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NASA Contractor Report 178316

Application of Superplastically Formed and Diffusion Bonded Aluminum to a Laminar Flow Control Leading Edge

M. D. Goodyear

LOCKHEED-GEORGIA COMPANY
A Division of Lockheed Corporation
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Contract NAS1-18036
August 1987

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FOREWORD

The technical work herein was accomplished under Task 1 Contract NAS1-18036 sponsored by NASA-Langley, Langley Research Center, Hampton, Virginia 23665-5225. Contract go-ahead was awarded in January, 1986. Mr. Dal V. Maddalon, Laminar Flow Control Project Office, NASA-Langley, is the Technical Representative of the Contracting Office.

Mr. Roy H. Lange, Lockheed Program Manager, LFC Projects, is responsible for the overall guidance and technical direction of the Laminar Flow Enabling Technology Development Contract, NAS1-18036. The technical work was performed under the direction of the Advanced Structures Department (D/72-77) of the Lockheed-Georgia Company in Marietta, Georgia. The key technical people working during this reporting period include:

R.H. Lange	Program Manager
M.D. Goodyear	Advanced Structures
P.D. Cox	Design Group
J.A. Bennett	Aerodynamics Department
B.J. Hagemann	Propulsion Department
R.M. Gray	Manufacturing Research
J.B. Clayton	Engineering Technical Contracts

This report has been given the Lockheed designation LG86ER0060.

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1.0 SUMMARY

This report documents Lockheed's results in designing and fabricating a laminar flow control (LFC) leading edge demonstration article for NASA. This program offers an alternative design relative to the composite/titanium design fabricated by Gelac and flight tested by NASA in the NASA Contract NAS1-16219. A slotted configuration similar to that used in the previous contract was used in order to provide a less costly design and fabrication task.

The overall objective of Task 1 of the program reported here (NASA Contract NAS1-18036) is to demonstrate the producibility of an all-aluminum leading edge article using advanced aluminum alloys and joining processes. The program demonstrated the improved producibility of the aluminum articles over the titanium/ composite article.

The Lockheed-designed aluminum Laminar Flow Control leading edge article is comprised of an outer sheet and slot ducts of IN9052 powder metal (PM) aluminum, superplastically formed 7475 aluminum hat section collector ducts, and an inner skin of aluminum-lithium (Al-Li) sheet, all of which are adhesively bonded to assemble the final article. The structure includes slot ducts, metering holes, and collector ducts. A new diffusion bonding of aluminum sheet technology was utilized. The outer skin and the slot ducts were produced simultaneously, using a diffusion bonding/thermal expanding process developed by Texas Instruments. This technique provided excellent shear strength and allowed the precise cutting of slot ducts after assembly with no springback or disbond of the aluminum sheets.

The materials were selected to provide the best combination of corrosion resistance, weight savings, and strength for the leading edge article. The IN9052 PM alloy has superior corrosion resistance over other aluminum alloys, has excellent formability, and is 5% lighter. It was selected for the outer skin and slot duct applications. The 7475 sheet used to super-plastically form the collector ducts provides strength and good formability. The Al-Li alloy provides high structural strength and stiffness, plus a 10% weight savings over other aluminum alloys.

Although the design concept was intentionally kept as simple as possible to assure producibility, a high degree of workmanship was required to meet the goal of the program. The approach of using diffusion bonding and superplastic forming of advanced aluminum alloys offered economically reasonable manufacturing and assembly processes. However, such processes have not been used for aircraft applications as this, and the program was to push the state-of-the-art beyond its current boundary while providing a proof-of-concept article.

The diffusion bonding technology was ambitiously utilized to avoid adhesive flow into the laminar flow control ducting and slots. This type of bond also provided a near-monolithic shear strength at the bondline, which prevented disbond. Hot forming to shape of the non-heat treatable alloy, IN9052, significantly reduced any residual stress, thus preventing springback.

The proof-of-concept article successfully demonstrated the use of diffusion bonding and superplastic forming of aluminum materials for aircraft structure. However, the surface smoothness tolerance of the outer skin, which is critical to achieve laminar flow, was not met over all the article. The problem was due to the tooling approach, not the fabrication technology used, and surface smoothness requirements can be met with close tolerance tooling.

2.0 INTRODUCTION

The recognition of potential long-term shortages of fuel, evidenced by dramatic increases in costs and periods of limited availability since 1973, emphasized the need for improving the fuel efficiency of long-range transport aircraft. In response to this need, NASA initiated a series of programs to develop a new technology for fuel efficiency. This new technology, Laminar Flow Control (LFC), offers the greatest potential for drag reduction, thus improving the fuel efficiency of transport aircraft over any other current technology. A program to fabricate a JetStar LFC leading edge was initiated in 1980 and completed in 1983 (References 1-6). The resultant flight article was flight tested until 1987. These flight service tests proved that laminar flow could be achieved for both the slot design of Lockheed and the perforated design of McDonnell Douglas.

The titanium/composite slot design proved successful in achieving laminar flow on the JetStar flight test; however, the design was difficult to fabricate. Producibility problems involving the titanium sheet and the adhesively bonded interface between the composite substructure and titanium proved difficult to overcome. It was determined that migration of the adhesive during the titanium-to-graphite faced core bonding process had plugged up a few of the slots, metering holes, or collector ducts in a random manner on the test article. The attendant loss of suction flow in these locations prevented the local attainment of conditions necessary for laminar flow. As a result, the attainment of laminar flow over the entire test article could not be realized during the flight testing.

The current program evaluated an alternative to the previous design by using advanced technologies in aluminum alloys and fabrication concepts. The new design concept maintains a configuration similar to the previous composite/titanium configuration. The program included detail design, analysis, and fabrication of an advanced aluminum adhesive/diffusion bonded laminar flow leading edge demonstration article. This report covers these efforts from contract go-ahead, January 8, 1986, through delivery of the all-aluminum leading edge article in March, 1987.

3.0 OBJECTIVE

The overall objective of Task 1 of NASA Contract NAS1-18036 is to demonstrate the producibility of an all-aluminum LFC leading edge article to be used for future LFC transport aircraft operations. The application of the best available material technology and bonding processes were utilized to optimize the design article for weight and structural integrity.

Specific objectives for Lockheed are to:

(a) Provide a leading edge segment of such a configuration to meet laminar flow control design criteria.

(b) Assure the producibility benefits of such a design.

(c) Fully evaluate the test article to check for disbond, springback, and contour.

4.0 CONCEPT FEASIBILITY STUDIES

The configuration of the advanced concept LFC demonstration component was intentionally designed to be similar to the flight test article from the previous contract (Reference 1). That design was the result of analytical evaluations consistent with the required distributed suction, physical limitations, and slot aerodynamic limits, and demonstrated laminar flow control using a slotted design. The new design involved this same configuration, but with a simpler approach using advanced aluminum alloys and advanced joining methods.

The article was confined to the same physical limitations as the previous article, with slot spacings at a minimum of 0.62 inch. Minimum nominal widths of the slots were about 0.0035 inch.

Several concept configurations were examined in the early stages of this program. The slotted approach was selected due to Lockheed's previous studies in this area, as well as the success of the earlier flight tests on the Northrop X21 program.

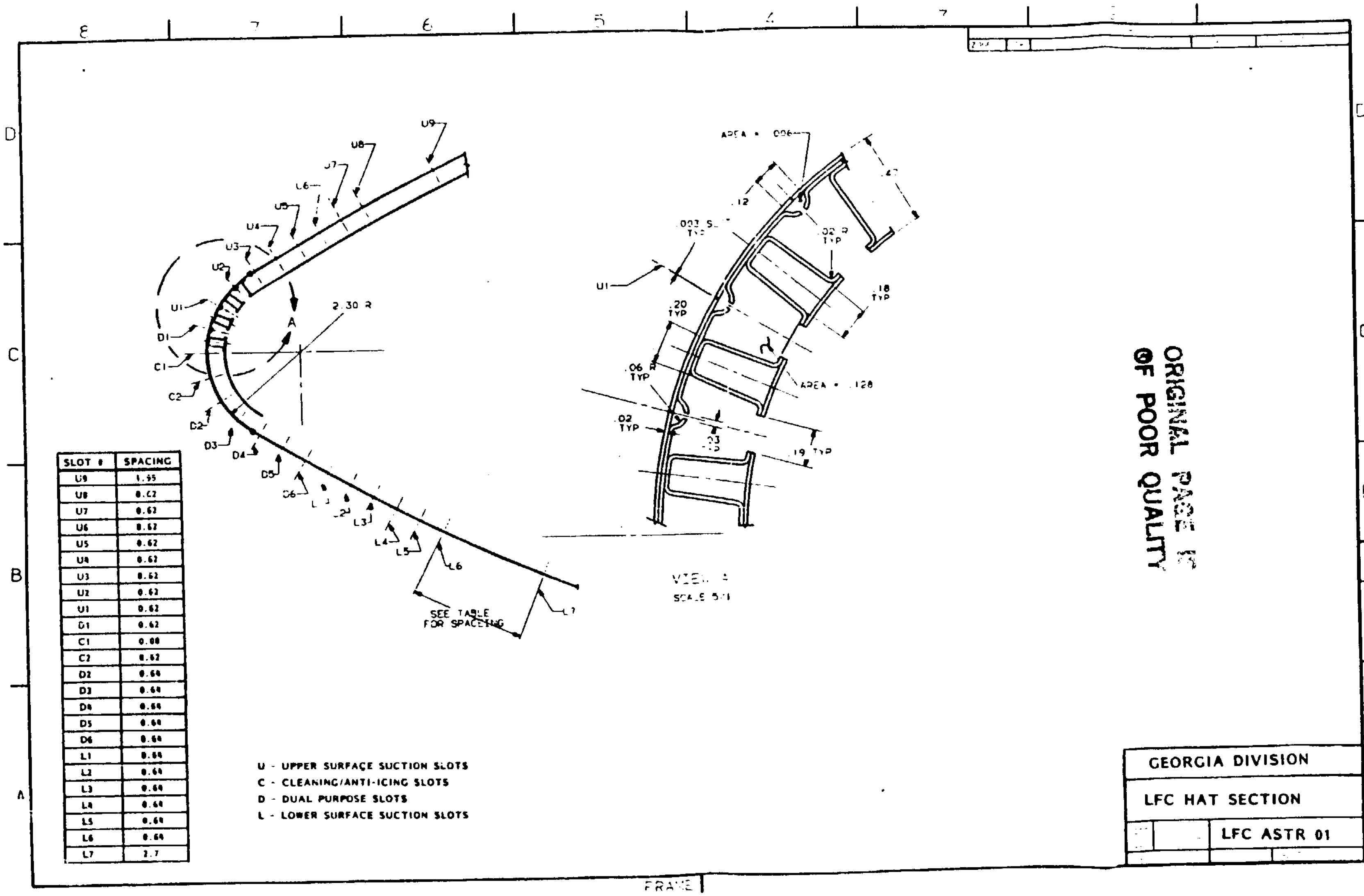
Manufacturing difficulties which have arisen in both previous programs are well documented. However, even with the manufacturing problems which both the X21 and the JetStar LFC components experienced, the flight articles achieved significant modification of the boundary layer to produce a substantial reduction in drag. Such promising results prompted Lockheed to re-examine the slot design with a different manufacturing and assembly approach.

The inherent structural concern with the slotted concept is keyed to the slots themselves. The cutting of slots in the outer skin of the leading edge results in small strips of material attached (usually adhesively bonded) to the substructure. The small bond area and the residual stresses caused during the forming operation combined for possible disbond and springback. Therefore, an approach was selected to compensate for these problems due to the close spacing of the slots.

Diffusion bonding of the outer skin to the slot ducts would achieve shear strengths five times that of any other type bond. In fact, the resultant shear strength of the bond would be 90 percent of the shear strength of the parent alloy. Lockheed determined that this process would eliminate any possible springback and disbonds, plus eliminate the possibility for adhesive flow blocking the slots which occurred in the fabrication of the JetStar leading edge. A hot forming operation was selected to form the small slot ducts to reduce any residual stresses. Lockheed demonstrated that this design was sound in providing the required processes to eliminate the major manufacturing problem on the previous flight article.

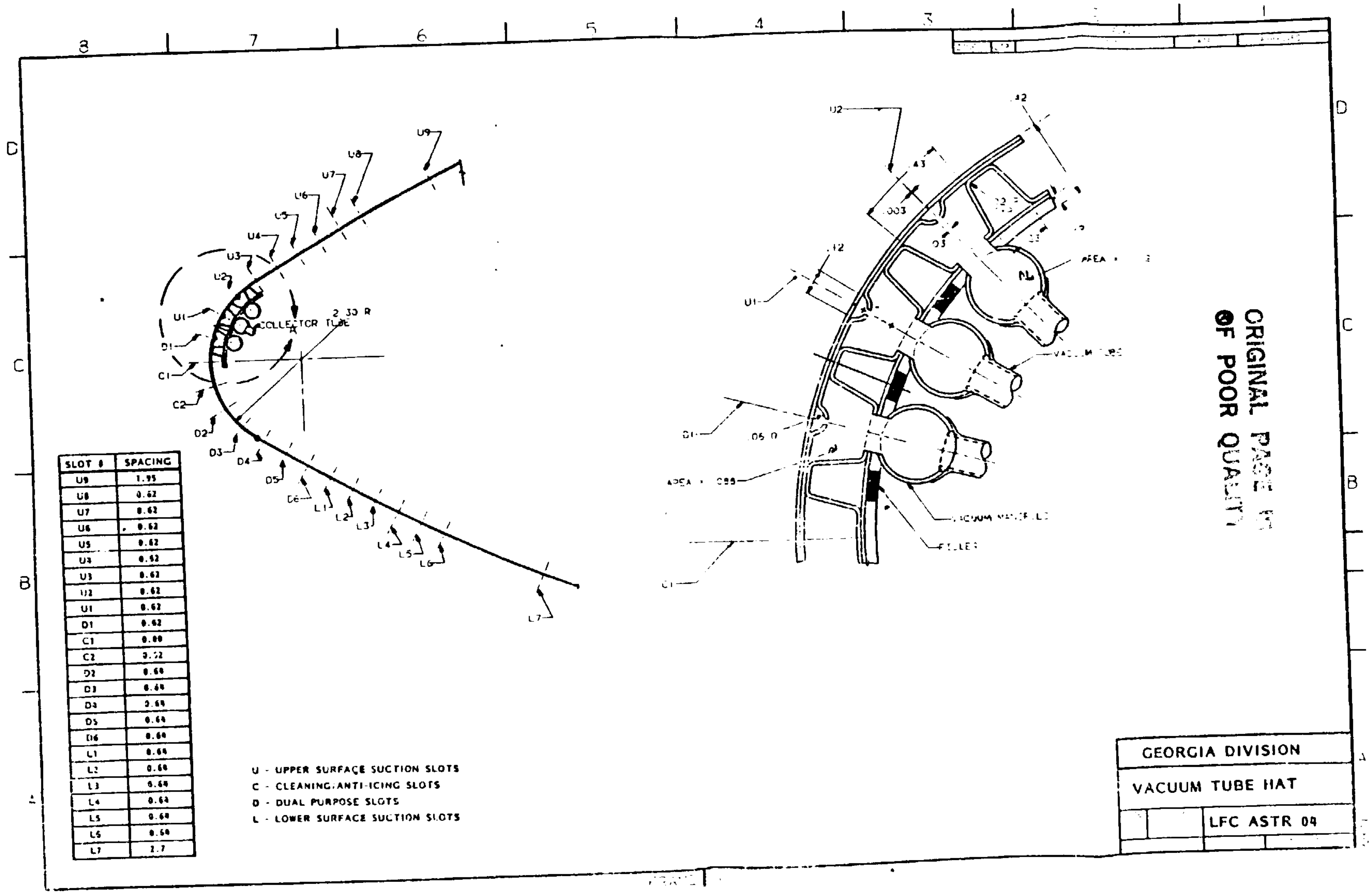
Various structural design concepts were evaluated to offer a simpler manufacturing approach than the JetStar design, as well as for meeting the LFC criteria. The JetStar surface geometry was aerodynamically selected, and there was no reason to change the skin contour. Preliminary design studies showed that the most feasible structural design concepts are shown in Figures 1 through 5. These concepts were all examined to meet the requirements for laminar flow.

The design concept shown in Figure 5 was selected, with the NASA monitor's approval, as the concept which best met the requirements of the program. This concept allowed the use of various innovative processes, such as diffusion bonding and superplastic forming of advanced aluminum alloys. It reduced the complexity of the structure, which enhanced the producibility and the scalability for a large leading edge structure.



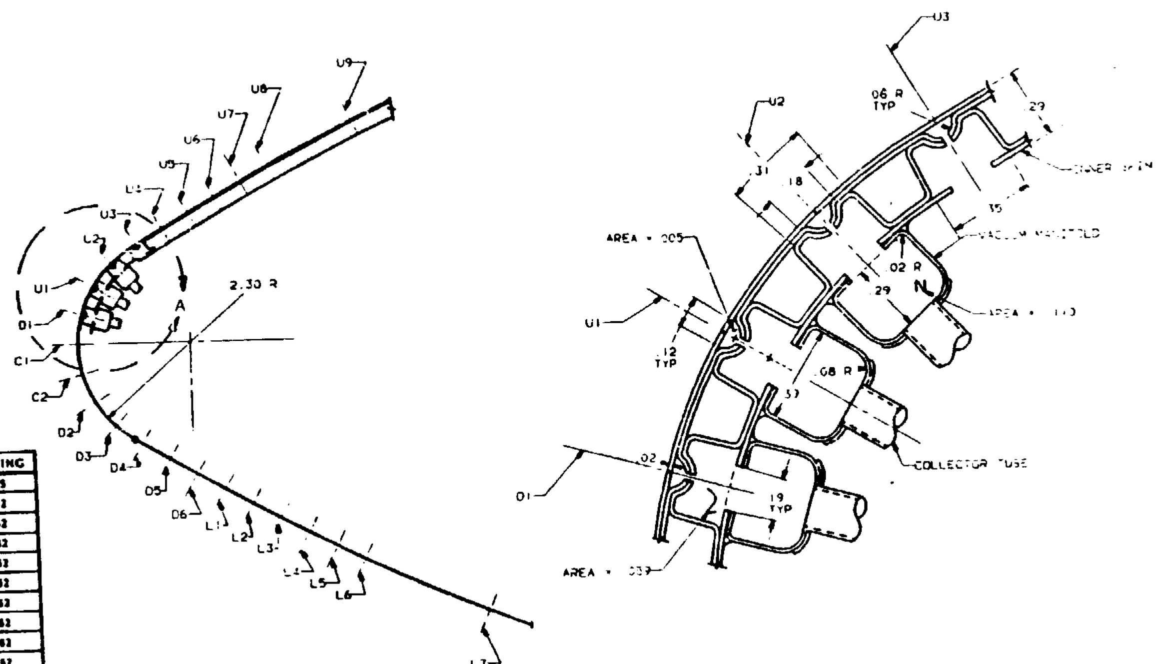
SLOT #	SPACING
U9	1.55
U8	0.62
U7	0.62
U6	0.62
U5	0.62
U4	0.62
U3	0.62
U2	0.62
U1	0.62
D1	0.62
C1	0.00
C2	0.62
D2	0.64
D3	0.64
D4	0.64
D5	0.64
D6	0.64
L1	0.64
L2	0.64
L3	0.64
L4	0.64
L5	0.64
L6	0.64
L7	2.7

Figure 1. Design Concept - 1



SLOT #	SPACING
U9	1.95
U8	0.62
U7	0.62
U6	0.62
U5	0.62
U4	0.62
U3	0.62
U2	0.62
U1	0.62
D1	0.62
C1	0.00
C2	0.32
D2	0.64
D3	0.64
D4	0.64
D5	0.64
D6	0.64
L1	0.64
L2	0.64
L3	0.64
L4	0.64
L5	0.64
L6	0.64
L7	2.7

Figure 2. Design Concept - 2



SLOT #	SPACING
U9	1.95
U8	0.62
U7	0.62
U6	0.62
U5	0.62
U4	0.62
U3	0.62
U2	0.62
U1	0.62
D1	0.62
C1	0.00
C2	0.62
D2	0.64
D3	0.64
D4	0.64
D5	0.64
D6	0.64
L1	0.64
L2	0.64
L3	0.64
L4	0.64
L5	0.64
L6	0.64
L7	2.7

U - UPPER SURFACE SUCTION SLOTS
C - CLEANING/ANTI-ICING SLOTS
D - DUAL PURPOSE SLOTS
L - LOWER SURFACE SUCTION SLOTS

GEORGIA DIVISION
HAT DIMPLED
LFC ASTR 05

Figure 3. Design Concept - 3

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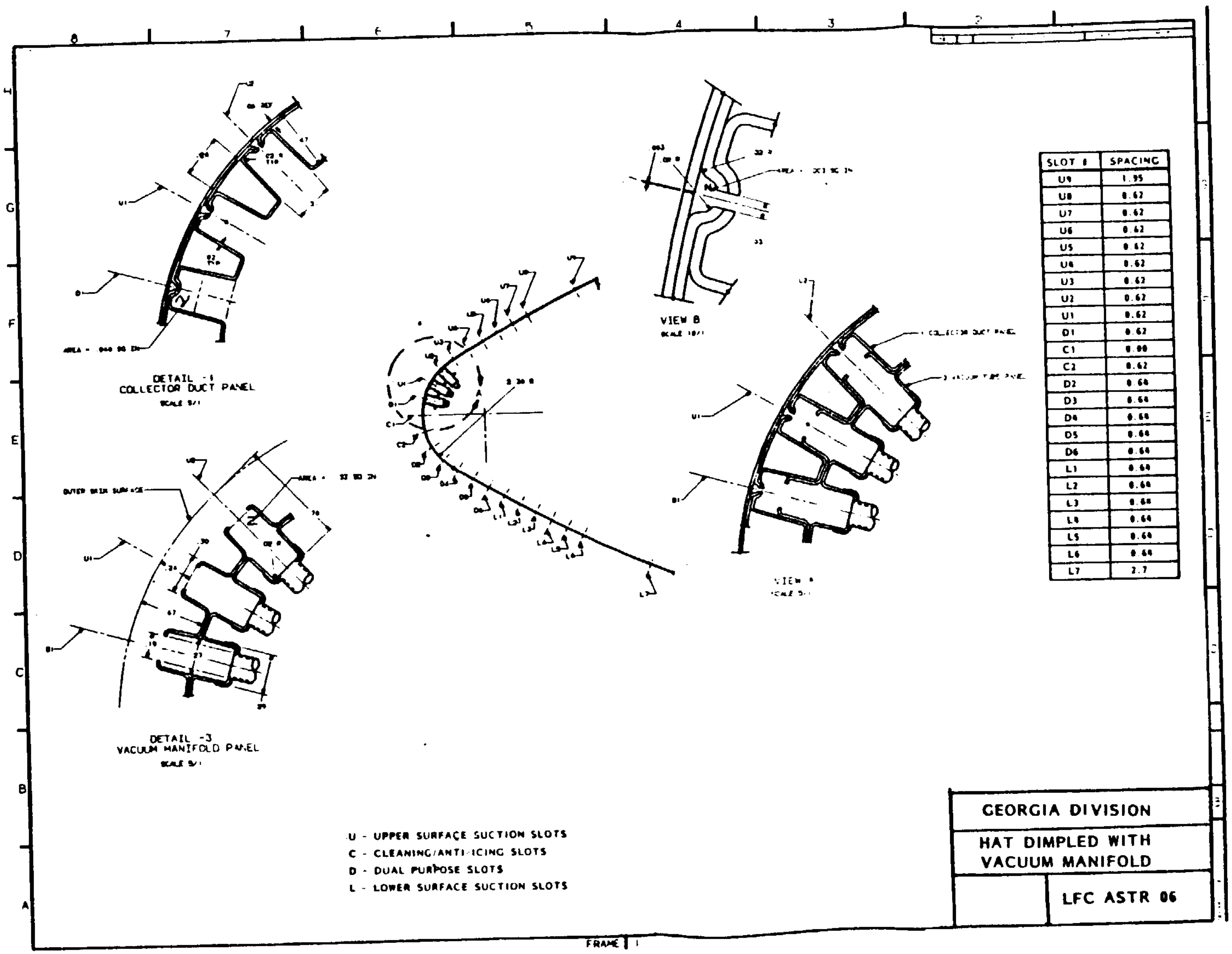
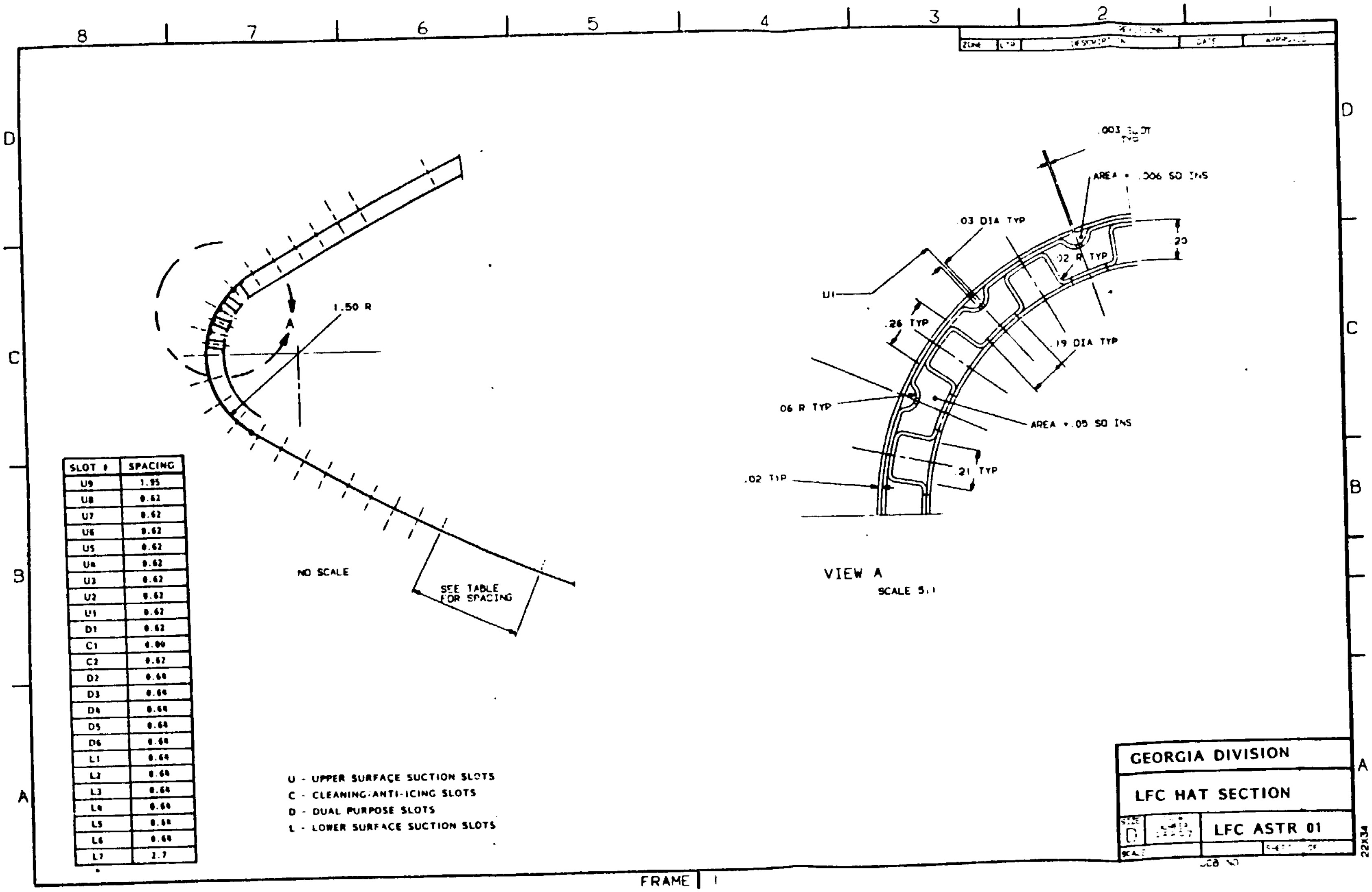


SLOT #	SPACING
U9	1.95
U8	0.62
U7	0.62
U6	0.62
U5	0.62
U4	0.62
U3	0.62
U2	0.62
U1	0.62
D1	0.62
C1	0.00
C2	0.62
D2	0.64
D3	0.64
D4	0.64
D5	0.64
D6	0.64
L1	0.64
L2	0.64
L3	0.64
L4	0.64
L5	0.64
L6	0.64
L7	2.7

Figure 4. Design Concept - 4



SLOT #	SPACING
U9	1.95
U8	0.62
U7	0.62
U6	0.62
U5	0.62
U4	0.62
U3	0.62
U2	0.62
U1	0.62
D1	0.62
C1	0.00
C2	0.62
D2	0.64
D3	0.64
D4	0.64
D5	0.64
D6	0.64
L1	0.64
L2	0.64
L3	0.64
L4	0.64
L5	0.64
L6	0.64
L7	2.7

Figure 5. Final Design Concept - 5

5.0 MATERIAL VERIFICATION

The materials selected in this article are all advanced aluminum alloys. Each of these alloys was selected for its own particular advantageous properties. The powder metal alloys, with excellent corrosion resistance, were selected for the outer skin and slot ducts. The superplastic aluminum alloy 7475-TMT was selected for fabrication of the collector ducts. The inner skin was formed from a low density Al-Li alloy. The combination of these alloys results in a lightweight design with the required stiffness and corrosion resistance.

The material candidates were selected based on Lockheed's experience with the advanced aluminum alloys. The material properties required for this program were corrosion resistance, formability, stiffness, strength, and density. The corrosion resistance and formability were the most important factors considered. The powder metal aluminum alloys were chosen because of their excellent corrosion resistance. Two alloys which have proven to be highly formable were selected for evaluation, IN9052 and 7064. Both alloys have demonstrated good corrosion resistance and formability in previous in-house programs. The superplastic alloy, 7475-TMT (Thermal Mechanical Treatment), was selected as an excellent material for superplastically forming the collector ducts. The aluminum-lithium (Al-Li) alloys were selected for possible application due to their adequate corrosion resistance, high stiffness, low density, and good structural strength to carry the required loads in the leading edge structure.

Salt tests conducted and reported in previous studies indicate adequate corrosion resistance. However, since de-icing fluid will be injected through the system, it was thought necessary to conduct a corrosion test in a de-icing fluid environment. The aluminum alloys offered good resistance in such an environment. Table 1 shows the results of these tests. Titanium, of course, provided the best protection, but the aluminum alloys were also quite adequate. The rating system is based on the ASTM standard exfoliation corrosion (EXCO) test. The "N" and "P" ratings mean "no apparent damage" and "slight pitting", respectively.

Table 1. Exfoliation Test Results

	30 DAY ALTERNATE IMMERSION
TITANIUM	N
IN9052 PM	P
Al-Li	P
747S TMT	P

N = NO APPARENT CORROSION
P = SLIGHT PITTING ON SURFACE

6.0 FORMING AND JOINING EVALUATION

Since the approach used to fabricate the demonstration article involved new and innovative joining and forming processes, these processes were examined to fully understand the benefits and risks involved. The primary joining concept was diffusion bonding, with adhesive bonding and spot welding as backups. Superplastic forming was used to fabricate the hat sections, which were used for the collector ducts.

Texas Instruments, located in Attleboro, Massachusetts, was subcontracted to conduct the diffusion bonding operation. Texas Instruments uses a cold roll bonding process. Prior to bonding, metal surfaces are chemically and mechanically cleaned to provide contaminant-free surfaces. Bonding is achieved by passing the metal sheets through a specially-designed rolling mill where extremely high reduction in the sheet gages forces the layers into intimate contact. During this bonding process, new surface is exposed, allowing bonding surfaces which are virtually defect-free. The thermal expansion process is introduced by placing specialized stop-off materials between the layers of metal before bonding. Thermal treatment after bonding eliminates any thermodynamic instabilities and allows for shared material grain at the bonded surface between sheets. This thermal treatment also causes the stop-off material to expand, forcing the unbonded sheet into shaped dies at the locations of the stop-off. The end result is a shaped configuration of the slot duct diffusion bonded to the outer skin, with shear strengths nearly equal to the shear strength of the monolithic alloy. This process is shown in Figure 6.

Figure 7 shows a small sample made using the diffusion bonding and forming process to be utilized. This section was bonded and formed flat. Figure 8 shows the same panel after forming to a curvature, with slots cut using a saw blade. No trouble was experienced with the hot forming operation or the slot cutting.

Joining tests were conducted to evaluate diffusion bonding, adhesive bonding, and spot welding. The results of these tests are shown in Tables 2, 3, and 4 for diffusion bonding, adhesive bonding, and spot welding, respectively. Table 5 shows the average of the shear tests for the three bonding processes. The diffusion bond process results in the highest shear strength, approximately 85 percent of the shear strength of the

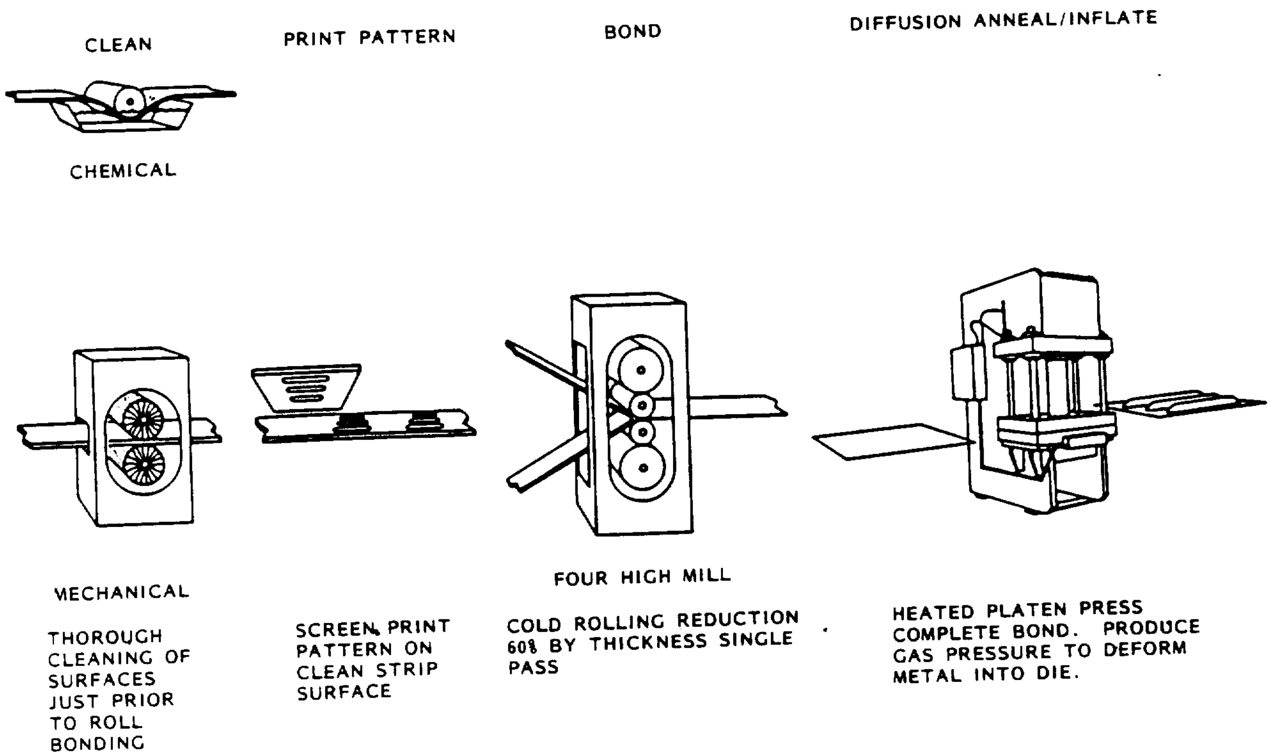


Figure 6. Texas Instruments Thermal Expansion and Diffusion Process

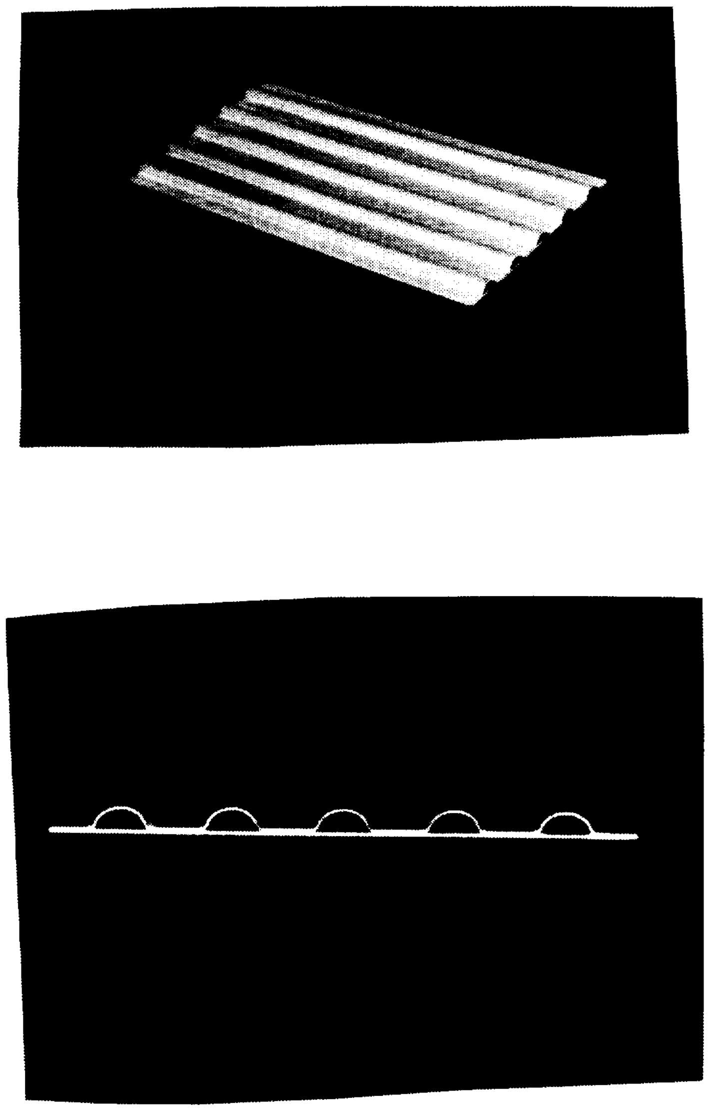
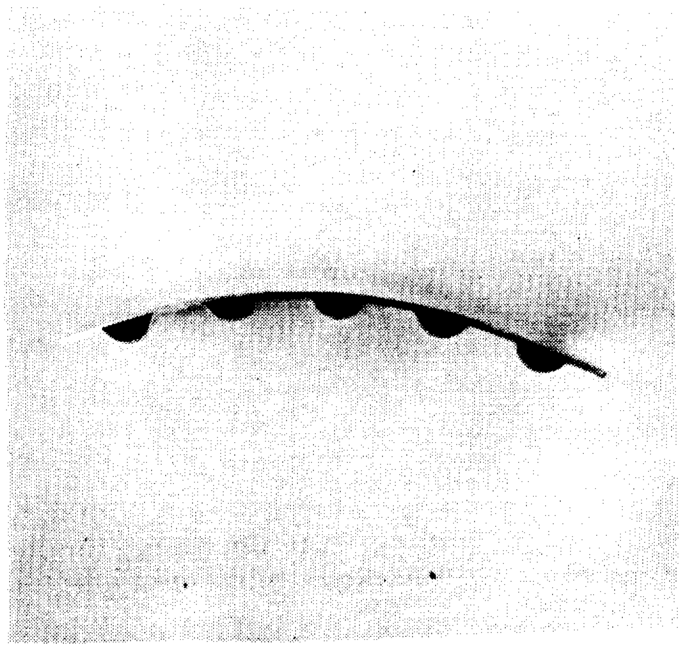
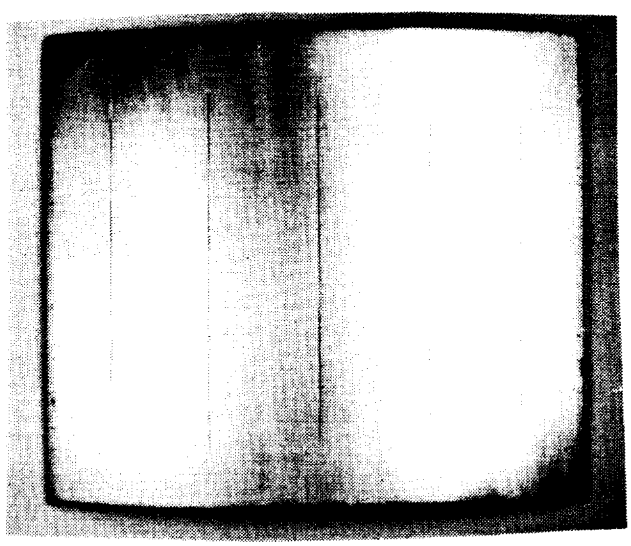


Figure 7. Slot Ducts Diffusion Bonded to Outer Surface in a Flat Panel



SIDE VIEW



TOP VIEW

Figure 8. Photographs of the Outer Sheet Diffusion Bonded with Slot Ducts

Table 2. Lap Shear Test Results of Diffusion Bonded IN9052 Sheet

SPECIMEN NO.	SHEAR STRENGTH (PSI)
PM-1	18,700
PM-2	17,700
PM-3	22,000
PM-4	18,000
PM-5	18,000
PM-6	16,900
PM-7	16,900
PM-8	16,600

Table 3. Lap Shear Test Results for Adhesive Bonded Lap Joint

SPECIMEN NO.	SHEAR STRENGTH (PSI)
7475-1	4,400
-2	4,900
-3	5,100
-4	5,400
-5	5,300
7064-1	5,300
-2	5,300
-3	5,400
-4	5,400
-5	5,500

Table 4. Lap Shear Test Results of Spot Welded Al-Li Specimens

SPECIMEN NO.		SHEAR STRENGTH (PSI)
Al-Li:	-1	5,746
	-2	6,168
	-3	6,469
	-4	5,589
	-5	5,440
	-6	6,255
	-7	6,377
	-8	5,838

Table 5. Average Shear Strengths of the Different Bond Processes

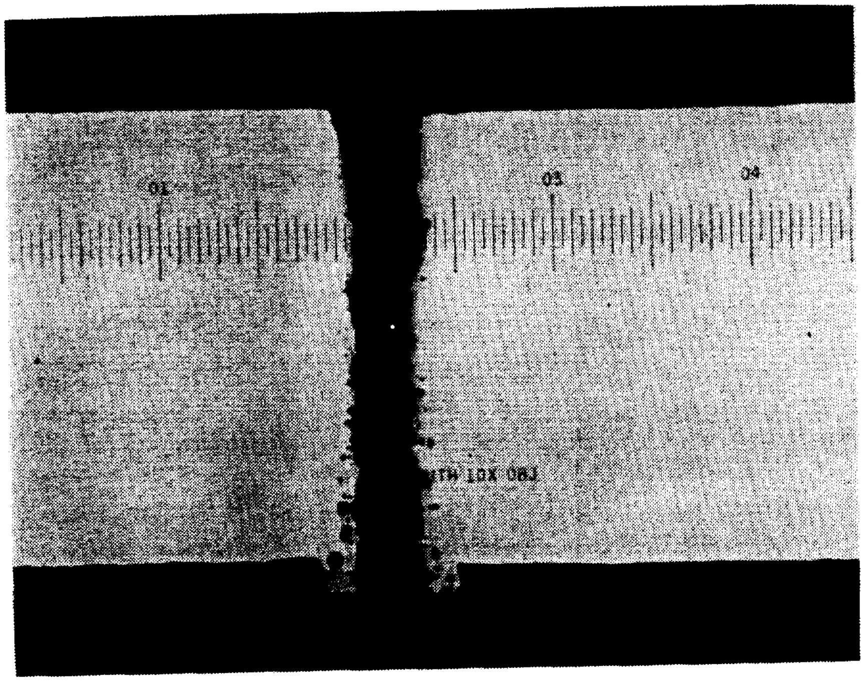
TYPE OF BOND	AVERAGE SHEAR STRENGTH (PSI)
Diffusion Bond	18,100
Adhesive Bond	5,200
Spot Weld	5,955

monolithic parent alloy. The adhesive bond and weld strengths were approximately equal. The diffusion bond process was selected for joining the outer skin and the slot ducts to avoid adhesive flow into the laminar flow control ducting and slots, and also to prevent springback. Although the diffusion bonding process offers the most advantages, the present technology prevents using this process in other areas. For example, a three-sheet layup could be used to bond the outer skin to the slot ducts and the slot ducts to the collector ducts in one operation. However, current technology prevents three-sheet layups. The adhesive bond was selected for utilization in interfaces where the diffusion bond process could not be used. The seam welding process requires a welding wheel to contact the bonding surface. The tight radius of the leading edge section will not allow adequate area for the wheel, thus preventing a proper weld.

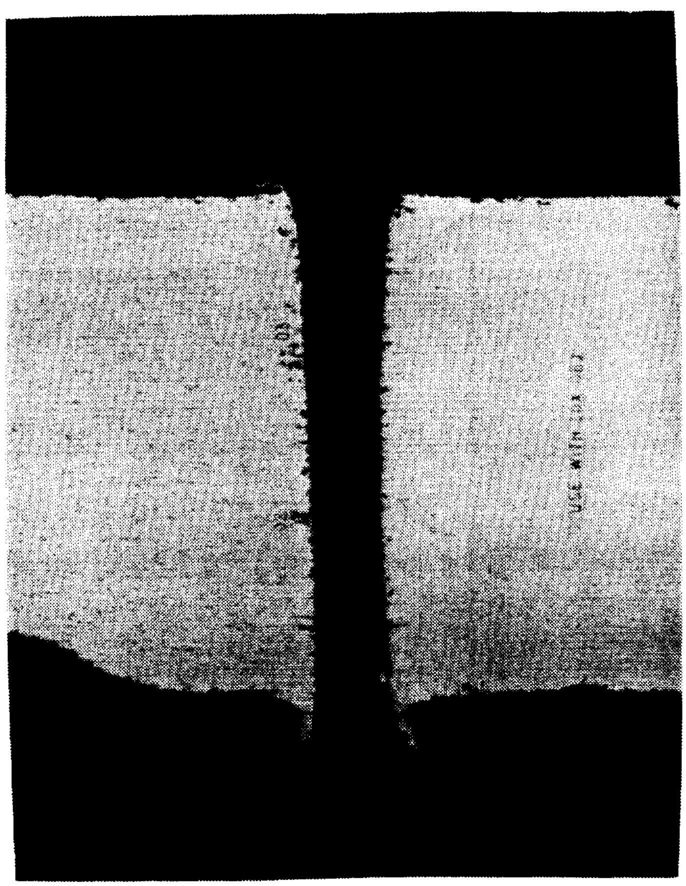
To evaluate cutting methods, a sheet of IN9052 was sent to Penn Research Corp. (PRC) for laser cutting of the slots. These slots were examined and compared to slots cut using a saw blade. Figure 9 shows a cross-section of the two types of cut slots. The laser cut slot had porous metal through the thickness, as well as on the back side. The saw blade slot had a much cleaner cut. Plus, the laser slot was measured to be 0.0045 inch wide and the saw blade cut was 0.003 inch wide. It was decided from this information to use the saw blade on the final article for a cleaner and smaller slot. One major concern in cutting the slots was to assure that the slots are over the slot ducts. The diffusion bonding process leaves an imprint on the outer surface which could be followed. However, these imprints disappear after cleaning operations. Therefore, X-rays were taken of the part and a film positive was made. The film positive was used as a template to follow the slot ducts. This technique did assure proper alignment between the slots and the ducts.

Lockheed performed trial superplastic forming operations using the 7475-TMT sheet to fabricate the collector ducts. The superplastic forming operation is graphically depicted in Figure 10. The flat sheets were placed over a female tool, enclosed and heated to 960°F. A regulated strain rate using argon gas was exerted from the top, thereby forcing the sheet to conform to the female mold.

The machined tool used to form the corrugated collector ducts is shown in Figure 11. The superplastically formed collector ducts taken from the die are shown in Figure 12.



Laser



Saw Blade

Figure 9. Cross-Section of the Two Types of Processes Used to Cut Slots

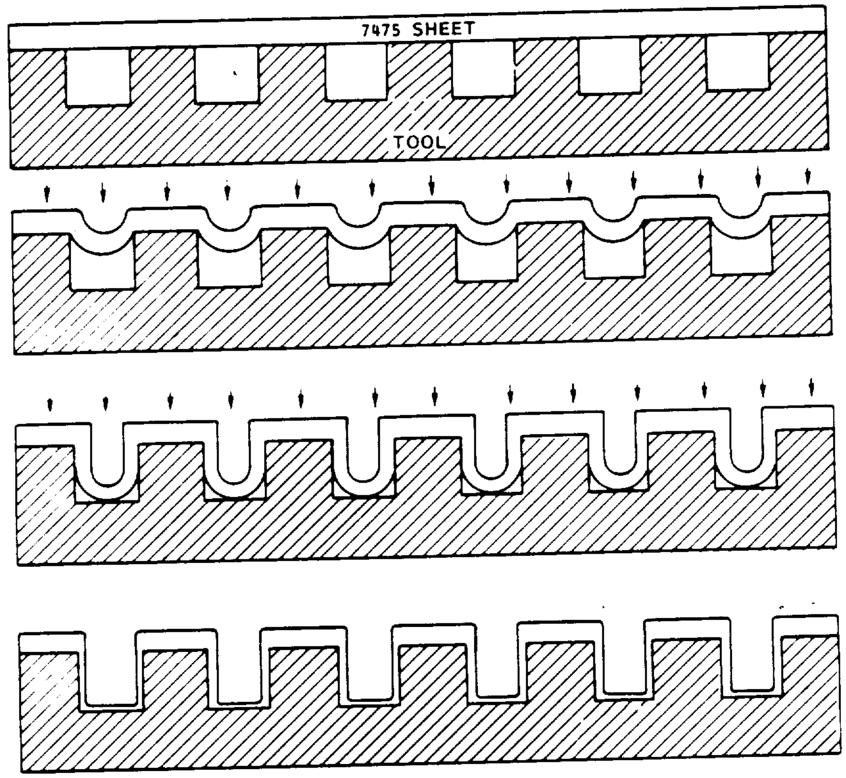


Figure 10. Superplastic Forming Process to Fabricate the Collector Ducts

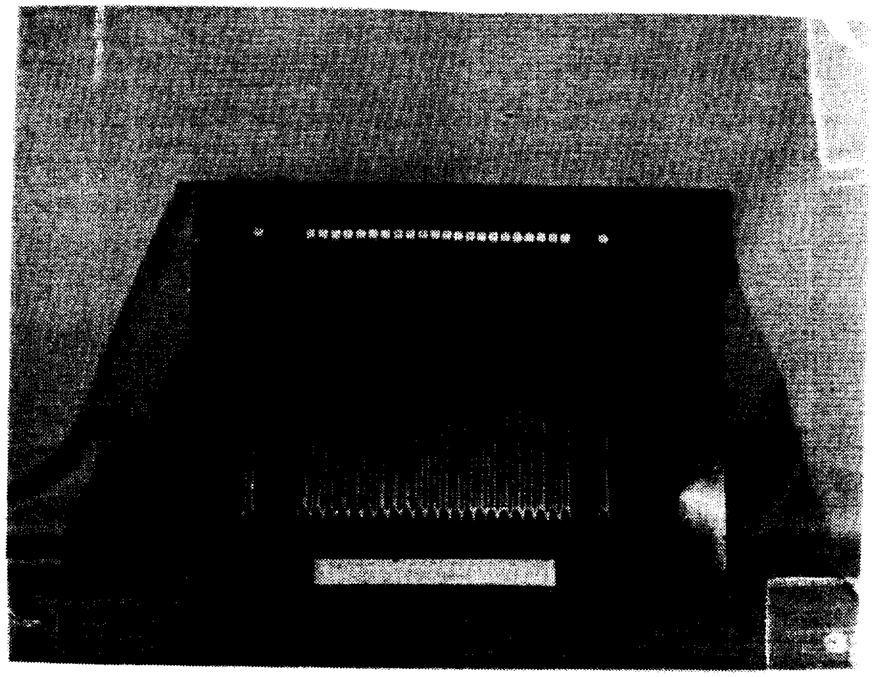


Figure 11. Photograph of Tool Used to Form Collector Duct

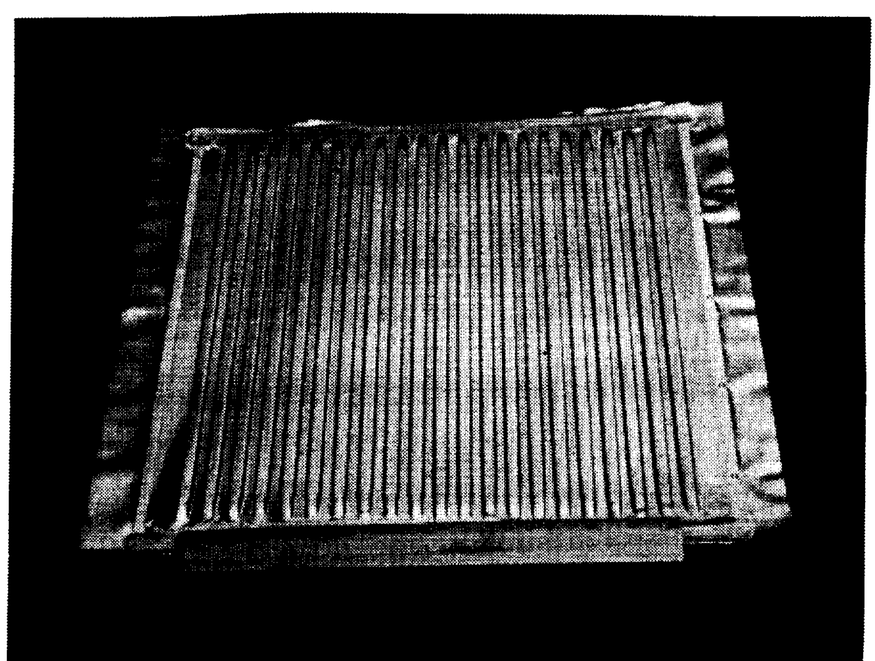


Figure 12. Superplastically Formed Collector Ducts in the Flat

7.0 PRELIMINARY STRUCTURAL DESIGN

Preliminary stress and aero analysis was conducted along with the production drawings of the tools and demonstration article. The optimum design configuration selected in the JetStar flight article program was selected as the desired geometry for this proof-of- concept article. An extremely tight leading edge radius was selected to demonstrate the producibility of the new approach. The JetStar configuration is shown in Figure 13. This cross-section shows the individual slot locations with their identification. Table 6 shows the slot spacing and slot widths at each location. The metering/ducting geometry of the JetStar LFC article is shown in Table 7. This geometry was selected for the demonstration article.

Several design concepts were examined; however, the concept selected appeared to possess similar geometry to that of the JetStar, which has successfully demonstrated laminar flow characteristics. The slot/duct geometry of the new design is shown in Table 8, which can be compared to Table 7, depicting the JetStar geometry. Both geometries are relatively similar.

The detail drawings of the tools and the leading edge demonstration article were made using Lockheed's Computer Augmented Design and Manufacturing (CADAM) system. The article shown in Figure 14 was 12 inches long in the spanwise direction and approximately 8 inches long in the chordwise direction. The production drawing of the article and corrugated tool to produce the collector ducts is shown in Figure 15.

Preliminary stress and aero analysis were conducted to verify that the structure would be able to handle the expected air pressures and loads for the leading edge and meet the requirements to achieve laminar flow.

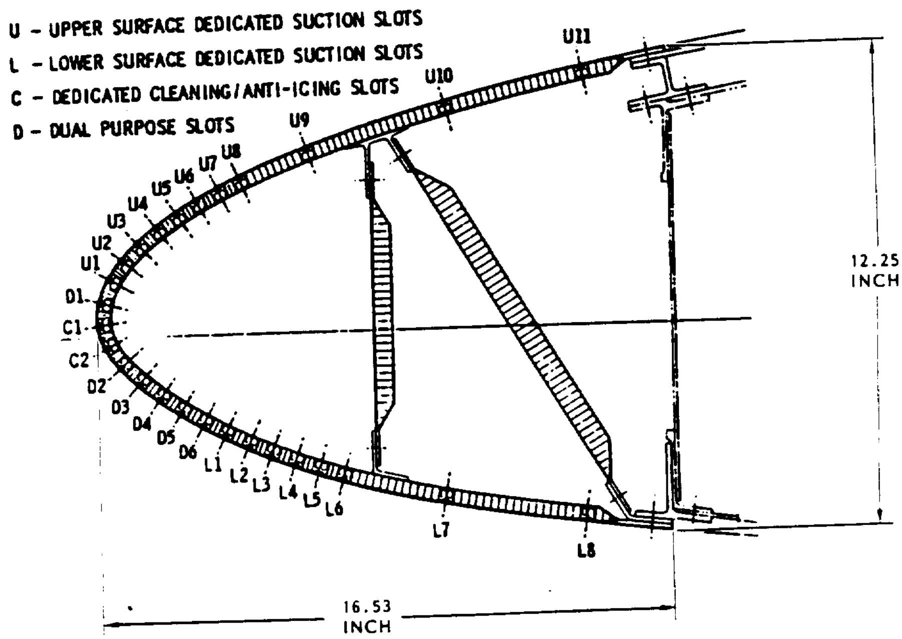


Figure 13. JetStar Leading Edge Slot Locations

Table 6. Slot Ducting Geometry

SLOT IDENT.	LOCATION x/c*	SLOT SPACING CN*		SLOT WIDTH W		MANIFOLD TUBE INSIDE DIAMETER		MANIFOLD ROUTING
		CM	IN	CM	IN	CM	IN	
D2	.00516	--	--	.0094	.0037	0.79	5/16	OUTBOARD
D3	.00929	1.63	0.64	.0094	.0037	1.11	7/16	OUTBOARD
D4	.01384	1.63	0.64	.0094	.0037	1.11	7/16	OUTBOARD
D5	.01865	1.63	0.64	.00945	.0037	1.11	7/16	OUTBOARD
D6	.02363	1.63	0.64	.0094	.0037	1.11	7/16	OUTBOARD
L1	.2874	1.63	0.64	.0094	.0037	1.11	7/16	INBOARD
L2	.03395	1.63	0.64	.00945	.0037	1.11	7/16	INBOARD
L3	.03925	1.63	0.64	.0094	.0037	1.11	7/16	INBOARD
L4	.04466	1.63	0.64	.0094	.0037	1.11	7/16	OUTBOARD
L5	.05011	1.63	0.64	.0094	.0037	1.11	7/16	OUTBOARD
L6	.05562	1.63	0.64	.0094	.0037	1.11	7/16	OUTBOARD
L7	.07922	6.86	2.7	.0102	.0040	1.11	7/16	INBOARD
L8	.10711	7.87	3.1	.0114	.0045	1.11	7/16	INBOARD

Table 6. Slot Ducting Geometry (Continued)

SLOT IDENT.	LOCATION x/c*	SLOT SPACING CN*		SLOT WIDTH W		MANIFOLD TUBE INSIDE DIAMETER		MANIFOLD ROUTING
		CM	IN	CM	IN	CM	IN	
C1	.00010	--	--	.0094	.0037	1.11	(7/16)	(COMBINED
C2	.00190	--	--	.0094	.0037	--	--	INBOARD)
D1	.00055	--	--	.0094	.0037	1.11	7/16	OUTBOARD
U1	.00269	1.57	0.62	.0094	.0037	1.11	7/16	OUTBOARD
U2	.00584	1.57	0.62	.0094	.0037	1.43	9/16	INBOARD
U3	.00967	1.57	0.62	.0094	.0037	1.27	1/2	INBOARD
U4	.01397	1.57	0.62	.0094	.0037	1.27	1/2	INBOARD
U5	.01857	1.57	0.62	.0094	.0037	1.27	1/2	INBOARD
U6	.02337	1.57	0.62	.0094	.0037	1.27	1/2	INBOARD
U7	.02829	1.57	0.62	.0094	.0037	1.27	1/2	INBOARD
U8	.03330	1.57	0.62	.0094	.0037	1.27	1/2	INBOARD
U9	.04951	4.95	1.95	.0102	.0040	1.27	1/2	INBOARD
U10	.08106	9.40	3.70	.0114	.0445	1.27	1/2	INBOARD
U11	.11299	9.40	3.70	.0127	.0050	1.27	1/2	INBOARD

Table 7. Metering/Ducting Geometry

SLOT DUCT	0.1520 CM (0.06 IN) RADIUS - SEMICIRCULAR	
METERING ORIFICE - DIAMETER	0.076 CM (0.030 IN) (EXCEPT 0.089 CM (0.035 IN) FOR U11)	
METERING ORIFICE - DEPTH	0.356 CM (0.14 IN)	NOMINAL
METERING ORIFICE - SPACING	0.508 CM (0.20 IN)	NOMINAL
COLLECTOR DUCT - WIDTH	0.787 CM (0.31 IN)	NOMINAL
COLLECTOR DUCT - DEPTH	0.406 CM (0.16 IN)	NOMINAL
COLLECTOR DUCT OUTLET - DIAMETER	0.478 CM (0.188 IN)	NOMINAL
COLLECTOR DUCT OUTLET - THICKNESS	0.203 CM (0.08 IN)	MINIMUM
COLLECTOR DUCT OUTLET - SPACING	15.24 CM (6.0 IN)	TYPICAL

Table 8. Metering/Ducting Geometry for Demonstration Article

SLOT DUCT	0.06 IN RADIUS
METERING ORIFICE - DIAMETER	0.030 IN.
METERING ORIFICE - DEPTH	0.024 IN.
METERING ORIFICE - SPACING	0.20 IN.
COLLECTOR DUCT - WIDTH	0.243 IN.
COLLECTOR DUCT - DEPTH	0.20 IN.
COLLECTOR DUCT OUTLET - DIAMETER	0.190 IN.
COLLECTOR DUCT OUTLET - THICKNESS	0.032 IN.

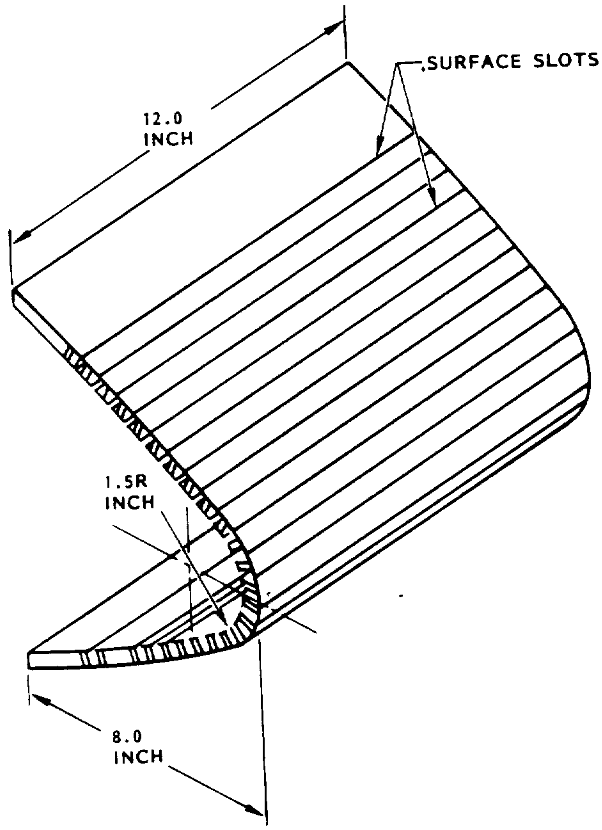


Figure 14. Demonstration Article

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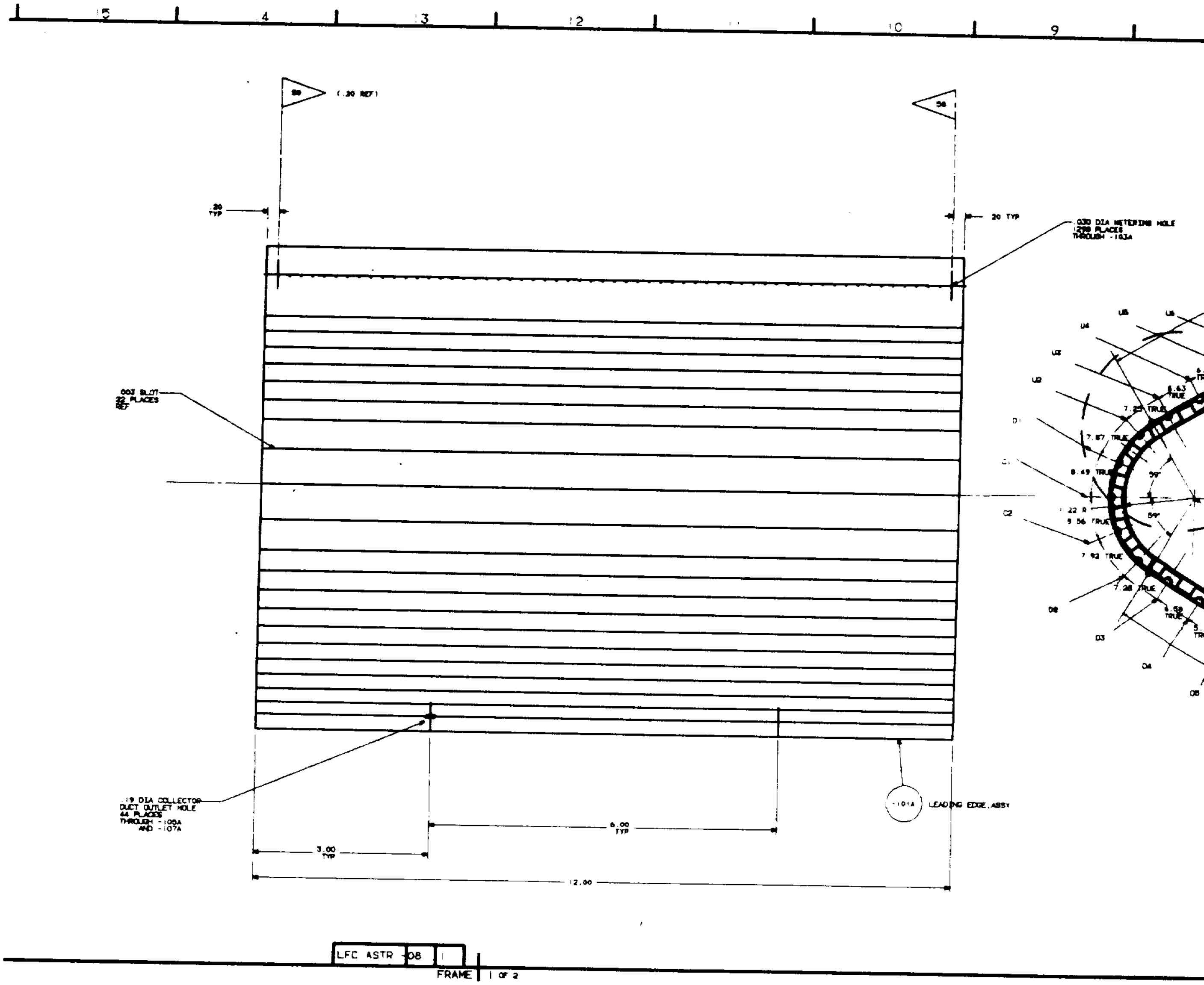
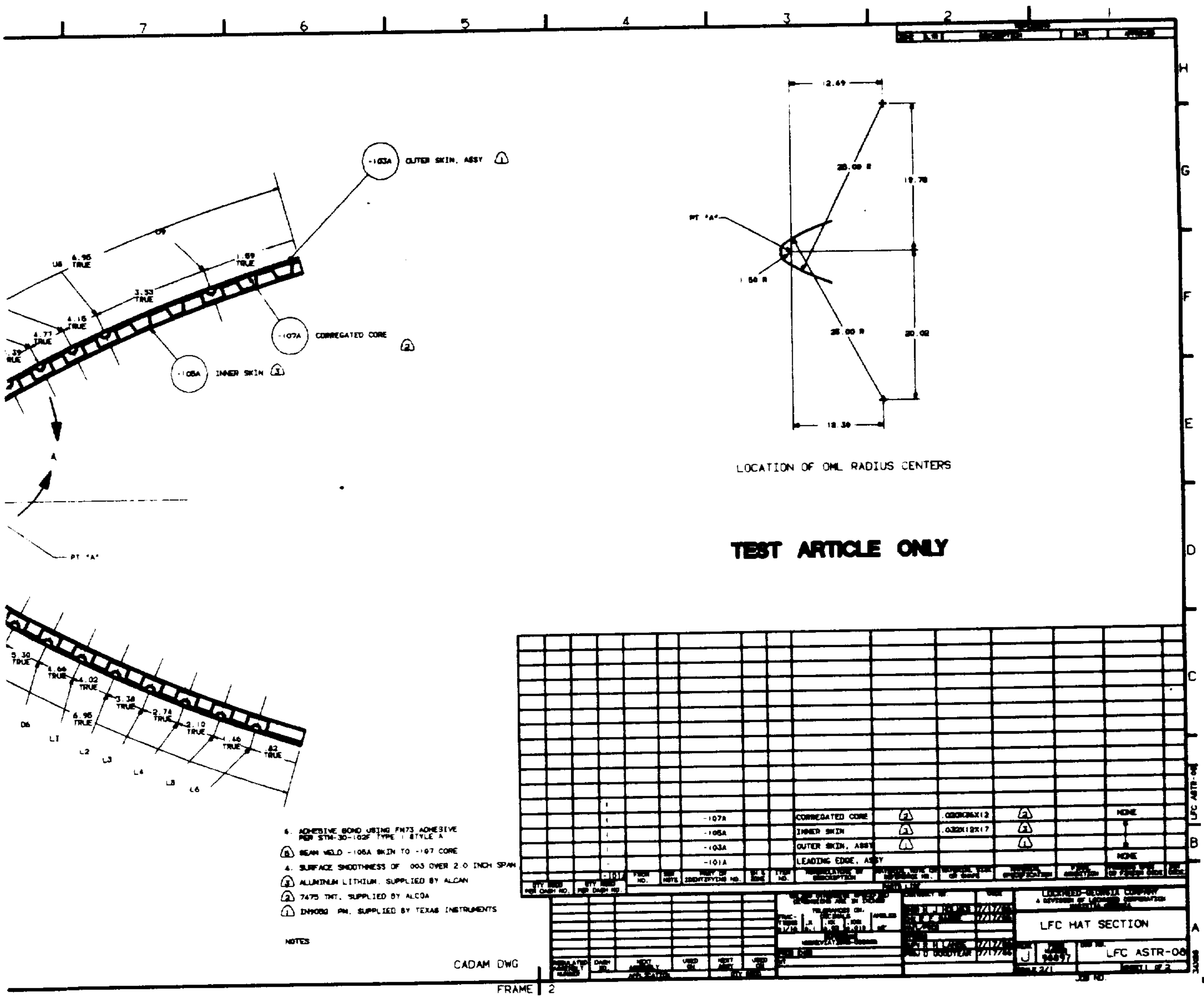


Figure 15. Production Drawing

FOLDOUT FRAME



of the Final Article (Sheet 1 of 2)

2 FOLDOUT FRAME

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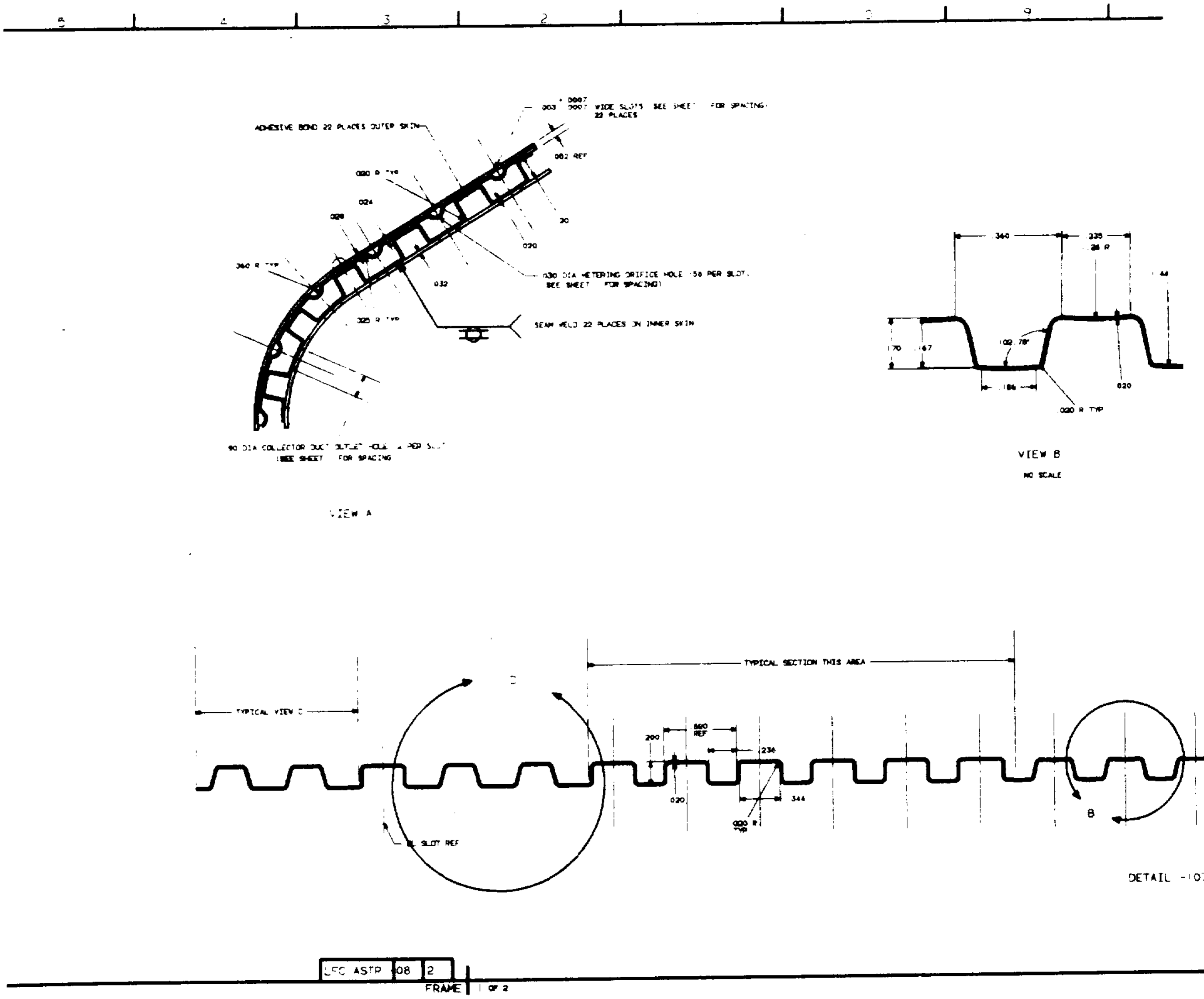

Figure 15. Production Drawing of

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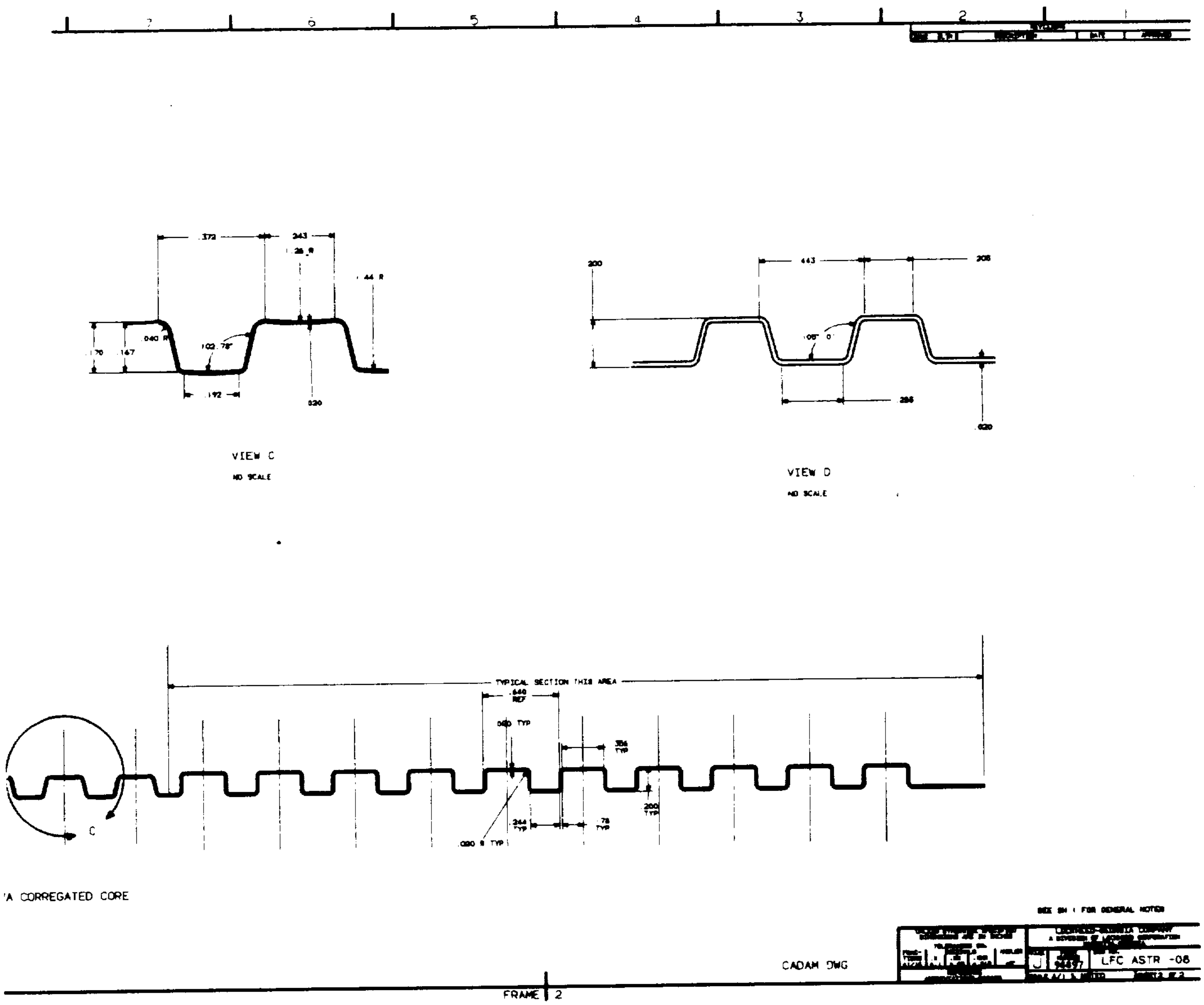

the Final Article (Sheet 2 of 2)

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8.0 FABRICATION OF DEMONSTRATION ARTICLE

Innovative manufacturing processes were used in the fabrication of the demonstration article. Diffusion bonding and superplastic forming of aluminum alloys are advanced processes beyond the current state-of-the-art. The diffusion bond offers the highest shear strength over any other current bonding system and can be done simultaneously with the forming operation. Superplastic forming is a cost-effective process, required in this instance due to the close proximity of the individual hat sections (collector ducts) to each other. It is much more effective to install an integrally connected series of hat sections than individual hat sections. Each of these two advanced processes provides a unique approach to overcome the inherent problems associated with the slotted concept, which are springback of the cut strips of the outer skin and avoiding the slot ducts and metering holes from being clogged with adhesive. Texas Instruments (TI), located in Attleboro, Massachusetts, had developed a diffusion bond and expansion process being evaluated by several aerospace companies. Due to this expertise, TI was subcontracted to conduct the diffusion bonding operation.

The outer skin and the slot duct were diffusion bonded using the powder metal alloy sheet IN9052. The collector ducts were superplastically formed using 7475-TMT sheet alloy in Lockheed Manufacturing Research's superplastic forming facility, which is shown in Figure 16.

The inner Al-Li skin was roll formed to the leading edge shape. All sections were adhesively bonded using FM300 adhesive film in an autoclave at 350°F.

Texas Instruments cold rolled 2024 sheet initially to demonstrate the feasibility of the diffusion bonding/thermal expansion process. First, a print layout was produced to provide the proper position of the disbonding and thermal expansion ink. This ink was then stamped out on one of the two mating sheets as it was fed into the 24-inch rolling mill. The cold rolling mill reduced the initial gages of both sheets by approximately 60 percent. The proper amount of ink, as well as a concise alignment, is required to produce an article with such tight tolerances and precise locations of disbond to form the slot ducts.

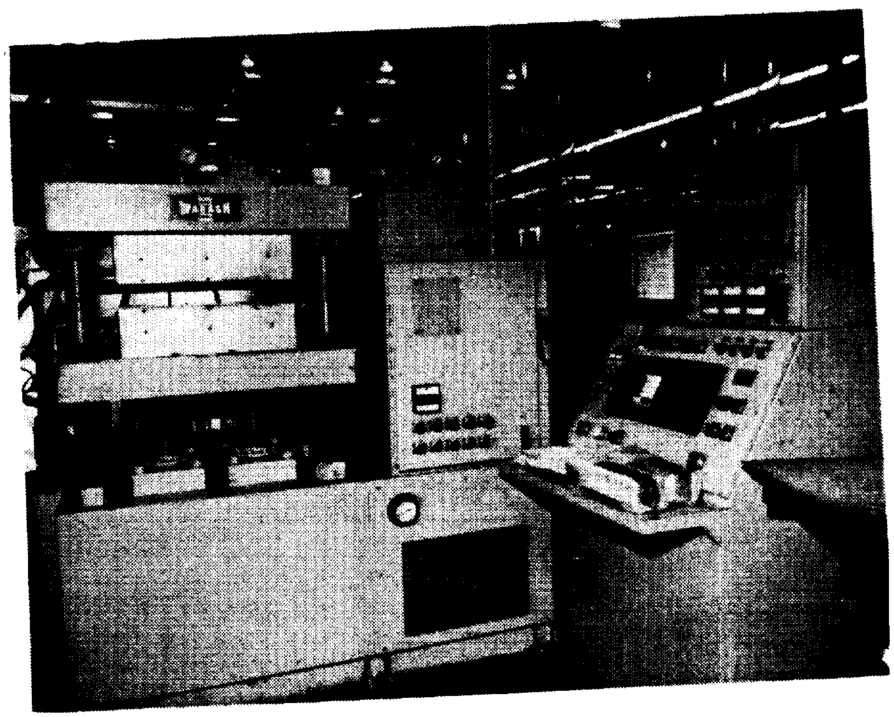


Figure 16. Lockheed's Superplastic Forming Facility Used to Form Collector Ducts

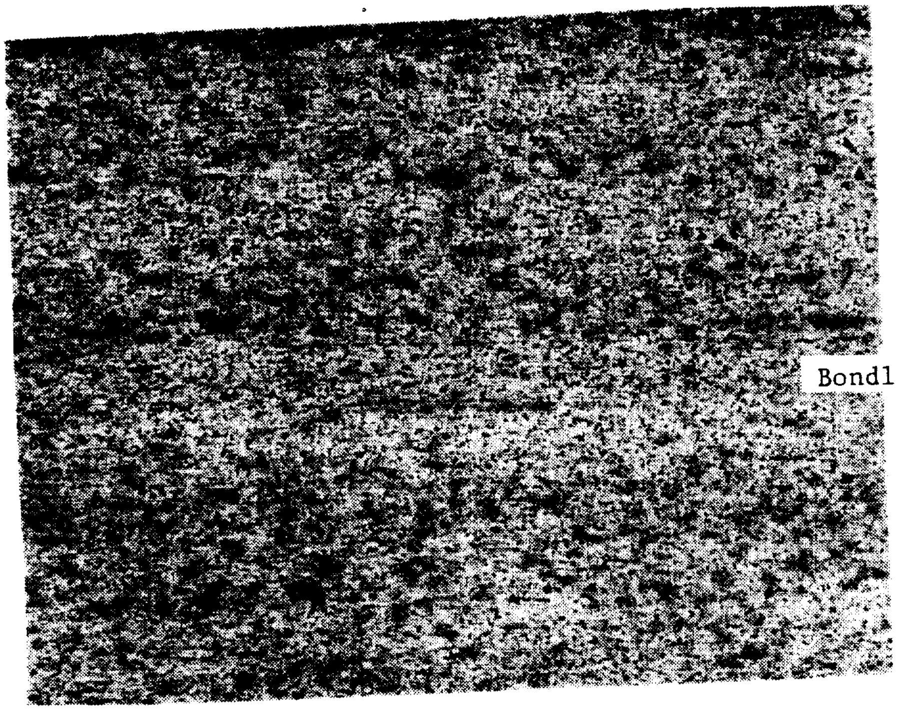
The two sheets were sintered after the cold roll operation to reinforce the "green" bond. A green bond is the initial bond after cold rolling,, which has yet to be heat treated to achieve the ultimate bond strength. Figure 17 shows a microstructural photograph of the two sheets after bonding. The operation causes grain growth across the bondline, producing a near-monolithic material. The bonded sheets were placed in a flat tool, which had slot ducts cut out for thermal expansion or "inflation". The platen press shown in Figure 18 was heated to cause the ink to vaporize. The pressure of the vapor expanded the lower surface sheet into the tool, producing the required slot duct geometry shown in Figure 19.

The flat expanded sheet was placed in a matched set of tools shown in Figure 20. The male tool, in the leading edge contour, had slot duct cutouts for proper alignment. The heated sheets were placed in the hot tools and formed to the leading edge curvature, as shown in Figure 21. The result was an expanded slot duct metallurgically bonded to the outer skin in the leading edge contour, as shown in Figure 22. These sections were shipped to Lockheed for final assembly. A closeup of a single slot duct as received from TI, is shown in Figure 23.

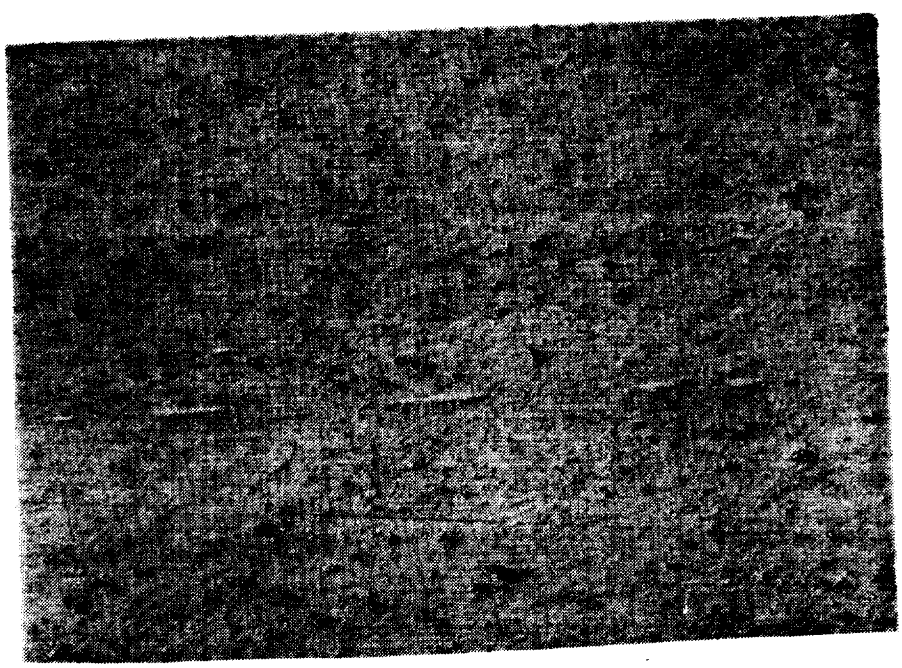
Lockheed, on delivery of the outer skin/slot duct sections, drilled metering holes in the slot ducts. The metering holes were 0.030 inch in diameter with 0.20 inch spacing, as shown in Figure 24.

Final assembly was accomplished in Lockheed's Manufacturing Research Department. The slot ducts, collector ducts, and the inner skin, which was cold rolled to the leading edge shape, were cleaned, anodized, and primed for adhesive bonding. A special mold fixture was manufactured to assure the final leading edge shape. This tool is shown in Figure 25. Figure 26 shows the Al-Li inner skin placed on the tool with the curved collector duct panel being placed over it. Figure 27 shows the collector duct panel in place and the outer skin and slot ducts placed on the tool.

A low flow adhesive, FM300, was used to ensure bond integrity with no adhesive buildup around the metering holes. The parts were bagged and placed in the autoclave for curing at 350°F. Figure 28 shows different views of the panel as taken from the autoclave.



Bondline of Interleaf



Bondline

Figure 17. Microstructural Photographs of the IN9052 PM Bondline

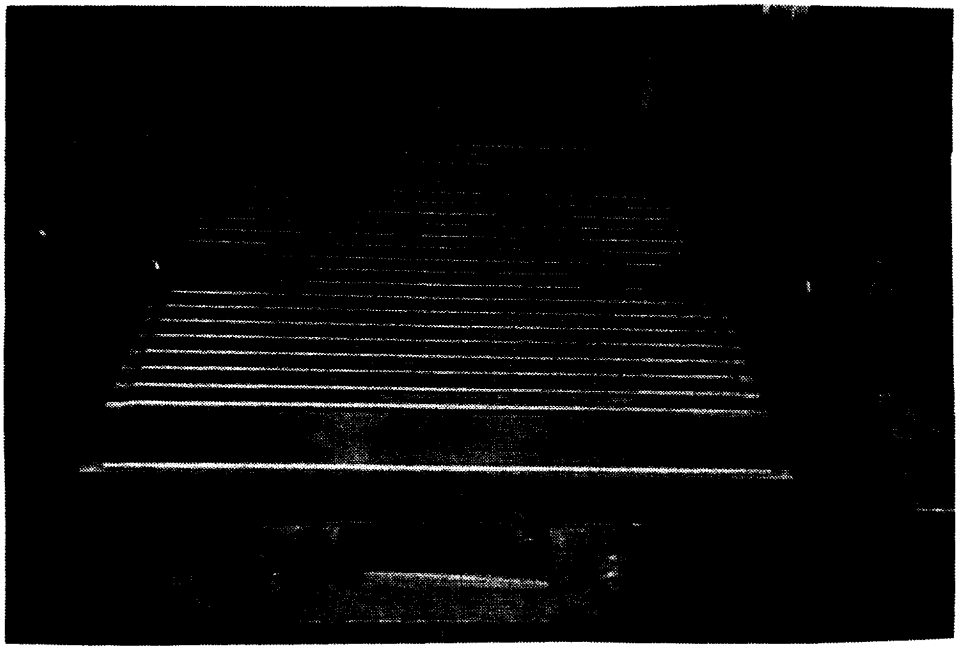


Figure 18. Flat Tool Used to Form Slot Ducts

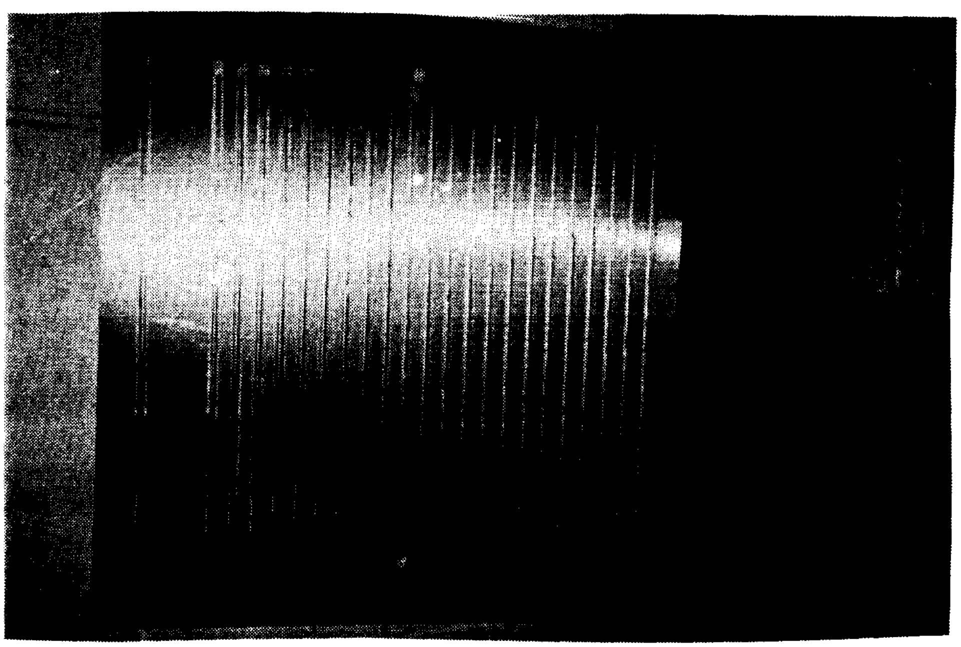


Figure 19. Formed Slot Duct Panel

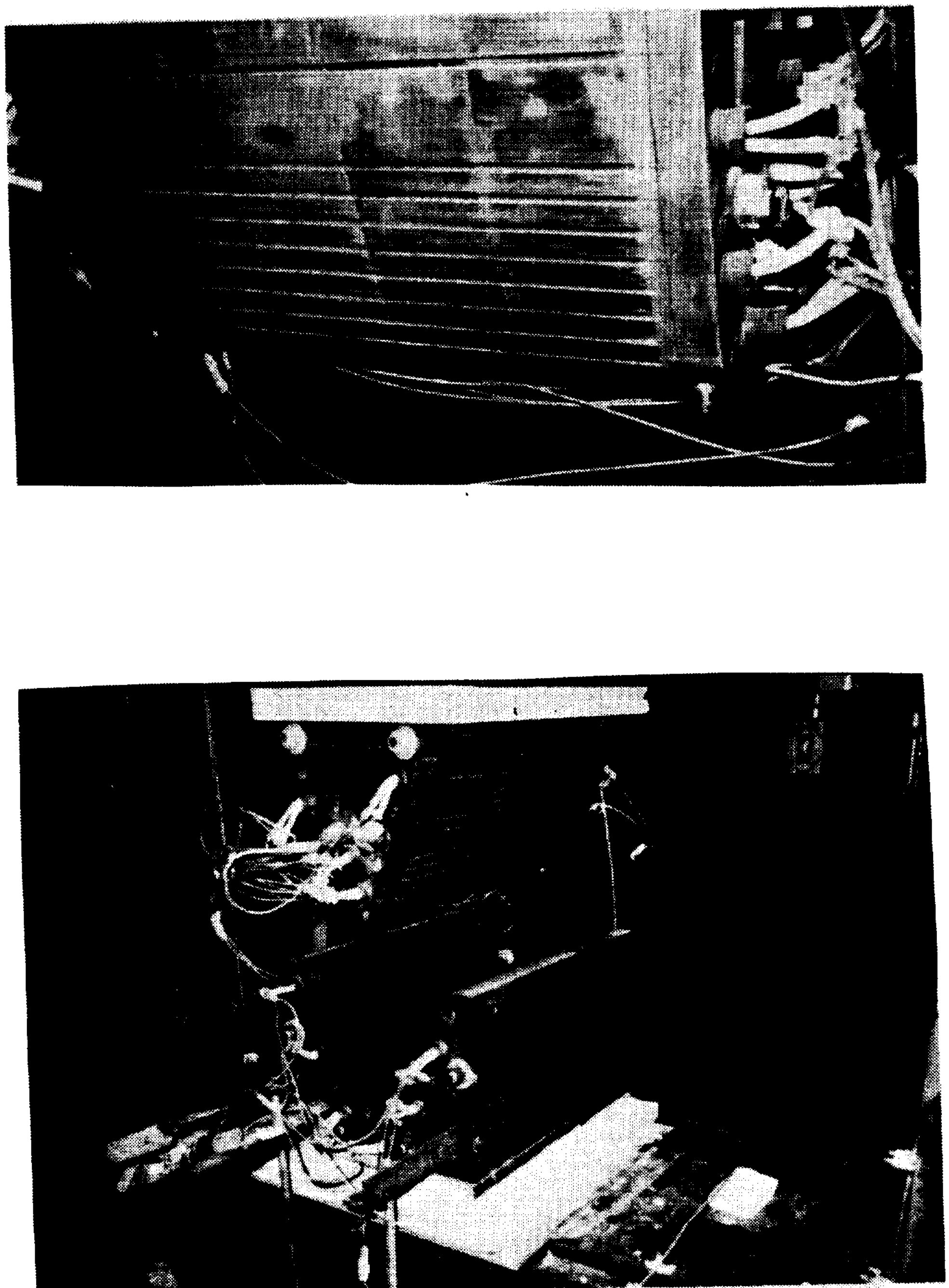
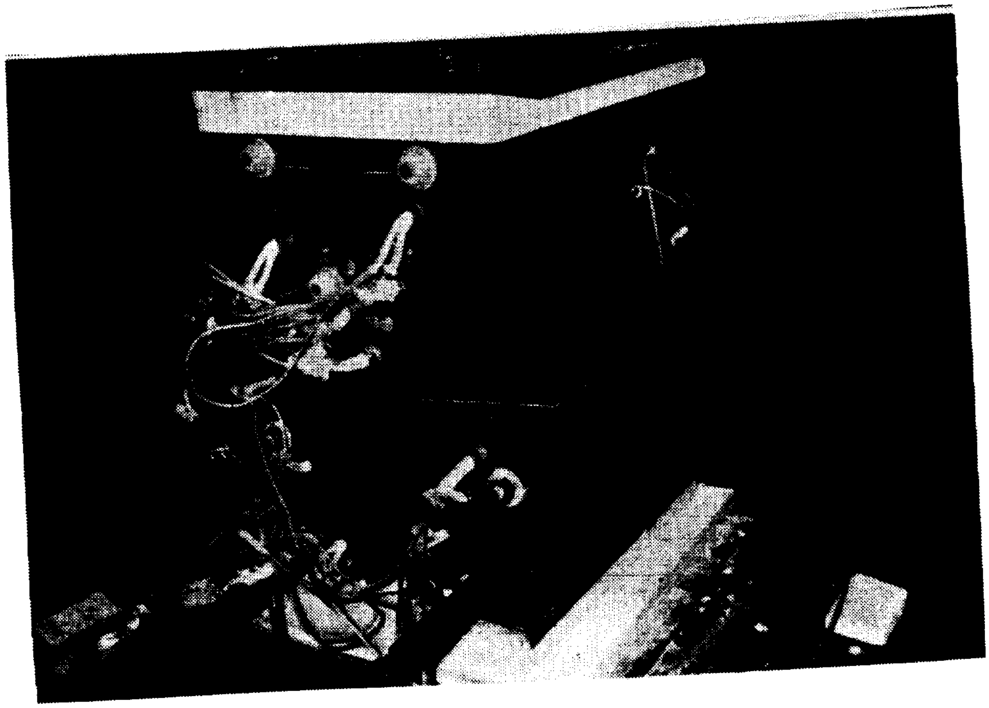
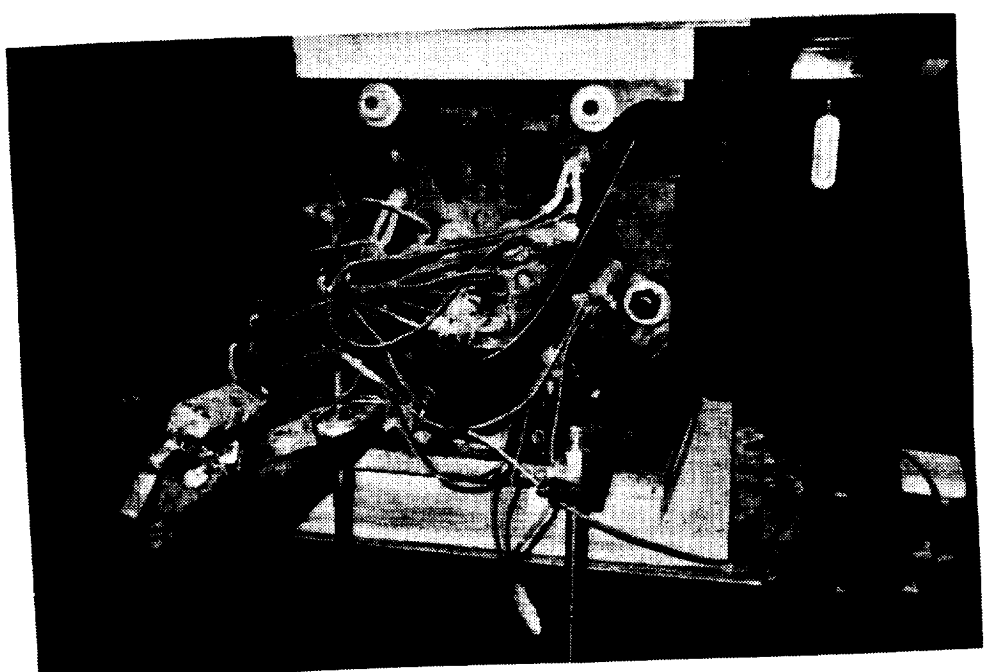


Figure 20. Closeup of the Matched Set of Tools



Female and Male Steel Tools



Slot Duct Panel Formed Using Female
and Male Tools

Figure 21. Diffusion Bonded Sheets Being Formed to Leading Edge Curvature

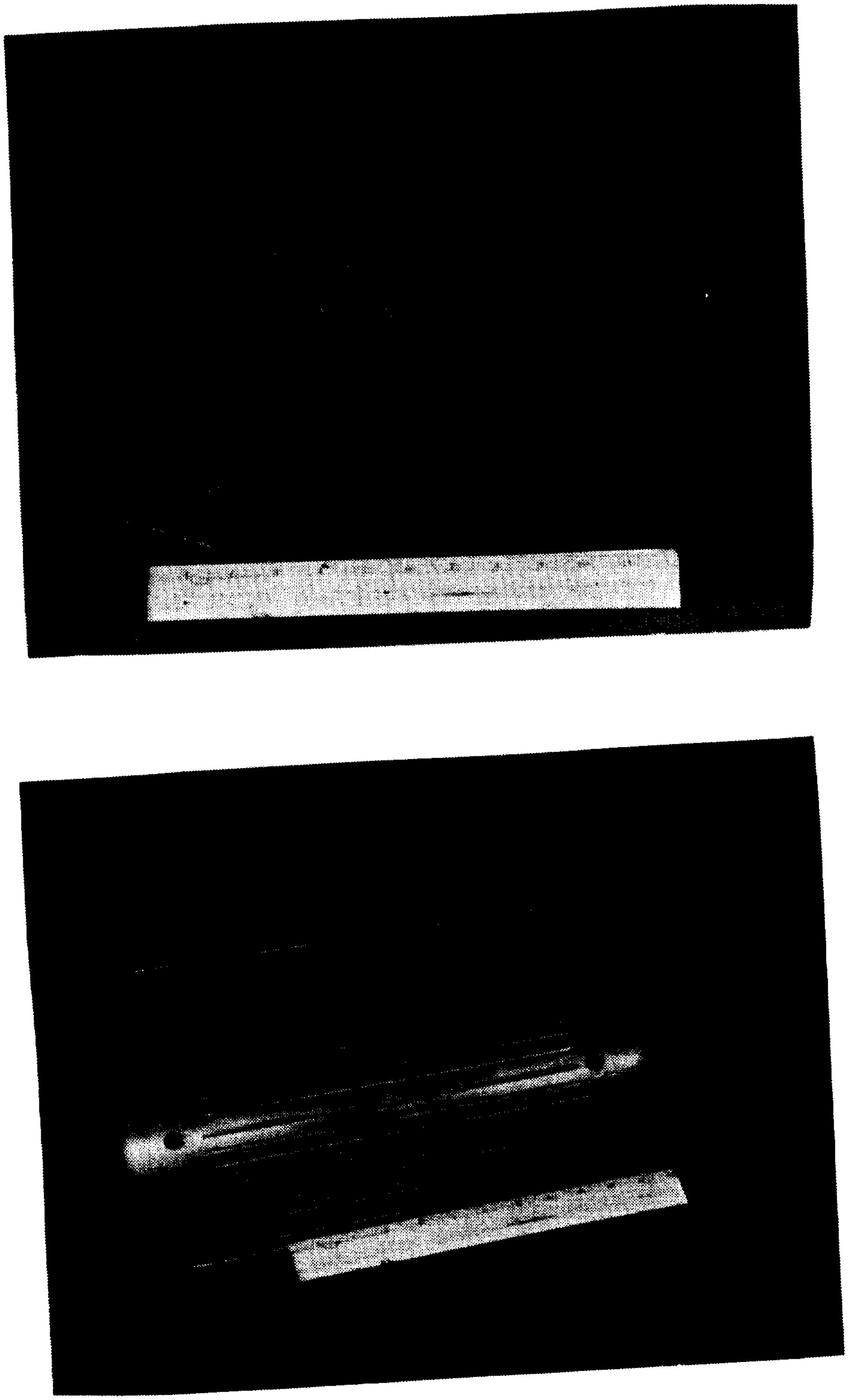


Figure 22. Formed Outer Sheet and Slot Ducts as Received from TI

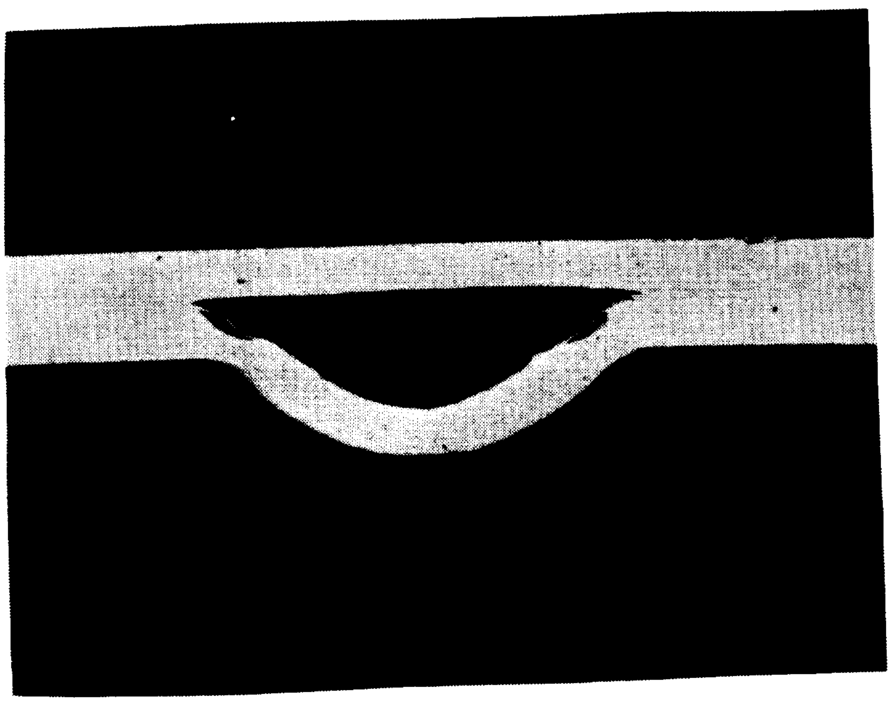


Figure 23. Closeup of a Single Slot Duct

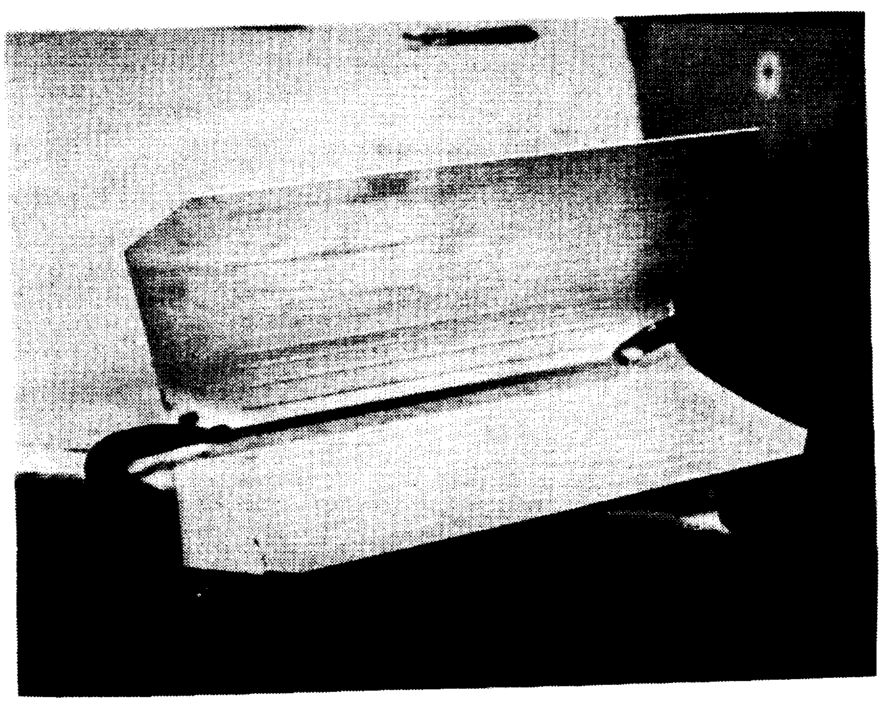


Figure 24. Drilling Metering Holes

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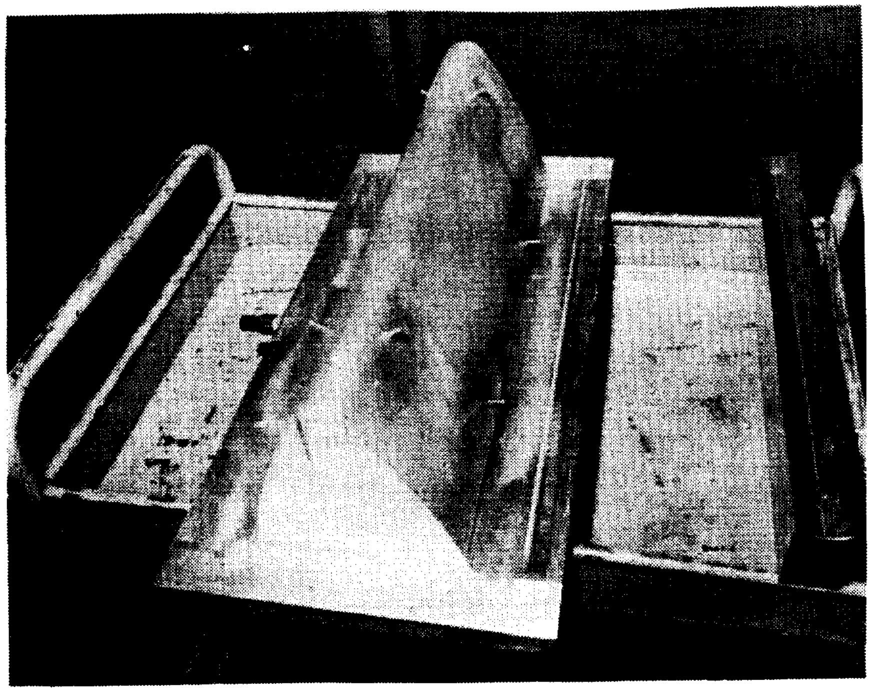


Figure 25. Bonding Tool

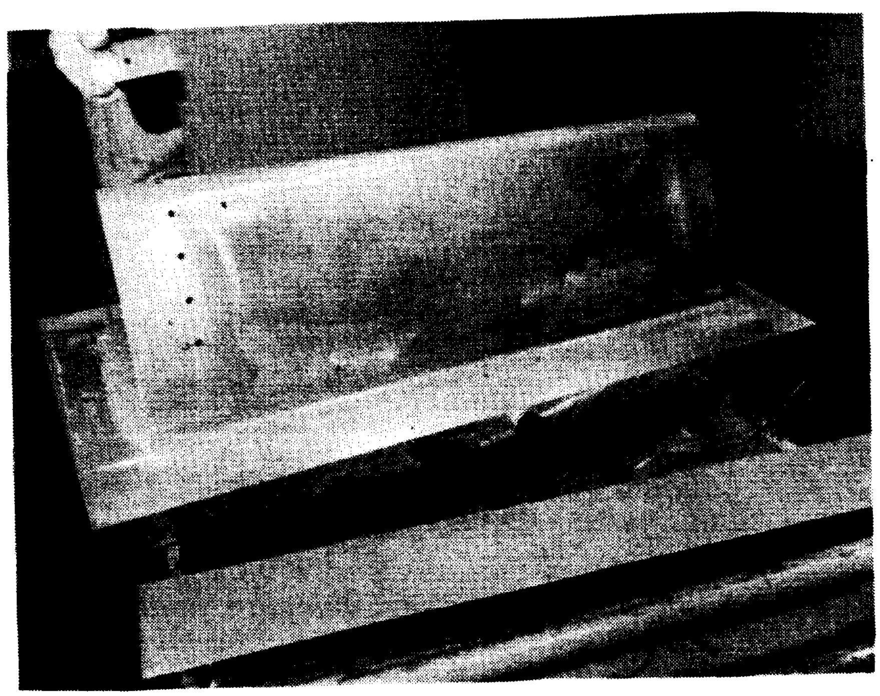
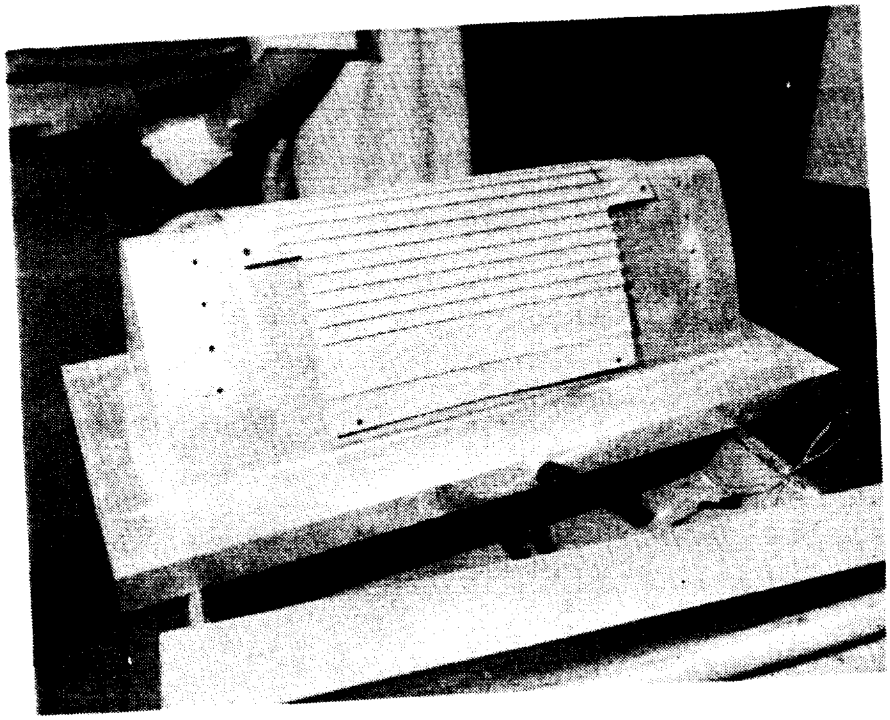
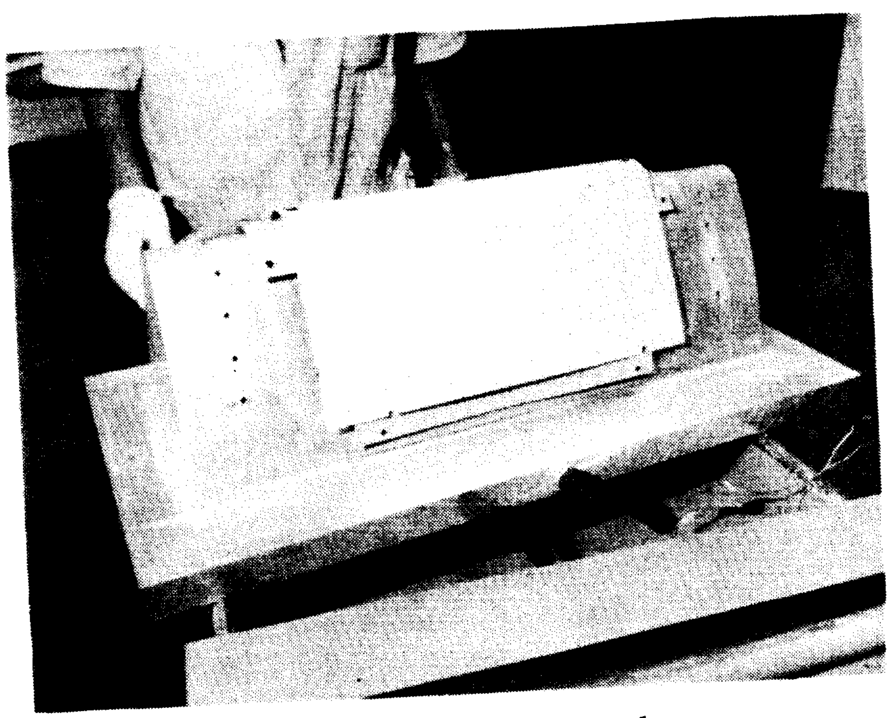


Figure 26. Inner A1-Li Sheet Being Used on Tool

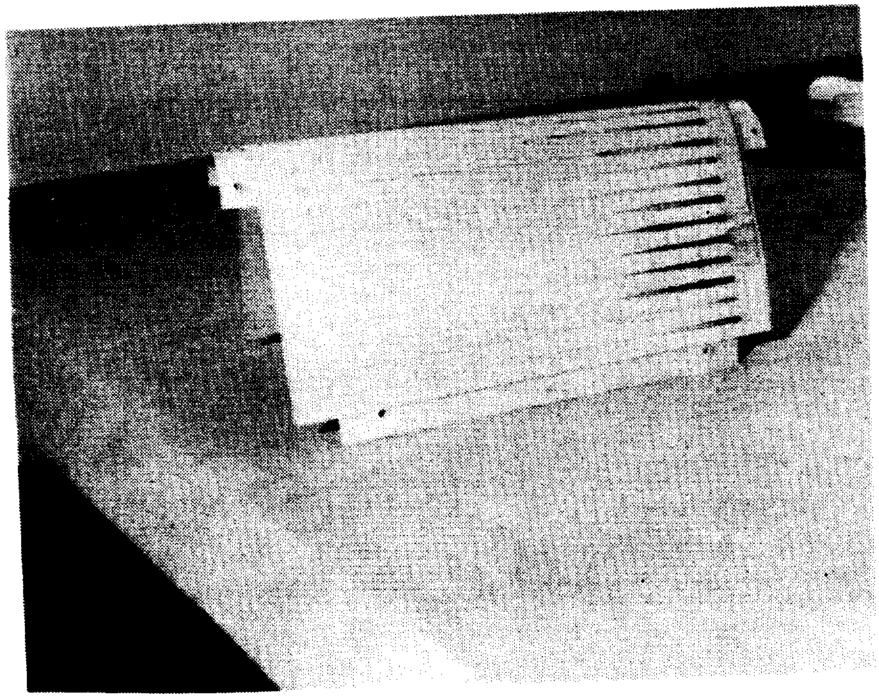


Collector Duct Laid Up on Tool



Outer Skin Laid Up on Tool

Figure 27. Layup of Collector Ducts and Outer Skin



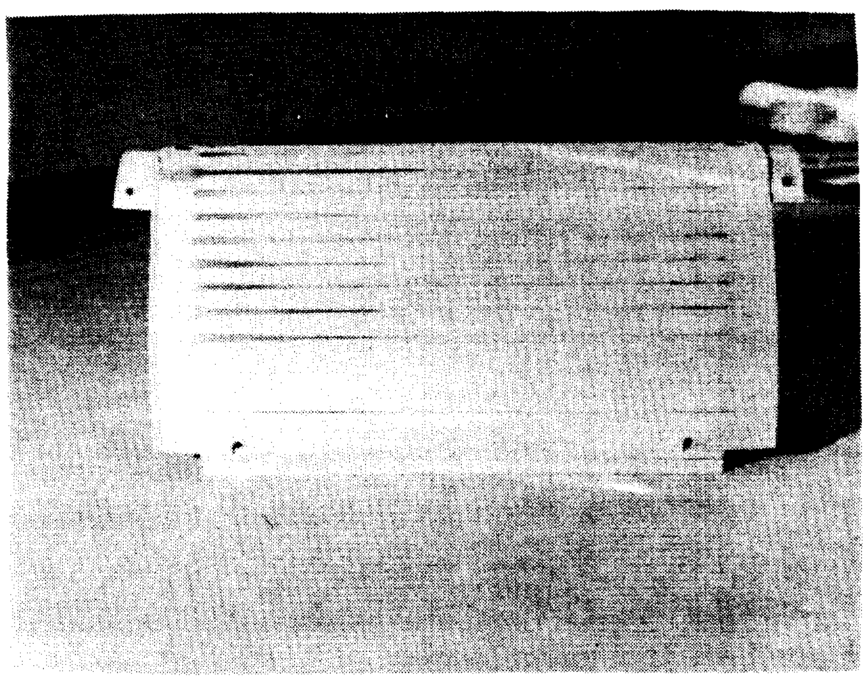


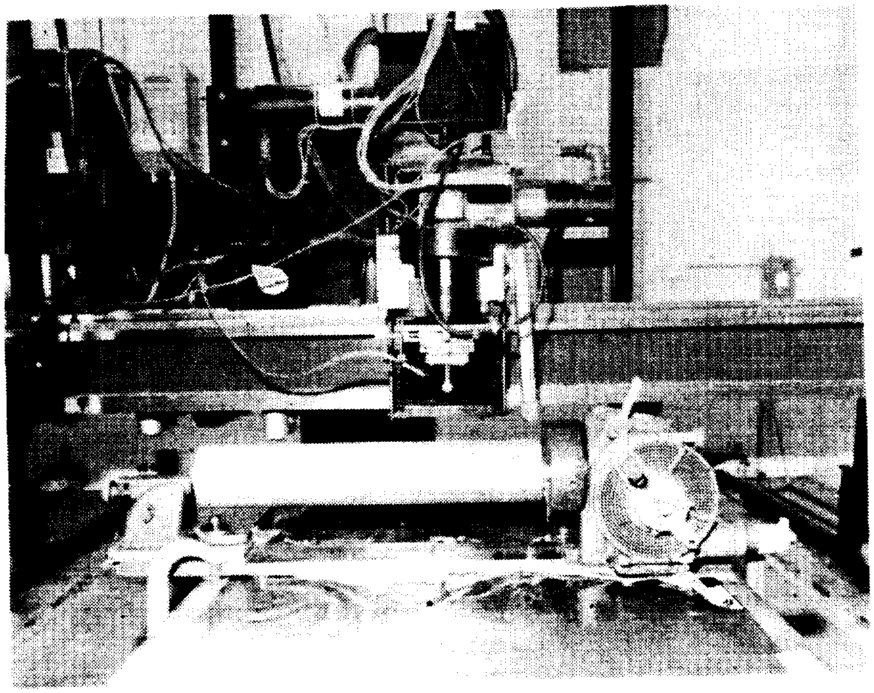
Figure 28. Leading Edge Article Taken from Autoclave

The bonded assembly was placed in an indexing fixture which rotated the part for slotting. Sawing was done with a one inch diameter by 0.0025 inch thick saw mounted on an air motor set up on a computer controlled gantry shown in Figure 29. A closeup examination of the final part, shown in Figure 30, shows that the inner and outer portions match, with no adhesive buildup. The slots were measured and found to be a maximum of 0.0035 inch wide.

The finished part was checked for waviness using a three prong dial indicator gage shown in Figure 31, which was also used in the previous JetStar flight articles. The readings were taken at 160 locations, as shown in Figure 32. The readings are shown in tabular form in Table 9 and graphically in Figure 33. Both sides of the slots were measured to record any appreciable springback. Readings indicate that the upper and lower surfaces were withn the required tolerances of $^{+}$.0015 over a 2 inch length. Readings could not be measured at the back edges and the forward areas due to the geometry of the three pronged dial. Measurements on both sides of the slot to record springback indicated that movement from one side of the slot to the other averaged 0.0005 inch. The maximum springback of .0021 inch occurred consistently at the intersection of the 1.5 inch radius to the 25 inch radius. A bump was discovered on the tool at these locations where the two radii did not meet properly. These areas were the main reason for the out-of-tolerance readings.

Since the three prong dial could not take a correct reading at the forward section of the leading edge article, another technique was used. The finished part was taken to Lockheed's computerized coordinate measuring machine to measure the contour dimensions and smoothness of the outer skin. The operation is CADAM-fed and computer operated, using a touch probe at measured increments. This touch probe measures the location at both sides of the cut slots for evidence of springback, in addition to the final contour of the leading edge article shown in Figure 34. The readings were taken at locations on both sides of each slot to measure any evident springback.

The result of this investigation again showed no appreciable springback after slots were cut. However, the forward section of the leading edge article did not meet the aerodynamic waviness requirements to achieve the optimum laminar flow.



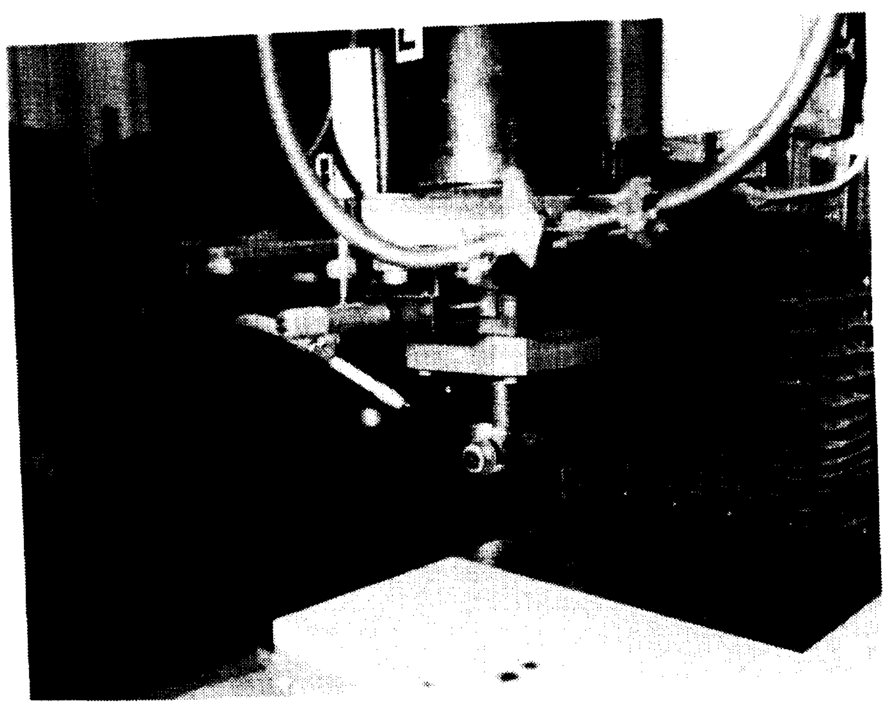


Figure 29. Photograph of the Indexing Fixture Used for Cutting Slots

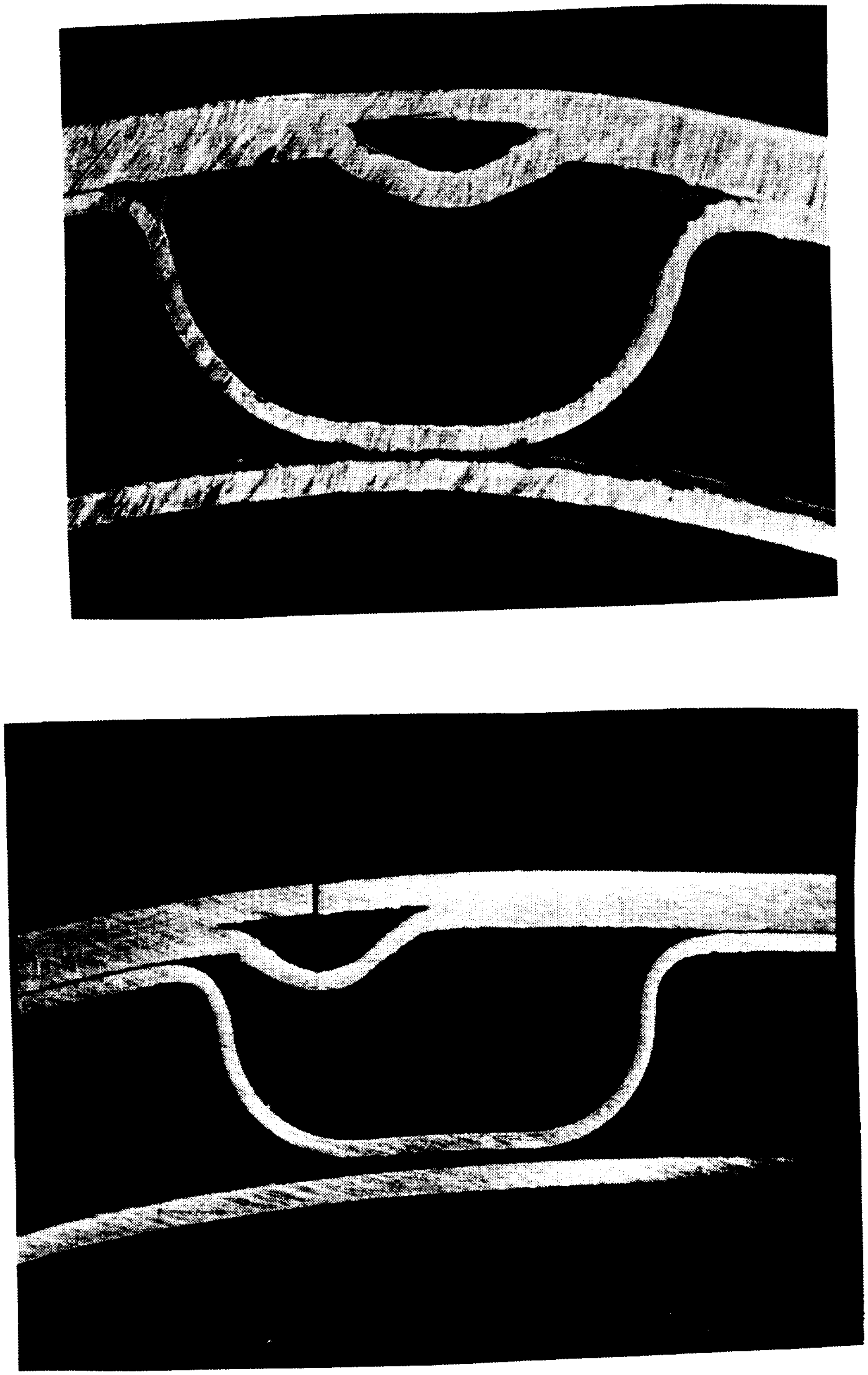
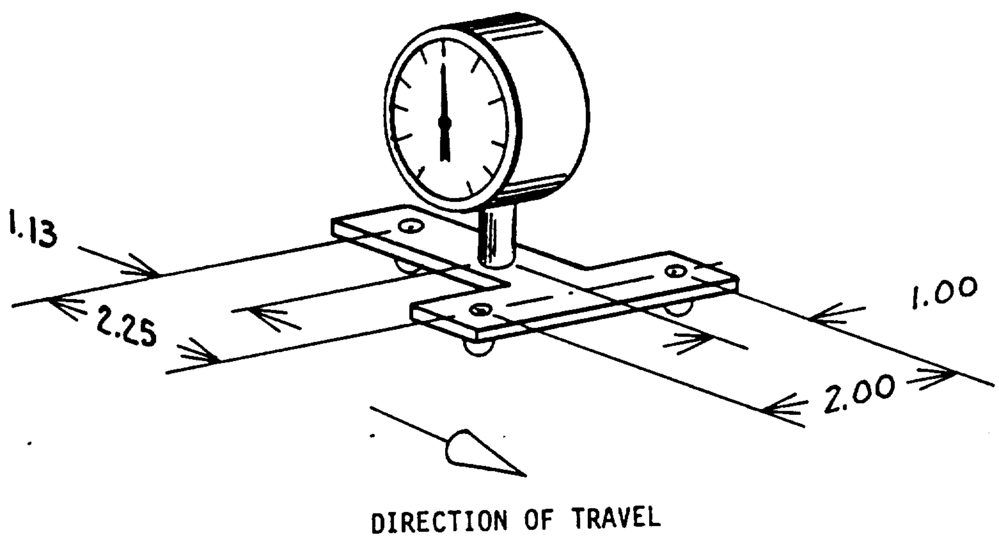


Figure 30. Cross-Sections of the Assembled Article



Measurements are in inches.

Figure 31. Three-Pronged Dial Indicator

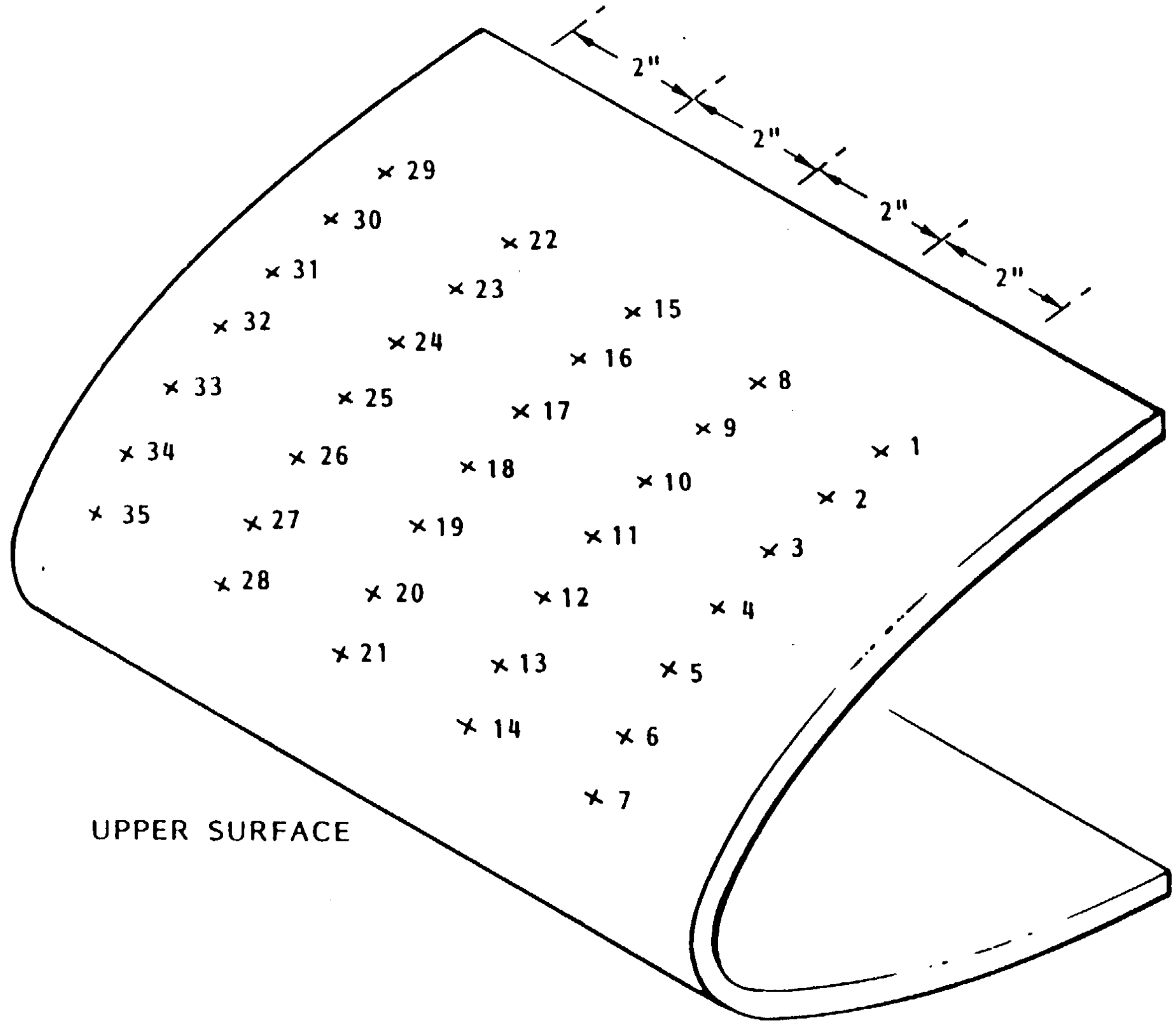


Figure 32. Measurement Locations for Panel Surface Waviness Test

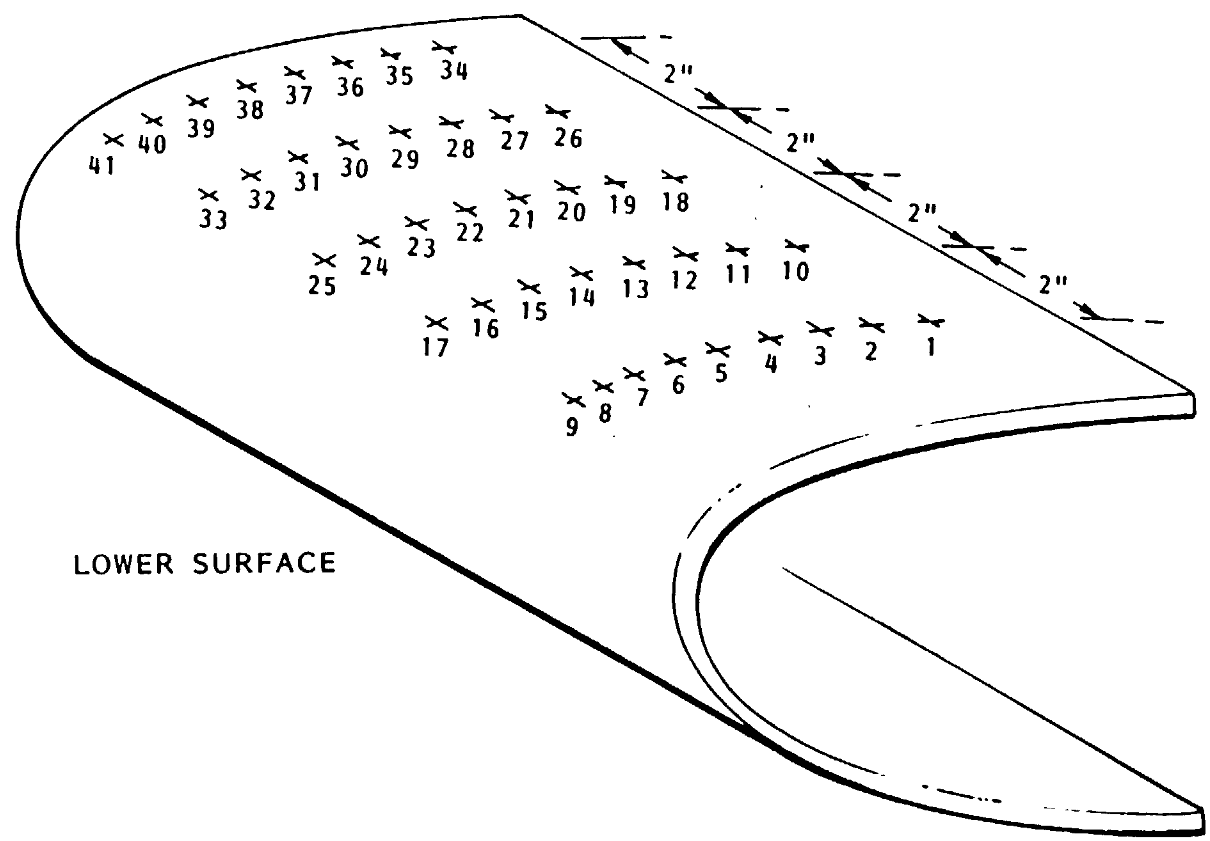


Figure 32. (Continued)

Table 9. Surface Deflection Values Using Dial Indicator

UPPER PANEL MEASUREMENTS

POINT	DIAL	POINT	DIAL	POINT	DIAL
1	+.0008	13	-.0015	25	-.0009
	+.0002		-.0012		-.0010
2	-.0008	14	+.0003	26	-.0015
	-.0006		+.0015		-.0017
3	-.0010	15	-.0001	27	-.0018
	-.0004		-.0002		-.0015
4	-.0006	16	-.0002	28	-.0001
	0*		-.0002		+.0015
5	-.0007	17	-.0002	29	+.0012
	-.0007		-.0009		+.0009
6	-.0003	18	-.0017	30	+.0006
	-.0007		-.0005		+.0002
7	+.0007	19	-.0009	31	-.0005
	+.0028		-.0013		-.0002
8	+.0004	20	-.0013	32	+.0001
	+.0006		-.0005		+.0001
9	-.0004	21	+.0001	33	-.0004
	-.0002		+.0023		-.0001
10	-.0015	22	+.0005	34	+.0005
	-.0008		+.0004		-.0002
11	-.0010	23	-.0008	35	+.0015
	-.0008		-.0007		+.0019
12	-.0019	24	-.0007		
	-.0017		-.0007		

POINT LOCATIONS AT SLOTS; READINGS WERE TAKEN AT BOTH SIDES OF THE SLOTS

*Reference Point

Table 9. Surface Deflection Values Using DIAL Indicator (Continued)

LOWER PANEL MEASUREMENTS

POINT	DIAL	POINT	DIAL	POINT	DIAL
1	0*	16	+.0002	31	-.0003
	+.0001		+.0002		-.0004
2	+.0005	17	+.0006	32	-.0006
	+.0007		+.0005		-.0008
3	+.0005	18	+.0010	33	+.0001
	+.0007		+.0012		+.0001
4	+.0004	19	-.0007	34	-.0009
	+.0004		-.0006		-.0008
5	+.0008	20	-.0008	35	-.0008
	+.0010		-.0010		-.0002
6	+.0015	21	-.0005	36	-.0003
	+.0015		-.0006		-.0001
7	+.0004	22	+.0001	37	+.0009
	+.0005		0		+.0006
8	+.0003	23	+.0002	38	+.0003
	+.0005		-.0003		+.0005
9	+.0010	24	-.0008	39	+.0007
	+.0009		-.0006		+.0007
10	+.0013	25	-.0008	40	-.0001
	+.0008		-.0007		0
11	0	26	-.0001	41	0
	-.0001		-.0002		+.0004
12	-.0001	27	-.0011	42	+.0012
	-.0002		-.0006		+.0009
13	0	28	+.0013	44	+.0008
	-.0003		-.0007		+.0011
14	-.0003	29	-.0007	45	+.0005
	0		-.0005		+.0016
15	+.0006	30	+.0002		
	+.0006		0		

POINT LOCATIONS AT SLOTS; READINGS WERE TAKEN AT BOTH SIDES OF THE SLOTS

*Reference Point

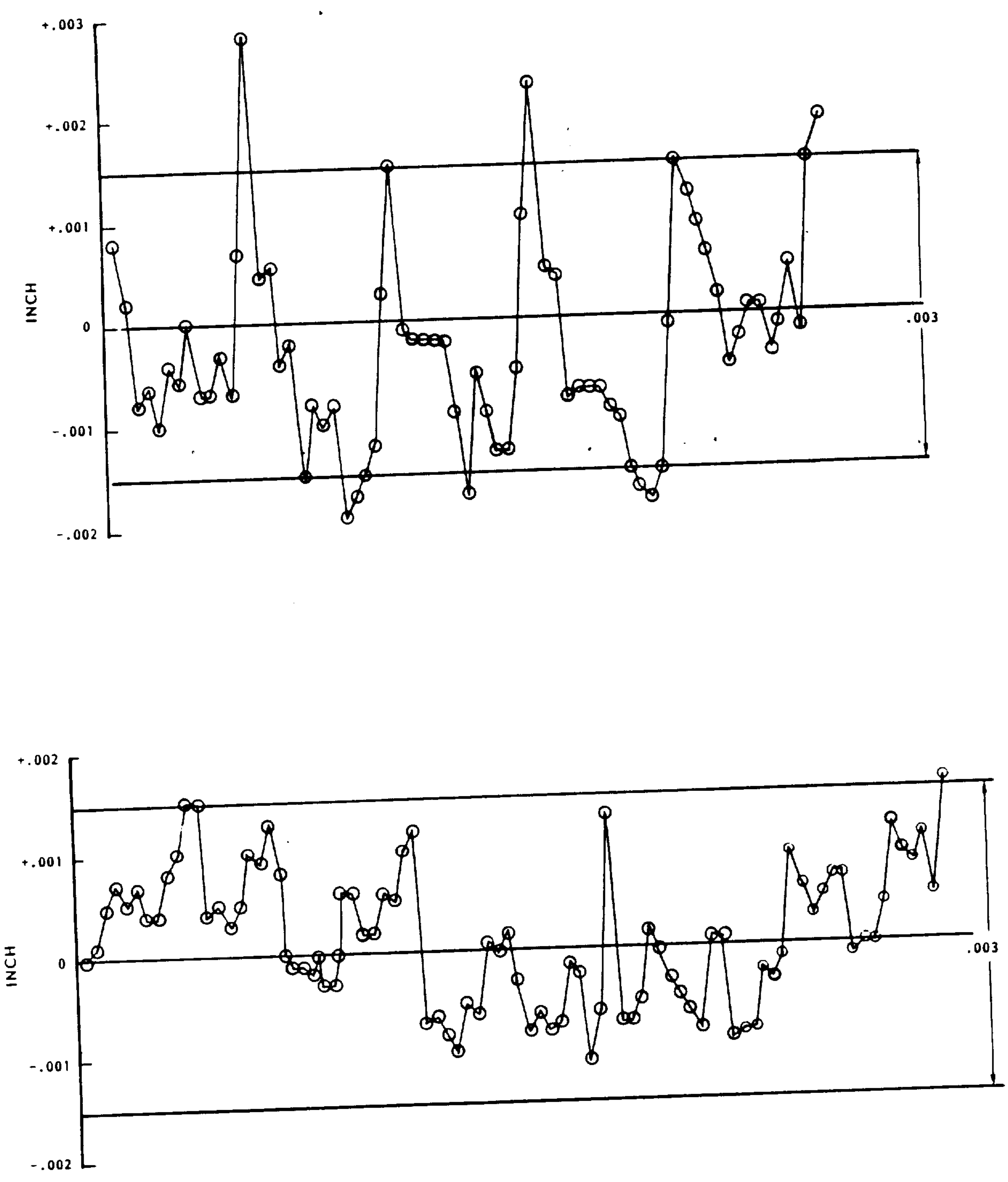


Figure 33. Panels of the LFC Demonstration Article

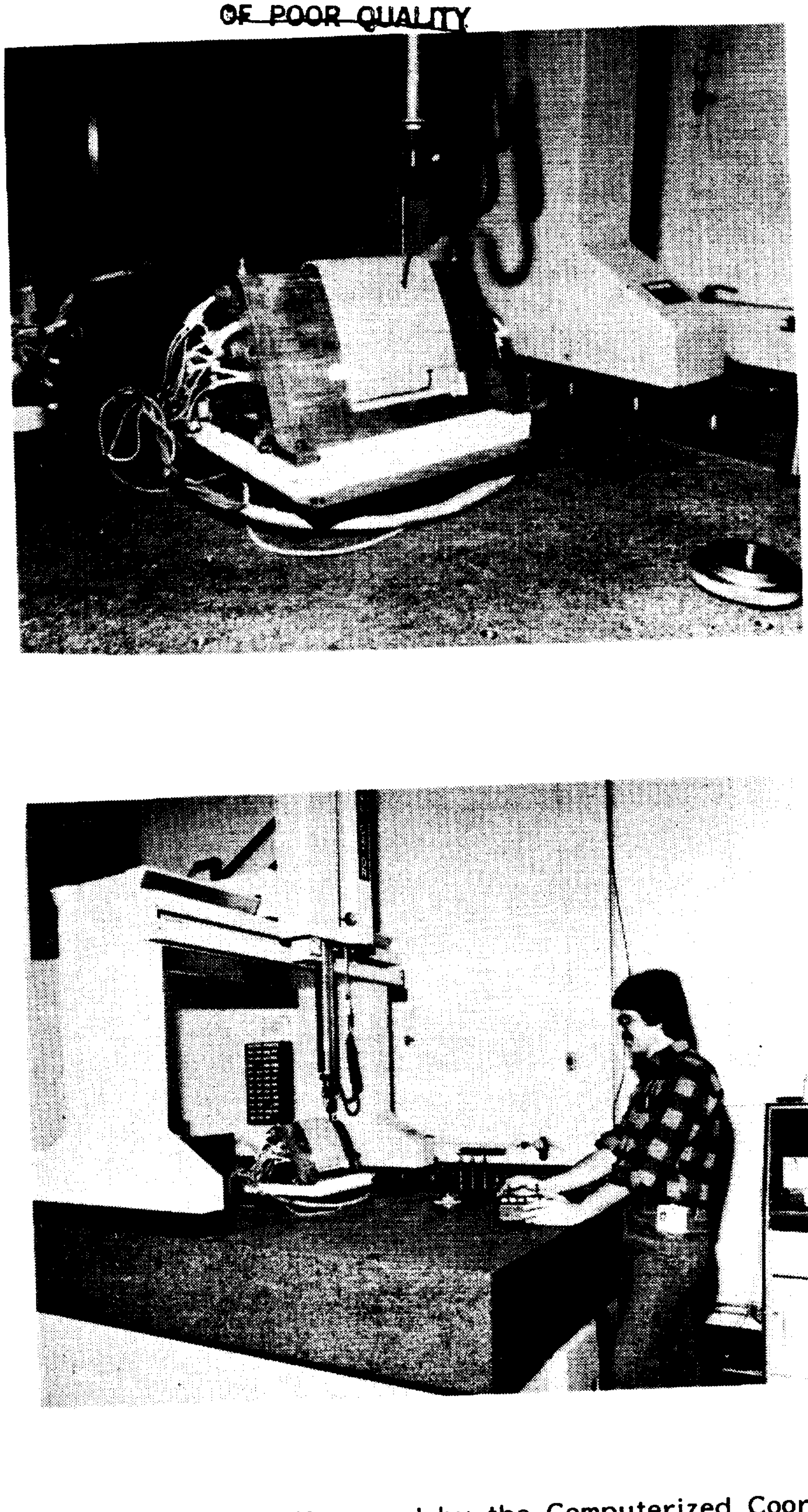


Figure 34. Waviness Being Measured by the Computerized Coordinate Measuring Machine (CCMM)

Measurements of the female tool and the outer skin of the fabricated article are shown in tabular form in Table 10. Figure 35 shows the location of these readings. Figure 36 graphically indicates the comparison of the readings of the tool and part to each other. The forward section of the article does not follow the pattern of the tool due to a slight incompatibility of the matched set of tools. This incompatibility die not allow the proper pressure to be placed on the forward section of the article, thus allowing a slight waviness to occur.

The smoothness of the tools, plus the use of matched tools to fabricate the outer skin bonded to the slot duct, proved to be the primary reason the outer skin did not meet the required surface waviness tolerance. The matched tools could not provide the required pressure needed to achieve the surface smoothness in the area of the forward section of the leading edge.

Lockheed
-Georgia Company

TABLE 10. SURFACE DEFLECTION VALUES OF THE FEMALE TOOL AND OUTER SHEET

TOOL INCH	LOCATION	PART INCH
-.0368	1	-.0849
-.0186		-.0769
-.0218	2	-.0346
+.0380		+.0060
0	3	+.0002
+.0001		+.0029
-.0004	4	+.0013
+.0006		+.0001
-.0020	5	-.0003
-.0008		-.0010
-.0038	6	-.0010
+.0039		-.0004
+.0011	7	-.0009
-.0017		-.0002
-	8	+.0007
-		-.0043
-.0001	9	+.0006
0		-.0002
-.0005	10	-.0022
+.0004		-.0013
-.002[illegible]	11	+.0020
+.0001		+.0041
+.0001	12	+.0013
+.0001		-.0044
+.0001	13	-.0026
-.0002		+.0043
+.0014	14	+.0047
-.0007		+.0011
+.0009	15	-.0019
-.0020		-.003
-.0011	16	-.0024
-.0035		-.0021
-.0011	17	-.0007
-.0039		-.0009
+.0015	18	-.0012
+.0035		-.0026
+.0004	19	-.0015
+.0019		-.0024
-.0010	20	-.0021
+.0010		-.0027
-.0017	21	-.0004
+.0001		+.0003
-.0029	22	+.0033
-.0014		+.0043
-.0040	23	+.0045
+.0009		+.0124

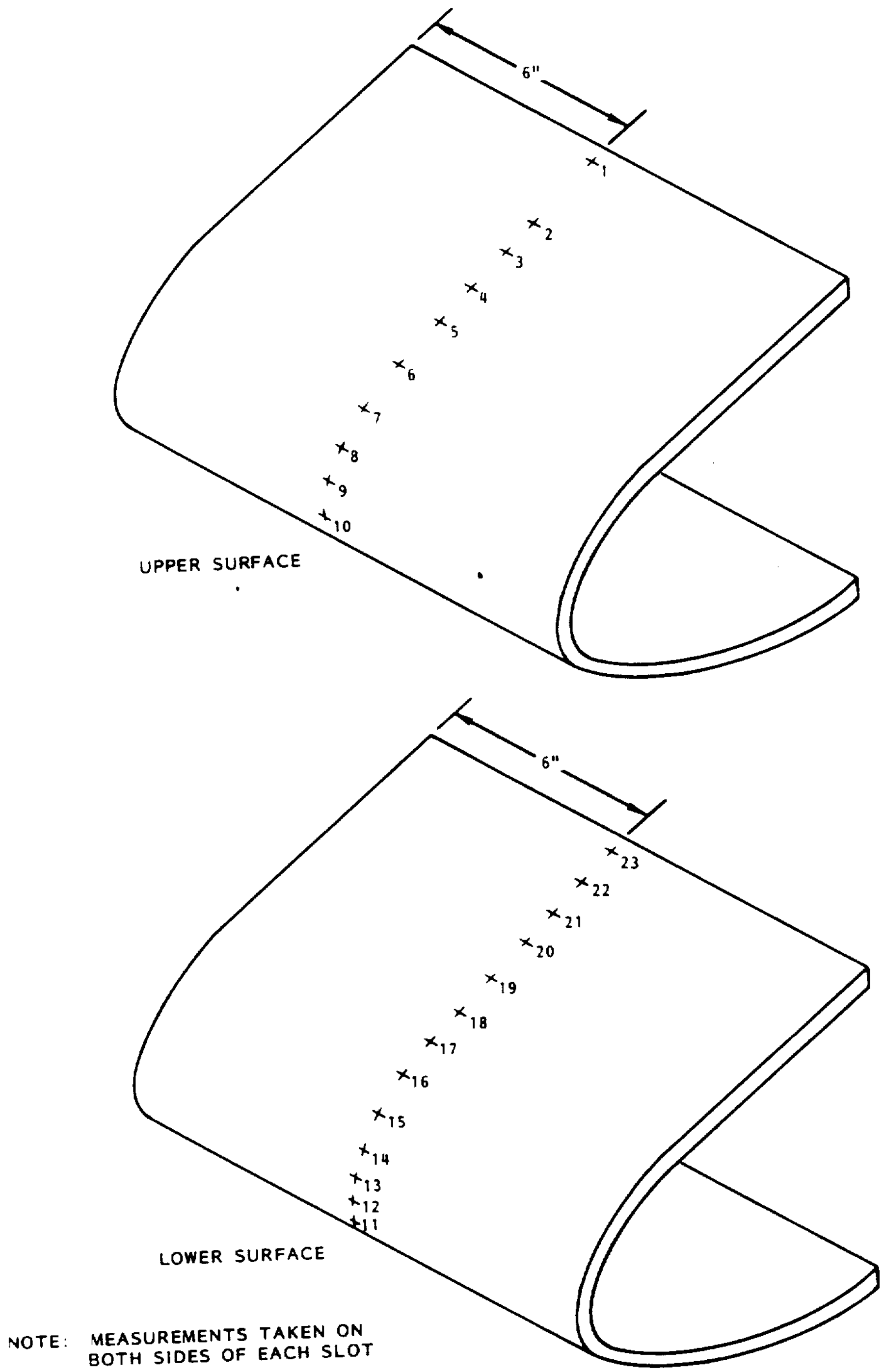


Figure 35. Location of Measurements Used by the CCMM Unit

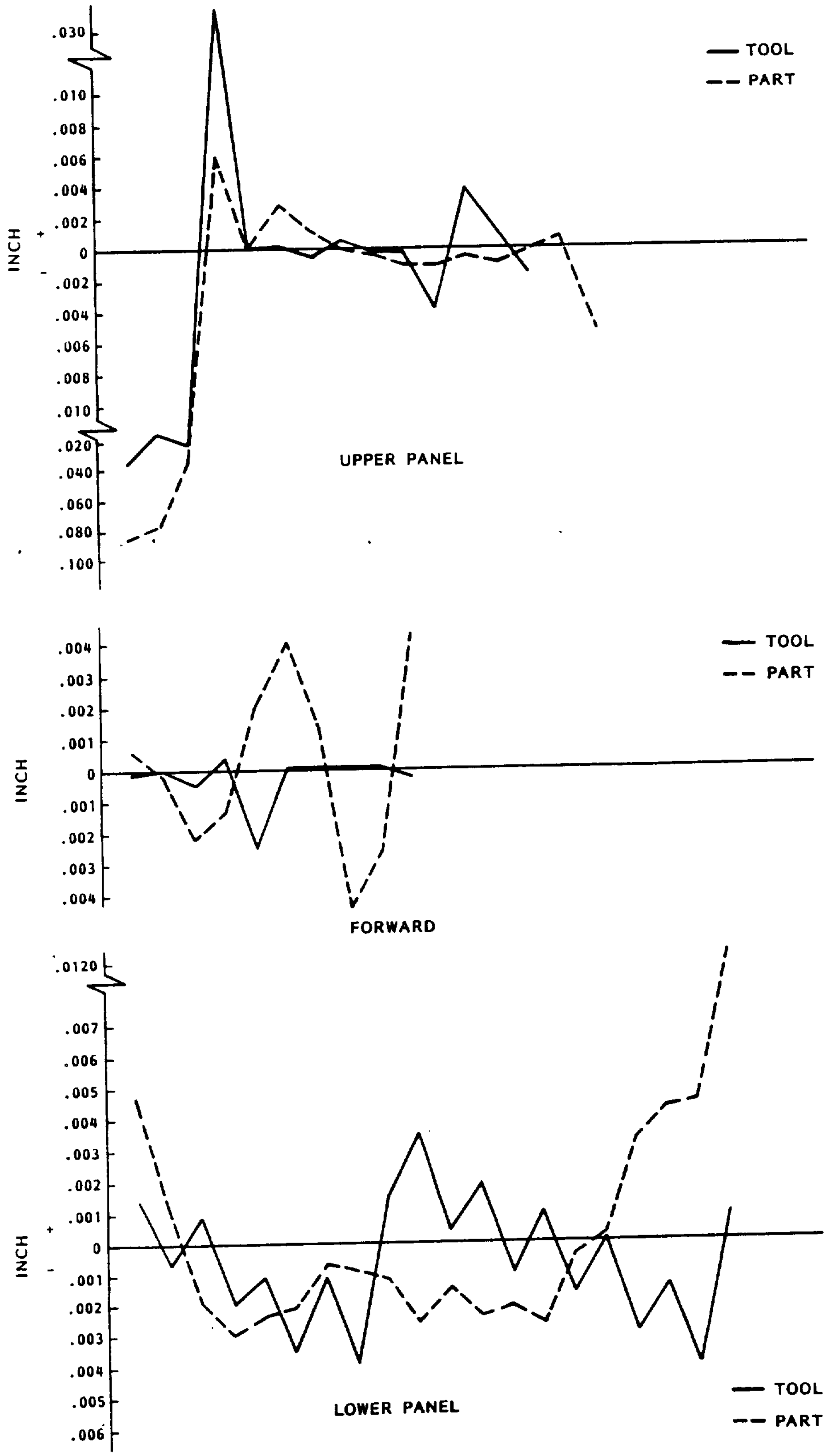


Figure 36. Surface Measurements of the Female Tool and Demonstration Article Shown Graphically.

9.0 CONCLUSIONS AND RECOMMENDATIONS

The advanced manufacturing processes used here to fabricate the proof-of-concept article (Figure 37) demonstrated a producible structure. The use of diffusion bonding of aluminum and superplastic forming allows a low risk, economical fabrication approach. The concerns inherently involved in a slotted design, such as springback and disbond, were eliminated in this demonstration article. The diffusion bonding process replaced the adhesive application, eliminating any possibility of adhesive runout into the ducts. The diffusion bond offered shear strength four times that of any adhesive bond strength. The process provided a near-monolithic reinforced outer skin with the expanded slot ducts bonded to the outer sheet. This type bond further decreases any opportunity of moisture absorption into the bond, degrading the strength. Superplastic forming proved to be a relatively simple approach to the fabrication of the collector ducts, providing an integral sheet to bond to the outer and inner skins.

The processes used could be directly applied to large scale articles. The current facilities, not the technology, limit the size of the panel. However, with a minimum number of splices, this can be overcome.

Tight tolerances on the outer skin are required to achieve optimum laminar flow. Therefore, the tooling used to produce the proof-of-concept article was of primary importance. The tooling process selected to fabricate the demonstration article was not sufficient to meet these requirements. Thus, the article did not meet the waviness criteria at the forward section. However, processing and tooling practices are available which will meet the desired surface smoothness, and this should not be a major obstacle. It is recommended that new tools be produced to fabricate a new article demonstrating the alleviation or the reduction of the waviness on the forward section.

It is recommended that structural tests that include impact tests and rain erosion should be conducted to lend credibility to this manufacturing approach. Although the approach eliminated springback and disbond during manufacturing, the panel should be tested to verify the bond strength in environments that an in-flight article will experience. It is also desirable to further investigate the cleaning system to avoid clogged slots due to insects or debris.

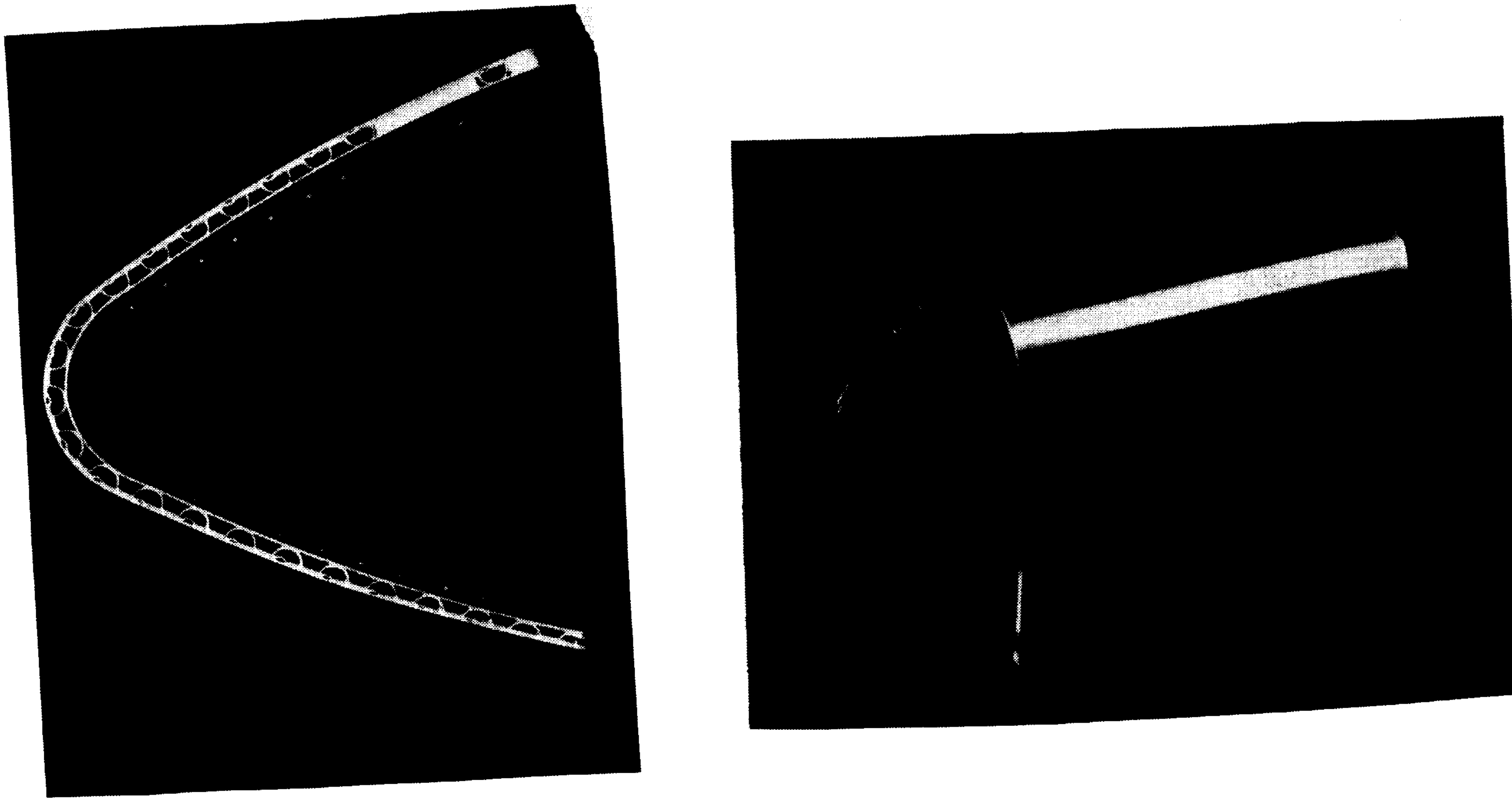


Figure 37. Photograph of Final Demonstration Article

REFERENCES

1. F.R. Etchberger, et al, LFC Leading Edge Glove Flight - Aircraft Modification Design, Test Article Development, and Systems Integration, NASA CR 172136, November 1983.

2. Wagner, Richard D., and Michael C. Fischer, "Developments in the NASA Transport Aircraft Laminar Flow Program," AIAA Paper 83-0090, Reno, Nevada, January 1983.

3. Lineberger, L.B., et al, "Development of Laminar Flow Control Wing Surface Composite Structures," NASA CR 172330, prepared by the Lockheed-Georgia Company, May 1984.

4. Lineberger, L.B., et al, "Structural Tests and Development of a Laminar Flow Control Wing Surface Composite Chordwise Joint," NASA CR 172462, prepared by the Lockheed-Georgia Company, December 1984.

5. Lange, R.H., "Design Integration of Laminar Flow Control for Transport Aircraft," Journal of Aircraft, Vol. 21, No. 8, August 1984, pp. 612-617.

6. Wagner, Richard D., Dal V. Maddalon, and Michael C. Fischer, "Technology Developments for Laminar Boundary Layer Control on Subsonic Transport Aircraft," presented at the 54th Meeting of the FLID Dynamics Panel Symposium on Improvement of Aerodynamic Performance through Boundary Layer Control and High Lift Systems, Brussels, Belgium, May 21-23, 1984.

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16. Abstract
NASA sponsored the Aircraft Energy Efficiency (ACEE) program in 1976 to
develop technologies to improve fuel efficiency. Laminar flow control was
such a technology funded by NASA. Two approaches for achieving laminar
flow were designed and manufactured under NASA sponsored programs - the
perforated skin concept used at McDonnell Douglas and the slotted design used
at Lockheed-Georgia. Both designs achieved laminar flow, with the slotted
design to a lesser degree on the JetStar flight test program.

The slotted design had several fabrication problems concerning springback
and adhesive flow clogging the air flow passages. This report documents
the Lockheed-Georgia Company accomplishments in designing and fabricating
a small section of a leading edge article addressing a simpler fabrication
method to overcome the previous program's manufacturing problems. This
report documents the design and fabrication using advanced technologies
such as diffusion bonding of aluminum, which has not been used on
aerospace articles to date, and superplastic forming of aluminum.

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