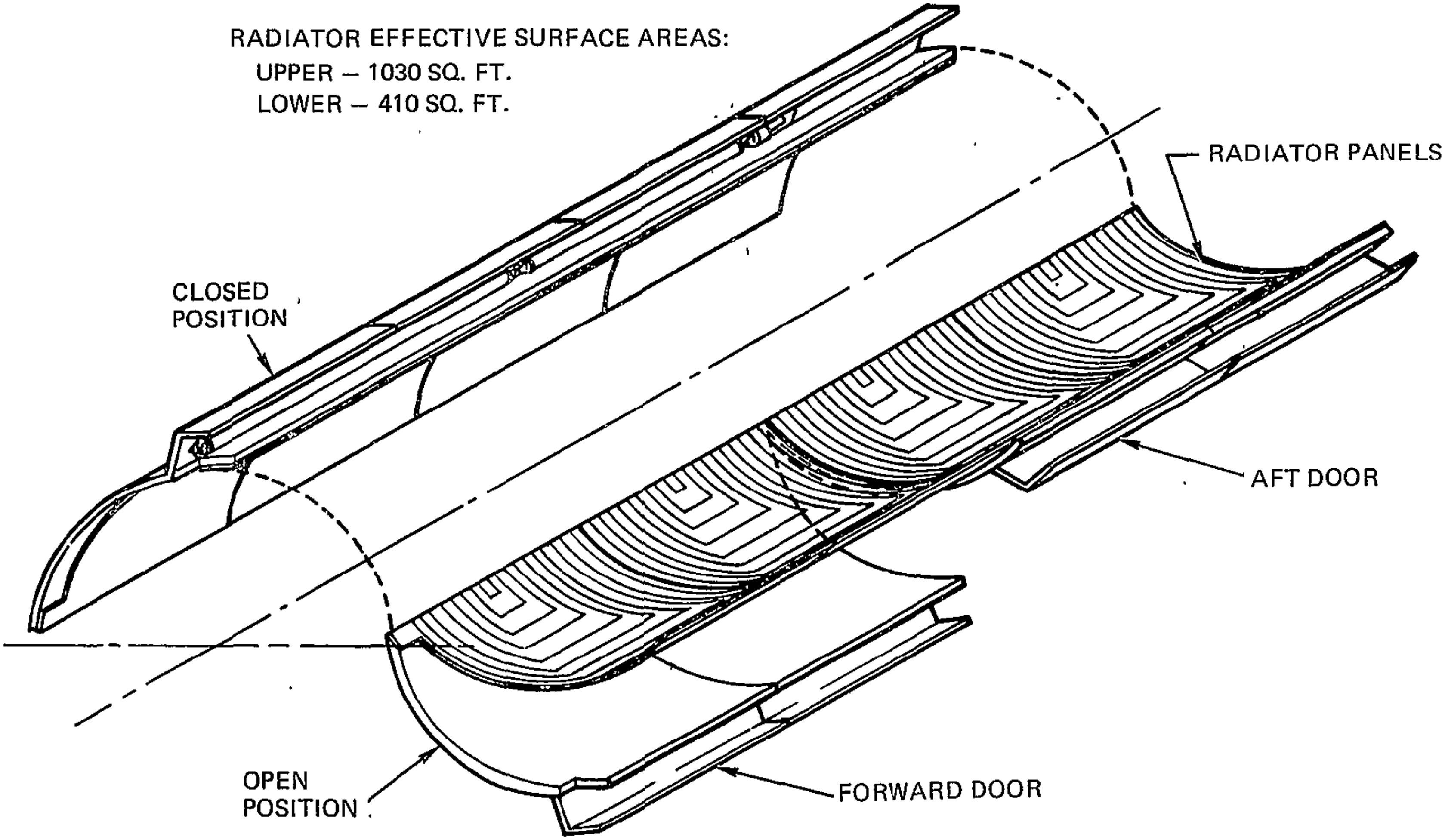

FIGURE 1–1 DEPLOYMENT OF SHUTTLE RADIATOR PANELS

1.1.1 Materials

Boron-aluminum composite was the material of construction for the radiator and associated investigations.. Use of the large diameter (0.0056 inches) fibers was considered. Assurance was required that the material purchased throughout the program was consistent in properties. A specification was written to establish acceptance criteria.

1.1.2 Material Compatibility

To establish compatibility of boron-aluminum with the heat transport coolant material, the boron-aluminum composite material was exposed four hours to the projected coolant at room temperature (liquid exposure) and at 800^{o}F (vapor exposure). While exposed, a tensile stress of 70% of composite yield strength was applied at the respective temperature in each case. Two specimens were run at each temperature in the longitudinal fiber direction with appropriate test methods and fixtures. Subsequent to exposure the specimens were examined for degradation (appearance, weight change, structure, generation of contaminants).

1.1.3 Thermal Control Coatings

The radiator application envisioned requires an on-orbit thermal control coating with an α/ϵ ratio in the approximate range of 0.2 to 0.25. A number of coatings were proposed to meet this requirement. Ideally, the coating should be reusable for a large number of missions. The two most promising systems (selected jointly by the contractor and technical monitor) were applied to small boron-aluminum discs to be tested for capability to maintain required optical properties following the launch environment and for reusability if multi-mission use is indicated. Application of coatings and testing of specimens was a NASA task.

1.2 Processing

The processing parameters for boron-aluminum multi-layer composites established in Reference 1 form the basis for process optimization and scale-up. Near the end of the program, a preliminary specification controlling processing and procedures for fabrication of large panels was required for inclusion in the final report.

1.2.1 Process Optimization

The bonding pressure, time and temperature are significant to the properties of resultant multi-layer composites. Of major concern is the formation of compounds such as AlB_2 and associated property degradation. A limited number of tests were conducted to identify permissible pressure variations and time-temperature profile variations at temperatures above 1000°F to provide for reasonable shop fabrication tolerances.

1.2.2 Process Scale-Up

Facilities information and manufacturing techniques that will adequately scale-up laboratory processes and accommodate larger size fabrication approaching six feet in width were developed. Material preparation including machining methods, fixturing, retort design, the method of providing a uniform heat for bonding were all primary areas of consideration.

1.3 Scale-Up Verification and Test

The process and techniques established under 1.2.2 for all fabrications in this task were used for the scale-up. Radiator studies furnished the basic requirements for design of the test article fabricated which represented an element of the flight hardware.

A radiator panel specimen 4 square feet in area having two flow pipes was thermally cycled between room temperature and 800°F thirty times to evaluate the resistance of the panel to warpage, and determine the configuration and degradation tendencies of the panel under thermal cycling conditions.

1.3.1 Structural Tests

A layout study for structural optimization of the radiator design was conducted. Significant structural configurations and locations where the adequacy of the boron-aluminum composite could be demonstrated were identified. Test specimens were prepared and tested to assess significant structural parameters.

1.4 Radiator Panel Studies

In parallel with the other tasks of this program, the radiator design being developed under contract NAS9-10534 (Reference 2) for applicability to space shuttle exterior mounting requirements was examined. Included were joints, tube spacing, and integrated shuttle skin structure. Although thermal transfer is a key factor in radiator design the panel must also withstand flight loads associated with skin panels. Consideration of the design methods of attachment of stiffeners, thermal isolation, attachment of primary structure and load paths was essential. External areas for locating radiators as defined through the contractor's interface with space shuttle Phase B contractors was studied. Load-temperature-time data was obtained from the shuttle contractors.

for use in a baseline. This interface was utilized to develop the design and identify thermal and structural considerations. A simplified design based on the above studies was used in the fabrication of the radiator test specimen. Integral with the design studies was analyses of costs incurred through change from conventional materials to boron-aluminum.

2.0 MATERIALS

2.1 Procurement

Composite materials for this program were procured from Amercom, Inc. All basic matrix material consisted of 6061 aluminum alloy. All material used for panel fabrication contained Borsic filaments (0.0057 inch diameter). Panel material was procured as monolayer tape 10 and 12 inches wide and as 4 ply (2 - 0^{o}, 2 - 90^{o}) sheet. The attempted creep forming was performed on 7 ply unidirectional sheet with 0.0056 diameter boron. A materials specification was prepared establishing the requirements and tests for composite Borsic aluminum tape and sheet material used for the panel. The specification terms were discussed and accepted by Amercom and the NASA contract monitor. The specification is presented in Appendix I. The material was generally of high quality and tests at Amercom indicated 160,000 to 200,000 psi tensile strength. Receiving tests of the tape at VMSC showed an average of 168,000 psi; within the requirements of the specification. The reason for properties as low as indicated by the tests was not metallurgically apparent. There was good appearance relative to spacing (over 45 v/o), filament soundness and consolidation. A retest of one sheet by Amercom showed a 165,000 psi average tensile strength. Again, the reason for lower strength was not apparent. However, the wide variation in strength was not considered detrimental to the process scale-up since the principles of layup, tooling and equipment operation could be fully assessed. Inspection of procured composite consisted of visual examination of the total material furnished as described in the specification. Edge peeling tests indicated excellent consolidation in all material. Radiographic and ultrasonic inspection was performed on material before and after processing. As stated above, tensile tests of each lot were performed by Amercom and by VMSC. The test fixture used by each facility was similar in that the specimen was gripped between special jaws bolted tightly prior to insertion in the tensile machine.

2.2 Materials Processed

The foregoing description of material applies to parts subsequent to the process optimization work described in 3.2. The material used initially for the process optimization was 0.004 inch diameter uncoated boron in the same matrix (6061 aluminum alloy). Strength properties for this material was substantially the same as the 0.0057 inch diameter Borsic reinforced material. Table 2-1 reflects the tensile strengths. The first 12 bonding runs used the 0.004 inch diameter boron material and the remaining runs used the 0.0057 inch diameter Borsic and all subsequent articles were made from the large diameter filament material.

TABLE 2-1

TENSILE RESULTS OF 0.004 INCH DIA. BORON/ALUMINUM TAPE USED FOR OPTIMIZATION RUNS

Specimen	Test Direction	Ftu Ksi
1		182.2
2	Axial	174.6
3		32.0
4	45°	34.0
5		8.0
6	90°	5.7

2.3 Materials Compatibility

The objective of this test was to evaluate the effects of exposing the composite material to Freon compounds expected to be used in the Shuttle environmental control system. The anticipated system exposure would be escaping liquid and vapor at various stages of charging the system, or release during ground operations or during flight. The worst would likely be during an in-flight release of the compound impinging upon the panel while at maximum equilibrium temperature.* Further, it was assumed that local loss of protective coating could be experienced at some time during the life of the vehicle and therefore the specimens were tested bare. For this test, 0.5 inch wide strips of 4 ply unidirectional borsic aluminum were stressed to 70% of the strength in flexure as measured in adjacent material and six separate specimens were immersed (2 each) in three different freon compounds (Freon 21, Freon 21 + Capella oil at 37.3 grams/pound and Freon 11).

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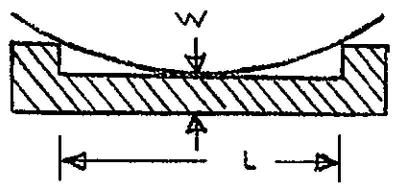
* Freons are known to react with aluminum materials at elevated temperatures under certain conditions. References (3) and (4) describe reactions of metals at elevated temperatures under severe conditions and indicate that long term exposure to moderate temperature (350°F) has a slight effect but at 775°F, decomposition is apparent. The test method described in the references includes passing hot vapors over heated metal filings.

The determination of bend angle to stress at 70% was as follows:



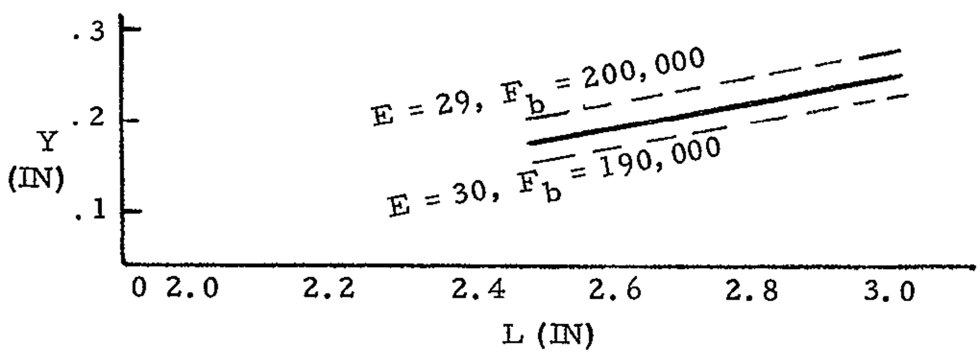
$$Y = \frac{WL^3}{48\ EI} \qquad\qquad Y\ \text{Deflection} = \frac{L^2\ F_b}{6\ E\ t}$$

$$F_b = \frac{MC}{I} = \frac{WLt}{BI}$$

$$F_b = .7\ F_{bu} = .7\ (195{,}000\ \text{psi})$$

$$E = 29.5 \times 10^6\ \text{psi}$$

$$t = 0.030$$



Freon was selected as the most likely heat transport fluid to be used on Shuttle. Capella oil was included in the test because valve lubrication may call for this or a similar lubricant. The lubricant ratio was as recommended by refrigeration manufacturers. Following immersion, the Freon and specimen were heated to 800°F allowing the Freon to boil off to the atmosphere in the process. No visible reaction was observed, no change in weight was measured to the nearest 0.001 grams and microscopic examination did not reveal any attack on the metal. Further evaluation was discontinued on the basis of these results which would indicate that in flight venting Freon or spilled Freon during servicing or checkout of the radiator would not be detrimental to the material.

Permanent set on the specimens after removal from the holding device was noted. Approximately 10% of the deflection remained, some of which recovered after a period of weeks. The slight permanent set on the specimens opens the question regarding creep at the stress level imposed on the specimens. Reference 5 is an analysis of available data which discusses estimates of creep rates of borsic-aluminum composites. The report shows that most of the total strain should occur in the first hour of the test. Based on this premise, the time required to conduct the compatibility test which was approximately 4 hours under stress, was sufficient to introduce creep deformation. An attempt to directly relate the referenced analysis to the compatibility test specimen deformation, however, is complicated by the thermal excursion from cryogenic temperature (LN_2) through 800°F, holding at room temperature and at 600 and 700°F for inspection.

2.4 Thermal Control Coatings

The evaluation of selected thermal control coatings is contingent upon the work being accomplished by NASA. Selection of the best coating to be used on the Shuttle radiators is also dependent on vehicle design. Externally mounted units are likely to require the maximum refurbishment while sheltered units, little or none. A readily replaced film may be appropriate for the external unit. However, a baseline coating was selected early in Phase C-D for the two-sided and sheltered radiator as well as a coating for inside the cargo bay door. The coating, (Z-93, as used on Apollo) should be no different when applied to boron-aluminum with 6061 aluminum matrix as when it was applied to the Apollo radiators which were also 6061 aluminum.

During the course of this program, three candidate coatings were examined on a more current time frame following a survey of numerous potential coatings. They were: (1) a low temperature capability Teflon film with metallized coating such as used on Mariner, OSO, OHO and OGO program, (2) a high temperature white silicone paint provided by NASA, Goddard and (3) a high temperature porcelain enamel being developed at Hughes for Marshall Space Flight Center. The teflon coatings, applicable to a sheltered radiator arrangement because of the low temperature constraints, was evaluated briefly at VMSC in conjunction with the thermal vacuum test programs on radiators as reported in Reference (6). More research on adhesive attachment material was shown to be required. The teflon film system consists of an outer layer of teflon, next, a vapor deposited metal (silver or aluminum), then, a coating of Inconel (optional) and, finally, the adhesive. The white silicone paint, a satin semi-gloss system having an initial solar absorptance of 0.23 and emittance of 0.88 would be thermally stable for externally mounted radiators; however, the procelain enamel system offers a more readily cleaned surface and a higher temperature capability, thus improving refurbishment action.

Boron-aluminum test coupons were furnished NASA-MSC for application of several test coatings. These coupons will be tested in an arc-jet, contamination tests and U.V. Simulation (Reference (7). These tests will be performed under the direction of the Materials Technology Branch, Structures and Mechanics Division, Manned Spacecraft Center.

3.0 PROCESSING

3.1 Procedures

All starting materials for this program were off-the-shelf consolidated boron or Borsic - 6061 aluminum monolayer tape or 4 ply (2-0°, 2-90°) sheet Borsic-aluminum. Processing development consisted of use of the foregoing starting material laid up and autoclave bonded in a retort at nominally 200 psi and 1080°F. Borsic, although approximately 20% more costly was used to assure successful processing plus permitting repeated flight-imposed excursions to 700-800°F without the dangers of filament degradation. (Borsic is a trademark of Hamilton Standard. Boron is coated with silicon carbide which enhances resistance to elevated temperature reactions.) The process evolved during the preceeding program (Reference 1) but scale-up was expected to expose more or less critical process conditions and steps as a result of increased size. The scale-up program revealed numerous problems and brought to light those process steps which were highly critical. "C" frame bonding processes were particularly critical and tool form was found to be uniquely sensitive as discussed below.

3.1.1 Tooling

By far the most critical process conditions were shown to be (1) tool movement during consolidation of the individual tape segments. (2) temperature uniformity over the entire part and (3) retort sealing. The latter two problems were systematically resolved by straightforward corrections to the insulation scheme and improved retort fabrication methods. The tool movement problem persisted and was resolved only after repeated trial runs with simulated (aluminum) parts. The configuration of the tools was adjusted for: (1) no bond at the flange extemities, (2) no bond at the flange-web radius, (3) wrinkles at the radius and mid-span, (4) no bond at one end, and (5) pinched flange edges. Radius wrinkles were reduced by increasing the top plate width and adding a thin copper sheet over the top plate and finally eliminated by using retaining straps. Retort end plates were trimmed back slightly because they were preventing full retort pressure at the frame ends. Flange edge pinching was corrected by adding an 0.050 inch diameter wire stand off at the base of the mold. Mid-span wrinkles were eliminated by maintaining more uniform heat distribution along the length and by slower cooling. Heater and retort tooling are shown in Figure 3-1, 3-2 and 3-3.

3.1.2 Lay Up Procedure - Frames

The scale-up procedure was essentially that developed during the previous program described in reference (1). The monolayer tape was cleaned and coated with polystyrene. 713 alloy foil was interleaved between each layer of tape which was laid up over the steel mold. A stainless steel type 321 sheet 0.005 inches thick which separates all tool components from

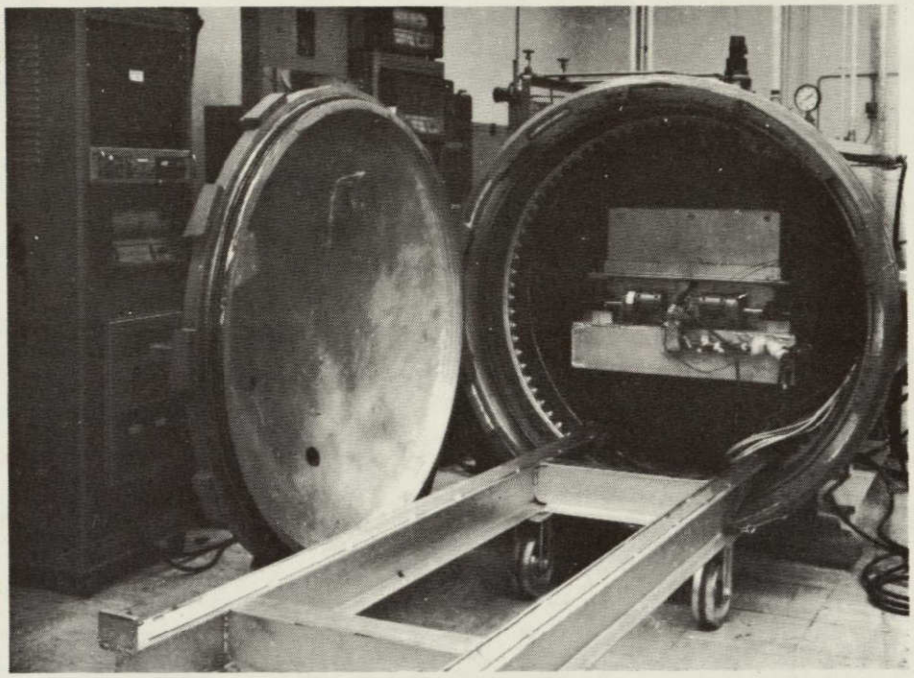


FIGURE 3–1 HEATER UNIT IN AUTOCLAVE

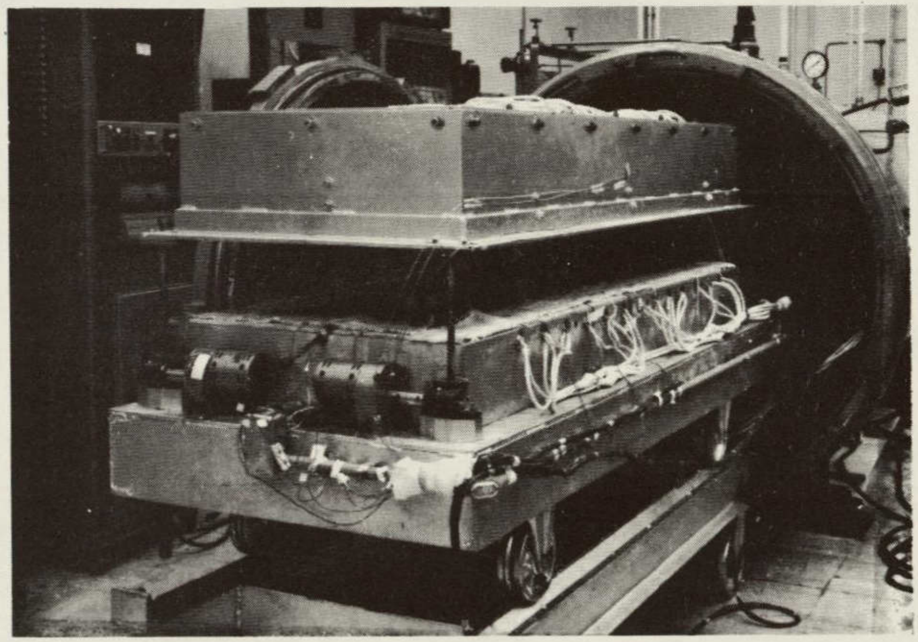


FIGURE 3–2 HEATER UNIT WITH GUARD HEATER RAISED

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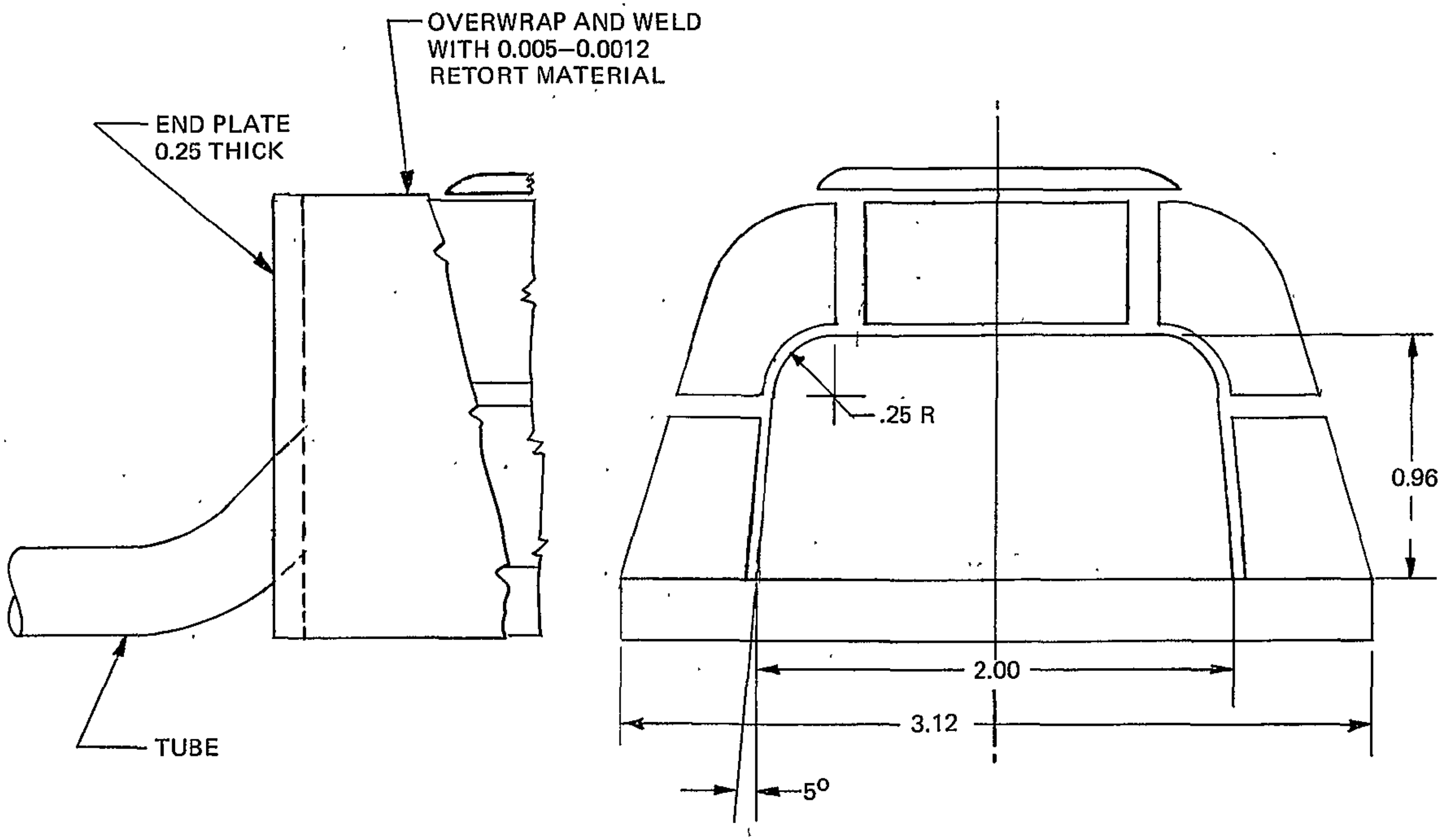

FIGURE 3–3 RETORT TOOLING FOR C FRAME

the part was coated with calcium carbonate solution to prevent joining of the part to the tooling. The assembly was enclosed in a 0.005 or 0.012 inch thick 321 stainless steel retort made vacuum tight by resistance seam and fusion welding. (Brazed retorts were abondoned when sealing difficulties were experienced.) End plates formed the close out of the retort envelope which also accommodated the vacuum line. Thermocouples were welded to the retort to monitor temperature during bonding. Twenty four channels were used throughout the program for monitoring various temperatures.

3.1.3 Autoclave Heating

The heat source used to bring the retort pack assembly to 1080°F was designed and fabricated specifically for the product of this program. Figures 3-1 and 3-2 illustrate the arrangement. The primary heat source was a heavy bottom platten 2 inches thick upon which the retort rested. Above the retort was a motor driven guard heater assembly which was lowered and raised to give access to the unit and to permit rapid cool-down following peak temperature in the bond cycle. The heater unit provided uniform heating in a space 5 x 12 x 48 inches. Add-on units could increase this space for a next step scale-up. Each of the two heater units was independently controlled by 175 ampere Phaser power controller units using Data-trak programmers through proportional controllers. Check-out tests were conducted to determine the thermal excursion of all parts of the heater unit both inside and outside of the working zone. The first series of runs were made at atmospheric pressure outside of the autoclave to arrive at the heating and cooling rates for both heaters with various loads on the platten. Surveys inside the autoclave followed, again with various loads. A check of temperatures on outside parts of the unit was made to determine the need for insulation to maintain safe autoclave wall temperature. No additional insulation was required. The survey showed a significant, but fully expected difference in heat up rates depending upon the size of the retort load. In all cases, however, temperature uniformity (within $\pm$ 20°F) could be maintained within 10 minutes after leveling off at peak temperature over the 12 x 48 inch working zone.

3.1.4 Autoclave

The small 4 foot x 10 foot laboratory autoclave shown in Figure 3-1 was modified for use on this program. The modification consisted of removal of the external insulation blanket, removal of internal heater units, the addition of feed-through power, thermocouple, nitrogen chilled water, pressure and vacuum lines. A 15 horsepower compressor and a 1 horsepower vacuum pump were installed.

3.2 Process Optimization

A study was conducted to establish certain process bonding conditions within the pressure constraint of the autoclave (200 psi). The previous work (Reference 1) had provided information relative to a method for secondary bonding of monolayer tapes under vacuum, external pressure and heat. The method utilized an intermediate layer of 713 (7.5% silicon-aluminum) alloy between each layer of tape. The tape material consisted of 45-50 v/o 0.004 inch diameter boron in 6061 aluminum alloy. Bonding cycles were determined for the aforementioned materials and process conditions. The purpose for that program was primarily to determine the potential of this material for use on a space radiator. This program was to assess certain manufacturing scale-up problem areas. Initially, it was necessary to examine in greater detail the time-temperature-pressure parameter applicable to the low pressure capacity of an autoclave. It had been assumed that substantial economies could be realized in this manner. As opposed to a true optimization of the process parameter which would require a large number of runs and tests, the approach on this program was to assume bounds for each process condition based on existing information and from this run sufficient tests to find a reasonable band of operating conditions where bonding would be accomplished. Test samples were bonded with variations from 1050 to 1090°F peak temperature, 40 minutes to 4 hours diffusion time, 940, 960, and 980°F diffusion temperatures, and 0 to 10 minutes dwell time at peak temperatures. Selected combinations of these variations were run as indicated in Table 3-1. Two conditions of material complicated the evaluation of the process testing, (1) tape strength varied between 160,000 and 218,000 psi UTS and (2) 713 alloy pre-bonded (braze-back) by the material supplier had been over-etched leaving a silicon rich surface. See Table 3-2. Neither time nor material was available to fully assess the impact of these variables on the already numerous process variables. The tests as conducted were sufficiently informative to establish the peak temperature at 1070-1090°F for 5 to 10 minutes and dwell time at 940° for 1 to 3 hours. Although pressure was not varied in test, it became apparent that any pressure substantially less than 200 psi would result in disbonds. Areas where tooling was restrained such that reduced pressure could take place invariably produced disbonds. Regarding use of 713 braze-back, it was shown that excessive cleaning can be detrimental to the process. Conceivably, overcleaning (severe etch) can change the temperature for optimum bonding and if production practices are established which do not control etching times or chemistry of the cleaners, unsatisfactory parts could be the outcome. The cause for erratic tape strength (though above specification minimums) was not explored since it is not an uncommon occurrence and was considered out of scope. There is also a wide variation reported by users in filament strength as supplied for tape manufacture.

3.2.1 Optimization Runs

Table 3-1 summarizes the process results used to establish, within reasonable limits, the operating conditions for autoclave bonding. The data is indicative of the time-temperature profile which will produce suitable bonds. It should be noted that strength properties do not complete the full assessment of the run. Of most significance was the general appearance and microstructure indicating bonding. Uniformity of thickness, microstructure of the sections cut, the slight squeeze-out of 713 alloy, and, of course, evidence of disbonded areas were highly indicative of the suitability of the run. There were instances where a complete, but weakly bonded specimen gave high strength results.

Flexure tests were used to compare process variables since bond between plies was the primary parameter. Flexural strength was measured in a fixture designed to measure deflection under load taken directly from the specimen, not the tensile machine cross-head. Measurements were determined on a Tinius Olsen 12,000 pound capacity tensile tester. Calculation of the test results were as follows:

$$F_b = \frac{3PL}{3wt^2}$$

where: F_b = stress in the outer fiber, psi

P = maximum load carried by the specimen, lb.

L = Span, in.

w = Width of specimen, in.

t = thickness of specimen, in.

$$E = \frac{11}{64} \quad \frac{L^3}{wt^3} \cdot \quad P/Y$$

where E = modulus of elasticity in flexure, psi.

11/64 = constant

L = Span, in.

w = width of specimen, in.

t = thickness of specimen, in.

P = load, lb.

Y = Deflection

3.3 Process Scale-Up

Using the process parameters determined in 3.2 above, a series of autoclave runs was made to not only check out the heater unit operation as described in 3.1.3 but to evaluate the effects of varying the size and weight of tooling representative of the range of retort assemblies scheduled for fabrication. The retort assemblies were (1) 6 inch long "C" frames having 2 inch web and 1 inch flanges, (2) 48 inch "C" frames (same cross-section), (3) secondary bond of 6 inch frames to 6 inch skin, (4) secondary bond of 48 inch frames to 12 inch wide skin and (5) two tubes bonded to 12 x 48 inch skin. Frames were simulated first using sheet aluminum where thermocouple readings were recorded at 10 to 12 positions on the retort. Tooling and insulation adjustments discussed in paragraph 3.1 were completed and bonding cycles unique to each size retort load were recorded. Acceptability of the process scale up was determined primarily through destructuve examination of the test pieces fabricated as well as shear tests performed on thick plates. Adjustment in process parameters followed as a result of the scale-up activities. The shear test results are shown in Table 3-3. This test was conceived to obtain a true interlaminar shear stress to failure using thick, short-beam flexural specimens in the following manner: Initial tests were conducted using the single point loading on 18 ply (0.135 inches thick) specimens. Shear failure was not evident in the specimens. Then 33 ply (0.260 inches thick) specimens were similarly tested with uncertainty in the failure mode. Finally, 2 point loading was used to test unidirectional and cross-ply specimens at room temperature, where most specimens visibly failed in shear.

TABLE 3-1

SUMMARY OF RESULTS - OPTIMIZATION OF PROCESS
FLEXURAL STRENGTH PROPERTIES

Run	(1) Peak Temp - °F Time - Min	Diffusion Temp - °F Time - Min.	Fb (2) Ksi	$E^{(3)}$ Psi $x10^6$	Remarks
1	1070-13	950-60	50.3 57.2 53.0 122.8 127.8	21.7 41.3 45.7 26.1 25.3 26.5	Ftu - 50.8 Ksi 41.6 Ksi 68.6 Ksi Spotty Delamination in Test Panel
2	1070-5	960-54	68.8 80.3 91.2 68.9 159.0 118.8	43.5 39.1 45.7 39.1 27.74 26.15	Ftu 44.0 KSI 44.0 Ksi Spotty Delamination in Test Panel
3	1030-0	980-43			No Test Delaminated
4	1070-0	980-41	127.2 124.3 159.8 153.2 157.8 159.1	29.4 27.7 29.5 26.7 30.9 28.2	Good Appearance in Test Panel
5	1050-10	940-60	106.7 103.5 108.4 116.6 128.3 121.2	30.7 30.6 25.7 24.5 29.2 30.3	Good Appearance but Weak Bonds in Test Panel

Notes: (1) Runs 1 through 12 were with 0.004 diameter boron-40 v/o Remainder with 0.0057 borsic - 45 v/o.

(2) $F_b = \frac{3PL}{4Wt^2}$

(3) $E = \frac{11}{64} \frac{L^3}{Wt^3} \frac{P}{Y}$

TABLE 3-1
(Continued)

6	1060-10	940-62	110.2 134.1 120.7 109.9 119.2	27.5 30.0 24.8 26.5 28.7	Good Appearance Spotty Delamination in Test Panel
7	1060-5	960-50	177.1 149.1 175.2 159.3 160.3	29.6 29.6 32.0 30.3 25.3	Good Appearance
8	1060-5	950-50	-	-	No Test Delaminated
9	1065-1	980-40	-	-	No Test Delaminated
10	1050-0	980-40	-	-	No Test Delaminated Retort Leak
11	1050-0	960-52	-	-	No Test Delaminated
12	1050-5	960-52	-	-	No Test Delaminated
A	1070-5	925-60	198.6 186.5	-	713 Alloy Interleaved

TABLE 3-I
(Continued)

B	1070-5	925-120	187.9 207.9	- -	713 Alloy Interleaved
C	1070-5	925-180	218.3 200.2	- -	713 Alloy Interleaved
C_1	1070-5	925-180	212.3 200.2 171.0 199.4	29.7	Braze-Back Tape Used
D	1050-10	925-120	193.0 197.3	29.3 30.0	Braze-Back Tape Used
X	Over 1095	None	149.5 150.6	30.7 28.1	Control of Temp. Lost due to Controller Malfunction and Filaments degraded
E	1050-10	930-240	155.1 168.3	- -	Braze-Back Tape Used
F	1050-10	930-60	-	-	Braze-Back Tape No Test Delaminated
G	1060-10	930-180	137.8 179.5	25.5 29.4	Spotty Delamination
H	1060-10	930-180	136.8 146.4	23.4 25.4	Spotty Delamination Braze-Back Tape Used

TABLE 3-1
(Continued)

I	1080-10	925-60	165.5 199.8 180.3	29.9 28.9 29.1	713 Alloy Inter- leaved Spotty Delamination
J	1090-10	925-60	152.4 172.9 149.8 159.9	29.5 28.5	Good 713 Alloy Interleaved

TABLE 3-2

SURFACE CHEMISTRY MEASUREMENTS
BRAZE-BACK MONOLAYER TAPE

Material Measured Type	Nominal Silicon in Alum. %	Counts/Second *
Pure Silicon	100	290
713 Alloy	7.5	11
4043 Alloy	5.0	5.5
6061 Alloy	0.6	1.5
Braze Back Monolayer Tape	7.5	50

* X-Ray diffraction counts indicate relative concentration of the element at the impinged surface.

TABLE 3-3

INTERLAMINAR SHEAR PROPERTIES
0.0057 BORSIC-ALUMINUM TAPE, AUTOCLAVE BONDED

Specimen			Test Temp.	Fs
Layup*	No. Plies	Thickness (in)	(°F)	(Ksi)
U-D	18	0.136	R.T	15.3
U-D	18	0.136		15.2
U-D	33	0.265		18.7
C-P	30	0.228		15.6
C-P	30	0.228		14.2
C-P	30	0.227		15.0
U-D	33	0.265	300	14.4
U-D	18	0.132		14.6
U-D	18	0.135		14.1
U-D	18	0.131	500	12.0
U-D	18	0.136		11.0
U-D	33	0.265		12.0
U-D	33	0.265		12.7
C-P	30	0.228		10.2
C-P	30	0.228	700	6.2
C-P	30	0.229		5.9
C-P	30	0.227		5.6
U-D	33	0.265		8.0
U-D	33	0.265		7.9
U-D	18	0.137		6.9
U-D	18	0.136		6.8
U-D	18	0.136		6.8
U-D	18	0.133		6.9

* Cross-Ply Layup Alternately 2 Plies at 0°, 2 Plies at 90° with Outside Plies at 0° to Long Axis of Specimen Nominally 1.5 Inches Long, 0.5 Wide

4.0 SCALE-UP VERIFICATION AND TEST

The scale-up of the process was essentially one of making the transition from a small boron-aluminum 3 inch square panel press-bonded at high pressure in the laboratory to a 4 square foot panel low pressure bonded in a laboratory autoclave. This involved obtaining a small autoclave, modifying it to utilize the process and determining how to make the 4 square foot panel. Outstanding among the many ramifications of this task included (1) a panel design representative of a shuttle space radiator which in turn brought to light many design factors involving the shuttle vehicle, (2) examination of the problems which would affect a production method, and (3) the complexity of the process as related to costs, reproducibility and reliability of a fabricated structure. To demonstrate if the process could be reduced to practice, it was considered necessary to assemble and bond a panel of sufficient size to uncover potential production problems and to provide information useful in the design. The panel selected was double-wall, frame stiffened 12 inches by 48 inches having 2 stringer frames along the 48 inch dimension and 2 flow passage tubes attached to one wall. Since the shuttle design may require one or more methods of attachment, spotwelding, riveting, bolting and diffusion bonding were all considered. The panel for this program was not intended as a structural test article except with respect to thermal loads. It is anticipated that future panel fabrications would incorporate a more elemental arrangement and a single attachment method for each panel would be appropriate for structural test and analysis. The panel was exposed to 30 cycles between room temperature and 800°F. Evaluation consisted of measuring warpage and examining the panel for degradation.

4.1 Panel Element Try-Out

Significant areas of potential fabrication problems were examined through a sequential approach for lay-up and bonding of the various configurations, (1) with conventional aluminum foils or sheets in 6 inch assemblies, (2) full length (48 inch) with conventional aluminum, (3) 6 inch uncoated boron-aluminum and finally, (4) full length Borsic-aluminum. A controlling factor for the use of conventional aluminum was to minimize material costs. Additionally, Borsic filament delivery to the tape manufacturer was highly uncertain at the time material was needed. The initial tryout runs brought out tooling deficiencies as discussed in 3.3. Changes in the tooling corrected these deficiencies and a retort leak problem was resolved by welding. Brazing the retort assemblies was discontinued. The discussion reported here regarding tooling difficulties is indicative of a need for good but not necessarily high precision tooling. The following outlines the problem and shows that tooling need not incur high costs.

4.1.1 Retorts

The techniques used to fabricate the retorts evolved also from the trial runs. Ultimately the C frame retort was made up by making a sleeve or tube out of .012 inch thick type 321 stainless, and resistance seam welding along both sides. The banded block assembly was inserted and 1/8 or 1/4 inch end plates were arc welded to the ends. One end of the assembly contained a 3/8 inch diameter vacuum line, type 321 steel. Secondary bonding of the C frame was accomplished in a similar retort arrangement illustrated by Figure 4-1.

4.1.2 Tool Development

All forming blocks were made from low alloy steel and the only critical dimensions were those contours involved with formation of the part radii. The difficulties were, for the most part, due to not understanding the assembly techniques. It was found that the side blocks tended to rotate and move upward upon application of autoclave pressure. This was corrected by adding another thin top plate which extended over the side blocks which was then pinned to the top block to prevent its movement. Finally, the assembly was banded with steel straps to prevent movement during insertion into the retort sleeve. These steps were successfully applied and no further tool shifting was experienced. Successful tooling for this application is a matter of placement and restraint rather than high precision, high cost dimensional control.

4.1.3 Assembly and Process Procedure

The details for assembling and processing the panel are presented in Appendix II. Specification 308-15-38, "Fabrication of Boron-Aluminum Components". In abbreviated terms, the process follows the sequence described below:

1. Tape material previously cleaned by the supplier recleaned with:

   (a) Alcohol degrease
   (b) Hot sodium hydroxide buffered with K_2CO_3
   (c) Hot water rinse
   (d) Nitric acid (15%)
   (e) Water rinse
   (f) Acetone dip
   (g) Polystyrene sealer

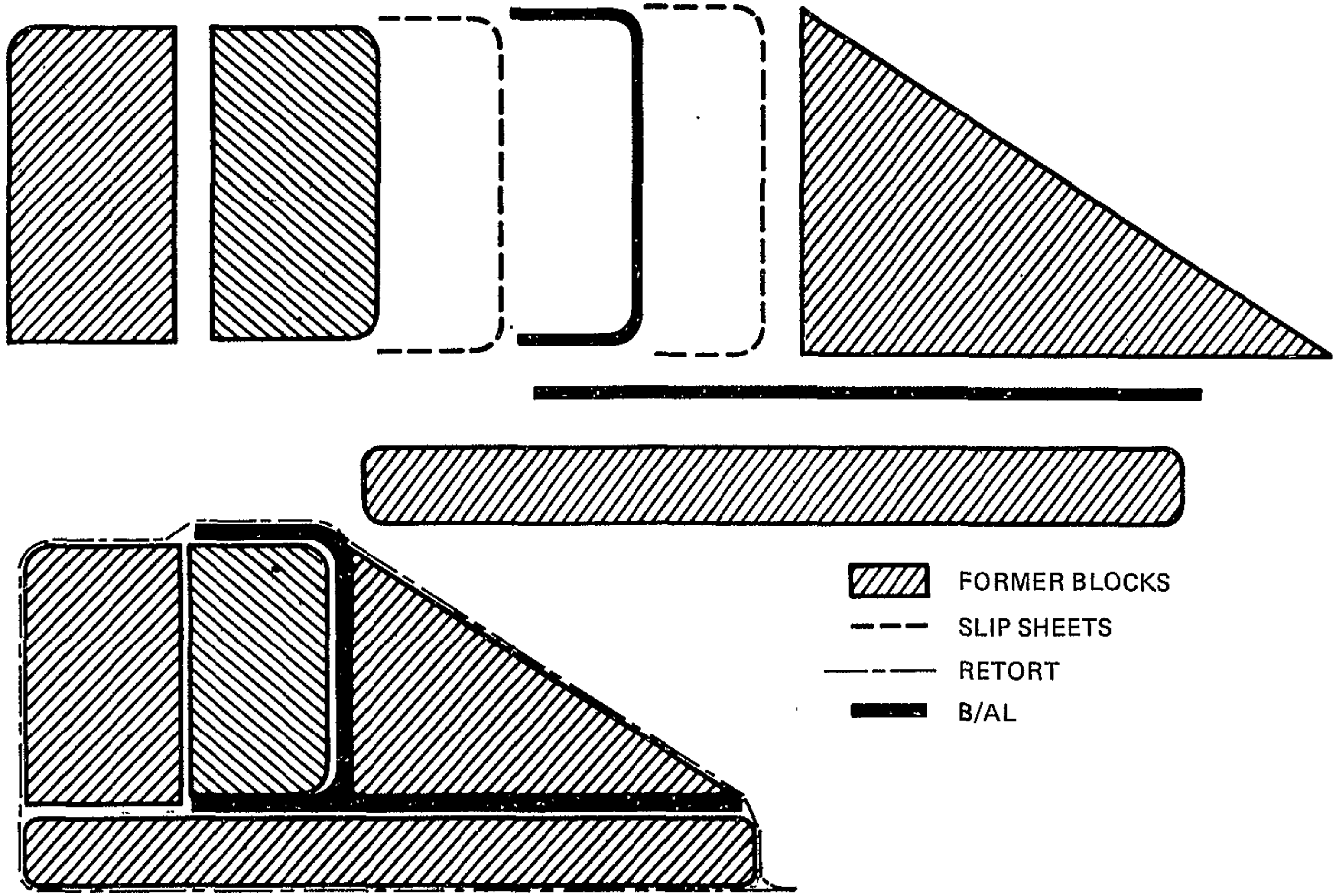

FIGURE 4–1 SECONDARY BONDING RETORT ASSEMBLY

2. Spray coat slip sheets with calcium carbonate slurry.

3. Assemble tapes and place glide sheets between inside and outside surface of tape assembly.

4. Assemble blocks around tape assemblies.

5. Insert block assembly into retort sleeve.

6. Close out weld both ends of retort.

7. Weld thermocouple junctions close-out ends and along retort sleeve at equal intervals (approximately 8 positions). Thermocouple leads feed through the autoclave connector. This installation is best performed as close as practical to the autoclave door.

8. Install retort assembly in heater cavity.

9. Lower guard heater to the closed position.

10. Place heater unit into autoclave and close door.

11. Turn on retort vacuum pump.

12. Set controllers and turn on power to platten and guard heaters.

13. Purge retort with nitrogen between 850 and 900°F.

14. Turn on high pressure system at 850°F.

15. Program to 1080°F, hold 10 minutes.

16. Cool down to 940°F, hold 3 hours.

17. Cut off power to cool slowly to R.T.

18. Remove retort from autoclave and heater unit.

19. Cut off retort.

20. Clean part in preparation for subsequent processes.

It was found that the weight and surface area of the retort significantly affects the bonding cycle. The significance of these weight differences may be noted in the process specification, Appendix II. It is essential to match heat cycles with the mass more precisely than is usual for standard heat treatment, for example. Additionally, the surface area of the retort in contact with the platten heater influenced the heating rates significantly. Table 4-1 shows the wide range of retort assembly weights and surface areas.

TABLE 4-1

RETORT ASSEMBLY WEIGHTS AND CONTACT SURFACE AREA

Retort Assembly	Weight - Lb.	Area - in^2
48" Frame	76.22	245
6" Frame	8.93	40
48" Secondary Bond	214	686
6" Secondary	16.27	56
6" x 6" Flat Sheet	14.52	64

4.1.4 Frame Fabrication

Since initial attempts to bond the frames showed that tooling and process control factors were critical and that process costs could be potentially lower, a re-evaluation of methods was conducted. In parallel with the improvements in heating uniformity and tooling discussed above, methods to hot creep form frames were examined in the interest of economy. It was thought that savings in process time due to lay-up and retort fabrication could result. Trial runs at Amercom and at VMSC were conducted to hot creep form a press bonded, 7 ply unidirectional laminate containing 0.0056 inch diameter boron filaments. While autoclave formed parts ultimately resulted uniformly spaced, well bonded radii as shown in Figure 4-2, the creep formed frames failed along the radii as shown in Figures 4-3 and 4-4. As noted in the photographs, two mill wire mesh made from rocket wire was applied to the outer ply during fabrication of the sheet at Amercom. The intent was for the mesh to resist cracks during forming and it is possible that, given added time and material a suitable process could be developed. At

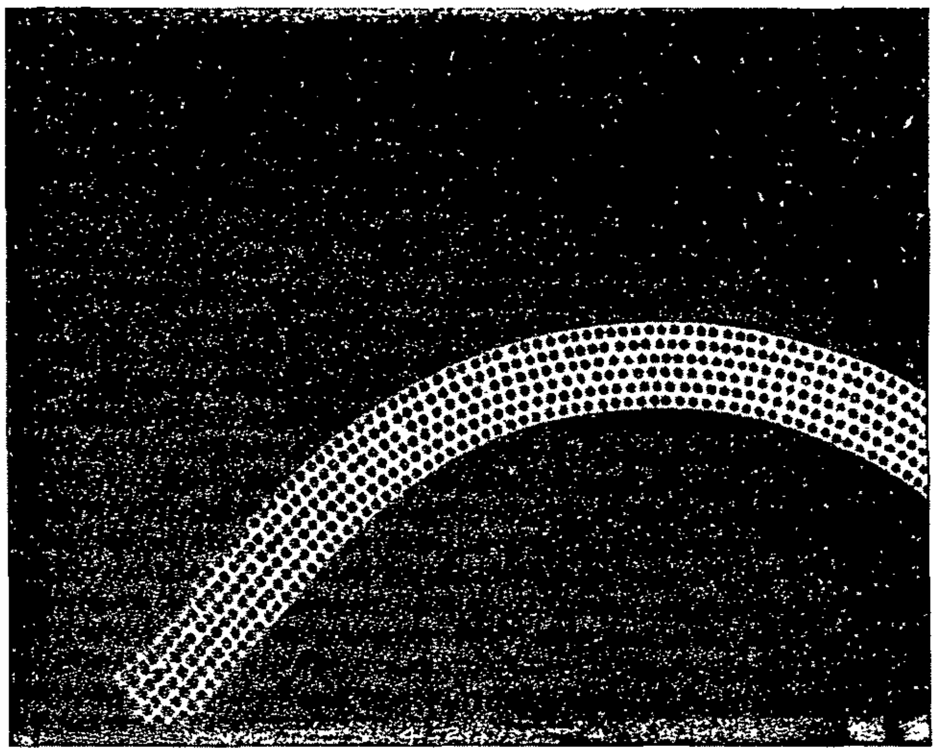

FIGURE 4–2 MACROGRAPH OF FRAME, AUTOCLAVE BONDED

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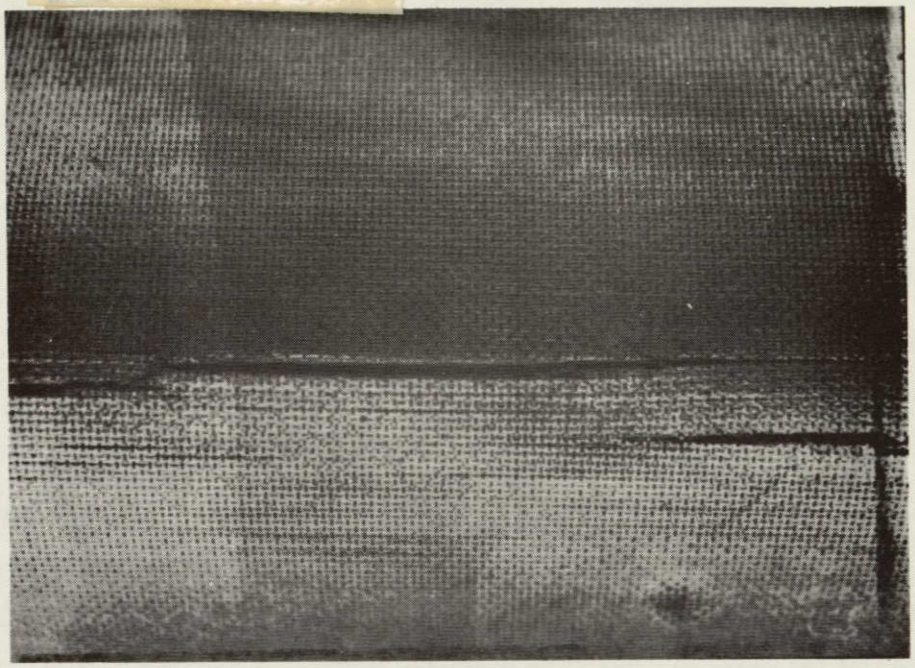

FIGURE 4–3 CREEP FORMED C FRAME SURFACE CRACKS

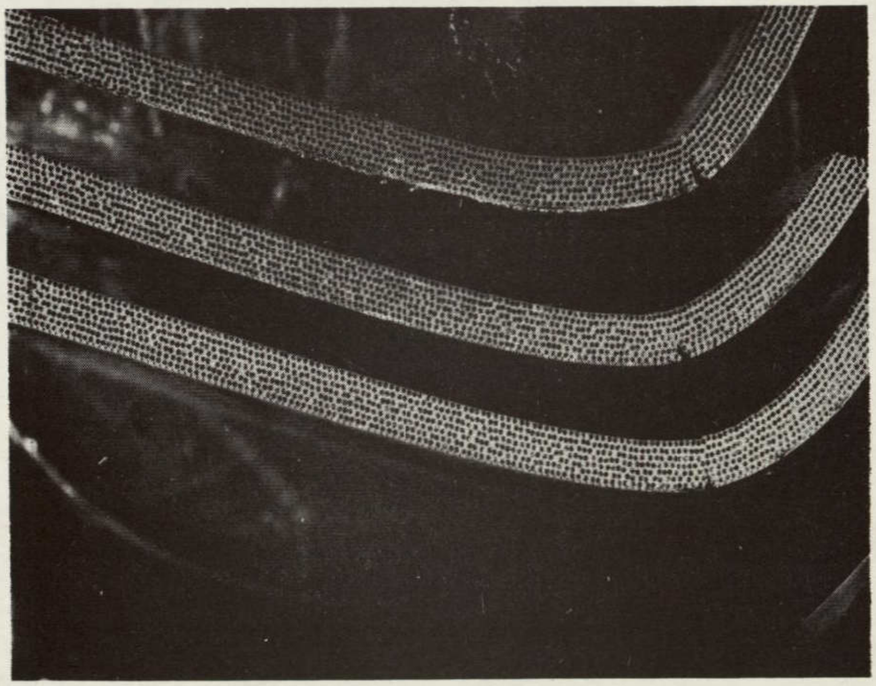

FIGURE 4–4 MACROSECTIONS OF CREEP FORMED C FRAME SHOWING EXTENT OF CRACKS

VMSC, the frame (48" long) was formed in two steps, first by contouring the part to about a 4 inch radius, then by flattening the web portion and wrap around of flanges in the second operation. Special tools were not developed for these operations, only tool forms made from the autoclave bond tooling. The forming was done at 1000°F in the first step and 900°F in the second. It is evident that filament crushing and compression failure at the inside surface occurred while the matrix was tearing at the outer surface. Autoclave bonded C frames made in 6 and then 48 inch lengths proved to be properly contoured following the preliminary trial runs. The tryout experience showed that minor changes in tooling were essential to successful fabrication. The top plate (see Figure 3-3), for example, was an addition to the original retort assembly. Other changes, as discussed in 4.1.2, Tool Development, as the work progressed. Following processing of the final C frame, it was found that an increase in the overall length of the heaters, a major change, was found to be necessary to avoid disbonds at the frame extremities. Available boron-aluminum tape was insufficient for the additional runs that would be needed following a heater extension change. Material was tested from one of the tryout frames with results shown in Table 4-2.

TABLE 4-2

TENSILE PROPERTIES REPRESENTING AUTOCLAVE BONDED "C" FRAME UNIDIRECTIONAL BORSIC-ALUMINUM

Specimen	Ftu - Ksi
1	135.6
2	128.9
3	133.5
4	136.5

4.2 Attachment

4.2.1 Diffusion Bonding

Diffusion bonding of the frame to the skin was accomplished by autoclave processing in a similar manner to that used to bond the frames. Figures 4-5 and 4-6 illustrate the method. 713 braze alloy is placed at the joint interface to promote diffusion. Appendix II describes the procedure in more detail.

4.2.2 Spotwelding

Spotwelding schedules as shown in Table 4-3 were determined for 4 and 6 ply material, however, the test panel was not welded so that additional tests could be performed on the panel in the future. Changing the frames can be accomplished by removal of the channel nuts. Table 4-3 presents the schedule which evolved during the welding effort. No significant difficulty was experienced in reaching a 350 pounds shear strength target in the 0.030 inch cross ply material.

4.2.3 Holes

Channel nut or rivet attachment hole tryouts were performed on test material using high speed diamond drilling methods and hand punching. A diamond core drill survived only thirteen holes and a solid diamond drill was virtually useless. The diamond grit would load up with aluminum following each hole drilling and required removal by drilling holes in a carburundum block flooded with lubricant. A hand punch, Roper Whitney No. 5 Junior shown being used in Figure 4-7, proved to be an extremely effective method for achieving a uniformly round hole with minimal set-up time. A template was used to position the holes on the sheet and frames. A diamond core drill slightly (0.005 inch) larger in diameter hand twisted about 10 revolutions in each hole improved the smoothness in the wall of the hole, however, the necessity for this reaming operation can only be decided by more extensive evaluation testing. Rivets which properly expanded in the holes tended to crush edges of the holes and the risk of such damage precluded application of rivet attachment in the panel. Disassembly and reuse of the panel for further tests reinforced the desire to use only channel nut attachment. Diffusion bonding was used to join one frame to one skin and the remaining three joints incorporated channel nut assembly.

TABLE 4-3

WELD SCHEDULES
Sciaky AC 100 KVA
Multi Pulse - One Each Direction
Initial Trial Settings

B/Al to B/Al	B/Al to 6061
2 Cycles	4 to 6 Cycles
Low Weld Heat	1/2 Coal Cycle
Over 2000 Pound Forge	Pre-Heat 60-75% Weldheat
Short Forge Delay	No Post Heat, Temper or Quench
	Clean Tips every 4 welds
	Class III 6-8" Tip Radius Alum Side
	Class I 12" to Flat on B/Al Side
	1200 - 1400 Pounds
	1800 Pounds Forge
	Long Delay

FINAL SCHEDULE
Sciaky Decatron

B/AL to B/AL

4 Ply 0 - 90 C.P.
to
6 Ply U.D.

Press.	PG-2	1400
	PG-1	1000
	EG	1300

Selector Vari., Const H & Var
Single Impulse
TH - OFF, THA - ON

Forge Delay	2.7
Cool	3.5
Heat	2
Weld 45%	
Current Decay	4
P. Heat 25%	
Squeeze	15
Hold	12
Phases	3 Par.
CL · I Tip 6-6	1/2 offset

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FIGURE 4–5 SECONDARY BOND ASSEMBLY FRAME TO SKIN. REMOVING FROM RETORT

FIGURE 4–6 SECONDARY BOND ASSEMBLY FOLLOWING REMOVAL FROM RETORT

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FIGURE 4–7 HAND PUNCHING B/AL FRAME

4.2.4 Tubes

Trial runs for braze bonding the tube to the sheet indicated that thermal expansion differences between the 6061 aluminum tubes and the composite sheet required special consideration. A series of experimental runs resolved most problems but it is evident that further development is needed. A 12 x 48 inch tube assembly was bonded suitable for the panel test. Improvement in the distortion control and tool refinement are clear cut and should result in a fully acceptable production part. For example, the use of form blocks covering all surfaces is apparently essential. This would have prevented excess braze material in the tube bend area. Thicker formers would minimize warpage. However, excellent bonding was evident visually and C scan ultrasonic evaluation indicated a good bond on the finally bonded tube assembly.

4.3 Thermal Test Apparatus

A rigid test fixture was fabricated to support the panel during thermal exposure. The panel was resting on insulation blocks 43 inches apart. One corner of the panel was clamped to the fixture, the remainder being free to expand. A water cooled radiation shield was located below the panel mounting assembly to protect instrumentation. Heating was provided by 110 Quartz lamps of 1 KW capacity each controlled by a Thermax and Ignitron Proportional Controller unit. Heat programming was with a Data Trak unit. Temperature was measured at 20 positions, one of which was at the Thermax for control and another for visual monitoring by digital display. The remainder of the thermocouples (chromel-alumel) were fed by cable through a reference junction to a data station which recorded on magnetic tape. Deflection was measured with 8 Schaevitz Model 400 and 500 DC deflectometers (linear variable differential transformers) and a transit mounted on a precision measuring stand. The deflectometer data was fed to the data station for tape readout and visual readings were taken through the transit at two positions at the panel surface, at the center and along one edge one foot from the end. Time, temperature, deflection plots were fed and stored in the data station computer from the deflectometer system. The deflectometer assemblies were attached to the edges of the panel with clips through which tungsten wires were hooked. Each assembly was spring loaded (0.02 to 0.05 pounds tension). The optical readings were taken on cycles 6, 7, 8, 22, 23, 28 and 29. Test apparatus arrangements are shown in Figures 4-8, 4-9, and 4-10. Figure 4-11 shows the panel during test exposure.

4.4 Thermal Testing

Preliminary runs with a dummy panel of aluminum were used to establish the programmer cycle chart. One initial run requiring 40 minutes was hand programmed on the panel. Once programming was established with a heat-up time of 5 minutes to 800°F and cool-down below 100°F in 25 minutes, the 30 thermal cycles were run on the boron-aluminum panel. The panel was instrumented with thermocouple and deflectometer arrays as seen in Figures 4-12 and 4-13. Positions for measurement were established where anticipated maximum thermal stresses might occur. The intent was to observe the effects of the thermal excursions and if failure resulted, to evaluate the data as it related to the failure. Since there was no failure following exposure, the data was not further analyzed and only a portion of representative data was reproduced from the data station computer and included in 6.4, Panel Test Results. However, future panel design activities using boron-aluminum could find the deflection history generated of some value, particularly since the thermal gradients created from heating one side were substantial, up to 450°F.

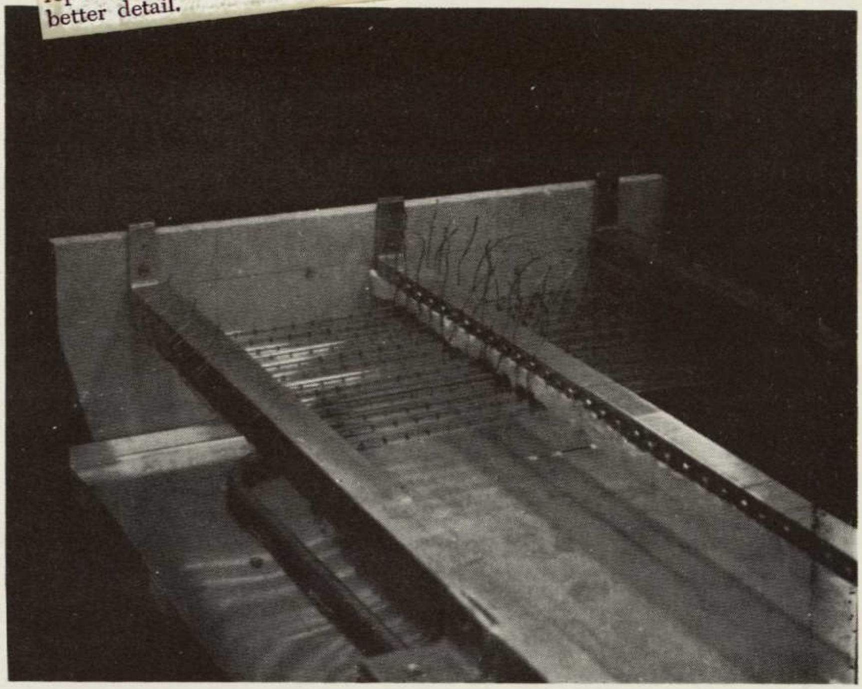

FIGURE 4–8 INSTALLATION OF QUARTZ HEAT LAMPS IN FIXTURE

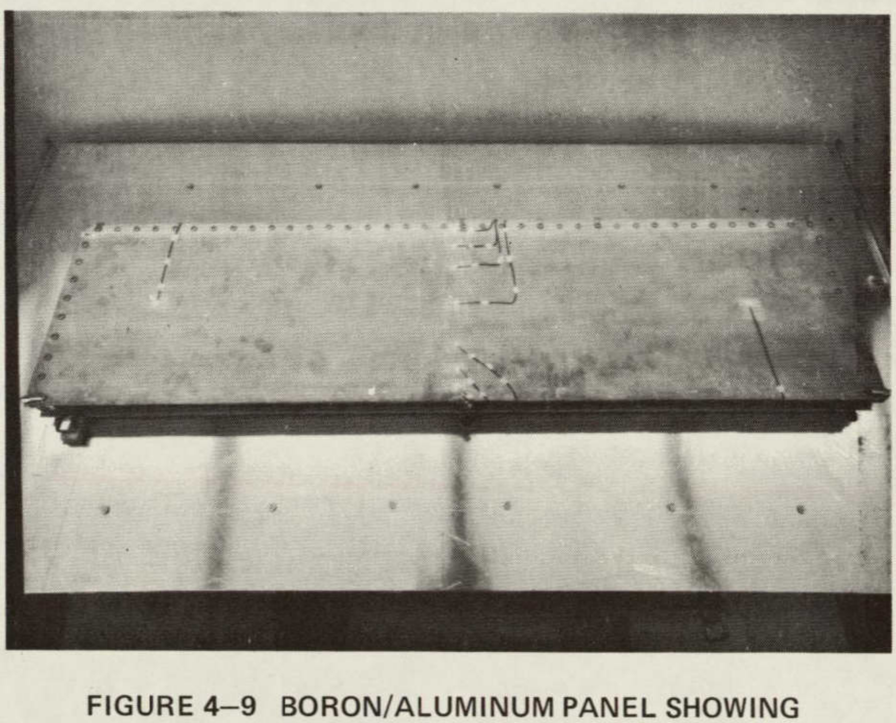

FIGURE 4–9 BORON/ALUMINUM PANEL SHOWING THERMOCOUPLES INSTALLED

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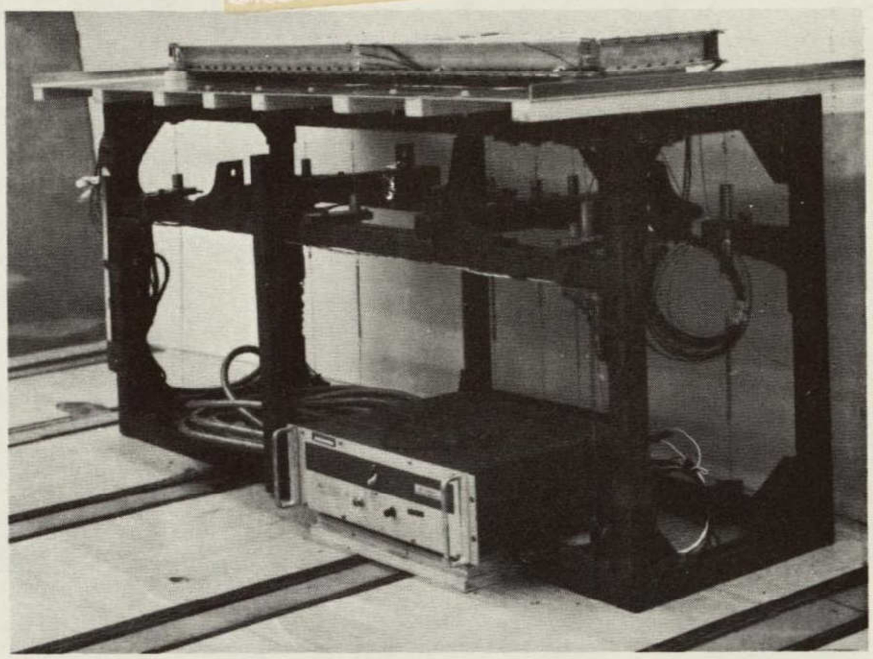


FIGURE 4–10 DEFLECTOMETER ARRANGEMENT UNDER TEST TABLE. UNITS ARE ATTACHED TO PANEL BY SPRING-MOUNTED WIRES

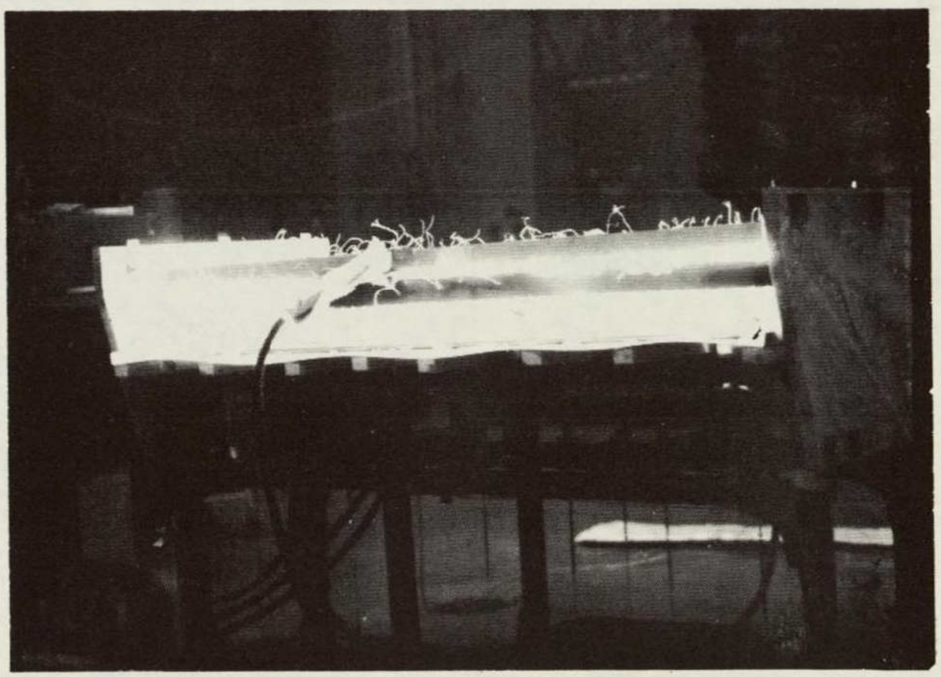
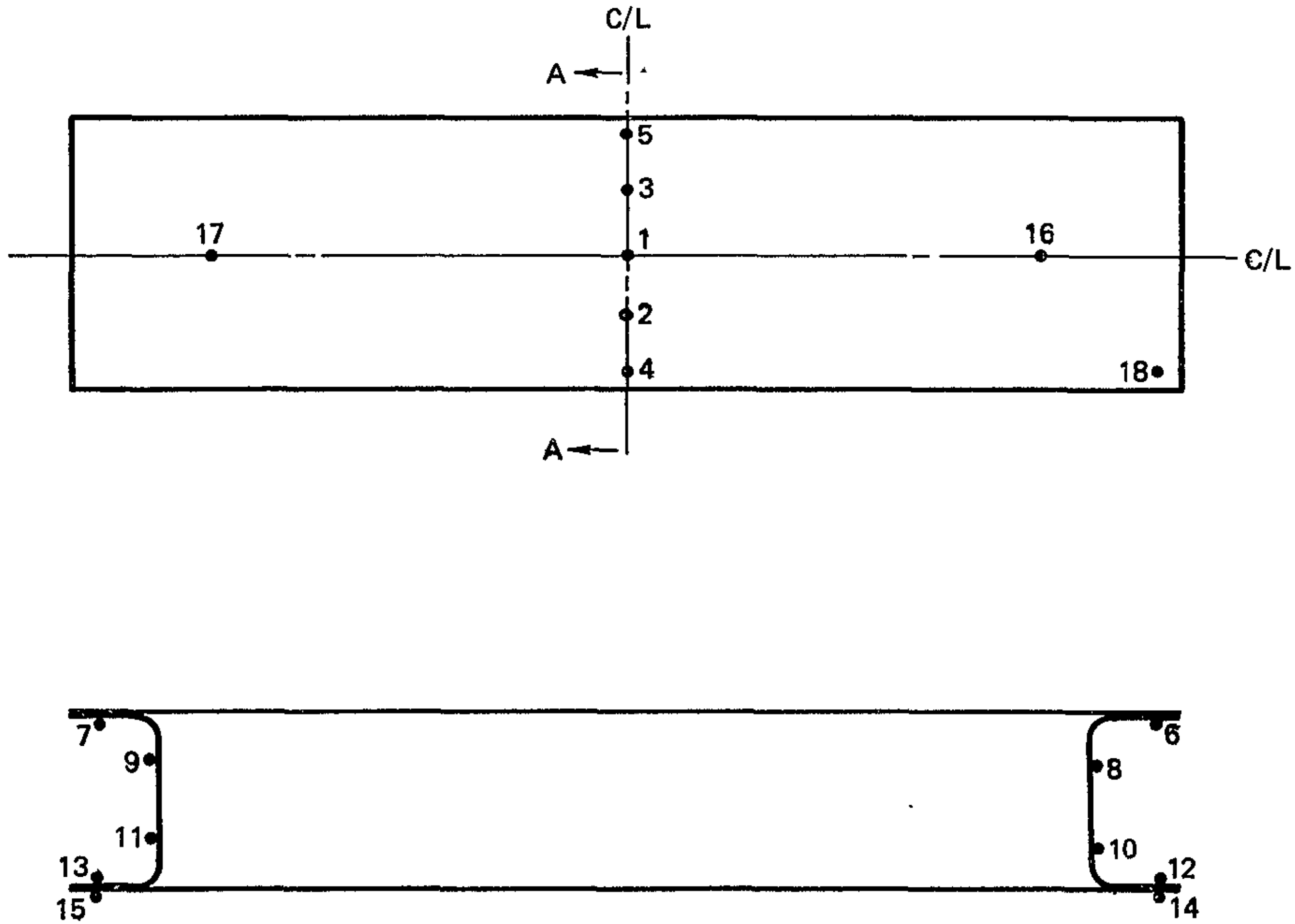
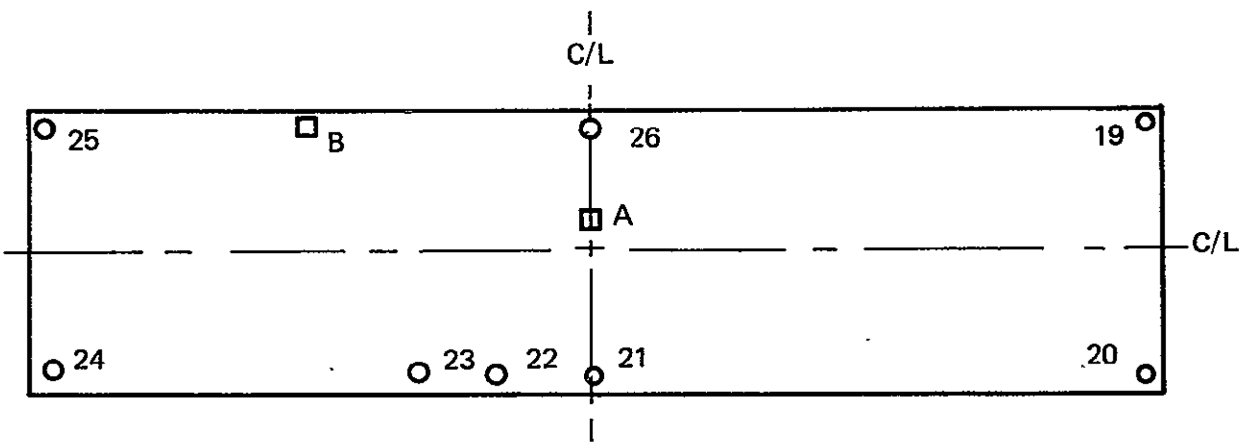


FIGURE 4–11 PANEL IN TEST



SECTION A–A (4 TIMES SIZE ABOVE)

FIGURE 4–12 THERMOCOUPLE JUNCTION LOCATIONS ON PANEL



19 THROUGH 26, DEFLECTOMETERS

A AND B, OPTICAL VIEWING POSITIONS

FIGURE 4–13 DEFLECTION MEASUREMENT LOCATIONS ON PANEL

4.5 Post Test Analysis

The panel was removed from the fixture, disassembled and each component part inspected for damage. Changes to the panel included slight delamination at the extremities and deformation at mid-length of the "C" frame which had been diffusion bonded to the skin. Figure 4-14 shows the panel disassembled. The condition was also readily apparent visually. The original condition of a slight twist in the panel was relieved at some time prior to the 20th cycle. X-ray and visual examination of the component parts indicated that no other damage resulted from the test. Noteworthy was a characteristic difference between deflected positions during heating as compared with cooling including a negative deflection occurring below 450°F during cool down. Most noticeable was the center of the panel skin which raised up more than 1/4 inch while either side of the center of the skin buckled downward. This distortion is considered adequate cause for permanent deformation at mid-length of "C" frame. The final condition of the panel was considered as structurally sound and would have been functional throughout a full life cycle required on the Shuttle.

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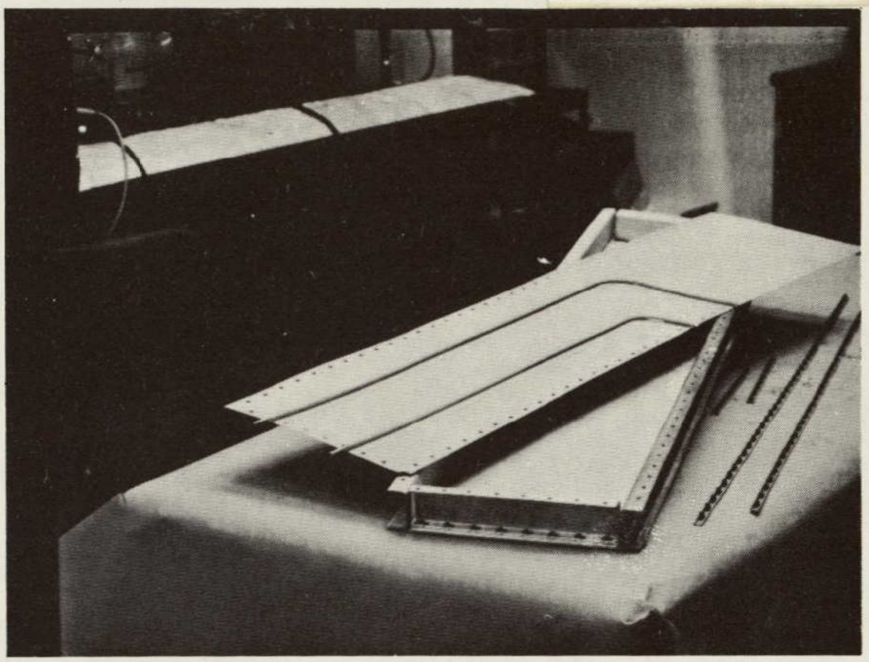


FIGURE 4–14 DISASSEMBLED PANEL FOLLOWING TEST

5.0 COSTS AND DESIGN STUDIES

5.1 Costs

Boron-aluminum material costs have been reduced through extensive development demands and their products through lower cost processes. However, since large production quantities have not been forthcoming as yet, the price of material is still $40 to $50/square foot/ply. A requirement for quantities such as might be needed for the Shuttle were projected to $30/square foot/ply. The following study was based on the $40 figure not on the possible $30 figure and is therefore conservative. The study was limited to recurring manufacturing costs and materials.

5.1.1 Cost Study

The purpose of this trade study was to make a cost comparison of radiator panels fabricated from aluminum alloy versus fabricated from boron-aluminum composite material. In addition, a combination of boron-aluminum skins and titanium frames was compared. The total costs cited herein reflect this comparison only and should not be construed as indicative of a price for any portion or total of the items cited.

Figure 5-1 shows a double faced radiator panel which was used for this cost analysis trade study. As shown in this figure, the radiator tubular elements are located on the exterior surfaces of the panel. Fluid flow restrictor assemblies are located at each inlet radiator tube in order to control the fluid flow at a uniform pressure throughout the assembly. The radiator, as configured, has a redundant set of tubes as indicated by the over-and-under tube configuration. The tubes in this figure are located on six inch spacing, however, the tube configuration used in this cost analysis was single tubes located on three inch center which function identical to that shown (i.e., every other tube is the primary system). For both the aluminum and the boron-aluminum panel the tubes, inlet manifold and return manifold are 6061 aluminum alloy.

The overall panel size is 117.0" x 117.0" and the depth of the panel is 2.0 inches which is representative of a radiator mounted to one of the orbiter's cargo bay doors. The orbiter configuration assumed for this study would require six of these double faced radiators located on the forward three (left and right) cargo bay doors and six single faced radiator panels located on each of the aft three cargo bay doors. The costs presented herein reflect only the cost (recurring) of one double faced radiator panel. Tooling costs are also presented and with the exception of the retort itself, could be used for subsequent panel fabrication.

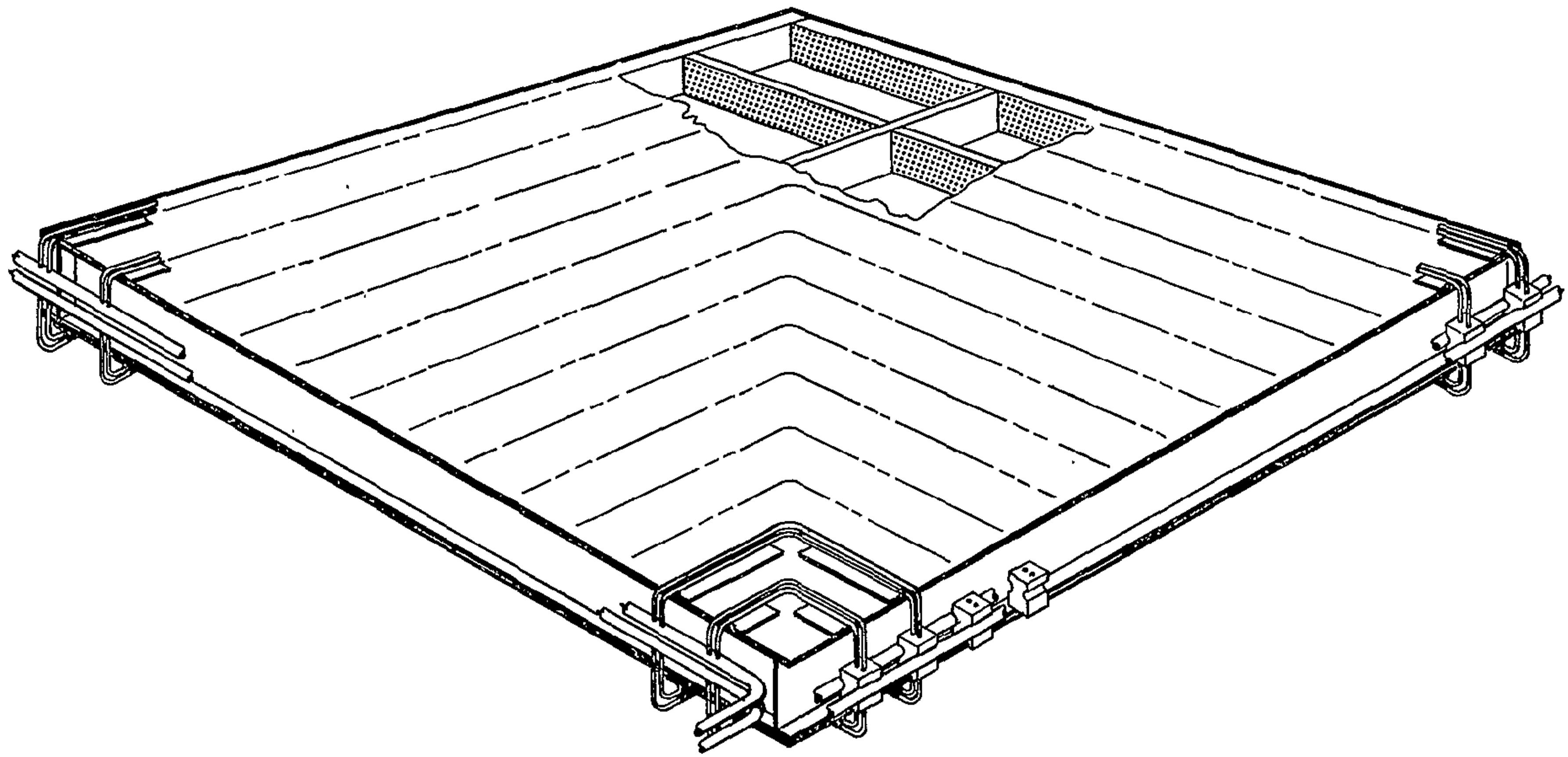


FIGURE 5–1 RADIATOR PANEL ILLUSTRATION

5.1.2 Approach and Costing Ground Rules

The initial effort was to develop a functional flow diagram which depicted the steps that had to be accomplished from the release of the engineering drawings to the fabrication of elements made from boron-aluminum composites. It should be noted that for this analysis it was assumed the tooling verification and test part fabrication for tool tryout had already been completed thus proving the process.

The next step consisted of dividing the radiator panel into each individual element, then determining the raw material requirements and the sequence of operation (planning) required in order to fabricate that individual element. This was followed by determining the assembly operations as well as establishing the tooling requirements for the detail and assembly operations.

Finally, costs were developed for each of the panels as well as the tooling by estimating the manhours required and the cost of the material. The manhour requirements were developed at the segment level. The material costs were developed by either determining the number of pounds of material required or, as in the case of boron-aluminum, the number of square feet required. These values were then multiplied by the appropriate cost/pound or cost/square foot. The following ground rules were used in this cost analysis:

(a) The boron-aluminum composite for the skin application will be procured to the required thickness (i.e., 4 ply unidirectional).

(b) For both the aluminum and the boron-aluminum radiator panel, radiator tubes and the skin splice plates will be fluxless brazed into a subassembly.

(c) Spot welding will be employed for attaching one skin/tube subassembly to the structural frame. The other skin will be mechanically attached using blind fasteners.

(d) The boron-aluminum channel fabrication layup operation is similar to fiberglass laminates, thus the standards for fiberglass were used for estimating manhours.

(e) The drilling operation for boron-aluminum will be similar to that of titanium, therefore titanium standards were used for estimating these manhours.

(f) A detail estimate for fabricating the radiator panel with boron-aluminum skins and titanium frames was not made, however, a material cost delta was made.

(g) The costs presented herein reflect the fabrication of one double faced radiator panel similar to the configuration shown in Figure 5-1.

(h) Both panels are identical in configuration, however, the gages are different for the skins; i.e., the panels were not designed for either aluminum or boron-aluminum application.

5.1.3 <u>Material Requirements and Fabrication Sequence</u>

Figure 5-2 shows the structural frame for each of the panels. In addition, the frame is contoured to a 96 inch radius in one plane, thus requiring the frame fabricated from contoured parts. The splice plate channels shown in this figure are straight.

Figure 5-3 shows a cross section of the structural frame assembly for the boron-aluminum panel and Figure 5-4 shows the cross-section for the aluminum panel. It should be noted that the splice channels differ between those fabricated from aluminum and those fabricated from boron-aluminum. The boron-aluminum consists of a channel which is subsequently mechanically fastened by rivets to fabricated angle clip. These configurations are shown in Figure 5-5 and 5-6.

Table 5-1 shows a detail breakdown of the material required for each of the panels considered in this cost analysis and Table 5-2 shows the detail fabrication for each element as well as the subassembly operations.

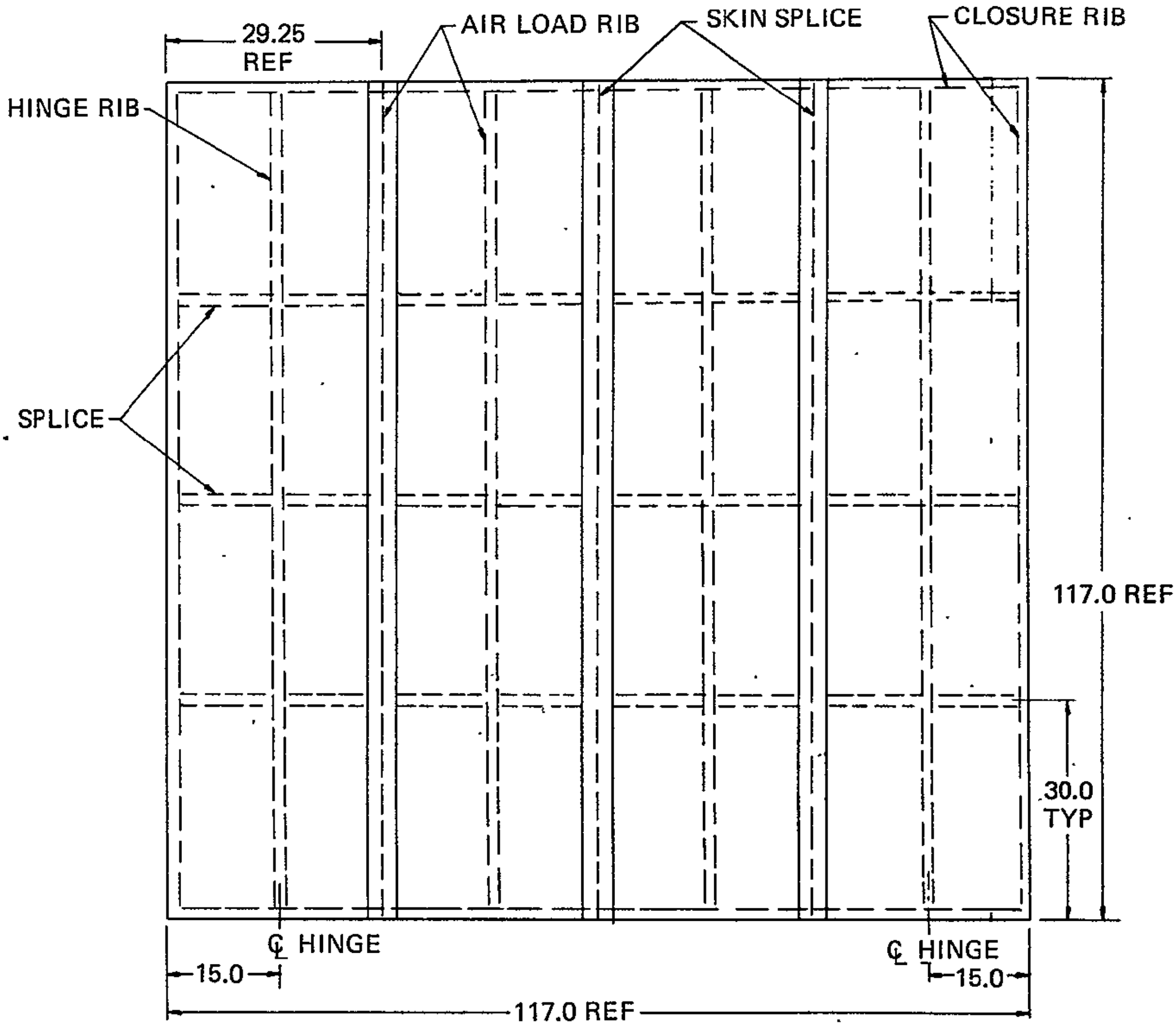


FIGURE 5–2 RADIATOR, SKIN, RIB, CLOSURE, SPLICE CONCEPT

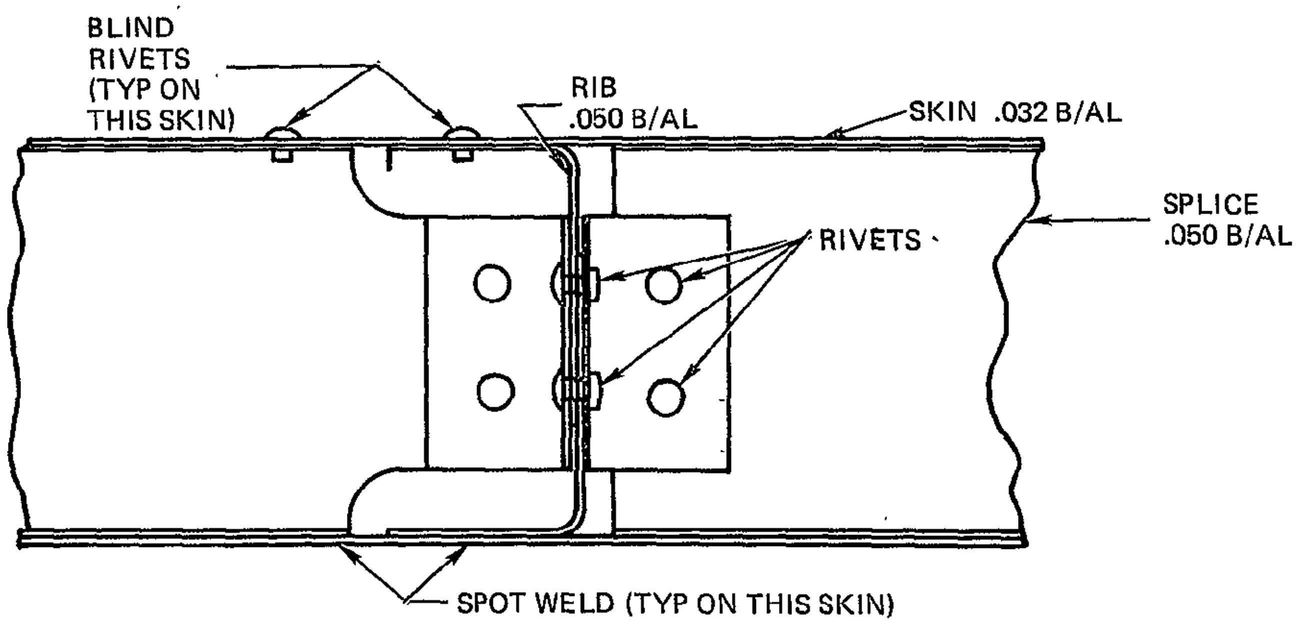


FIGURE 5–3 TYPICAL JOINT, BORON/ALUMINUM DUAL SIDE RADIATOR

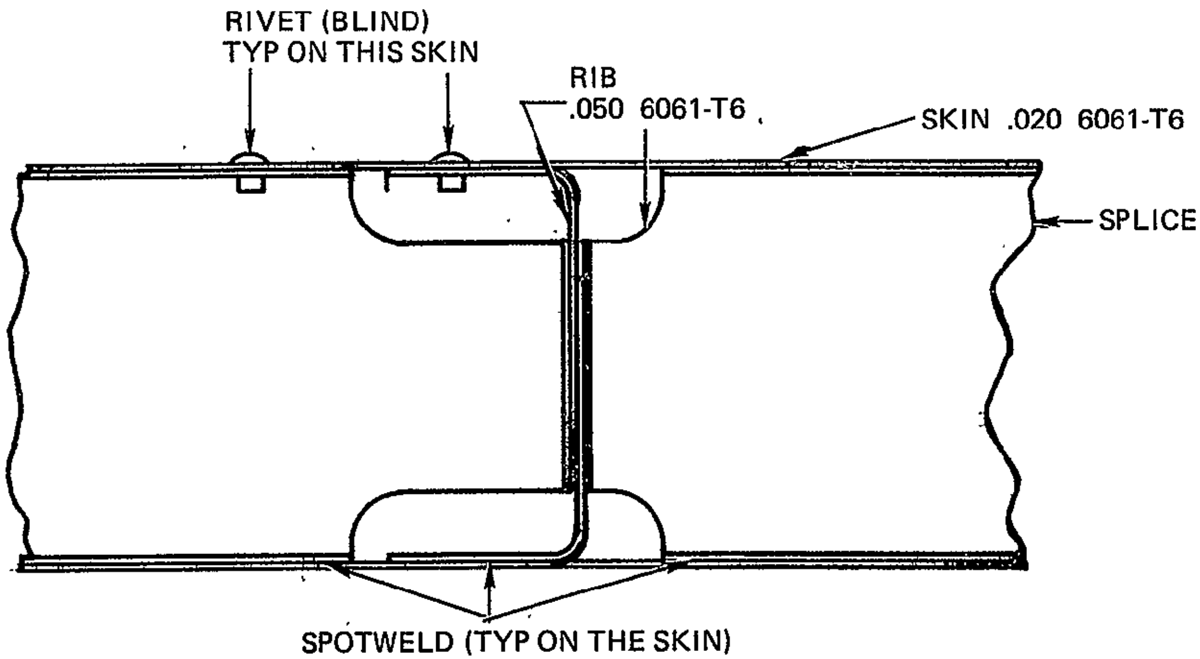


FIGURE 5–4 TYPICAL JOINT, ALUMINUM DUAL SIDE RADIATOR

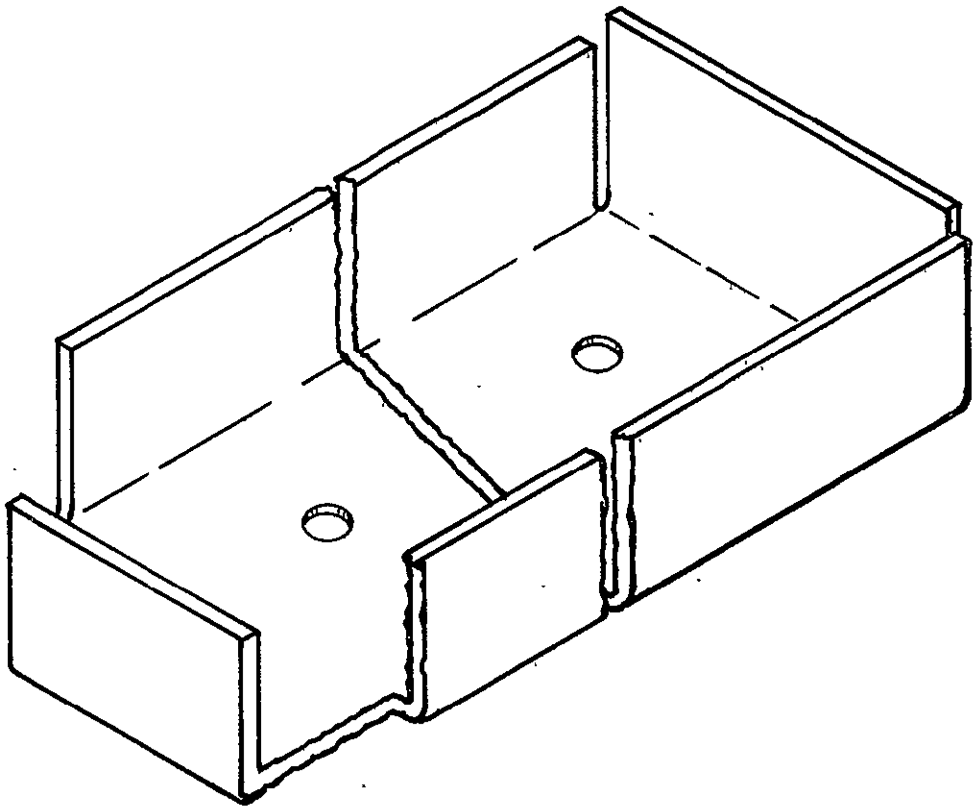


FIGURE 5–5 TYPICAL ALUMINUM RADIATOR SPLICE CHANNEL (LONGERONS)

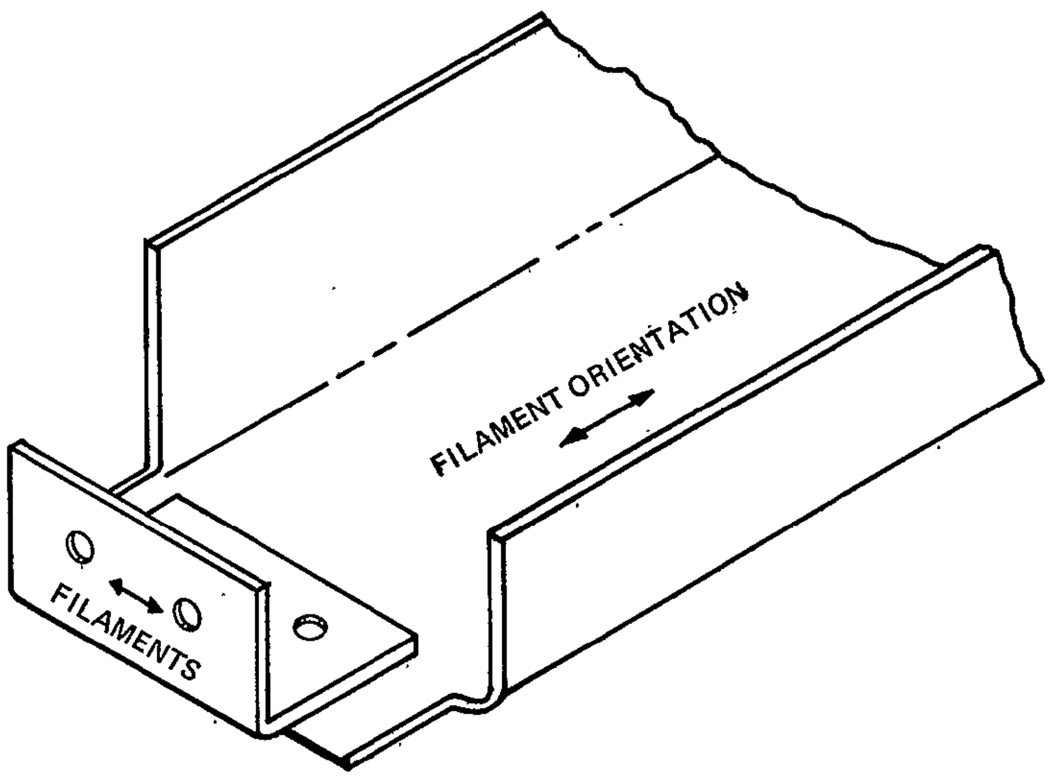


FIGURE 5–6 TYPICAL BORON/ALUMINUM RADIATOR SPLICE CHANNEL (LONGERONS)

TABLE 5-1 MATERIAL REQUIREMENTS

	Aluminum Radiator	Boron Aluminum Radiator
Skins (8 req'd) (Ea 29.25 x 117.0)	.020 thick 6061-T6 - Procure	.032 thick B/AL 4 ply (unidirectional) - Procure
Skin splice plates (6 req'd) (Ea 3.0" x 117.0")	.020 thick 6061-T6 - Procure	.032 thick B/AL 4 ply (unidirectional)
Ribs (channels 2.0" depth and 1.0" legs) length 117.0" (7 req'd)	.050 thick 6061-0 - Procure Mtl	.050 thick B/AL 6 ply (filaments in long dim.) - Procure .008 B/AL foil.
Splice (channels 2.0" depth and 1.0" legs) length 15.0" (24 req'd)	.050 thick 6061-0 - Procure Mtl	.050 thick B/AL 6 ply (filaments in long dim.) - Procure .008 B/AL foil.
Closure rib curved channel 2.0" depth and 1.0" legs 117.0" long (2 req'd)	.050 thick 6061-0 - Procure Mtl	.050 thick B/AL 6 ply (filaments in long dim.) - Procure .008 B/AL foil.
Closure rib straight channel 2.0" depth and 1.0" legs 117.0" long (2 req'd)	.050 thick 6061-T6 - Procure Mtl	.050 thick B/AL 6 ply (filaments in long dim.) - Procure .008 B/AL foil.
Clips angle 1.0" legs 2.0" long (18 req'd)	.050 thick 6061-T6 - Procure Mtl	.050 thick B/AL 6 ply (filaments in long dim.) - Procure .008 B/AL foil.
Inlet manifold tubing 5/8" dia (2 req'd) 120" long	6061-T6 - Procure Mtl	Same as for aluminum radiator

TABLE 5-1 (CONTINUED)

	Aluminum Radiator	Boron Aluminum Radiator
Return manifold tubing (2 req'd) 120" long	6061-T6 - Procure Mtl	Same as for aluminum radiator
Radiator tubing 1/8 dia	6061-0	Same as for aluminum radiator
Flow restrictor assy. (38 req'd)	6061-0 - Procure Mtl	Same as for aluminum radiator
713 brazing alloy	As required - Procure Mtl	As required - Procure Mtl

TABLE 5-2 DETAIL FABRICATION

	Aluminum Radiator	Boron Aluminum Radiator
Ribs (channels)(curved) (9 req'd)	Shear .050 AL sheet 4.5" strips x 144	Clean .008 B/AL foil strips
	Brake form channel	Clean 713 brazing alloy
	Stretch form to 96" R	Clean retort tooling
	Clean	Layup laminate (6 plies)
	Heat treat to -T6 condition	Diffusion Bond/Braze in autoclave
	Final trim and deburr Clean and anodize	Final trim and deburr Clean for subsequent operation
End closures (2 req'd)	Shear .050 AL sheet 4.5" strips x 144	Same as for B/AL curved rib channels (make 6 identical channels)
	Brake form channel	
	Final trim and deburr	
	Clean and anodize	
Splice channels (24 req'd for AL radiator)	Shear .050 AL sheet 6.5 x 20.0	M/F three end channel closures
	Route to req'd configuration	Trim to length
	Drill tooling holes (2/part)	Remove legs on one end to clear interface channel

TABLE 5-2 (CONTINUED

	Aluminum Radiator	Boron Aluminum Radiator
Splice channels (continued)	Form (Hydro Press)	
	Clean	
	Heat treat to -T6 condition	
	Final trim and deburr	
	Clean and anodize	
Clips (18 req'd)	Blank .050 AL sheet 1.75" x 2.25"	M/F one end channel closure (45 req'd)
	Brake form (90°)	Cut to length 1.75"
	Deburr	Cut channel to make 2 angles
	Clean and anodize	Final trim and deburr
Inlet manifold (5/8 AL tubing) (2 req'd)	Cut to length	Same as for aluminum radiator
	Drill holes for restrictor assy. Install tube end fittings. Clean.	

TABLE 5-2 (CONTINUED)

	Aluminum Radiator	Boron Aluminum Radiator
Return manifold (5/8 AL tubing) (2 req'd)	Cut to length Drill holes for radiator tubes. Install tube end fittings. Clean	Same as for aluminum radiator
Restrictor assy. (40 req'd)	Fab orifice details and body	Same as for aluminum radiator
SKIN/RADIATOR TUBE SUBASSEMBLY		Boron Aluminum Panel
Details		
Skins (8 pieces)	Shear 29.25 x 117.00	Cut 29.25 x 117.0
Skin splice plates (6 req'd)	Shear 3.0 x 117.0	Cut 3.0 x 117.0
Radiator Tubing	Form per dwg.	Form per drawing

TABLE 5-2 (CONTINUED)

	Aluminum Radiator	Boron Aluminum Panel
Assy (Brazing/Diffusion Bonding)		
Clean Skin, Tubing, splice plate and brazing alloy	Degrease, caustic etch, acid clean. Coat with styrene disolved in solution.	Same as aluminum radiator.
Clean tooling	Degrease and coat with stop-off material	Same as aluminum radiator
Lay up operation	Lay up on tooling in retort half (braze alloy at interfaces) on lower half of heating platen	Same as aluminum radiator
Seal Retort attach thermocouples.	Fusion weld retort and check for leaks (vacuum leak check)	Same as aluminum radiator
Transfer to brazing area and prepare for brazing.	Hook up electrical elements thermocouples and vacuum pump and final leak check. Lower upper heating die over retort, allow clearance between upper die and retort.	Same as aluminum radiator
Brazing operation	Heat part to 850°F. Purge retort with nitrogen. Pull full vacuum (28" HG) and heat to 1075°F ± 10°F. Hold at temperature for 10 minutes, cool to 940-950°F, hold for 3 hrs; cool to room temperature.	Same as aluminum radiator

TABLE 5-2 (CONTINUED)

	Aluminum Radiator	Boron-Aluminum Panel
Assy (Brazing/Diffusion Bonding) (Continued)		
Remove from retort	Open retort, remove tooling and brazed assembly.	Same as aluminum radiator
Clean for subsequent operation	Degrease, caustic etch, acid clean	Same as aluminum radiator
RADIATOR FRAME ASSY		Boron Aluminum Radiator
Frame Assy		
Locate Ribs	Use assy fixture	Same as aluminum radiator
Locate edge closeouts	Use assy fixture	Same as aluminum radiator
Locate splice frames and clips	Use assy fixture	Same as aluminum radiator
Drill (3/16) rivet attach holes (180 holes)	Use assy fixture	(Drilling holes higher for B/AL)
Deburr holes	Use assy fixture	Same as aluminum radiator
Rivet (180 rivets)	Use assy fixture	Same as aluminum radiator
Inspect	Use assy fixture	Same as aluminum radiator

TABLE 5-2 (CONTINUED)

	Aluminum Radiator	Boron-Aluminum Radiator
Frame Assy (Continued)		
Remove from fixture	Use transportation dolly and handling fixture.	Same as aluminum radiator
Clean for subsequent operation	Use transportation dolly and handling fixture.	Same as aluminum radiator
FINAL ASSEMBLY		
Inner skin to frame assy	Clamp skin/tube assy to frame assy (use weld fixture)	Same as for aluminum radiator
	Spot weld skin to frame (sequence welding from center of panel to edges) (approx. 850 spots)	
Outer skin to frame assy	Pilot drill skin panel (use drill template)(approx. 850 holes)	(Drilling holes higher for B/AL)
	Locate skin panel on frame assy (assy fixture)	
	Drill .188 dia. holes (skin and channel legs)	
	Disassemble, deburr holes and remove chips	
	Reassemble skin to frame	
	Rivet skin to frame using blind rivets.	

TABLE 5-2 (CONTINUED)

	Aluminum Radiator	Boron-Aluminum Radiator
Manifold assemblies	Locate return manifold tubing.	Same as for aluminum radiator
	Fusion weld manifold supports	
	Fusion weld manifold ends	
	Inspect return manifold assy	
	Locate inlet manifold tubing	
	Fusion weld manifold supports and tube ends	
	Fusion weld restrictor body assy to manifold tube	
	Inspect inlet manifold assy	
Final Assembly	Locate return manifold assy	Same as for aluminum radiator
	Form radiator tubes to interface with manifold	
	Fusion weld radiator tubes to return manifold assy	
	Locate Inlet manifold assembly	

TABLE 5-2 (CONTINUED)

	Aluminum Radiator	Boron-Aluminum Radiator
Final Assembly (Continued)	Form radiator tubes to interface with manifold restrictor body	Same as for aluminum radiator
	Fusion weld tubes to restrictor body	
	Inspect fusion welds	
	Pressure check radiator	
	Conduct fluid flow tests and adjust restrictors to provide uniform flow throughout radiator system	
	Fusion weld pintal to restrictor body	
	Clean radiator panel	
	Paint with thermal control coating	
	Final inspection	

5.1.4 Material Costs

The material costs for each of the panel configurations is presented in Table 5-3 . As can be seen in this table, the boron-aluminum material cost is $78, 873. 80 as compared to $4, 536. 80 for the all aluminum panel. Also shown in this table is material costs for a panel fabricated with just boron-aluminum for skins but titanium for structural frames. If this combination was used the material cost could be reduced to approximately $60, 373. 00. It should be noted that if this configuration was employed the skins would be completely mechanically fastened together rather than spot-welding one skin to the structural frame.

Using these material costs and the estimated manhours required for detail fabrication, subassembly fabrication and final assembly, the total costs of each panel was developed which is shown in Table 5-4 . The aluminum radiator panel would cost approximately $32, 200. 00 and the boron-aluminum radiator panel would cost $115, 671. 80, which represents an increase of 3. 6 times when compared to that of aluminum. It should be noted that the manufacturing is only about one-third higher for the boron-aluminum radiator panel, which is primarily attributed to the additional effort associated with the fabrication of the channels and the drilling and trimming of the boron-aluminum material. The standards for titanium drilling were used for estimating this cost. Also shown in this table is the cost per square foot of panel radiating surface. ($160 for aluminum and $580 for boron-aluminum).

Table 5-5 presents the tooling costs for each radiator panel fabrication. Also specified in this table are the types of tooling costed and what they are used for. As shown in this table the tooling for the aluminum radiator panel is $35, 646. 30 and $54, 735. 50 for the boron-aluminum which represents a 54 percent increase. This is primarily attributed to the tooling for the boron-aluminum channel fabrication which required diffusion bonding in a retort to make the laminate.

The tool cost associated with the braze/diffusion bonding of tubes with electrically heated dies was not estimated since this cost could be common to both concepts.

TABLE 5-3 MATERIAL COST

	Aluminum Radiator Lbs	Aluminum Radiator Cost	Complete Boron Aluminum Radiator	Sq.Ft.	Cost	Boron Aluminum Skins and Titanium Frames	
Skins .020" x 36" x 120 (8)	69.12	127.87	.032 x 36 x 120 (8 x 4)	960	38,400.00	B/AL skins	38,400.00
Splice plates (6) .020 x 36 x 120 (1)	8.64	15.98	Included in skin mtls			Included in skin mtls	
Ribs (9) .050 x 36 x 144 (2)	51.84	95.90	.008 x 5.0 x 120 (54)	225	9,000.00	.050 6AL4V Ti (83.0 lbs)	996.00
Closure (2) .050 x 36 x 120 (1)	21.60	39.96	.008 x 5.0 x 120 (12)	50	2,000.00	.050 6AL4V Ti (35.0 lbs)	420.00
Splice channels (24) .050 x 36 x 120 (1)	21.60	39.96	.008 x 5.0 x 120 (24)	100	4,000.00	.050 6AL4V Ti	420.00
Tubing (Radiator tube) 850 ft	--	2,550.00	Same as aluminum radiator		2,550.00	Same as AL radiator	2,550.00
Tubing (Manifold) 45 ft.		135.00	Same as aluminum radiator		135.00	Same as AL radiator	135.00
Bar Stock 2" x 2" x '60"	64.00	118.40	Same as aluminum radiator		118.40	Same as AL radiator	118.40
Brazing alloy	5.00	17.50	Same as aluminum radiator .001 x 5.0 x 120 (75)		17.50 17.50	Same as AL radiator	17.50
Misc Parts		100.00	Same as aluminum radiator		100.00	Same as AL radiator	100.00
Total		3,240.50			56,338.40		43,156.90
Mtl Bur G & A @ 40%		1,296.22			22,535.40		17,262.80
Total Mtl Cost/Panel		4,536.80			78,873.80		60,419.80

TABLE 5-4

PANEL COST

	Aluminum Radiator Cost	Boron-Aluminum Radiator Cost	
Materials	$4,536.80	$78,873.80	17.4 x Al
Manufacturing			
Detail Fabrication			
Shop and Quality Subtotal	9,521.10	15,496.00	
Sub Assembly Fabrication			
Shop and Quality Subtotal	8,103.00	9,249.60	
Final Assembly			
Shop and Quality Subtotal	10,020.90	12,052.40	
Total Manufacturing	27,645.00	36,798.00	1.33 x Al
Total Cost (Materials + Manufacturing)	$32,181.80	$115,671.80	
	$160.91/sq ft radiating surface	$578.36/sq ft radiating surface	3.6 x Al

TABLE 5-5 TOOLING COST

	Aluminum Radiator Cost		Boron-Aluminum Radiator Cost	
Tooling Materials	$5,490.00		$6,500.00	
Tool Fabrication				
Stretch Block (Channels)	850.50		-	
Blanking Die (Splice Channels)	388.80		-	
Locating & Holding Fixture (Manifolds)	486.00		486.00	
Detail Part Cleaning Fixture	486.00		486.00	
Brazing Fixture (Skin/Tube Assembly)	18,225.00		18,225.00	
Diffusion Bonding Fixtures (Channels)	-	Straight Channel or Curved Channel	18,103.50	
Cleaning Fixture (Skin/Tube Assembly)	486.00		486.00	
Slitter Cutting Fixture (Channels)	-		1,215.00	
Sub Assembly Fixture (Structural Frame)	3,645.00		3,645.00	
Transportation Dolly	729.00		729.00	
Spotweld Holding/Locating Fixture	3,645.00		3,645.00	
Drill Template (Skin/Frame)	1,215.00		1,215.00	
Subtotal Tool Fabrication	$30,156.30		$48,235.50	
Total Tooling	$35,646.30		$54,735.50	1.54 x Al

5.2 Design Studies

5.2.1 Test Panel Design

The initial effort consisted of accomplishing the preliminary design of an integral fuselage panel/radiator. Loads and temperatures representative of a section of a space shuttle fuselage panel were obtained and the sizing was completed. The resulting structural radiator panel was not efficient because of the low shear strength inherent in filamentary composites.

As the shuttle design concept evolved it became apparent that the shuttle wing planform combined with the open cargo door operation precluded that all of the radiator modules being structurally integrated into the fuselage. This indicated that, (1) the radiator should be attached to the inside of a conventional door, or (2) the entire door should be of boron-aluminum with an integral radiator. The first option offers no direct advantage for boron-aluminum because the radiator would be possibly heavier than an aluminum radiator and the high temperature capability would be of no apparent value since the radiator would be protected from the elevated temperatures of exit and entry flight through the atmosphere. The second option, having a boron-aluminum cargo bay door with an integral radiator, appeared more attractive because it could allow removal of the external thermal protection system currently considered for an aluminum door and utilize the high temperature capability of the boron-aluminum for a lighter overall design.

A proposed design for a Phase B baseline cargo bay door was utilized to size a structurally equivalent door of boron-aluminum. Assuming that initially the shuttle doors would be aluminum, any constraints of that design which would affect the subsequent retrofit of a boron-aluminum door were considered.

The door design consisted of a door which was 120 inches long, with a shell radius of 95 inches and subtending approximately 90 degrees of arc. The support points were each end of two frames 20 inches in from each end. These main frames were called hinge frames and the smaller intermediate stiffening frames were called airload frames. The loading conditions which were considered for design consisted of a symmetrical 1.5 psi burst pressure on the doors and an unsymmetrical 1.3 to 1.8 psi burst pressure. With the hinge frames remaining fixed, both 10 inch and 20 inch airload frame spacings were investigated. The thickness of the double walled skins were selected to prevent flutter problems with each frame spacing for the trajectory anticipated for shuttle launch. Three, four, five and six inch door thicknesses were investigated with the frames weight decreasing as height increased. See Figure 5-7 and Tables 5-6 and 5-7 for weight comparison of different door thicknesses and different frame spacings.

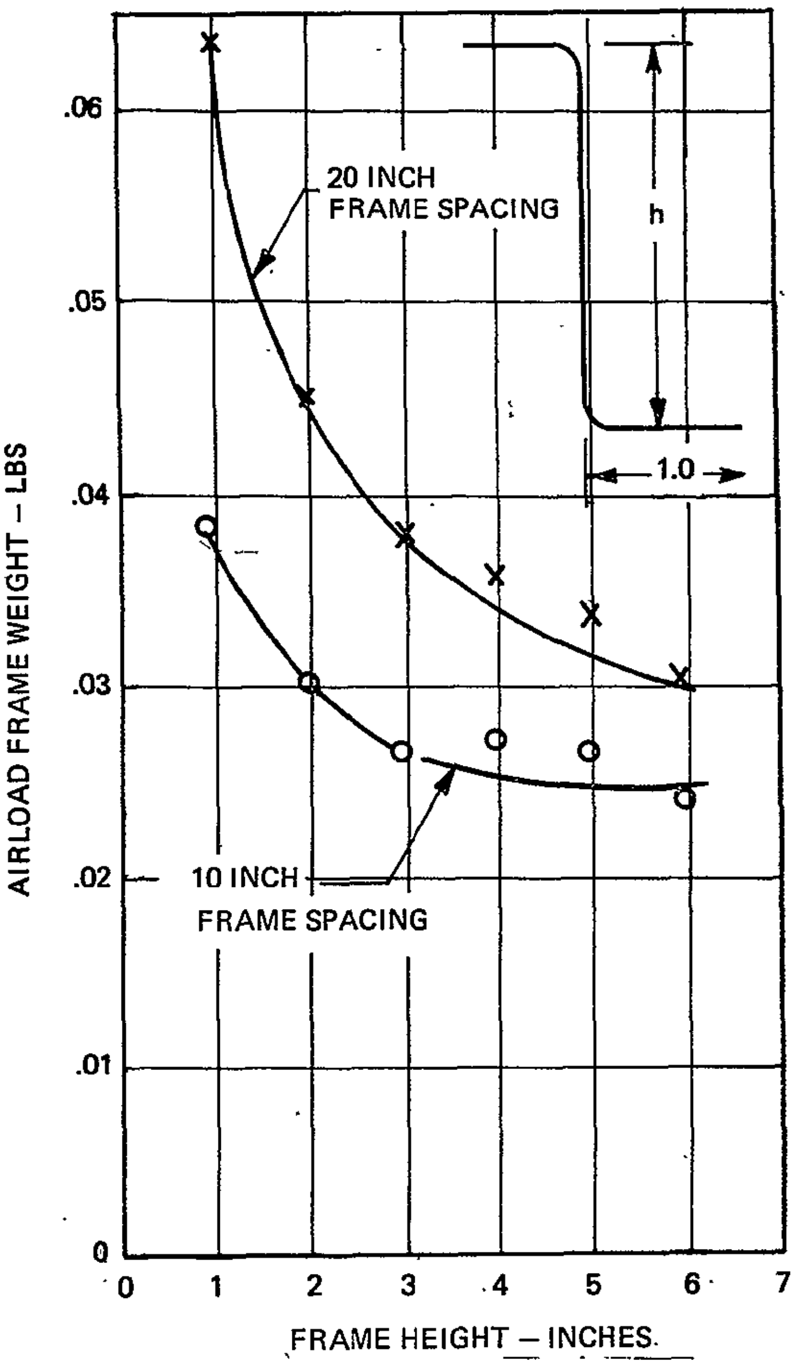


FIGURE 5–7 FRAME WEIGHT ANALYSIS

TABLE 5-6

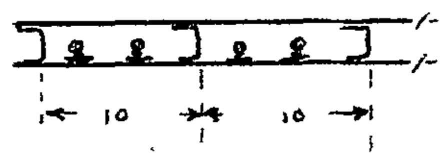
WEIGHT ESTIMATES FOR BORON-ALUMINUM
PANELS - 10 INCH FRAME SPACING

Panel	Material	Element	No. of Elements	Material Thickness (inches)	Weight (lbs)	Panel Weight (lbs)
2	B/Al	Hinge Frame	2	0.195	24.542	171.99
	Al	Tube	24	-	22.464	
	B/Al	Air Load Frame	13	0.075	42.904	
	B/Al	Skin	2	0.030	82.08	
3	B/Al	Hinge Frame	2	0.135	20.438	163.416
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.0525	28.510	
	B/Al	Skin	2	0.045		
4	B/Al	Hinge Frame	2	0.0975	17.150	160.775
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.045	25.568	
	B/Al	Skin	2	0.045	123.120	
5	B/Al	Hinge Frame	2	0.0825	16.450	159.105
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.0375	26.439	
	B/Al	Skin	2	0.045	123.120	
6	B/Al	Hinge Frame	2	0.0675	15.090	154.669
	Al	Tube	24	-		
	B/Al	Air Load Frame	13	0.030	35.035	
	B/Al	Skin	2	0.030		

Notes: (1) ρ of B/Al = 0.095 pounds per cubic inch.

(2) Weight of Al = 0.0078 pounds per linear inch.

(3) Panel dimensions: 120 x 120 inches.



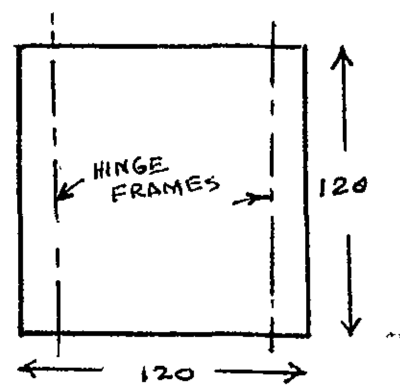


TABLE 5-7

WEIGHT ESTIMATES FOR BORON-ALUMINUM PANELS - 20 INCH FRAME SPACING

Panel	Material	Element	No. of Elements	Material Thickness (inches)	Weight (lbs)	Panel Weight (lbs)
2	B/Al	Hinge Frame	2	0.195	24.542	199.
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.075	35.070	
	B/Al	Skin	2	0.045	123.120	
3	B/Al	Hinge Frame	2	0.135	20.438	189.
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.0525	28.510	
	B/Al	Skin	2	0.045	123.120	
4	B/Al	Hinge Frame	2	0.0975	17.150	183.
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.045	25.568	
	B/Al	Skin	2	0.045	123.120	
5	B/Al	Hinge Frame	2	0.0825	16.450	183.
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.0375	26.439	
	B/Al	Skin	2	0.045	123.120	
6	B/Al	Hinge Frame	2	0.0675	15.044	179.
	Al	Tube	18	-	16.848	
	B/Al	Air Load Frame	7	0.030	23.581	
	B/Al	Skin	2	0.045	123.120	

Notes: (1) ρ of B/Al = 0.095 pounds/in^3.

(2) Al = 0.0078 pounds/in.

(3) Panel dimensions: 120 x 120 inches.

5.3 Panel Sizing

Early stages of the design effort concentrated on quickly establishing the configuration of a 4 square foot radiator panel. The autoclave size, its associated tooling, heater configuration and boron-aluminum material procurement depended on an early decision on the dimensions of the panel including the number of plies and orientation of the filament and the size and type of frames. The design concept assumed a structural panel capable of carrying the cargo bay (P/L) door loads defined by Phase B Shuttle studies. The 1 by 4 foot panel shown in Figure 5-8 was designed based on this criteria. Subsequent reviews of progress in Phase C-D studies altered many of the early concepts so a continuing follow-up was established to permit seeking out opportunities to utilize the boron-aluminum composite as new concepts evolved. In broad terms, the following concepts set forth had a definite impact on the design of boron-aluminum radiator:

(1) Affixed to the inside of P/L Doors.

(2) Affixed to the outside of P/L Doors.

(3) Separately actuated, two sided units inside the doors, capable of remaining over the P/L if desired.

(4) Mounted aft of the P/L doors over the ABES compartment and/or forward sides of the fuselage and fin areas.

During Phase B studies the use of a high conductivity metal which could also withstand the maximum equilibrium temperatures was considered. The Phase B studies revealed some inconsistencies as indicated by the cross-over of isometric lines. However, the reentry profile had not been precisely defined at the time this report was prepared so an arbitrary temperature excursion was selected for test purposes. (5 minutes to 800^{o}F in center of panel, hold 1 minute at 800^{o}F, cool for a total cycle of 30 minutes.)

Studies over the past years at VMSC have followed a changing pattern as Shuttle concepts evolved. Space radiators occupy a significant area of a vehicle, and are needed only during orbital flight and are oriented for effective heat rejection.

The thermal performance of the radiator is dependent on the flow passage orientation and spacing between flow passages. The spacing is dependent on conductivity parallel to the surface between the passages. However, it was essential to examine the structural property interaction with thermal properties relative to selection of the fin material in the radiator.

It was obvious that conventional high conductance materials such as aluminum would not be suitable in the environment. Beryllium or beryllium aluminum alloys may be candidates but availability in large sizes is a problem and piecing together many small panels seemed an undesirable approach. The progress of reinforced aluminum programs was encouraging, which showed boron-aluminum to have the necessary high temperature strength and could have acceptably high thermal conductivity as well. Both the high conductivity properties and retention of elevated temperature strength properties have been firmly established. VMSC (reference 1) measured conductivity and verified properties at elevated temperatures (to 800°F) in the preceding phase of this program. Diffusion bonded tape data of any kind was sparse and no useful conductivity data existed. Thermal conductivity from -200 to +300°F was determined in two directions (0° and 90°) parallel to the surface of unidirectional and cross-ply bonded tape. Results showed the anisotropic characteristics of the property, varying from 45 to 75 BTU/HR FT °F depending on the filament orientation. Choice of radiator design was constrained by not only the thermal characteristics of the material but upon structural strength. Numerous concepts were examined which varied from very lightly loaded assemblies studied in Phase B concepts where the radiators were attached to structural payload doors to fully loaded fuselage panels. Most of the effort was limited to the door area where the lower air load levels would be experienced.

Radiator panel studies associated with Shuttle Phase B revealed a wide choice in concepts primarily in methods of deployment and deployment mechanisms. No Phase B contractor baselined externally mounted radiators. This study did examine problems of external modules, but an attempt made to utilize boron-aluminum to withstand primary fuselage loads was not pursued beyond a superficial look. The radiator concepts were for structurally isolated panels and would carry air loads and hinge loads where carry-through to the fuselage would be floating pin joints. Conceptual designs were drawn to mount (1) externally in the P/L door area, (2) inside but hinged to be separable from the P/L door, and (3) inside and affixed to the P/L and

ABES doors. Weight analyses were conducted to assess the affected area including (1) an all-aluminum door and radiator unit protected with 15 pound/cubic foot ablative coating 0.5 inch (ave.) thick, (2) an all-titanium door and aluminum radiator with no external insulation, and (3) a boron-aluminum/titanium radiator assembly. Table 5-8 summarizes the weight analyses where boron-aluminum panel skins attached to titanium structural frames which were substituted for boron-aluminum frames. There was no significant difference in weight compared with an all boron-aluminum panel. It should be noted in the table that the dominating weight consists of skin material.

TABLE 5-8

WEIGHT

TITANIUM AND BORON ALUMINUM PANEL DESIGN

Part	Calculation	t	Material	Weight
Outer Skin	.0278 x 7.5 x .098 x 116.4 x 164	.0417	B/Al	78.00
Inner Skin	.0278 x 1.5 x .098 x 116.4 x 153.4	.0417	B/Al	72.50
Seal	Same as T187L000001		Sil.Phen.	4.72
Edge Closeout	.025 x 2.5 x 116.4 x .167	.025	Titanium	1.214
Frame Stub (9)	Same as T187L000001 (Matl Chg)	.025	Titanium	.20
Longeron-Lower	.040 x 7.3 x 116.4 x .167	.040	Titanium	5.67
Clip-Airload Frame (6)	.040 x 2.12 x 3.1 x .167	.040	Titanium	.53
Frame Airload (3)	Matl Chg	.030	Titanium	19.40
Upper Hinge Half (4)				7.36
Bolt Assy (2)				.46
Hinge Frame (2)	Matl Chg	.040	Titanium	24.3
Doubler-H.F. (4)	.0973 x .098 x 2.0 x 160	.0973	B/L	12.00
Doubler-A.L.F. (6)	.0417 x .098 x 2.0 x 153.4	.0417	B/Al	7.50
<u>Splices</u>:				
H.F. (2)	.040 x 5.0 x 24.00 x .167		Ti	1.60
A/L Frame (3)	.030 x 5.0 x 24.00 x .167		Ti	1.80
Closeout Frame (2)	.029 x 5.0 x 24.00 x .167		Ti	1.00
Intercostal	Mtl Chg	.020	Ti	1.87
Longeron-Upper	Mtl Chg	.025	Ti	2.63
Breather Fwd	.051 x 4 x 164 x .167	.051	Ti	5.57
Breather Aft	.051 x 4 x 164 x .167	.051	Ti	5.57
Seal & Bond	Same			1.06
Fasteners	Same			10.00
Hinge Frame Clip	.040 x 2.0 x 4.70 x .167 (2)			.13
				265.08
Paint				5.08
				270.16

6.0 DISCUSSION OF RESULTS

This section covers the results of the boron-aluminum materials testing, processing, design and cost activities during the contractual period. The tests and studies were conducted specifically for application of the advanced composite in space shuttle radiators. Three principle categories of interrelated data were required to demonstrate effective use of the material; (1) boron-aluminum qualities and consistency, (2) processing procedures for fabricating component parts from the material and (3) shuttle design requirements for radiators.

6.1 Materials

Consistency of boron-aluminum tape material (single layer of filaments bonded into the matrix) was of primary concern at the outset of the program. This, because the final product, which must be of fully predictable quality, could not be realized unless the tape was consistent. Minimum tensile strength was obtained in the tape, however, the wide range of properties (160 to 200,000 psi) was indicative of an undesirable lack of consistency. A range of 180,000 to 200,000 psi had been anticipated. Minimum properties (155,000) were being met by Amercom and the material was used throughout the program but the wide range emphasizes the need for further improvement n material. The limited evaluations failed to assess the reason for the inconsistency. Metallurgical and non-destructive inspection indicated good quality material, well consolidated with well spaced and aligned filaments. Quality of the filaments appeared to be good but a full assessment of filament properties was not in scope. Appendix I presents the specification for procured material.

6.2 Processing

Processing, based on the methods established in prior work (reference 1) resulted in a procedure presented in Appendix II, Boron-Aluminum Bonding, Process Specification for. The procedure was the product of process variable studies where flexural test coupon properties were related to time-temperature optimization runs. Results were indicative of a range where good bonding could be predicted, however, inconsistencies were noted during this experimentation which were considered related more to the basic material inconsistancies noted in 6.1 than to the process parameter being evaluated. A general examination, including visual and metallographic was quite informative relative to the adequacy of the process. Having established reasonable process parameters, the final task of scaling up tooling to a 1 x 4 foot panel was much more complex. The results of this effort demonstrated that the bonding temperature uniformity over the parts was more critical relative to maintaining straightness than to proper bonds. The prior work with small panels could not explor this aspect. One 48 inch long "C" frame which experienced a large (over 70^{o}F) thermal gradient from mid-length to both ends was severely buckled in the middle and was not bonded at the ends. It was apparent that expansion and contraction through the process temperature range produced the buckling loads.

6.3 Design

Metal matrix composite systems, previously screened in the program reported in Reference (1), resulted in selection of boron-aluminum for this study. The design objective of this program was to incorporate the boron-aluminum in a test panel representative of a possible modular radiator that could be used on the Space Shuttle. The studies were concerned with determining the applicability and effectiveness of the material in a structure characteristic of that required to carry loads transmitted through a door-like component, not primary airframe loads. The unique material properties which characterize boron-aluminum strongly influenced the design include anisotropic behavior. In such large, light panels deflection becomes critical and anisotropic buckling of primary concern. Although primary fuselage loads were not considered as applicable to radiators, local air loads, engine acoustics and boundary layer conditions were assessed. From the above preliminary design effort the one foot by four foot test panel shown in Figure 5-8, representative of a full module design, was selected. The curvature was eliminated for simplicity and frame height was decreased to two inches for economy of material. Ten inch frame spacing was selected and two radiator tubes spaced at five inches were diffusion bonded to the inside of one skin. End stiffeners, while not part of the door design, were added to simulate the continuity inherent in a continuous door. The stiffeners were channel sections of unidirectional filament orientation of .045 inch thickness (six plies) and the skins were .030 inch thick 0° - 90° cross plied skins. The design allowables in Table 6-1 were selected early in this phase and were based on conservative evaluations of data reported in the literature. Subsequent testing in tension and flexure resulted in strength values in excess of those assumed for preliminary design. The test panel was designed within the constraints of the frame-skin size trades, but with assumptions that the thinner material would uncover the more serious problems in fabrication while incurring lower costs. Skin thicknesses of 0.030 and 0.045 inches had been evaluated in these studies. The panel size was nominally 12 x 48 x 2 inches, sufficiently large to effect an assessment of processing temperature and pressure effects over large surface areas.

It was recognized that the structural effectiveness of the composite can best be realized when the high performance of the unidirectional material can be utilized. Crossplying for biaxial load capabilities decreases performance with tensile strength reduced by nearly 50%, but is necessary where the stresses are multidirectional. Joining of the frames to the skin included several possible methods required to assembly a full modular panel. It was considered likely that one surface (exterior) should be made smooth and although spot-welding would accomplish this, spotwelding may

TABLE 6-1

ASSUMED STRUCTURAL DESIGN ALLOWABLES

Material	Property KSI	Direction	Temperature RT	300	500	700
B/AL 50 v/0 U.D.	Ftu=Fcu	Long (0°) Trans (90°)	140 12	125 10	130 5	105 2
	Fsu		10	7	5	2
	Fte	Long (0°)	75			
	Et=Ec	Long (0°) Trans (90°)	32,000 18,000	31,000 10,000	28,000 5,000	24,000 4,000
	G		7,000	6,000	5,000	4,000
	(Dimension-less)	Long (0°) Trans (90°)	.28 .17			
B/AL 50 v/0 0.90 C.P.	Ftu=Fcu		70	60	55	50
	Fsu		13	10	7	5
	Et=Ec		17,000	16,000	15,000	13,000

not be possible over the total area so diffusion bonding may be appropriate. Riveting and bolted (channel nut) methods were determined to be acceptable for joining the frames to the skins, however, riveting was subsequently found to be a source of hole edge damage.

6.3.1 Cost

The recurring manufacturing and material cost for an aluminum radiator panel is approximately $32,200, whereas the cost for a similar panel fabricated from boron-aluminum is approximately $115,700. ($160/sq. ft. aluminum, $580/sq. ft. boron-aluminum radiating surface). The majority of this increased cost is directly attributed to the current high cost of the boron-aluminum composite material (i.e. $40.00 per square foot per ply. The material cost for fabricating the boron-aluminum panel is approximately 17.4 times the cost of the materials associated with the aluminum panel. The panel fabrication cost of the boron-aluminum panel is approximately 33% higher than the aluminum panel which is attributed to the fabrication of the channel laminates (basic structure) and the drilling and trimming operations which require special diamond tip cutters. Subsequent to the completion of cost analyses punched holes were found to be superior to drilled holes. Cost studies might show a cost savings. In the event that titanium was used for the channels, the boron-aluminum panel material cost could be reduced by approximately $18,500.00. This panel would then employ boron-aluminum for the radiator panel skins only. This concept represents minimum development risk since boron-aluminum laminates for skins are readily available and titanium sheet metal shaped formers have been in aircraft hardware for nearly 20 years. In addition, thermal isolation could be aided through use of the low conductivity titanium framing.

6.4 PANEL TEST RESULTS

Figures 6-1 through 6-12 present the total and selected thermal-deflection records processed during the tests with instrumentation as shown in Figures 4-12 and 4-13. The local deformation which occurred on the unsupported edge were mot pronounced in the first 10 cycles, thereafter becoming essentially stable. In a full panel design, interface structure would avoid such an unsupported edge. Slight dis-bonding at the extremities of the frame contributed to the magnitude of the deflection. In any case, the deformation would not degrade fit or function of the radiator.

Figure 6-1 shows measurements where maximum deflection probably occurred. They were measured optically rather than with the more precise deflectometers. The curve reflects a characteristic negative deflection on cool down below 450°F measured at the center of the panel face with a return to 0 deflection at the end of the cycle. The deflectometers also indicated this characteristic in the range of 400 to 600°F. Total temperature-deflection history shown in two parts for clearity in Figures 6-2 and 6-3 show that the measured points apparently deflected permanently as much as 0.250 inches in the first 10 cycles with little change occurring in subsequent cycles. It was noted that the panel corner at deflectometer number 24 had lifted from the supporting frame following the initial heating check cycle. This corner gradually lowered until it appeared to be resting again on the frame after the 9th or 10th cycle. This condition accounts for the apparent high deflection at positions 21, 22, 23 and 24. The twist in the panel was probably due to releaving residual stresses induced during assembly of the rather flexible component parts. Since there was no failure, a detailed analysis of deflection history was not further examined. For future designs, the data could be useful for dimensional tolerance information.

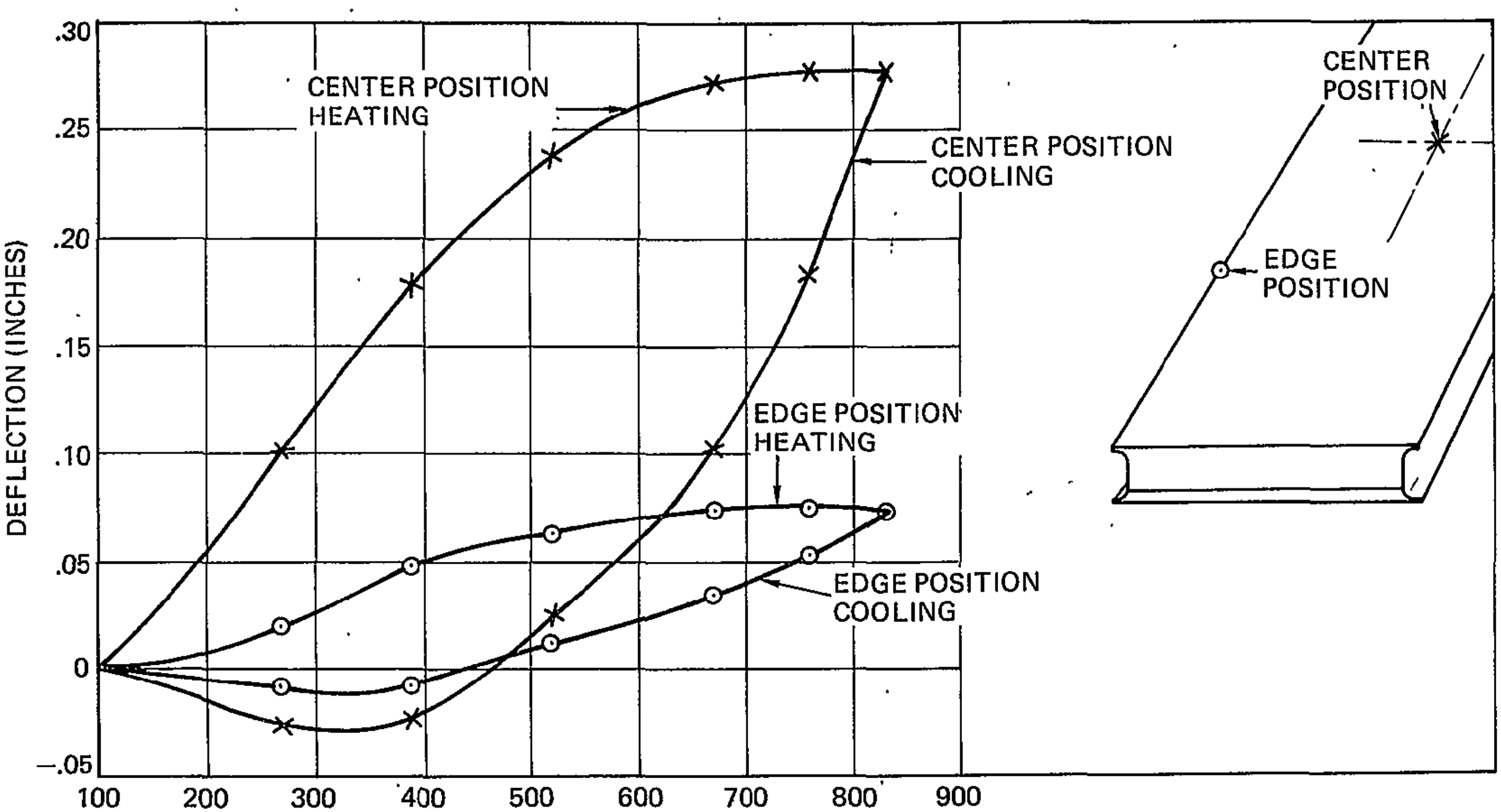


FIGURE 6–1 OPTICAL MEASUREMENT OF DEFLECTION

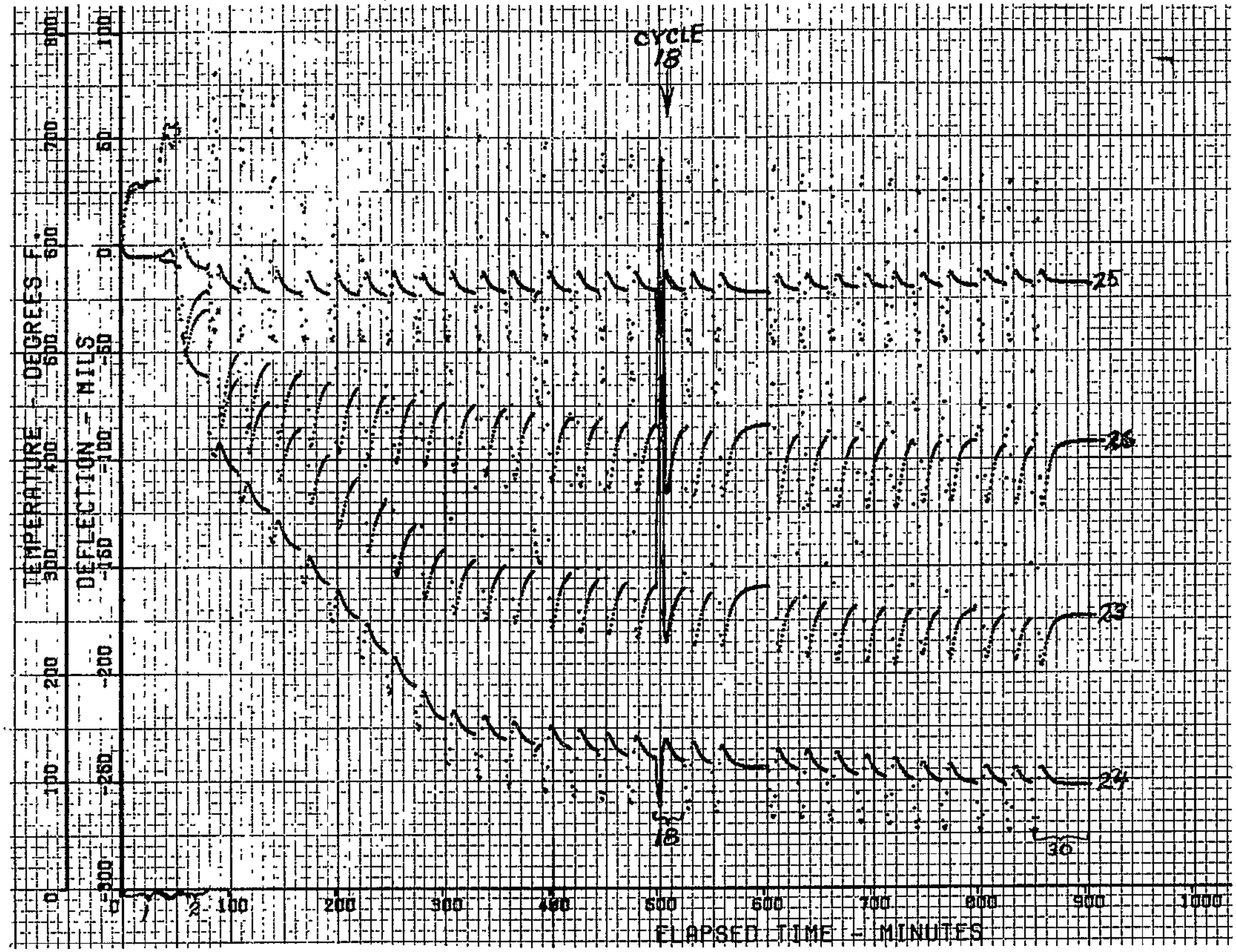


FIGURE 6–2 TOTAL TEMPERATURE-DEFLECTION HISTORY

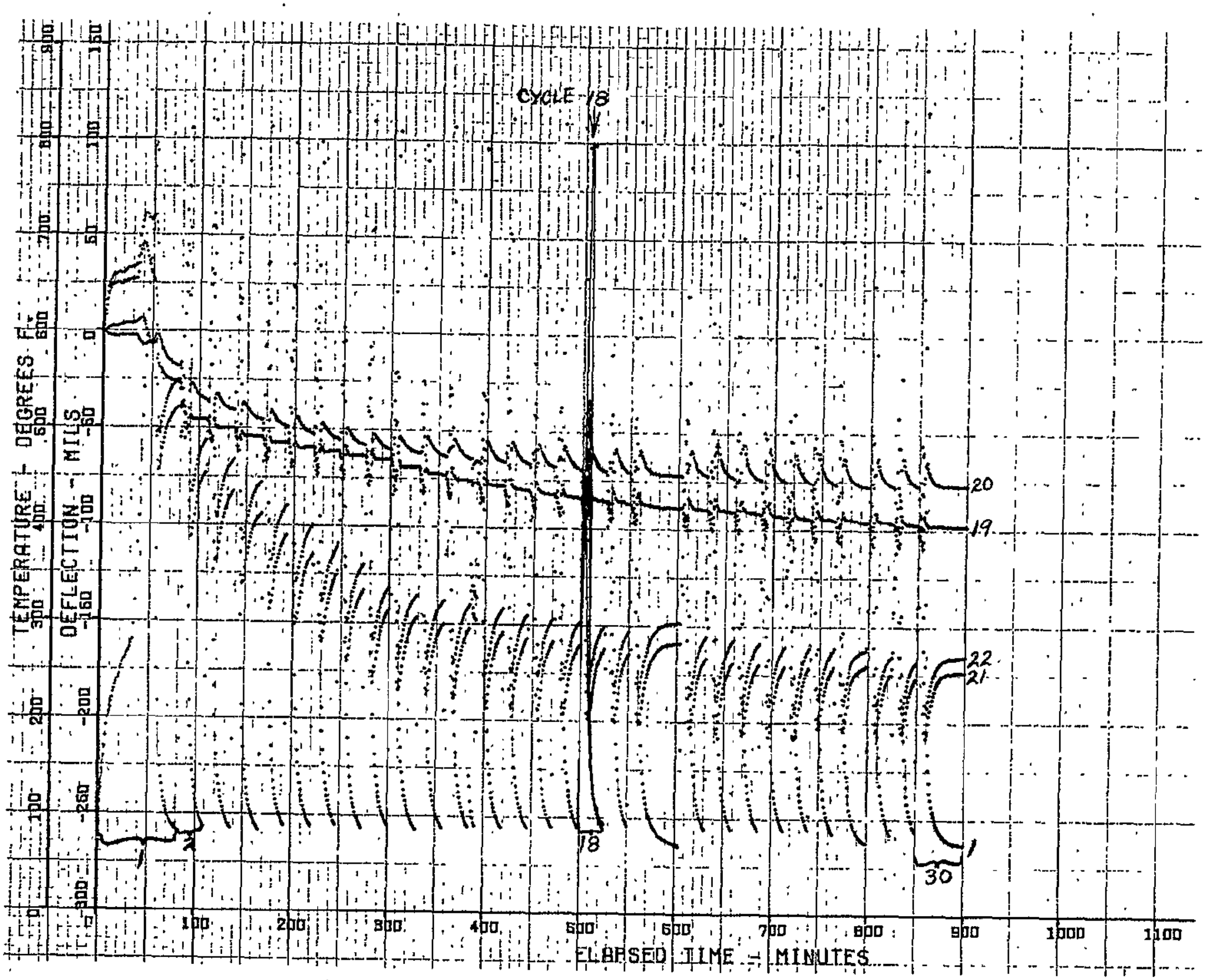


FIGURE 6–3 TOTAL TEMPERATURE-DEFLECTION HISTORY

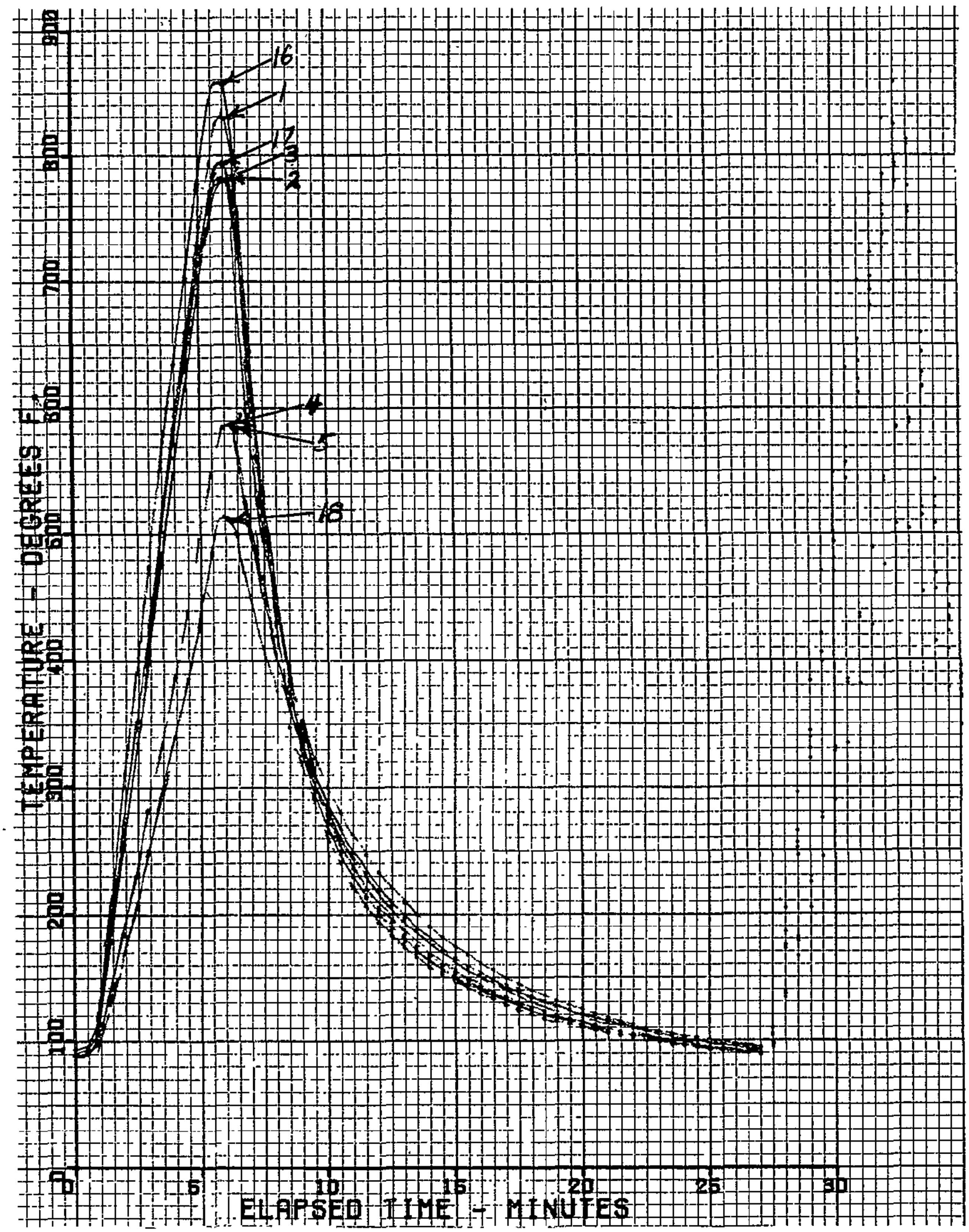


FIGURE 6–4 CYCLE 18 TEMPERATURE PROFILE (GROUP 1)

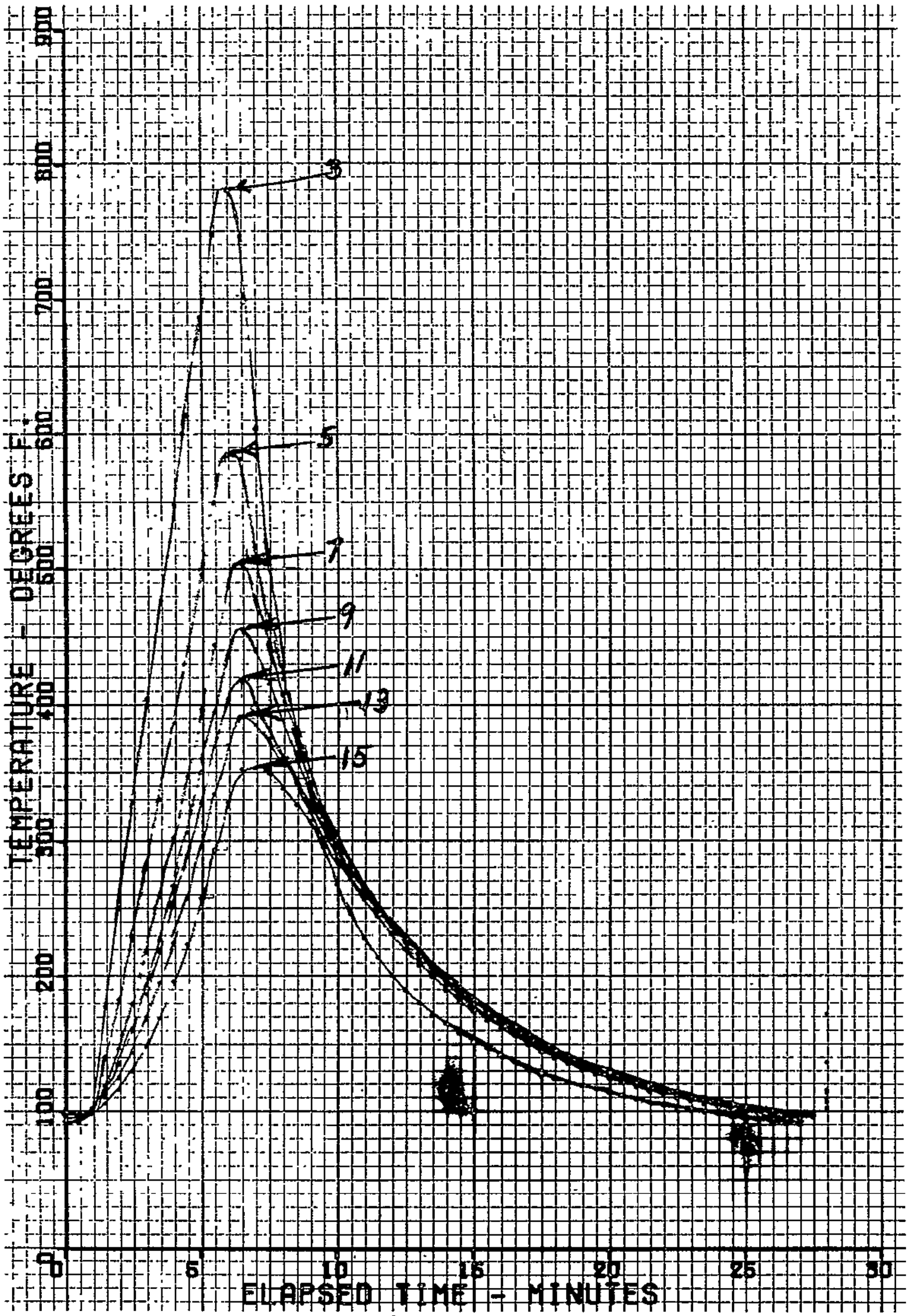


FIGURE 6–5 CYCLE 18 TEMPERATURE PROFILE (GROUP 2)

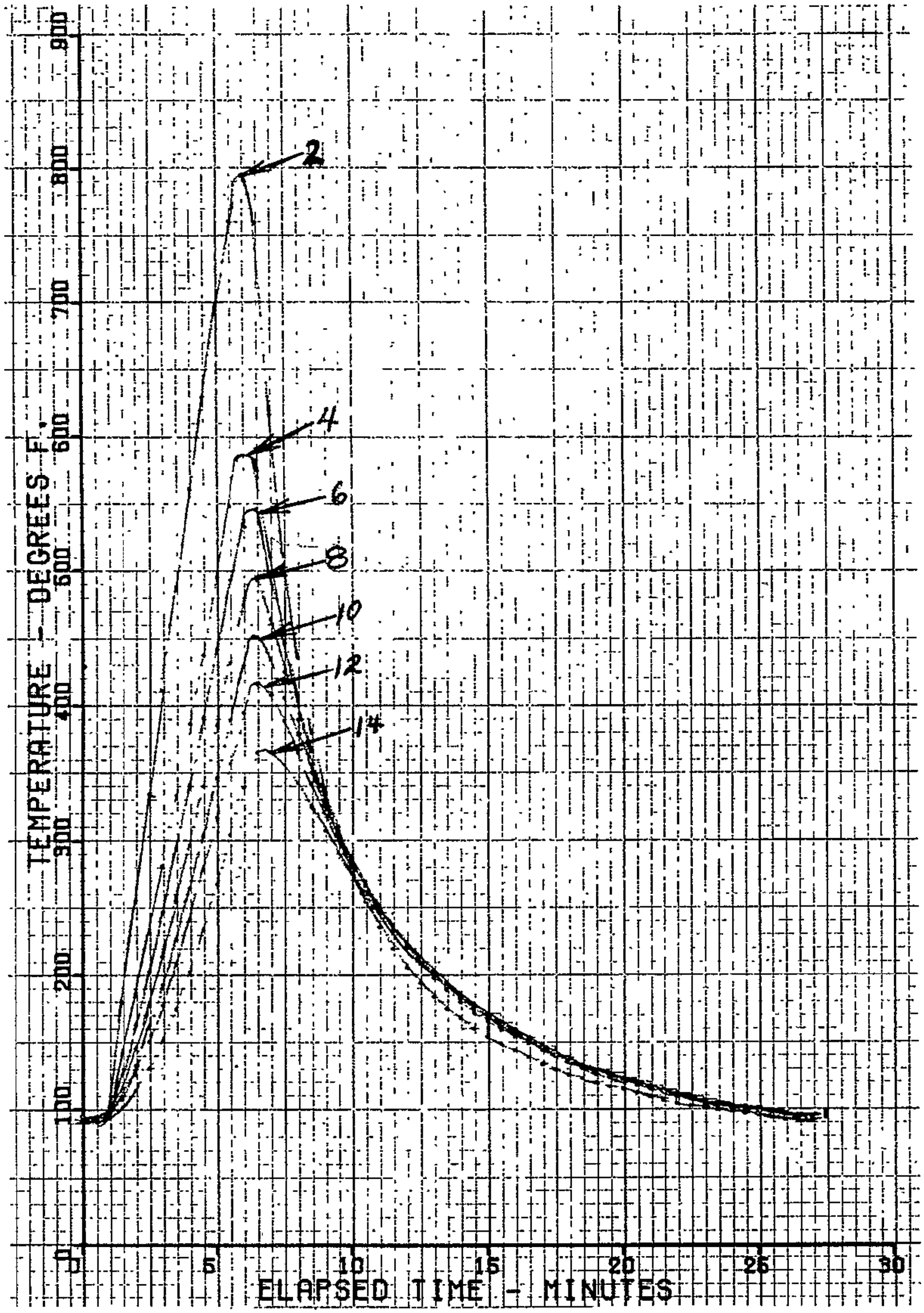


FIGURE 6–6 CYCLE 18 TEMPERATURE PROFILE (GROUP 3)

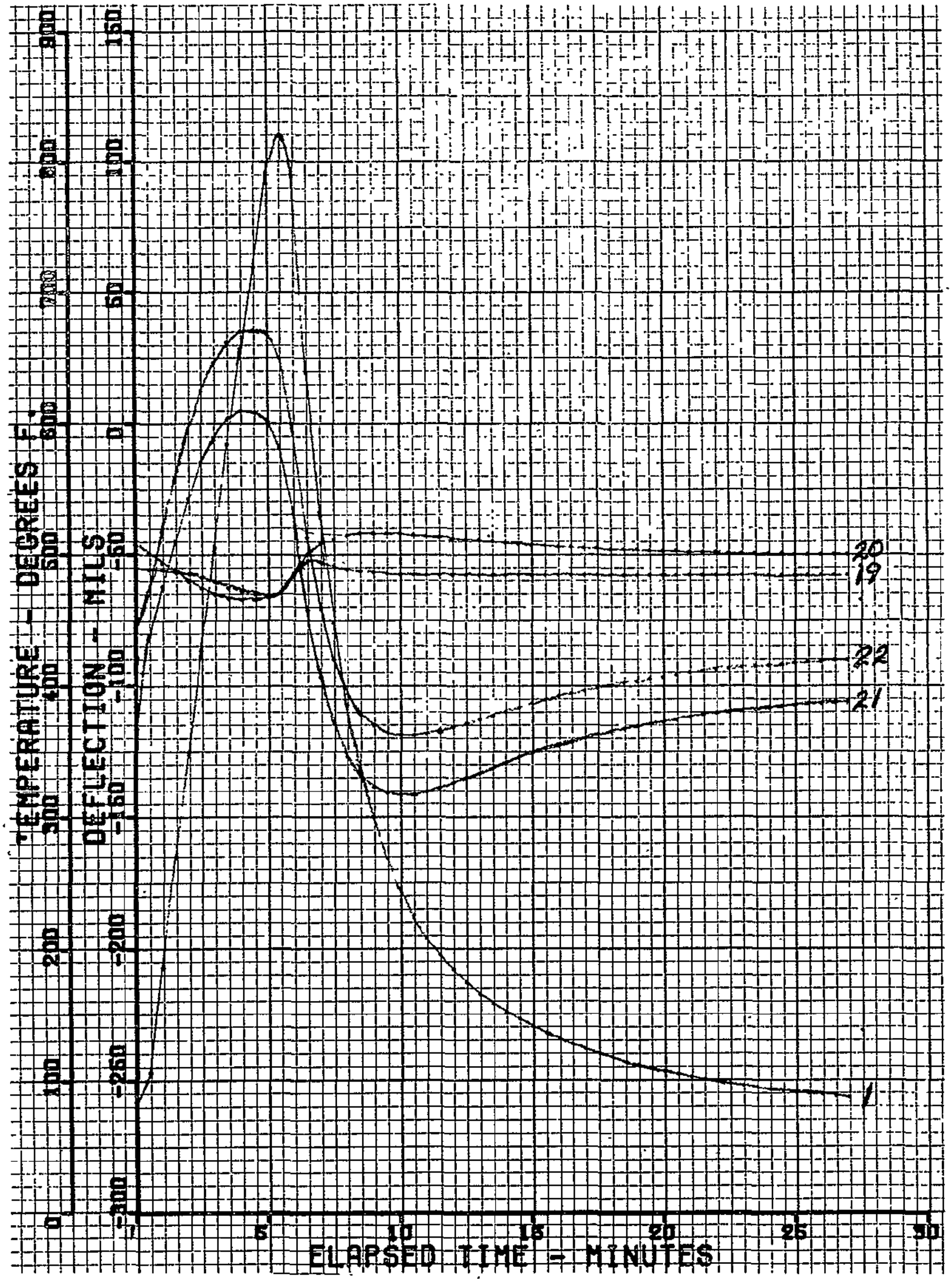


FIGURE 6–7 CYCLE 6 DEFORMATION

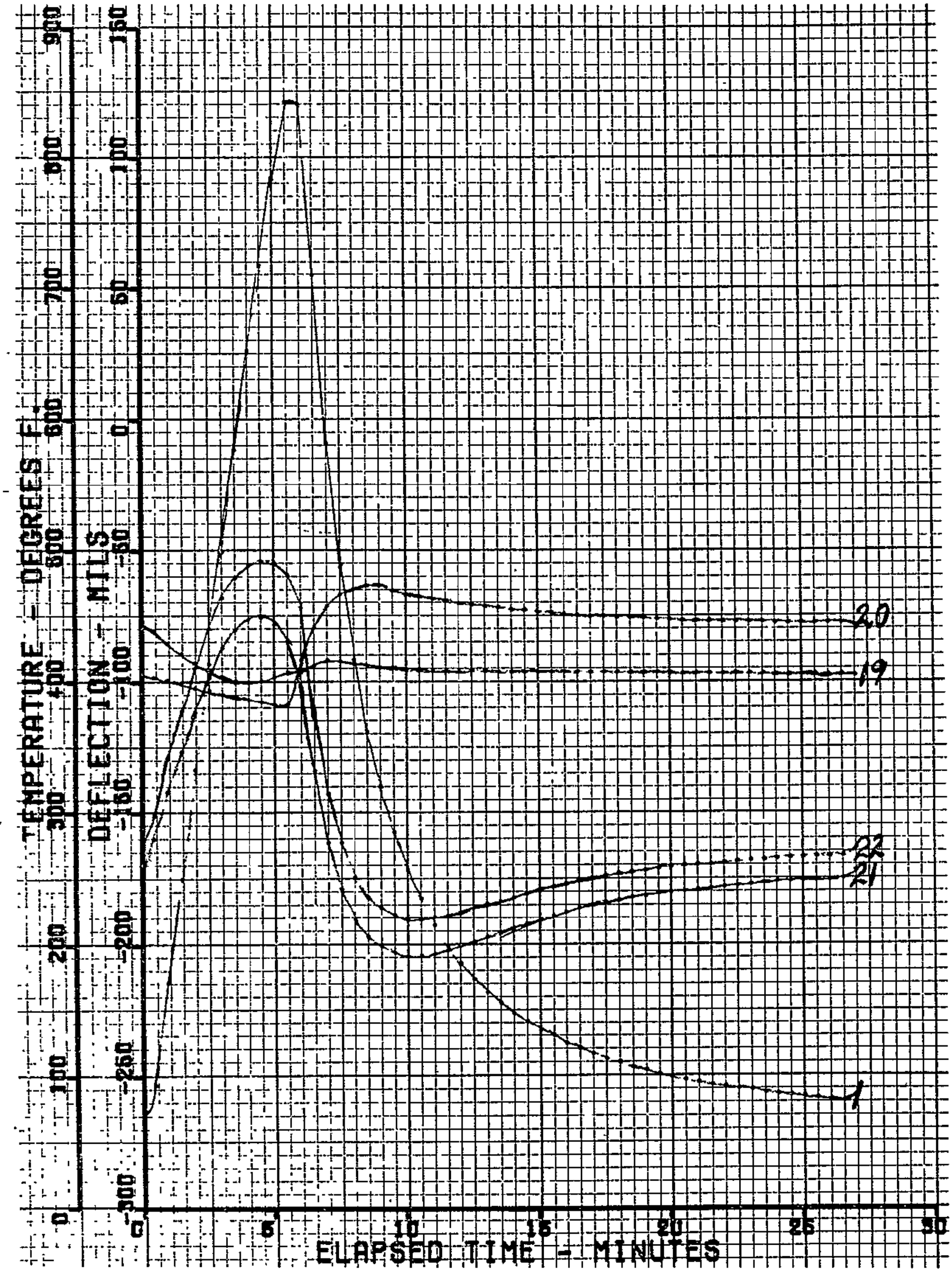


FIGURE 6–8 CYCLE 18 DEFORMATION

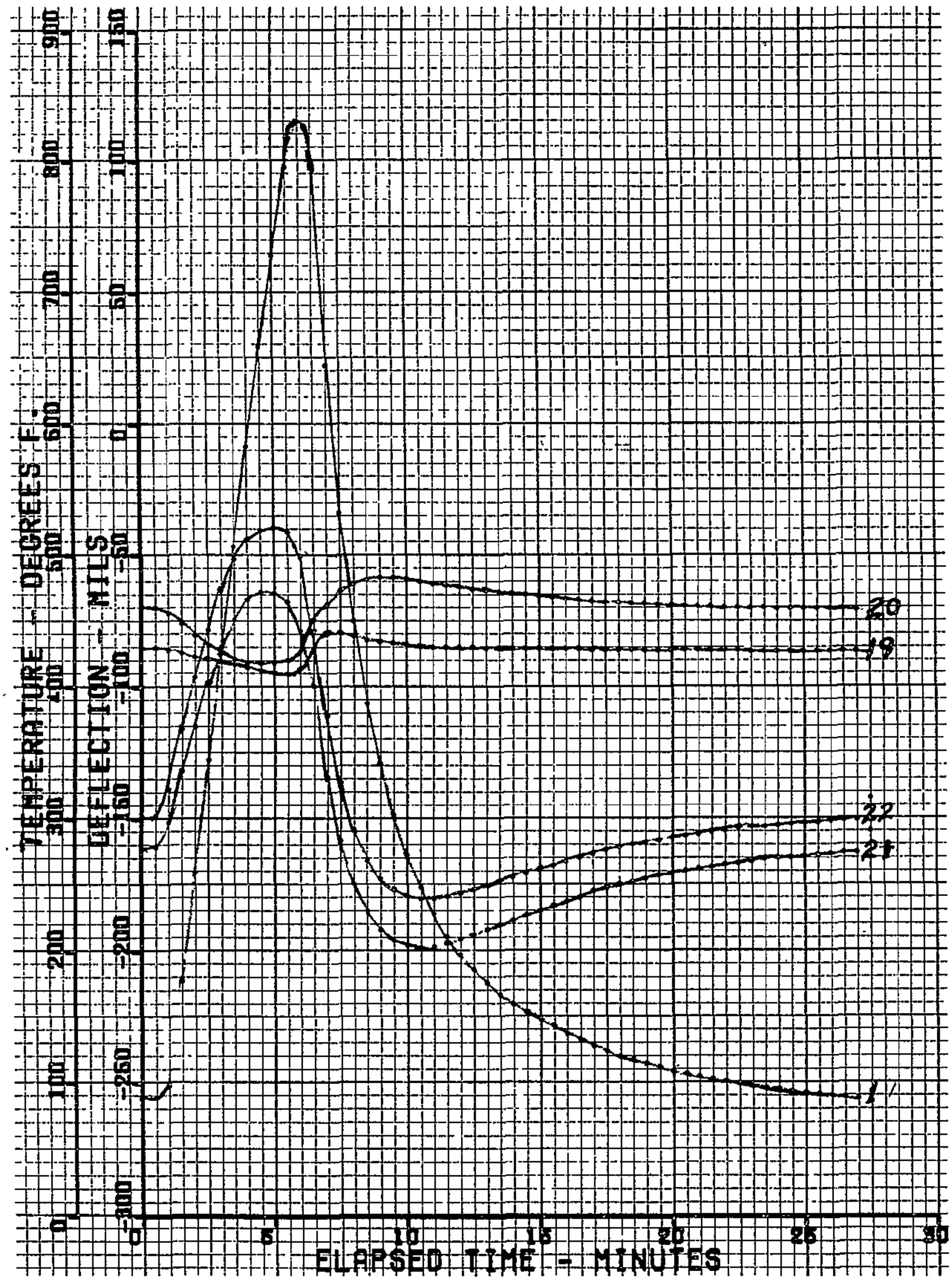


FIGURE 6–9 CYCLE 28 DEFORMATION

2 of 2

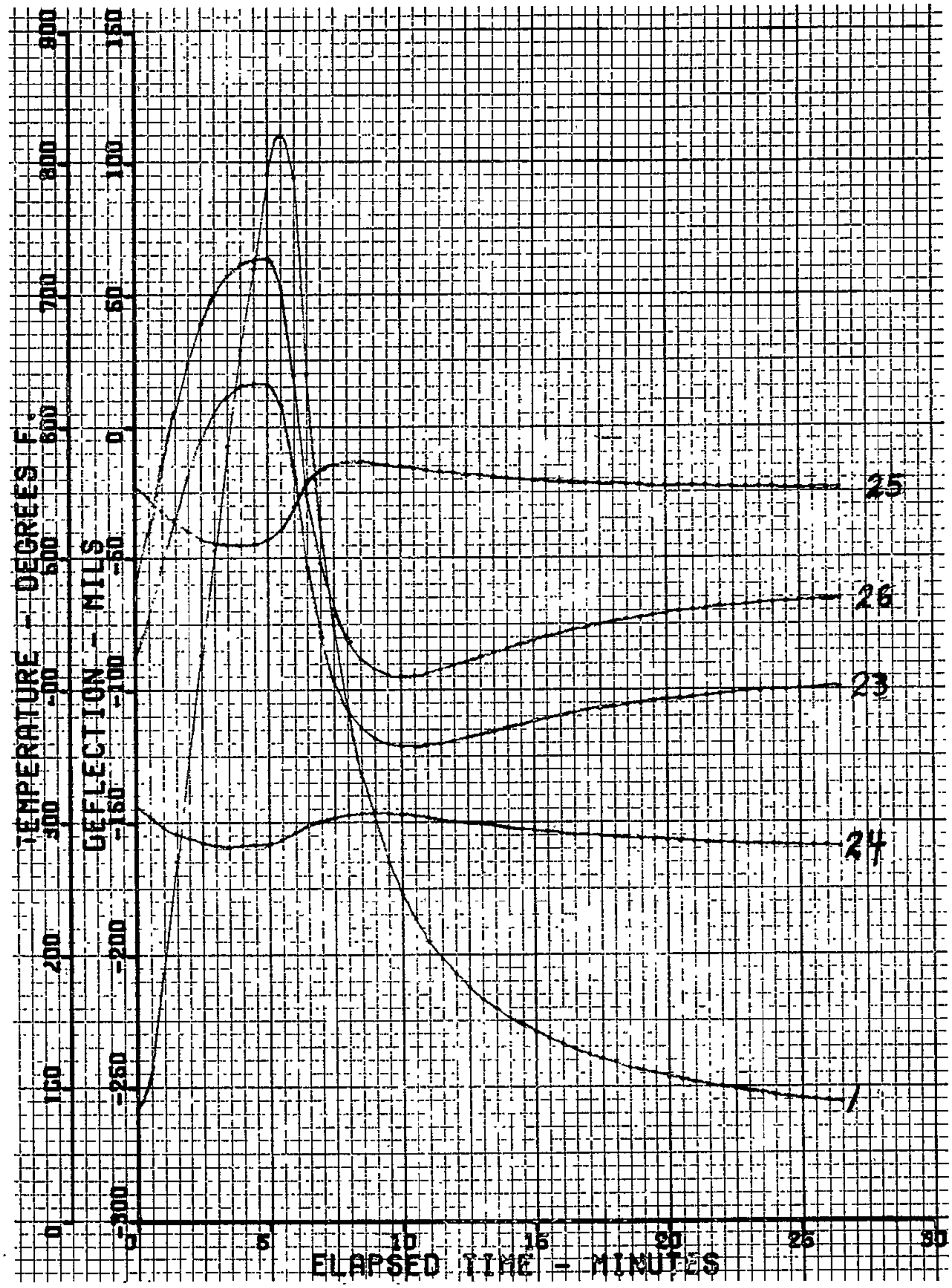


FIGURE 6–10 CYCLE 6 DEFORMATION

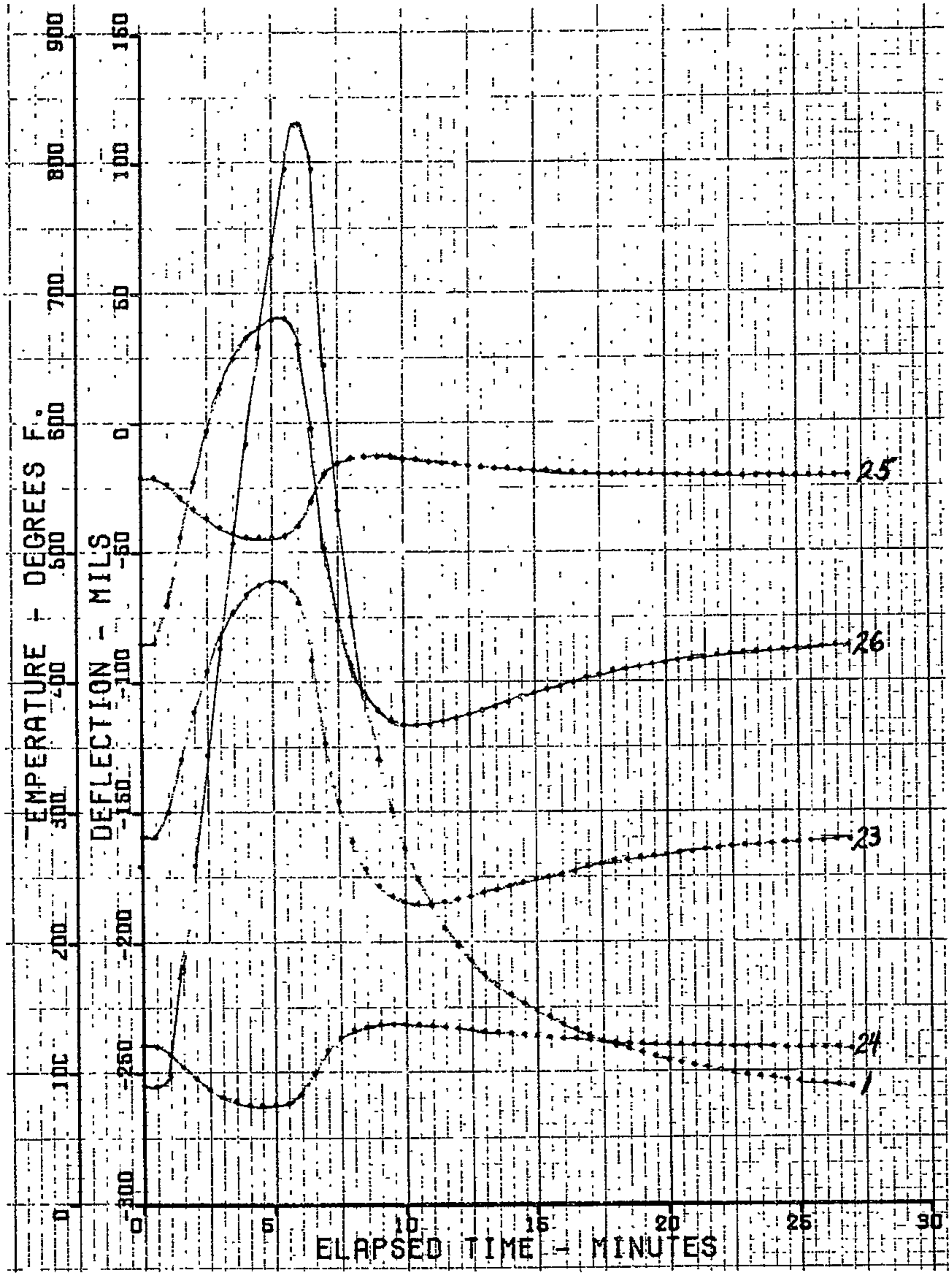


FIGURE 6–11 CYCLE 18 DEFORMATION

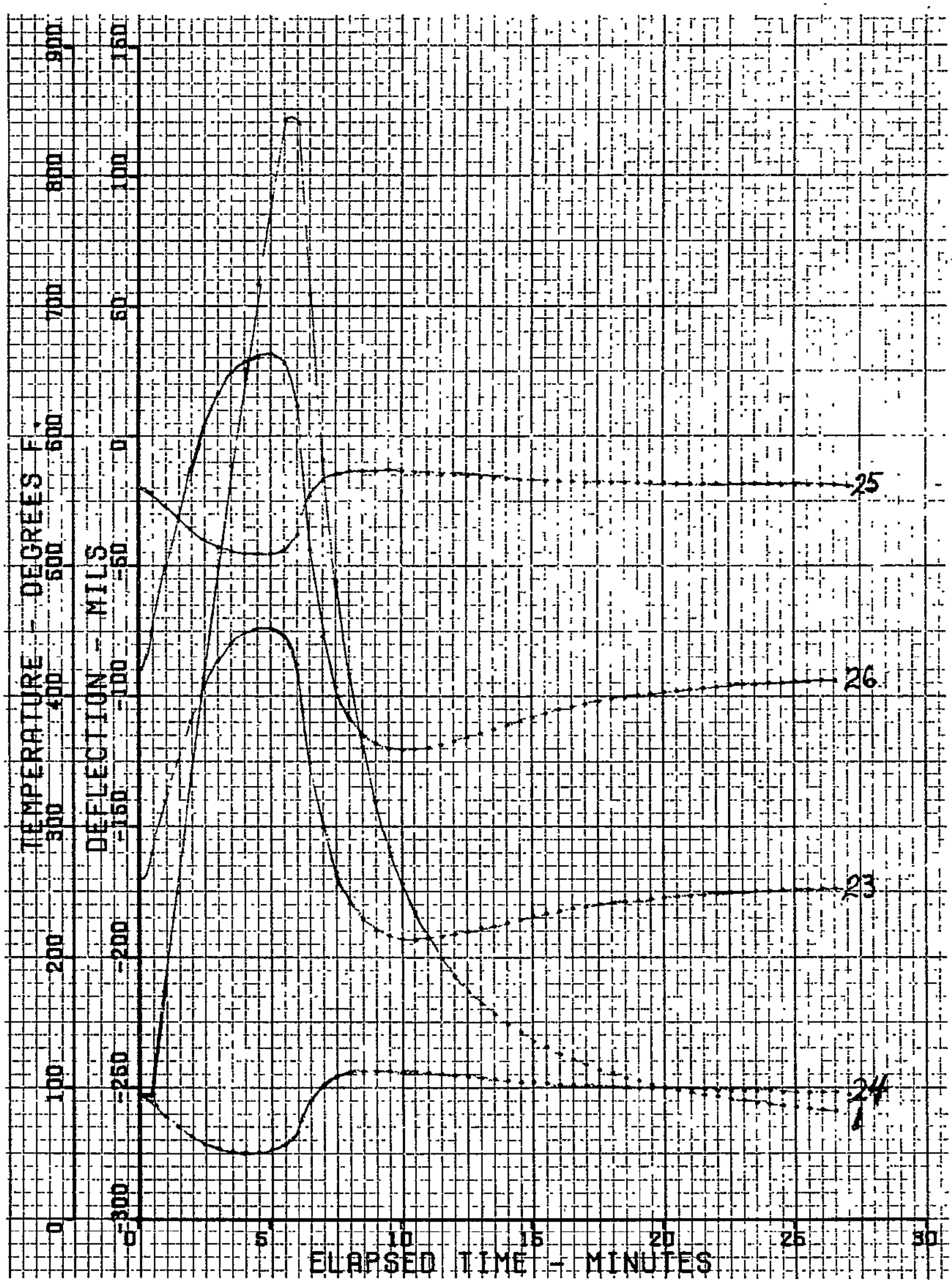


FIGURE 6—12 CYCLE 28 DEFORMATION

7.0 CONCLUSIONS

7.1 Material. Boron/aluminum tape material procured for this program was of acceptable quality although a wide range of tensile properties indicated possible irregularities n the filament quality. No other deficiencies were detected to explain the scatter from 165 to 202,000 psi tensile strength.

7.2 Processes. Of primary interest in this program was demonstration that low pressure (200 psi) diffusion bonding of large metal-matrix components was superior to the high pressure techniques by reason of reduction in capital investment and production costs. Low pressure autoclaves are readily available. Although high pressure diffusion bonding has been used successfully for manufacture of numerous small components, large and complex diffusion bonded shapes would require prohibitively high cost presses, complex dies plus long process-time production schedules. However, the process was shown to produce fully usable shaped parts and promising enough to warrant a continued effort to establish optimum tool design and process parameters. On this program it was necessary to resolve certain tool technique problems but it was most significant that the heating units, steel dies and the retorts could be readily and inexpensively machined and assembled.

7.3 Radiator Costs and Design. The possible installation of a boron-aluminum modular panel on Mark I shuttle was a basic target for the design activity. Boron-aluminum material can be used to reduce the weight of a shuttle orbiter through elimination of 1032 pounds of thermal protection insulation now baselined for exterior surfaces. On this basis, weight saved per vehicle would be 1032 pounds. Using a two-fold approach where (1) the total payload door area-radiator would be boron/aluminum structure and (2) the same assembly would be boron-aluminum skins with titanium frames and stringers, the weights would be approximately equal and the cost would be \$465/pound (\$579/sq. ft. of radiating surface) for the former and about \$420/pound for the latter. The radiator configuration, size, coolant system arrangement, thermal isolation and insulation appeared to be insensitive to the application of boron/aluminum as a substitution material except that venting provisions would be required during reentry heating. However, lay-up economies, attachment designs, detail material and panel thicknesses were distinctive and important factors relative to its application. Most significant was that the most complex boron-aluminum shape was a simple "C" frame.

7.4 Panel Test. Panel deflections during thermal exposure to 800°F were locally severe enough to cause slight permanent deformation but not sufficient to nullify flight serviceability. This deformation was only along unsupported edges which, if interfaced with adjoining structure, would not have been deflected. Damage at the points of maximum deflection noted at the tip ends of the diffusion bonded frame was due to disbonding at these ends, existant prior to the test. The test provided useful data regarding a distortion profile which could be anticipated for a boron-aluminum radiator subject to the temperature estimated for shuttle.

8.0 RECOMMENDATIONS

An extension of the studies begun on this program should include fabrication of a full scale radiator panel. The panel should then be thermal vacuum tested to qualify a total system containing boron/aluminum material of construction. A stress analysis needs to be completed and the failure criteria established. Manufacturing processes (tape and consolidated parts) need further refinement and positive quality control procedures should be advanced.

The full scale radiator fabrication could be part of an overall program directed at the flight test of a boron-aluminum panel experiment on Mark I Shuttle. The panel could be designed to replace one installed on the vehicle and possibly for retrofit action on all Mark II shuttles. The potential advantage of this kind of change is payload growth by removal of high density (15+ pounds/cubic foot) ablators currently planned for covering payload doors.

9.0 REFERENCES

1. Report No. 00.1471, "Evaluation of Metal Matrix Composites", K. P. O'Kelly, Vought Missiles and Space Company, LTV Aerospace Corporation, 1971.

2. Modular Radiator System Development for Shuttle and Advanced Spacecraft, Dietz, Fleming, Tufte (LTV) and Morris (NASA) ASME 72-ENAv-34, Aug 1972.

3. duPont Bulletin B-2 "Freon Fluorocarbons"

4. duPont Technical Bulletin B-5 "Stability and Corrosive Properties of Freon-12 "Dichlorodifluoromethane"

5. "Plasticity and Creep Analysis of Filamentary Metal-Matrix Composites, Sandia Labs, CIDEP 347.40.00.00-GO-132, Mar 1972.

6. M. L. Fleming, et. al., "Space Shuttle Thermal Control and Radiator Design Study", LTV-MSD Report No. 00.1376, 11 January 1971.

7. Communication with Steve Jacobs SMD NASA-MSC, C. W. Bert

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NO. 307-15-15

WRITER J. E. Dugan

ENGINEERING DEPARTMENT SPECIFICATION

DATE

MODEL General

CODE IDENT. NO. **11813**

SHEET COMPOSITE BORON/ALUMINUM ALLOY

MATERIAL SPECIFICATION FOR

APPROVALS	LEAD DESIGN ENGINEER	QUALITY CONTROL	9-2		
	DATE	DATE			
ORIG. GROUP	MATERIAL	STRUCTURE	RELIABILITY	PROGRAM MGT. PROJ. ENGR.	ENG. SPEC.

REVISION PAGE

REV.	DATE	REVISED BY	PAGES AFFECTED	REMARKS
N/C		Dugan	---	Initial issue.

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ø symbol indicates change

1. SCOPE

1.1 Scope. This specification establishes the requirements and tests for composite boron/aluminum tape and sheet material.

1.2 Classification. The material covered by this specification shall be classified in the following types:

(a) Type I - Single ply tape with 45.00 (±2.50) percent by volume silicon carbide coated boron filaments.

(b) Type II - Two ply tape with 45.00 (±2.50) percent by volume silicon carbide coated boron filaments.

(c) Type III - Single ply tape with 45.00 (±2.50) percent by volume uncoated boron filaments.

(d) Type IV - Multiple ply sheet 50.00 (±2.50) percent by volume silicon carbide coated boron filaments.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect at the time of use, form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.

SPECIFICATIONS

Federal

QQ-A-250/11	Aluminum Alloy 6061, Plate and Sheet
QQ-B-655	Brazing Alloys, Aluminum and Magnesium Alloys, Filler Metal

Military

MIL-I-8950	Inspection, Ultrasonic, Wrought Metals, Process for
MIL-B-20148	Brazing Sheet, Aluminum Alloy

STANDARDS

Federal

FED-STD-245	Tolerances for Aluminum Alloy and Magnesium Alloy Wrought Products
FED-STD-406	Plastics, Methods of Testing

Military

MIL-STD-453	Inspection, Radiographic
MIL-STD-649	Aluminum and Magnesium Products; Preparation for Shipment and Storage

3. REQUIREMENTS

3.1 Material Form. The material shall be furnished as a composite tape or sheet formed by diffusion bonding of coated or uncoated boron filaments and aluminum alloy in such a manner the filaments are solidly embedded in an aluminum alloy matrix. The tape shall be material having not more than two layers of filaments. The specific form shall be as required on the contract or purchase order in accordance with Table I.

3.2 Material Composition.

3.2.1 Filaments. The filaments shall be boron silicon carbide, and shall be 0.0057 (±0.0001) inch diameter coated, or 0.0056 (±0.0001) inch diameter uncoated, unless otherwise specified on the contract or purchase order.

3.2.2 Matrix Alloy. The matrix alloy shall be 6061-0 aluminum alloy and/or 713 silicon-aluminum alloy as specified on the contract or purchase order and shall meet all the requirements of QQ-B-655, MIL-B-20148, or QQ-A-250/11, as applicable.

3.2.3 Filament Alignment and Direction. All filaments comprising a single ply shall be laid parallel to one another within one degree of the long axis of the ply. Filaments comprising a ply in a multiple ply laminate shall be laid parallel or at a specified angle to one another within 3 degrees of the specified filament direction. Multiple ply filament directions as related to the long axis of the tape or sheet shall be as specified on the contract or purchase order.

3.3 Dimensions. Unless otherwise specified on the contract or purchase order, size and form shall meet the requirements of Table I.

3.3.1 Tolerances. Unless otherwise specified, tolerances shall be as specified in FED-STD-245.

3.4 Mechanical Properties of Materials As Supplied. The mechanical properties relative to the direction of filaments shall conform to the requirements of Table II.

3.5 Finish. Unless otherwise specified on the contract or purchase order, material shall be supplied mill finished.

TABLE I

MATERIAL SIZE AND FORM

TYPE	SIZE* (INCHES)	FORM
I	12 x 48	1 ply, silicon carbide coated filament
II	5 x 48	2 ply, unidirectional
III	12 x 48	1 ply, bare filaments
IV	12 x 48	As specified

*Denotes dimension of fully useable material.
Trim in excess of these dimensions acceptable.

TABLE II

MECHANICAL PROPERTIES AT 77°F ± 5°F (25°C ± 3°C)

TYPE	AVERAGE TENSILE STRENGTH - KSI		YOUNGS MODULUS OF ELASTICITY - PSI x 10^6
	Axial	Transverse 90°	Axial
I	155	12	30
II	155	12	30
III	155	12	30
IV	75*	75*	20*

* Cross ply strengths to be negotiated.

3.6 Surface Defects. The surface shall be free of excessive oxide, dirt, stain or other foreign elements that will affect the working qualities of the material. Rolls, wrinkles, laps and indentations shall be removable such that dimensional tolerances specified in Table I may be maintained. Cracks shall not be permissible except parallel to filaments of unidirectional materials. Cracks shall not exceed 10 percent of the length of Types I, II and III tape material as supplied and no cracks are permissible in Type IV sheet. Edge delaminations shall not be visible following removal of excess (trim) material.

3.7 Internal Defects. The material shall be free from deleterious voids, delaminations, stray or broken filaments, misaligned plies or filaments, oxidized filaments, oxide inclusions, carbonized adhesive, or other foreign elements that will affect the working qualities of the material. Stray or broken filaments or misaligned plies or filaments should under no condition exceed 5 percent of the sheet area.

3.8 Filament Percent by Volume. Material percentage of filament content by volume shall be in accordance with the type as specified herein.

3.9 Product Markings. The material shall be legibly identified with the following information.

(a) 307-15-15 and applicable type
(b) Purchase order number
(c) Manufacturer's name
(d) Alloy and temper as applicable
(e) Size of material
(f) Lot number

The marking material shall resist obliteration during normal handling and shall be removable by normal cleaning methods; however, ghost images of the characters may remain. Each piece of material shall be marked to permit positive traceability to the purchase order number.

3.10 Workmanship. The material shall be of uniform quality and condition, free from protruding filament ends and burns except along edges in the excess "trim" area. Surfaces of the material shall be of uniform color and texture.

4. QUALITY ASSURANCE PROVISIONS

CAUTION

Clean, white, cotton gloves must be worn at all times while handling the material. Flexing, bending, or abrading of the material shall be avoided.

4.1 Responsibility for Inspection and Test. The responsibility for all inspection and test requirements as specified herein shall be mutually agreed upon at the time of procurement. VMSC-T reserves the right to perform any or all of the inspections set forth herein where such inspections are deemed necessary to assure that the material furnished conforms to the prescribed requirements.

4.2 Witnessing of Tests. VMSC-T reserves the right to have a representative present during acceptance testing. Notice prior to testing shall be given VMSC-T to allow witnesses 3 days to arrive at the suppliers test facility. If test witnesses are unavailable, testing shall proceed as scheduled.

4.3 Test Facility Approval. Except as otherwise specified, the supplier may use his own facilities or any commercial laboratory acceptable to VMSC-T.

4.4 Suppliers Certification. The supplier shall furnish with each shipment an affidavit certifying that the material shipped meets the acceptance requirements of this specification. The affidavit shall include the purchase order number, specification number and type of the material and all inspection test results.

4.5 Inspection Records. Inspection records of examinations and tests shall be kept at the suppliers facility and available to VMSC-T for a period of time not less than 6 months following delivery to VMSC-T. These records shall contain sufficient data necessary to trace the certification documentation required in 4.4.

4.6 Classification of Examination and Tests. The examination and tests of the material shall be classified as follows.

(a) Qualification verification
(b) Acceptance verification
(c) Receiving inspection

4.6.1 Qualification Verification. Qualification verification shall consist of all the examinations and tests specified herein. Material of the classification specified herein (1.2) shall have been qualified and approved prior to placement of purchase order.

4.6.2 Acceptance Verification. Acceptance verification shall be performed on at least two representative samples of each lot of material purchased and shall consist of the following:

(a) Examination of product - 100%
(b) Tensile strength - two specimens per lot
(c) X-ray inspection
(d) Ultrasonic inspection

4.6.3 Receiving Inspection. VMSC-T receiving inspection shall consist of visual examination of all of the material and such additional sampling as deemed necessary to verify the suppliers acceptance verification certification enclosed in the shipment package. Tapping for soundness shall be performed only as directed by Engineering.

4.7 Rejection. Material that does not meet the requirements of this specification shall be rejected. The failure of a lot sample to meet the requirements of this specification shall be cause to review the quality of the entire lot. The supplier shall evaluate the acceptability of the lot of material and prescribe action required to segregate and salvage sufficient material to meet the requirements of the purchase order.

4.8 Test Methods.

4.8.1 Examination of Product. The material shall be examined to verify that the markings, size, surface, form and workmanship conform to the requirements of this specification. Soundness of Type IV material shall be verified by procedures agreeable to VMSC-T. In addition, adequacy of surface layer bonding shall be verified by inserting a knife edge under a ply of the sheet and peeling back. Peeling up of up to 1/2 inch cannot exist on more than 10% of the total material edge area.

4.8.2 Tensile Tests.

4.8.2.1 Specimen. The test specimen shall be a straight sided coupon with adhesive-bonded tabs. Specimen edges shall be ground to the required length and width dimensions with abrasive finer than 400 grit. The fibers shall be parallel to the specimen axial direction for Types I, II, and III. The fibers may be parallel to the specimen axial or transverse direction for Type IV. The specimen configuration is described in Figure 1.

9-10

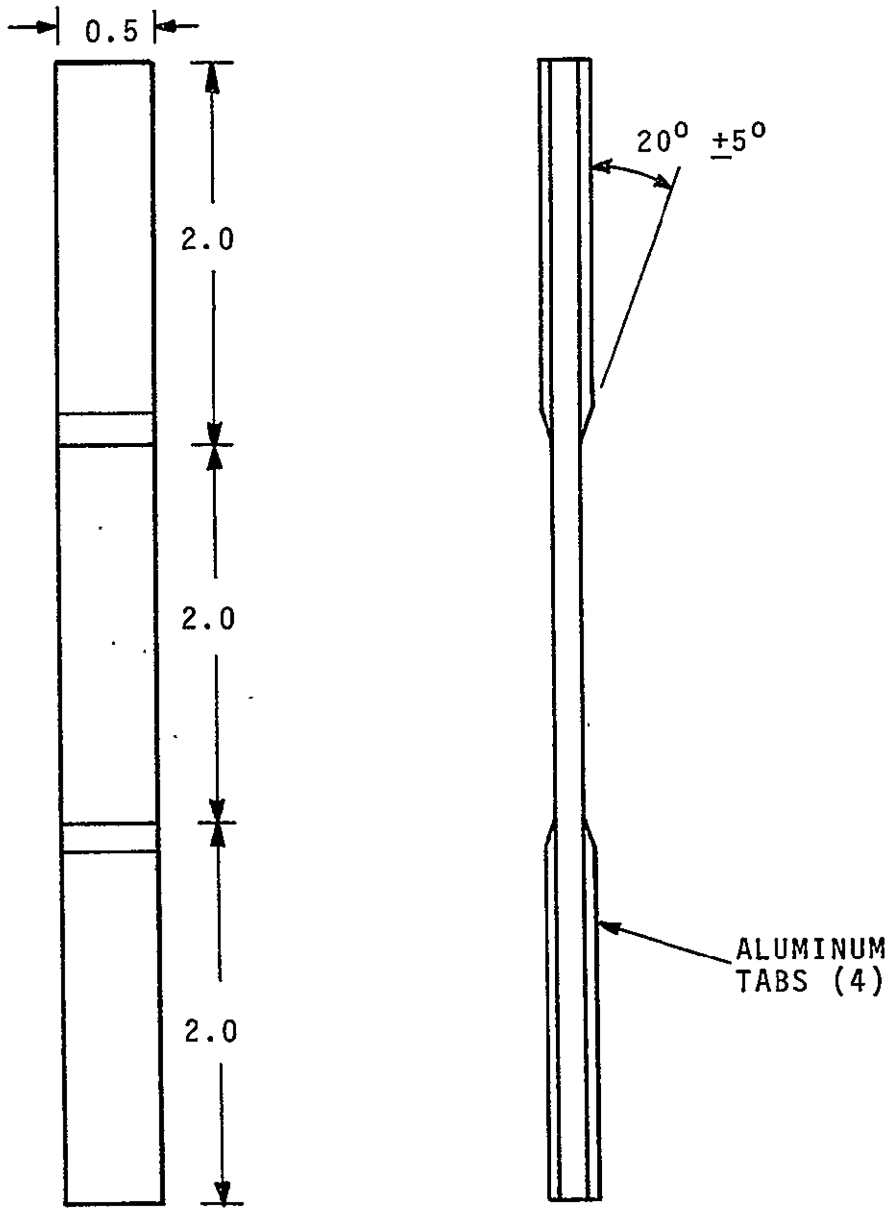

Figure 1. Tensile Test Specimen

4.8.2.2 Procedures. Unless otherwise specified, the test shall be conducted in accordance with FED-STD-406, Method 1011. The specimen shall be loaded to failure at a 0.050 ($\pm$0.005) inch per minute crosshead speed in a testing machine using either strain gage or extensometer readings for strain measurement. Test temperature shall be 75° ($\pm$10°)F.

4.8.2.3 Calculations. A mean value based on a minimum of three determinations shall be reported for both tensile strength and modulus using the formula given below, and shall meet the requirements specified in Table II.

(a) Ultimate tensile strength

$$Ftu = \frac{Pt}{A}$$

where Ftu = Ultimate tensile strength
Pt = Maximum tensile load carried by the specimen, pounds
A = Specimen cross-sectional area, square inches.

(b) Modulus of elasticity. Obtain the modulus of elasticity by extending the initial straight-line portion of the load deflection curve and graphically determining the ratio of stress to corresponding strain. The ratio of the difference in stress corresponding to the difference in strain expressed in pounds per square inch shall be reported to three significant figures. The method is illustrated in Figure 2.

4.8.3 Internal Defects. Compliance with the requirements of 3.7 shall be determined by visual, radiographic (MIL-STD-453) or ultrasonic techniques (MIL-I-8950) or as mutually agreed upon by VMSC-T and the supplier.

4.8.4 Filament Percent by Volume. Compliance with the requirements of 3.8 shall be determined by a weight differential measurement.

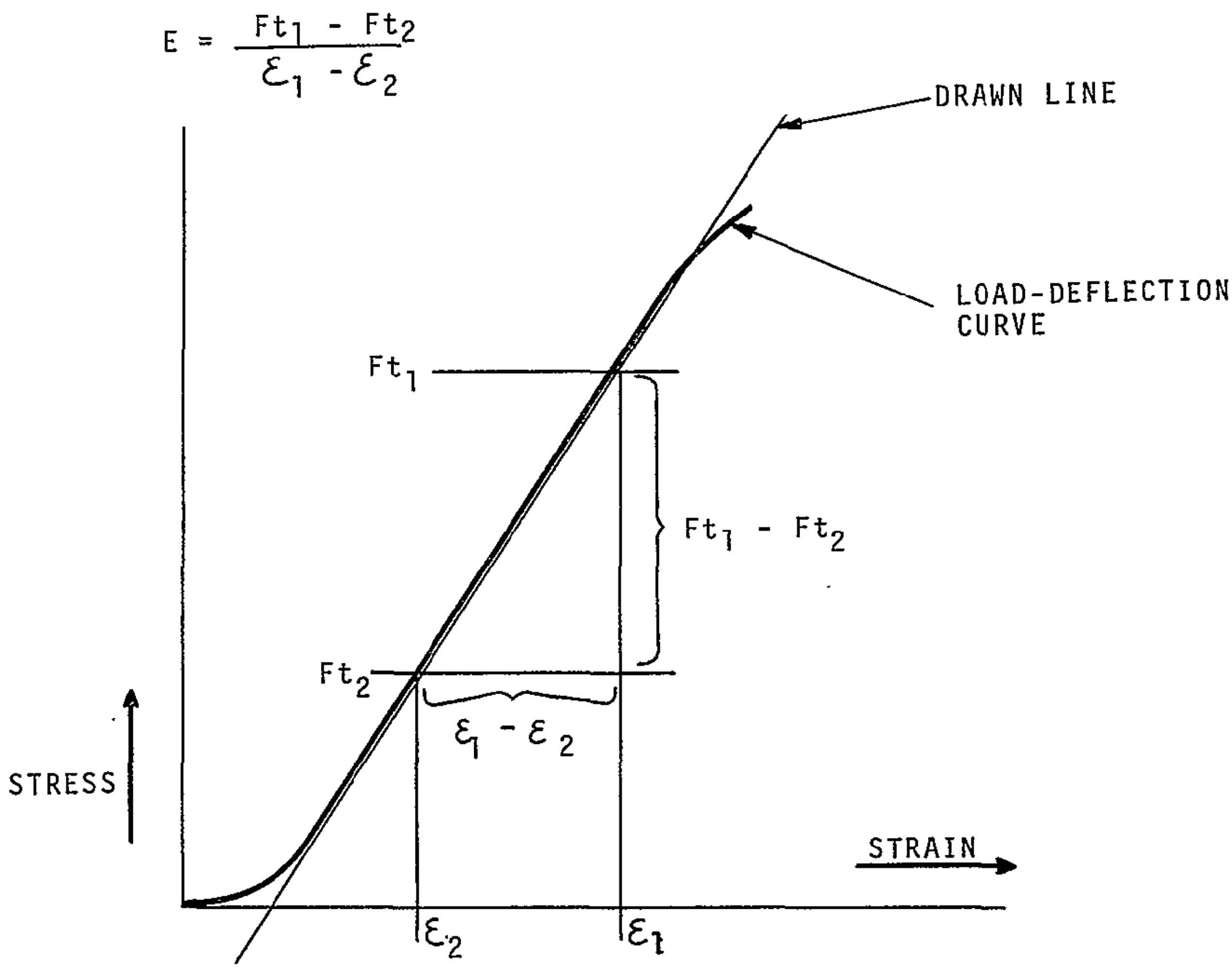

Figure 2. Illustration of Load Deflection Curve

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5. PREPARATION FOR DELIVERY

5.1 Preservation and Packaging. Preservation and packaging (MIL-STD-649) of all material furnished under this specification shall be sufficient to afford adequate protection against corrosion and physical damage during handling, shipping, and storage. Each package or container shall contain only material from the same lot or if more than one lot is packaged, each piece of material shall be identified by lot number.

5.2 Packing. The material shall be packaged as specified in 5.1 and packed in a manner which will ensure acceptance by common carrier at lowest rates and will ensure protection against damage during shipment.

5.3 Marking for Shipment. Each shipping container shall be identified with label, tag or marking which includes the following data.

(a) 307-15-15, Type
(b) Purchase order number
(c) Manufacturer's name
(d) Material description
(e) Quantity and unit size
(f) Lot number
(g) Precautionary, handling, and storing warnings as applicable

6. NOTES

6.1 Intended Use. The material covered by this specification is intended to be used in the manufacture of structural components when the composite properties of high modulus filament and aluminum matrix are desirable. Use is not restricted to this application.

6.2 Ordering Information. The following information should be included on the purchase order.

(a) Number and title of this specification
(b) Type of materials and matrix alloy
(c) Number of plies and ply direction
(d) Quantity

6.3 Definitions.

(a) VMSC-T - Vought Missiles and Space Company - Texas.

(b) Lot - A lot shall consist of material produced by the same tooling, from material having the same matrix lot and filament lot, by the same production technique, at one facility and in a consecutive production run. A consecutive production run which is interrupted by a period of time exceeding 5 days shall be construed as not meeting the definition of a single lot.

APPENDIX I

APPROVED SOURCE LIST

All products listed herein have been qualified under the requirements of this specification. Revisions of this list will be issued as necessary. The listing of a product does not release the vendor from compliance with the provisions of this specification.

VMSC-T DESIGNATION	VENDOR'S DESIGNATION	VENDOR'S NAME AND ADDRESS
307-15-15, Types I thru IV		Amercom, Inc. 9060 Winnetka Ave. Northridge, California 91324

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ORIG. ______ NO. 308-15-38

WRITER A. B. Featherston

ENGINEERING DEPARTMENT SPECIFICATION

DATE ______

MODEL General

CODE IDENT. NO. 11813

BORON - ALUMINUM BONDING

PROCESS SPECIFICATION FOR

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APPROVALS

	QUALITY CONTROL			CHIEF PROJ. ENGR.	
	DATE	DATE	DATE	DATE	DATE
ORIG. GROUP	SYS. DESIGN ENGR.	STRUCTURES	AVIONICS PROJ. ENGR.	VEHICLE SYSTEMS PROJ. ENGR.	ENG. SPEC.
DATE	DATE	DATE	DATE	DATE	DATE

1. SCOPE

1.1 Primary Bonding. This specification establishes the processing, materials, equipment and quality control requirements to be used in assembly and bonding of Boron/Aluminum monolayer tape and multi-layer sheet material meeting the requirements of VMSC-T Specification 307-15-15.

1.2 Secondary Bonding. This specification establishes the processing, materials, equipment and quality control requirements to be used in secondary bonding of fabrication details in making an assembly.

1.3 Training of Personnel. Personnel shall be trained to operate the autoclave, heating system and in the handling and lay-up of the boron/aluminum material.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect at the time of processing, form a part of this specification to the extent specified herein.

SPECIFICATIONS

Vought Missiles and Space Company - Texas
LTV Aerospace Corporation

307-15-15	Material Specification for Sheet Composite Boron/Aluminum Alloy
308-20-10	Vapor Degreasing

STANDARDS

Military

MIL-STD-453 29 October 1962	Inspection, Radiographic
MIL-STD-810B 15 June 1967	Environmental Test Methods

(h) Oven, 250°F

(i) Vacuum pump, mechanical

(j) Nitrogen regulator, low pressure

(k) Thermocouple spot welder

(l) Flexure test fixture

(m) Tensile test tooling

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3. MATERIALS AND EQUIPMENT

3.1 The following material, or equivalents, are required for the tests and processes specified herein.

(a) Boron/Aluminum sheet composite - Specification 307-15-15

(b) Silicon/Aluminum alloy foil, 1 mil. 7 1/2% silicon

(c) Polystyrene beads - Styron 475B, Dow Chemical

(d) Acetone - commercial grade

(e) Toluene - commercial grade

(f) Sodium Hydroxide - commercial grade

(g) Sodium Bicarbonate - commercial grade

(h) Nitric Acid - commercial grade

(i) Distilled Water - CVA-10-414

(j) 321 Stainless Steel Sheet Annealed - .012 inch

(k) 321 Stainless Steel Sheet Annealed - .004 inch

(l) Calcium Carbonate Powder. Reagent Grade, ACS

(m) Tubing, Stainless Steel, 3/8 inch

3.2 Equipment.

(a) Autoclave, 200 psig operating pressure

(b) Autoclave heater cart. - $1250^{\circ}F \pm 25^{\circ}F$ operating temperature

(c) Cleaning tanks, five

(d) Spray gun

(e) Programmed Proportional Power Supplies (Two)

(f) Multi Point Recorder

(g) Thermocouples, Chromel.Alumel

4. PROCEDURES

4.1 General. This specification outlines the procedures for diffusion bonded boron/aluminum composite sheet parts fabricated from monolayer boron/aluminum tape material meeting the requirements of VMSC-T 307-15-15. The orientation of filaments, number of monolayer plys and configuration of composite parts shall be specified by Engineering Drawing.

In addition, the procedures to obtain secondary diffusion bonded assemblies made from the diffusion bonded or other details are specified.

4.2 Cleaning and Preparation of Assemblies. All materials to be diffusion bonded shall be cleaned and coated to maintain clealiness prior to and during assembly. Residual oxides, oils and fingerprints shall be removed from surfaces of tape, foil, diffusion bonded details or other details in preparation for bonding in accordance with the following procedure.

(a) Pre-clean parts by solvent wiping or vapor degreasing in accordance with 308-20-19.

(b) Alkaline clean in a solution of 5 grams sodium hydroxide and 5 grams sodium bicarbonate per liter of solution. Parts should be cleaned for 1 to 3 minutes at $165^{\circ}F \pm 15^{\circ}F$.

(c) Rinse in hot tap water ($145^{\circ}F \pm 15^{\circ}F$).

(d) Clean in acid solution at room temperature containing 10 volume percent of 42° Bamue nitric acid in distilled water for 1 to 3 minutes.

(e) Dip or flow rinse in distilled water to remove acid solution. Allow excess water to drain but do not dry.

(f) Immerse or flush immediately in acetone for about one minute to remove remaining water. Allow excess to drain but do not dry.

(g) Immerse or flush with sealer solution immediately. The sealer solution shall consist of 5 grams polystyrene, 500 milliliters and 250 milliters of acetone.

(h) Drain excess sealer solution from part, then air or oven dry.

CAUTION

When preparing acid solutions, the acid shall always be added to the water.

The solvent vapor and solutions are flamable.

4.3 Layup of Assemblies. Cleaned and sealer coated monolayer tape, silicon-aluminum alloy foil and details shall be laid up with the number of plies and filaments in accordance with the Engineering drawings.

4.3.1 Adhesive Bonding. Each ply, each layer of silicon aluminum foil and each detail to be bonded shall be boated with polystyrene adhesive, containing 7 grams polystyrene per 100 milliliters of toluene, and placed in position while the adhesive is still wet. Excess adhesive shall be squeezed out and wiped off by hand pressure or roller to prevent entrapment of air between surfaces to be bonded. When lay-up is complete, firm pressure shall be applied and maintained during drying by weights, clamps or tooling.

CAUTION

Toluene vapors evolved during drying operation are flamable.

4.3.2 Drying of Adhesive. Assemblies shall be dried or cured in hot air oven at 150°F for 2 hours minimum. The assemblies shall be carefully handled to prevent shifting. Remove from oven and allow to cool below 100°F before removing restraints. Excessive adhesive may be removed with toluene.

4.4 Application of Release Solution. Dried assemblies and slipsheets shall be spray coated with a stop off or release solution to prevent unwanted bonding during thermal/pressure processing. The release solution shall be prepared by dissolving 5 grams of polystyrene in 100 milliliters of toluene and then adding 20 grams of calcium carbonate powder. The dispersion shall be shaken thoroughly before applying.

4.4.1 Slip Sheets. Slip sheets made of oxidized 321 corrosion resistant steel as specified by Engineering Drawing shall be spray coated. The release solution shall be shaken well to disperse the solids and double criss-cross sprayed and air dried between coats to obtain a uniform coating on the side of the slip sheet which will face the assembly.

NOTE

Slip Sheets shall be available to lay the release solution coated assemblies at the time they are coated.

4.4.2 Assemblies. The assemblies shall be uniformly spray coated on all sides and allowed to air dry. The release solution shall be shaken well and a criss-cross coating applied to one side, drying between coats. Place the coated surface on the proper coated slip sheet. The process to coat all surfaces of the assembly shall be repeated and then be allowed to air dry.

4.5 Tooling and Retort Assembly. Tooling and retort design shall be as required by Engineering Drawing with retort construction being made from 0.005 to .0012 inch thick weldable, stabilized or low carbon stainless steel (Type 321, 347, 316L, etc.). Retorts shall be of welded, not brazed construction.

4.5.1 Mold Assembly. The release solution coated assembly and slip sheets shall be placed in the tooling and tooling retaining pins, if any inserted. Proper alignment of tooling is essential to obtain proper pressure, as necessary or when required by Engineering. 0.004 inch thick 321 corrosion resistant steel shall be used as restraining straps and spot welded to prevent molding assembly from shifting during handling during retort installation and processing.

4.5.2 Retort Fabrication. The geometry of the parts to be bonded will determine the retort design.

(a) Preforming may be required to facilitate insertation of the mold assembly into the fabricated retort.

(b) The retort shall be fusion or resistant welded and as complete as possible before the molding assembly is installed into the retort.

(c) One or more 3/8 inch evacuation tubes of weldable corrosion resistant steel (Type 321, 347 or 316L, etc.) shall be installed in the fabricated retort or during closure.

4.5.3 Retort Closure. The molding assembly shall be carefully placed in the fabricated retort and the close-out weld joint made. The welded retort shall be a vacuum tight sealed unit. Leak testing shall be performed by immersion in water tank, pressurized to 3 psig with nitrogen for 10 minutes to check for leaks. Equivalent methods shall be utilized for retorts too large for tanks. Observed leaks shall be marked, weld repaired and again leak checked until free of leaks.

4.6 Bonding. The retort assembly shall be installed on the platten of the autoclave heater cart, instrumented, cart placed in autoclave and thermal/pressure bonding cycle completed.

4.6.1 Retort Placement. The retort assembly shall be placed on the autoclave heater cart platten as near the center as possible. Care shall be taken not to damage the platten heater control or monitoring thermocouples.

4.6.2 Instrumentation. The heater cart, autoclave and retort shall be instrumented with chromel/alumel thermocouples. The autoclave and retort vacuum system shall have adequate gauges to determine pressure.

(a) The autoclave shall have a pressure gauge reading in 5 pound increments from 0 to 250 psig. A thermocouple shall be attached by spot welding to the top of the autoclave over the heater cart when the door is closed. Another thermocouple shall be spot welded to the autoclave high pressure air line immediately before the valve which pressurizes the autoclave.

(b) Heater Cart. The heater cart platten shall be instrumented with a minimum of three thermocouples spot welded to the platten face. One shall be designated as the control thermocouple and connected to the power supply system consisting of a probrammer, proportional controller and a power supply. The other two shall be used for monitoring temperatures of the platten. The guard heater shall be instrumented in a like manner with one connected to a second power supply. A single thermocouple shall be spot welded to the heater cart outer wall to monitor cart temperature. This should be located in a "HOT" area previously determined.

(c) Retort. The retort shall be instrumented with a minimum of five thermocouples to give a good sampling of retort temperature. Large retorts will require additional thermocouples to obtain adequate sampling. These thermocouples shall be monitored simultaneously. When the vacuum line is attached to the retort a vacuum gauge shall be in the line between the valve to the line entering the autoclave and the retort. This will allow monitoring of the retort vacuum with the pump out of the system.

4.6.3 Autoclave Installation. The heater cart assembly containing the retort shall be placed in the autoclave in preparation for processing.

(a) Position heater cart in autoclave.

(b) Connect vacuum line to retort.

(c) Start vacuum pump and pump down retort until gauge reads minimum of 28 inches of mercury.

(d) Check vacuum system for leaks by closing valve going into autoclave and monitoring gauge. Correct any leak and repeat until vacuum holds minimum of 28 inches of mercury for a minimum of 5 minutes when isolated from pump.

(e) Close and lock door to autoclave following autoclave operation instructions.

4.6.4 Processing. The thermal processing shall be pre-programmed and controlled by a data trak through a thermax proportional controller and a phaser. The thermal cycle resulting will vary depending on the heat load required for the particular retort configuration. The autoclave pressure will be raised to a predetermined level and the peak temperature of the heaters maintained for a specified time to insure equilibrium inside the retort. The temperature shall then be lowered rapidly to the diffusion range and held for a minimum of three hours. The retort shall be further cooled to below 500°F before the vacuum is released to minimize warping and oxidation.

(a) Start thermal cycle, start both data-traks and multipoint recorder.

(b) Raise autoclave pressure to 5 - 10 psig.

(c) When heaters reach 850°F to 900°F place data-traks to hold a purge retort with 1 - 3 psig N_2. Immediately start pumping to below 25 inches of mercury. Repeat purging operation three times.

(d) Start pressurizing autoclave to 200 psig.

(e) Turn data-traks to run and continue to peak temperature.

(f) Monitor retort temperature while heaters are controlling to maximum (peak) temperature. Hold retort at temperature for specified time based on retort configuration. Lower autoclave pressure to 150 psig.

(g) Cut power to heaters, raise guard heater and allow to rapid cool to diffusion temperature (940 - 950°F).

(h) Lower guard heater, set data-traks to diffusion cycle and then turn on power to heaters.

(i) Hold diffusion temperature for three hours unless otherwise specified.

(j) Shut off power to heaters, raise guard heater 2 inches and allow to cool.

(k) When temperature of heaters and retort do not exceed 500°F lower pressure to ambient in autoclave and open door.

(l) Raise guard heater two more inches, cut off vacuum, disconnect vacuum line to retort.

(m) Remove retort from heater cart and allow to cool to handling temperature.

(n) Open retort and extract diffusion bonded article from tooling.

4.6.5 Cleaning Processed Article. The diffusion bonded article will contain release compound on the surface. This should be removed prior to cleaning the article.

(a) Flush or dip the article in a solution of approximately 10% nitric acid in water.

(b) Flush with tap water to remove acid, brush or scour with nylon pads (Scotch-Brite) as required.

(c) Clean in alkaline cleaner, rinse as in paragraph 4.2

6.0 QUALITY ASSURANCE PROVISIONS

6.1 Responsibility. Quality Control shall maintain control over all processes to assure compliance with procedures and training requirements specified herein.

6.2 Testing. Testing of the article or test specimens shall be as required by the engineering drawing. When test specimens are required they shall be representative of the production bonding and shall be inspected and tested in the following order.

(a) X-ray (6.3.1)

(b) C-scan Ultrasonic (6.3.2)

(c) Flexural (6.3.3)

(d) Metallographic

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6.3 Test Methods.

6.3.1 X-ray. X-rays shall be examined for alignment of filaments and splicing gaps. Filament alignment shall be within 5^{o} of engineering drawing requirement. Parallel splices shall exhibit no gap in excess of three filament widths. Butt splices shall exhibit no gap in excess of 0.10 inches unless otherwise specified by drawing.

6.3.2 C-scan Ultrasonic. The C-scan shall be examined for disbond areas which shall not exceed 0.25 inches.

6.3.3 Flexural. Flexural strength on test specimens when tested in accordance with the latest ASTM procedures for boron/aluminum shall be a minimum of 160 ksi.

6.3.4 Metallographic. Designated specimens shall be mounted, polished and examined for uniformity of filaments, broken or degraded filaments and volume percent of boron filaments. Degradation of filaments, gross broken filaments and non-uniformity as well as volume percent below drawing requirements shall be cause for rejection.

6.4 Workmanship. Articles shall be examined visually (3X magnification maximum) for workmanship and dimensional requirements within the state-of-the-art and geometric configuration of the article.

6.5 Rejection Criteria. Any article or test specimen representative of an article which fails to meet the requirement shall be rejected and submitted for review and disposition by Engineering.

THE FOLLOWING PAGES ARE DUPLICATES OF ILLUSTRATIONS APPEARING ELSEWHERE IN THIS REPORT. THEY HAVE BEEN REPRODUCED HERE BY A DIFFERENT METHOD TO PROVIDE BETTER DETAIL

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