PROGRESS IN MANUFACTURING LARGE PRIMARY AIRCRAFT STRUCTURES USING THE STITCHING / RTM PROCESS

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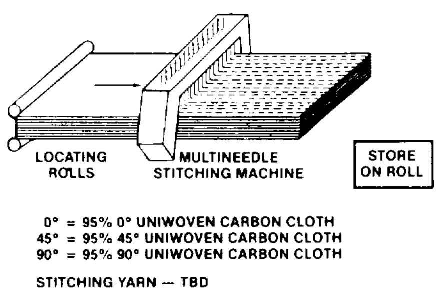
INTRODUCTION

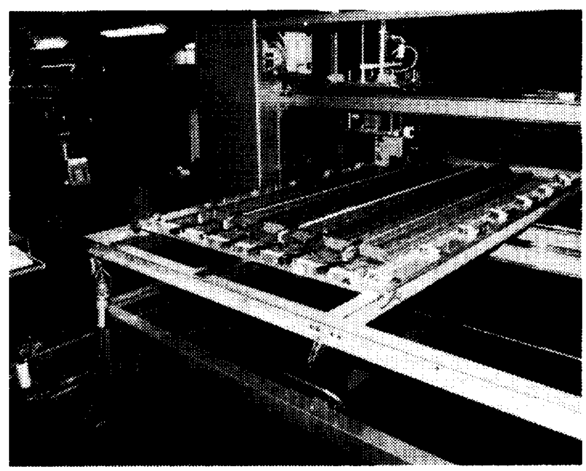
The Douglas Aircraft/NASA Act contract has been focused over the past three years at developing a materials, manufacturing, and cost base for stitched/Resin Transfer Molded (RTM) composites. The goal of the program is to develop RTM and stitching technology to provide enabling technology for application of these materials in primary aircraft structure with a high degree of confidence. Presented in this paper will be the progress to date in the area of manufacturing and associated cost values of stitched/RTM composites.

Figure 1 below describes the stitched/RTM approach being developed at Douglas.

STITCHING CONCEPT

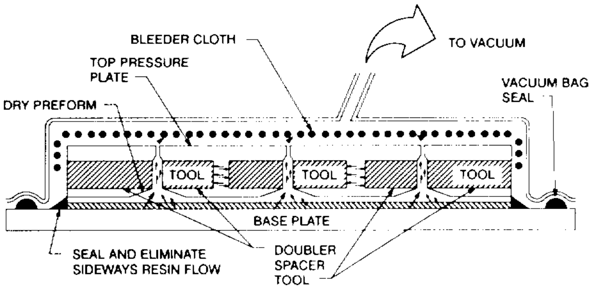


MULTI-NEEDLE STITCHING IS USED TO PROVIDE DAMAGE TOLERANCE TO WING SKINS

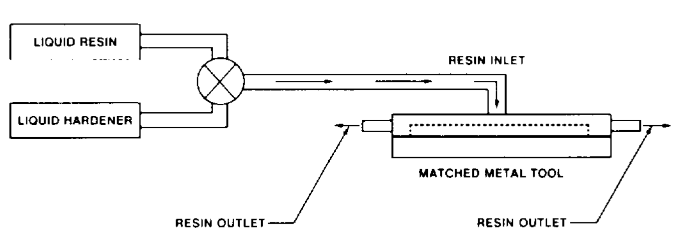


COMPUTER CONTROLLED SINGLE NEEDLE STITCHING IS USED TO PERFORM STITCHING ASSEMBLY OPERATIOINS

RTM FABRICATION METHODS



RESIN FILM INFUSION IS USED FOR WING COVER PANEL FABRICATION



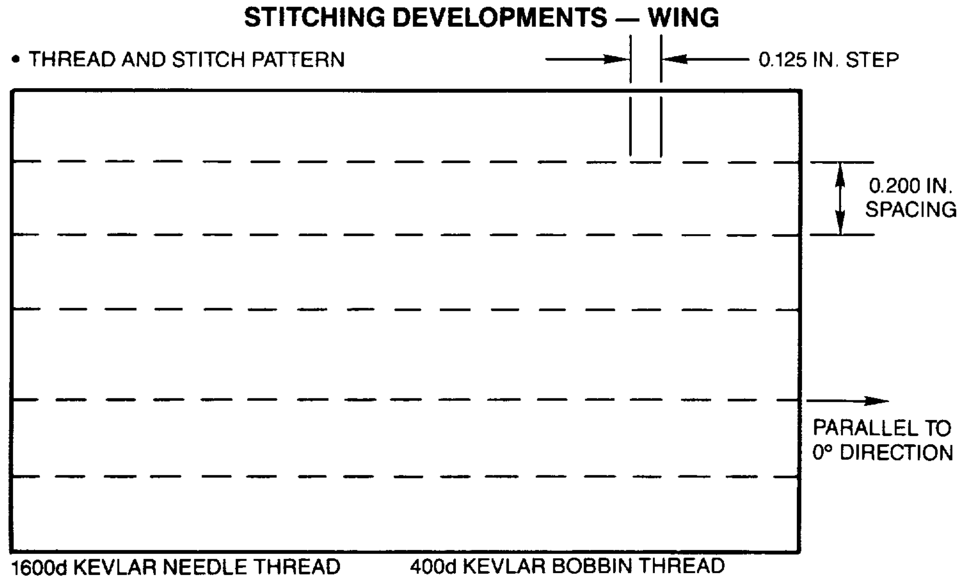
PRESSURE IMPREGNATION IS USED FOR FUSELAGE SHELL FABRICATION

Figure 1

PREVIOUS DEVELOPMENTS

Douglas Wing Structures

Over the course of the first two years of development, Douglas concentrated its efforts in two areas: 1.) wing development using resin film infusion with stitched preform and, 2.) fuselage development using pressure injection RTM with stitched preforms. Figures 2 through 5 cover the development in stitching, tooling, and processing for both the wing and fuselage over that two year period.



In the development period, stitching patterns and thread selections were based upon many tests and the capabilities of existing stitching machines. Figure 2 shows the stitching thread and pattern now used in wing preforms.

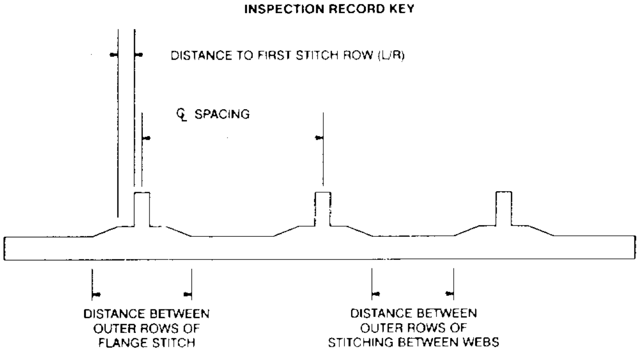
Figure 2

PREVIOUS DEVELOPMENTS

Douglas Wing Structure

DAC established the requirements necessary to make high quality carbon fiber preforms. Dimensional requirements for the preform were established for fabrication tool fit-up. To meet these requirements, specialized tooling was created for stitching the wing skin, stiffeners, and attaching the stiffeners to the skin (Figure 3).

- PREFORM QUALITY REQUIREMENTS



PROGRAM QUALITY REQUIREMENTS

ITEM 1
S/N DATE

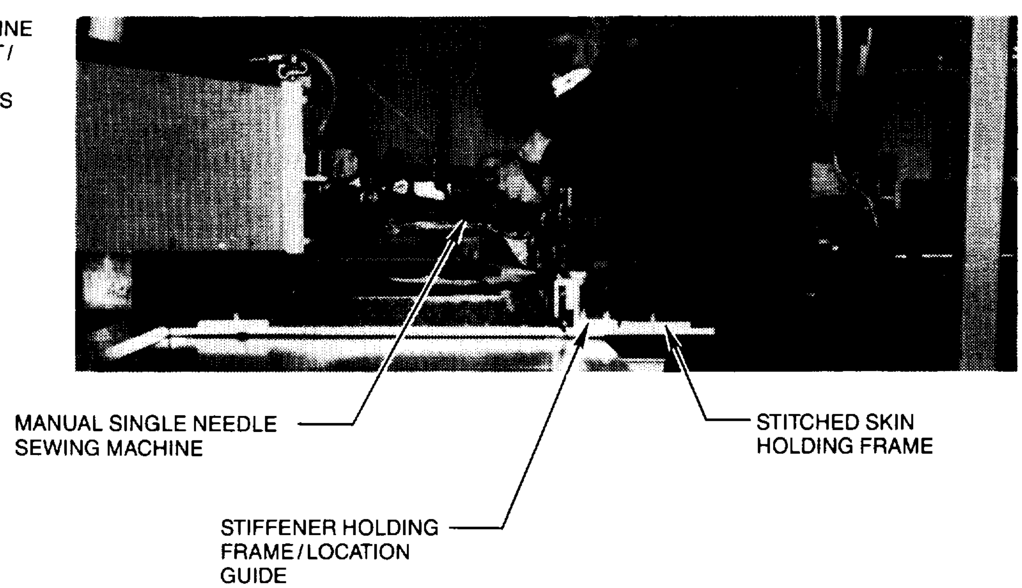
RIGHT STIFFENER WAS 8 ROWS OF STITCHING
STITCHING SPACE · 0 1875 IN
STITCHING STEP AVERAGE 7 IN

P THRASH

CHARACTERISTIC	VALUE	LEFT WEB		CENTER WEB		RIGHT WEB		LEFT	RIGHT
℄ - ℄ SPACING BETWEEN STIFFENERS	7 0								
DISTANCE TO 1st STITCH ROW	0 37/ 0 44	L	R	L	R	L	R		
DISTANCE BETWEEN OUTER ROWS OF FLANGE STITCH	2 68/ 2 81								
DISTANCE BETWEEN OUTER ROWS OF STITCHING BETWEEN WEBS	4 19/ 4 32								

STITCHING DEVELOPMENTS — WING

- SEWING MACHINE DEVELOPMENT/ TOOLING REQUIREMENTS



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Figure 3

PREVIOUS DEVELOPMENTS

Douglas Wing Structures

Tooling for wing panels was designed to achieve a major cost savings benefit by RTM of a preform in which the rib clips and stiffeners are stitched to the skin. This tooling, Figure 4, utilizes a graphite/epoxy upper tooling plate to hold the matched metal aluminum details in place during the RTM autoclave cure process. To help insure the thermal compatibility of the upper tool with the lower tool, a graphite/epoxy lower plate was also used.

FABRICATION DEVELOPMENTS — WING

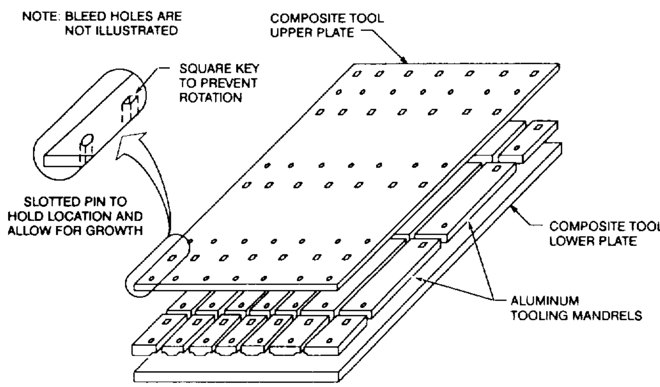
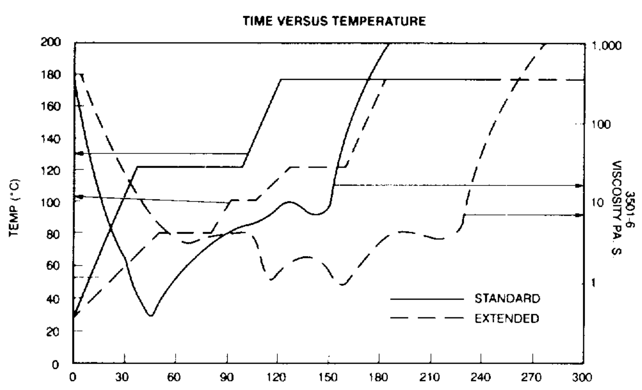


Figure 4

PROCESSING DEVELOPMENTS

Douglas Wing Structures

In developing a single step resin infiltration and curing cycle, the subcontractor team of Virginia Polytechnic Institute and William and Mary College played a critical role. Findings from their work established that preform thermal equilibrium and application of initial pressure are essential to a single step cure cycle. Figure 5 below, shows an extended cure cycle based upon their work versus the earlier standard created to achieve thermal equilibrium.



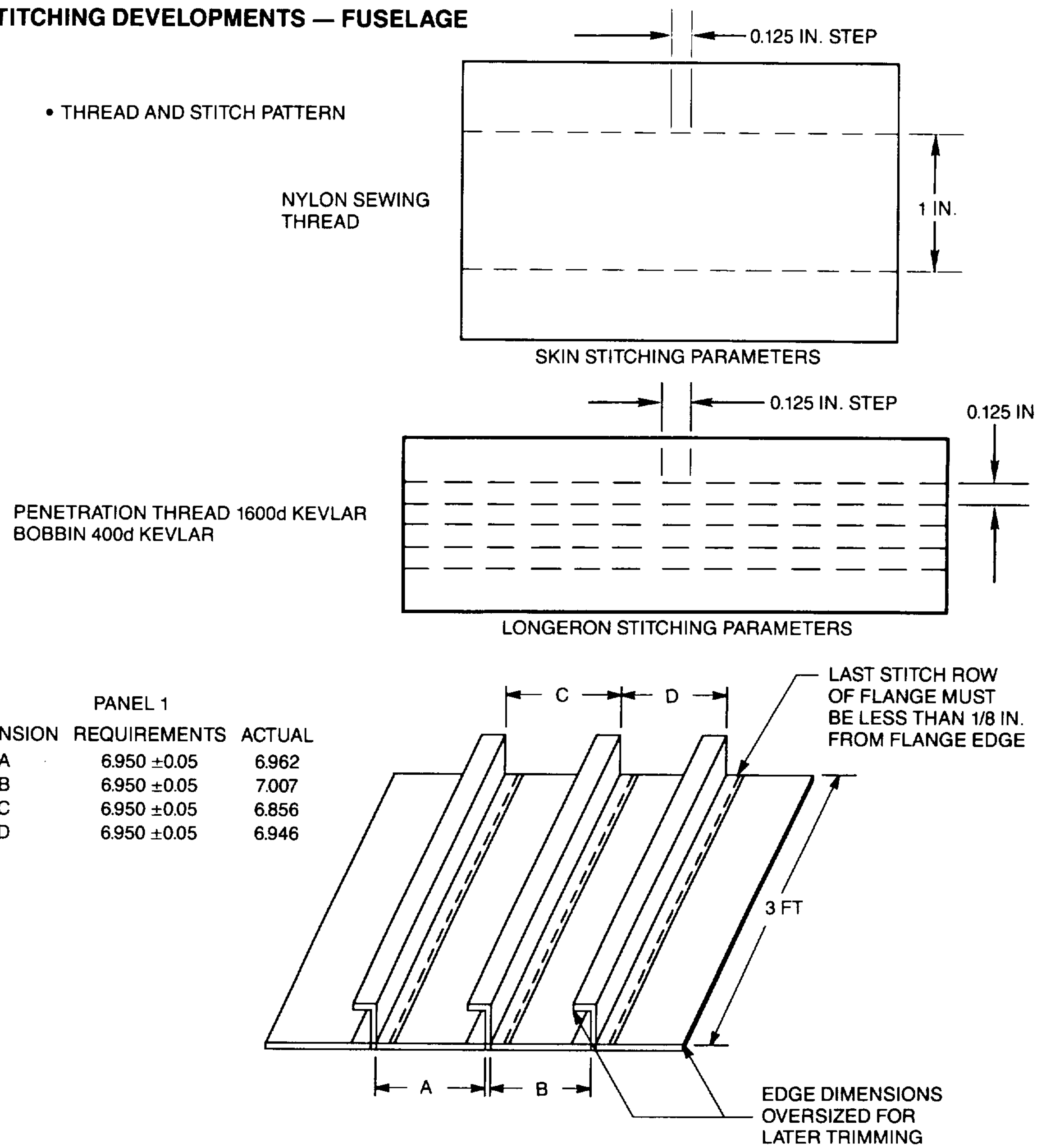
MULTIDWELL CURE CYCLE DEVELOPED TO ALLOW PREFORM THERMAL EQUILIBRIUM DURING INFILTRATION

Figure 5

Douglas Fuselage Structures

As in the case of the wing, many test results were used to establish both stitch parameters and material selections for the fuselage. Below are the stitching parameters with preform quality requirements developed for the fuselage. In this concept, the fuselage skin preform is lightly stitched with nylon thread to facilitate handling whereas the longerons are stitched with heavy Kevlar thread in a dense pattern. The longeron flanges are stitched to the skin to complete the preform.

STITCHING DEVELOPMENTS — FUSELAGE



PANEL 1

DIMENSION	REQUIREMENTS	ACTUAL
A	6.950 ±0.05	6.962
B	6.950 ±0.05	7.007
C	6.950 ±0.05	6.856
D	6.950 ±0.05	6.946

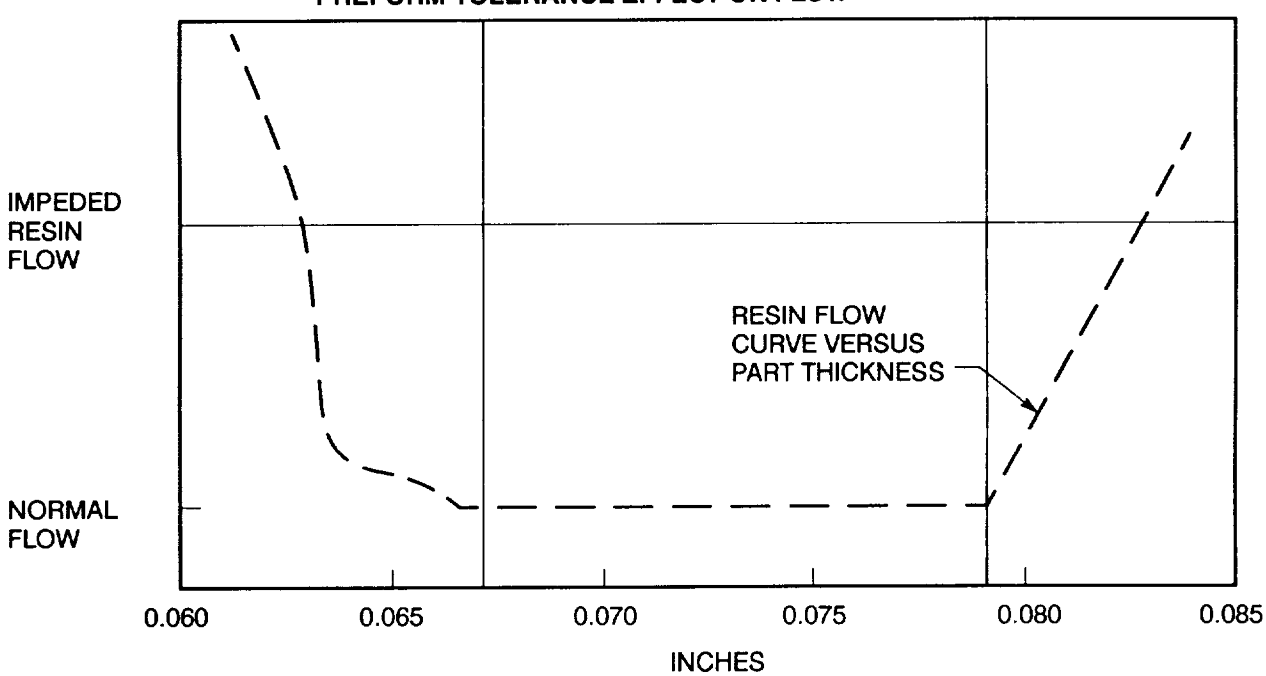
Figure 6

Douglas Fuselage Structures

To achieve the desired fiber loading in fuselage panels, the matched metal tool must be closed to stops. This requires approximately 48 psi compaction pressure. Preform fit to the final (net) size is critical to avoid edge path travel of the resin and excessive tolerance (< ∓ 0.01) mismatches which cause non-uniform resin flow paths.

Edge path travel was a frequent problem in the tooling development. To avoid unwanted edge travel, a tooled edge or O-ring was devised and can be used to apply greater compaction along the edge of the part, thus forcing resin to stay within the preform. Figure 7 below, illustrates the tolerance range for uniform non-impeded resin flow and the tooling approach for eliminating edge path flow effects. In the curve below, the vertical line between 0.67 and 0.79 represents the area of normal or acceptable resin flow. Areas to either side of these lines represent areas of impeded resin flow.

PREFORM TOLERANCE EFFECT ON FLOW



EDGE EFFECT TOOLING APPROACH

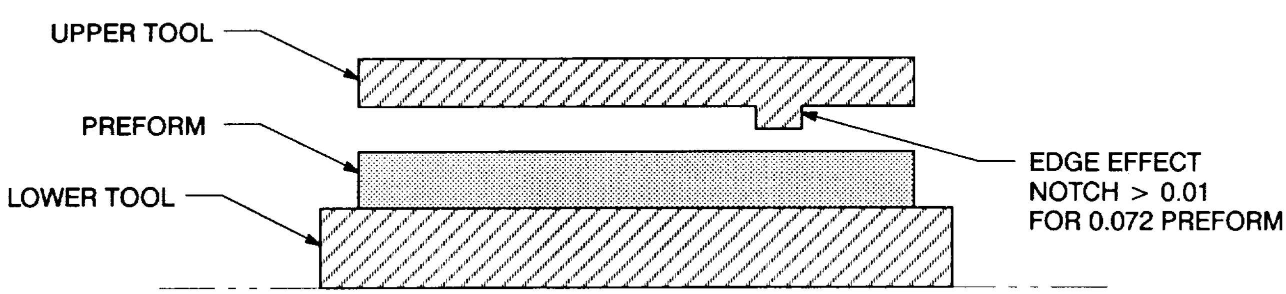
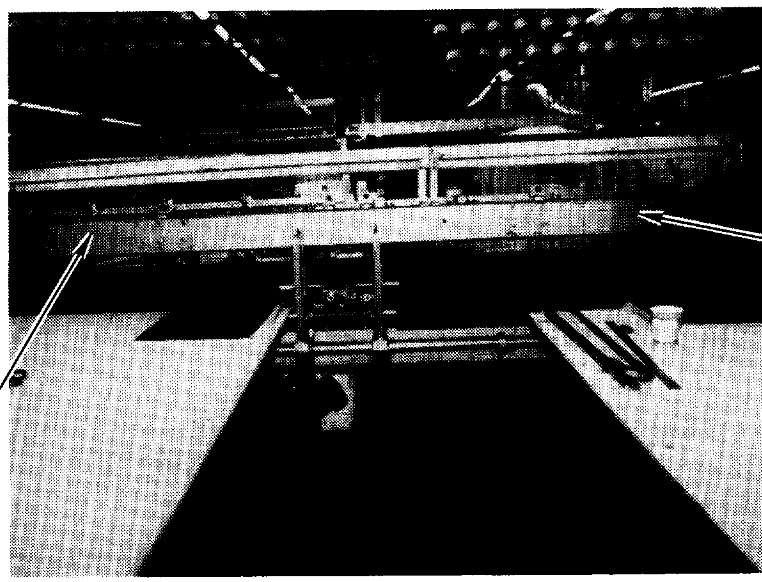


Figure 7

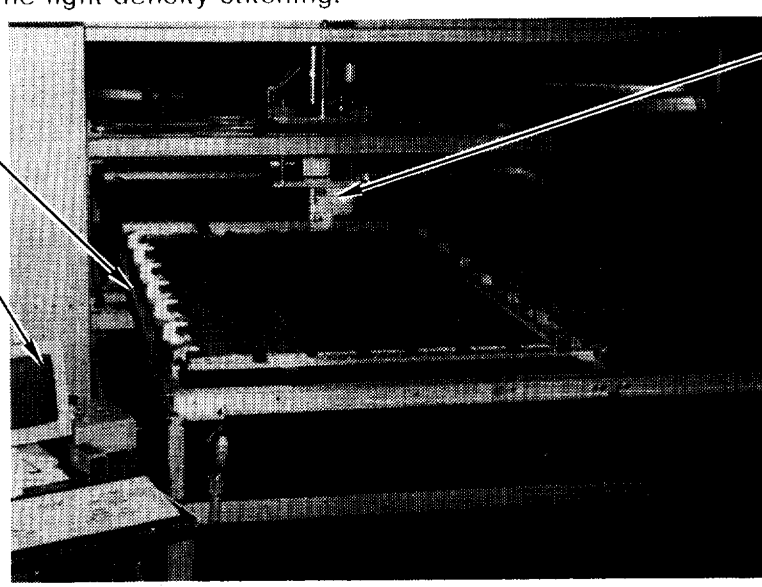
CURRENT STATUS

Douglas Wing - Stitching

Since the inception of this program, Douglas has been developing two sewing machines to stitch dry graphite wing preforms. These machines represent a first generation version of cost effective preform fabrication using a stitching process. Shown below in Figure 8 are the 128-needle sewing machine and a computer controlled single needle machine that are products of this development. Contractor for the machines is Pathe, Inc.



- The multi-needle machine made use of an existing 128-needle machine and was split into two machines: a right hand side to do the heavy density stitching and a left hand side to do the light density stitching.



- The single needle machine is a machine newly designed to Douglas specifications.

Figure 8

Douglas Wing - Stitching

The Douglas fabrication approach for stitching 4- by 6-foot stiffened wing skins is shown in Figures 9 through 13. As shown in Figure 11, the multi-needle (128-needle) machine is used for both light density 9-ply stack stabilization stitching and the heavy density damage tolerance stitching of the skin plank and stiffeners.

MULTINEEDLE MACHINE WORK FLOW

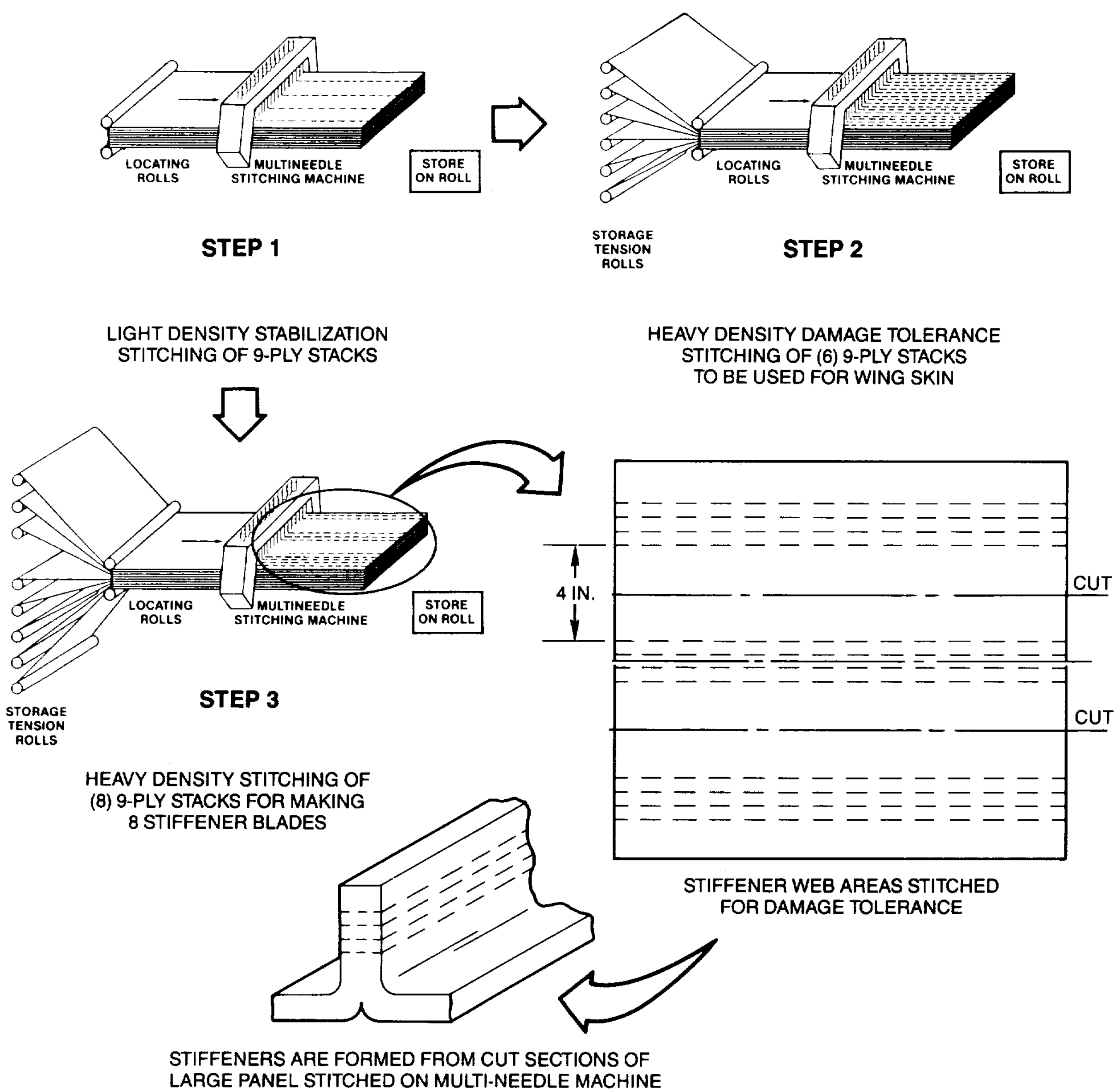


Figure 9

CURRENT PROGRESS

Douglas Wing - Stitching

The multi-needle machine (Figure 10) has been modified to perform the heavy and light density stitching. The left hand side is for heavy density stitching while the right hand side is for light density stitching. In this photo, the multi-needle machine is stitching a test specimen with 0.200-inch parallel row heavy density Kevlar stitching.

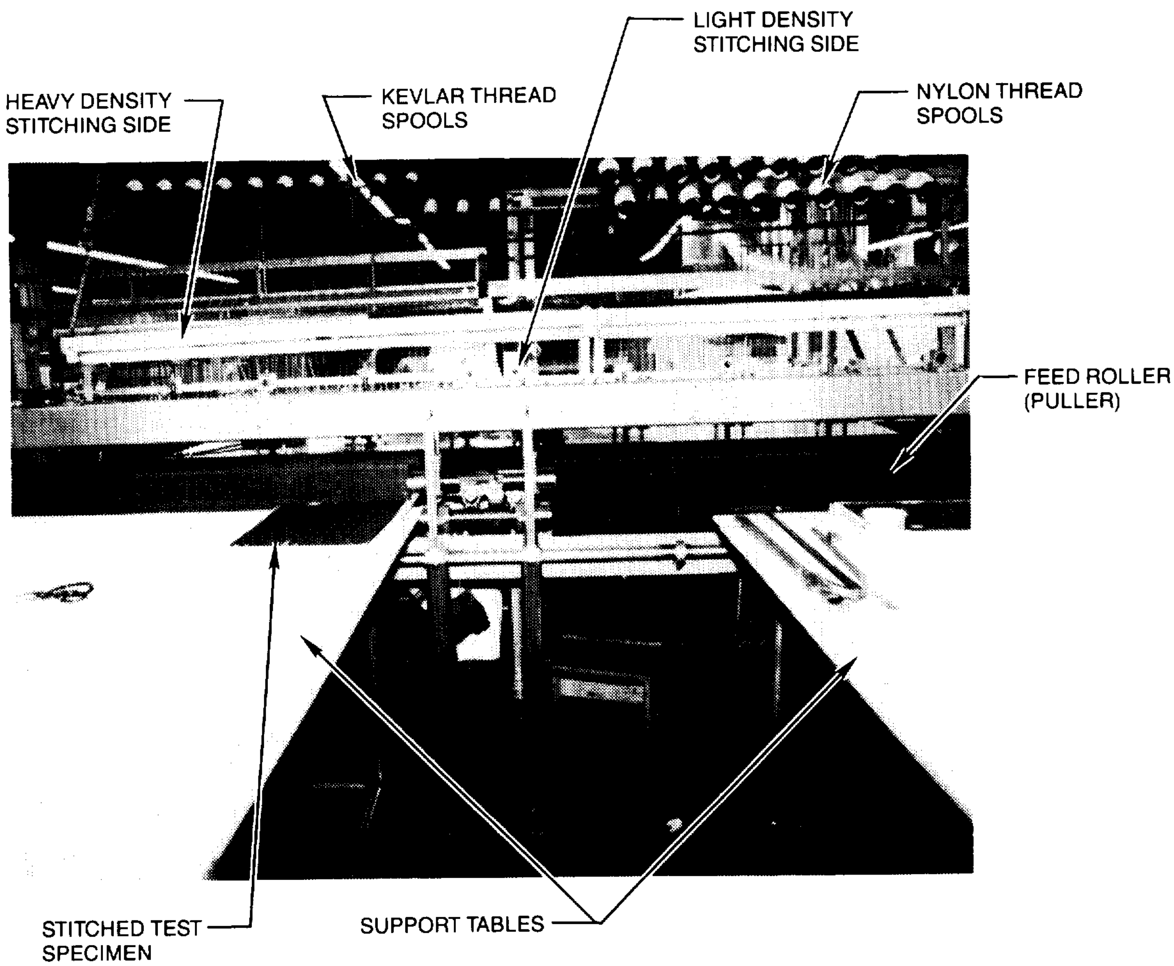


Figure 10

CURRENT PROGRESS

Douglas Wing - Stitching

Figure 11 shows the single needle computer controlled machine. This machine is used for high speed stitching of wing rib clips as well as all attachment or assembly stitching.

SINGLE NEEDLE COMPUTER CONTROLLED MACHINE

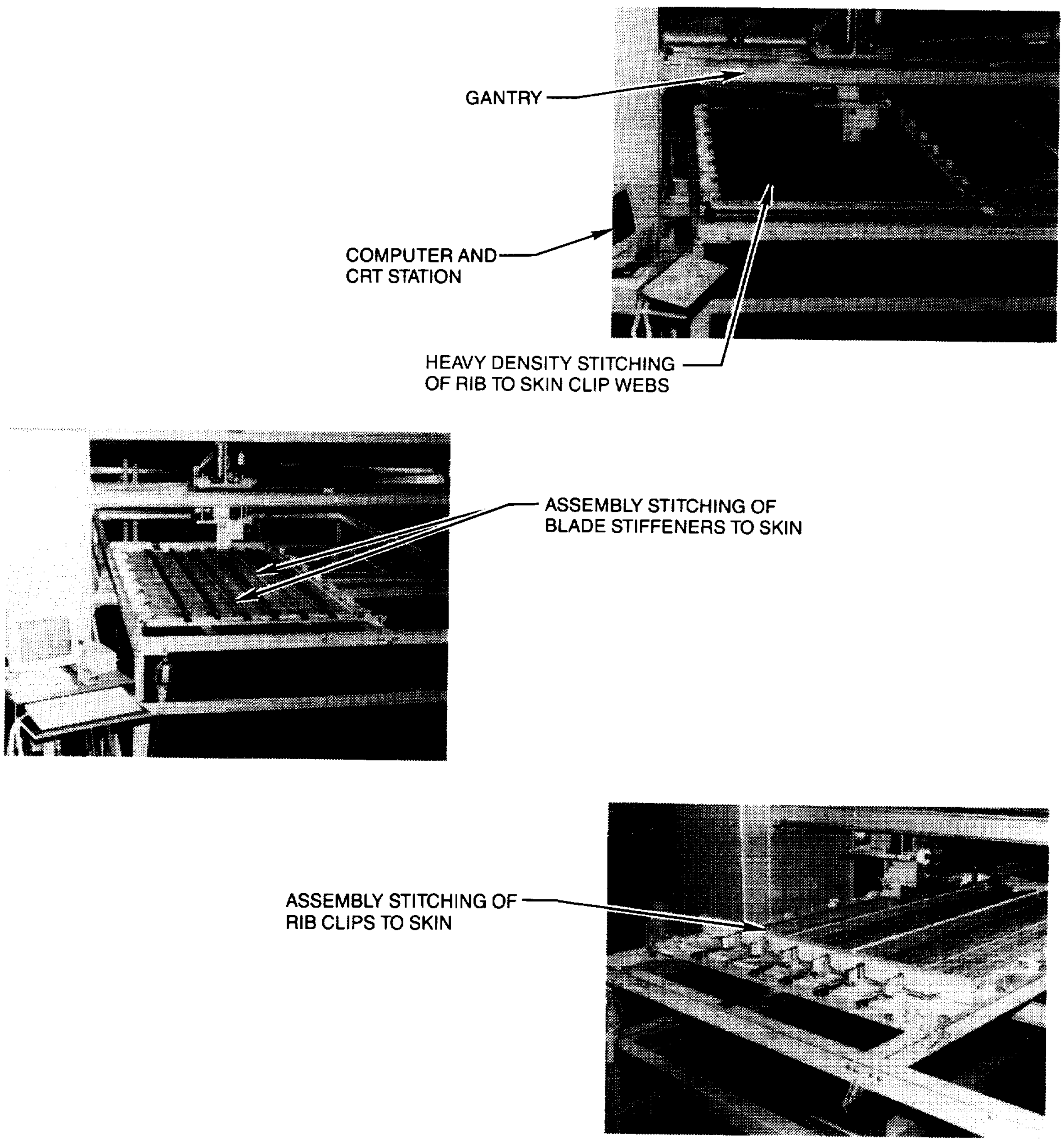


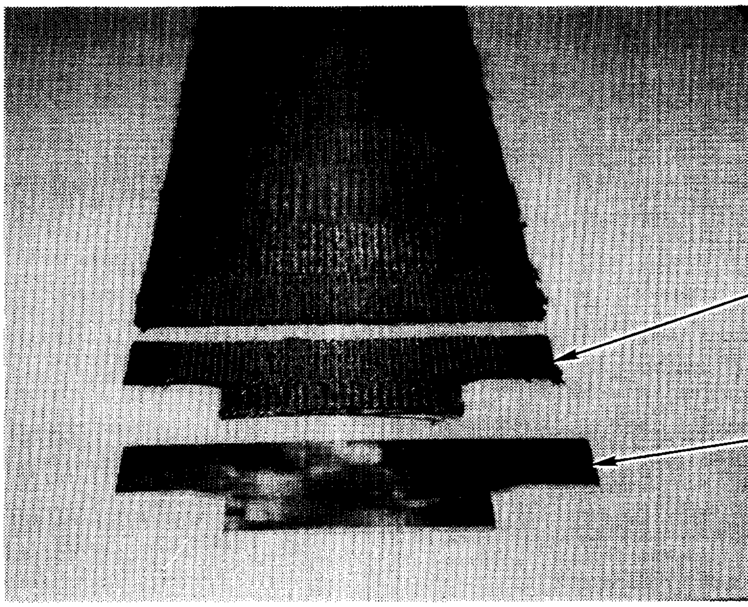
Figure 11

CURRENT PROGRESS

Douglas Wing - Stitching

Some of the steps involved in making stitched preforms for rib clips are shown in Figure 12. The computer controlled single needle machine is used to stitch patterns for the wing rib clips. Upon completion, rib clip patterns are cut from the stitched goods. Shown below is the stitched fabric from the single needle machine being cut into rib clips using a template. Also shown are the clips being placed into the rib/skin attachment location frame. Similar procedures are used to make panel stiffener preforms.

RIB-CLIP PATTERNS WITH TEMPLATE



RIB/SKIN ATTACHMENT LOCATION FRAME

Figure 12

CURRENT PROGRESS

Douglas Wing - Stitching

Once all stiffeners and rib clip preforms have been fabricated, the computer controlled single needle machine is used to assemble the details into a stiffened wing preform. In a series of photos shown below, the single needle computer controlled machine is shown attaching stiffeners and rib clips to a 4- by 6-foot stitched wing skin.

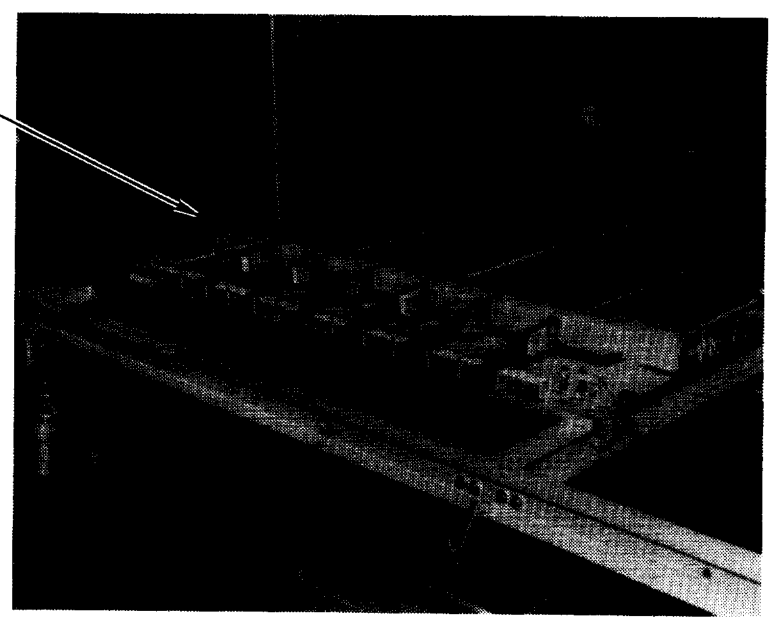
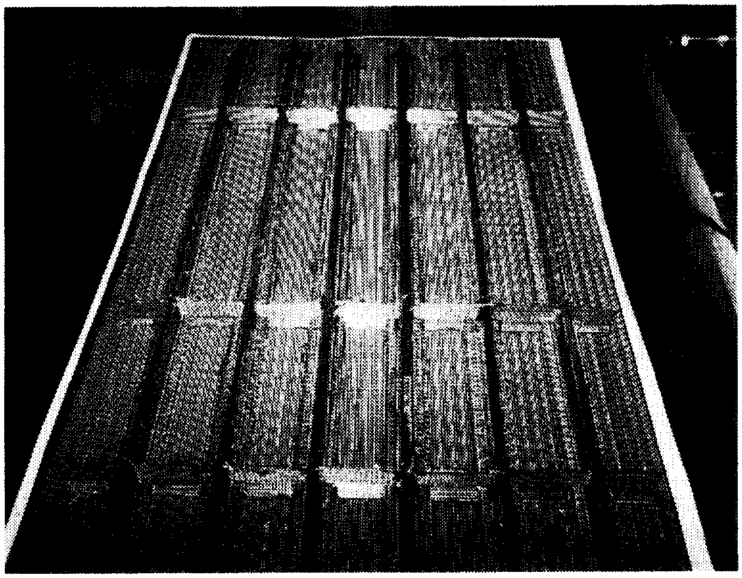


Figure 13

CURRENT PROGRESS

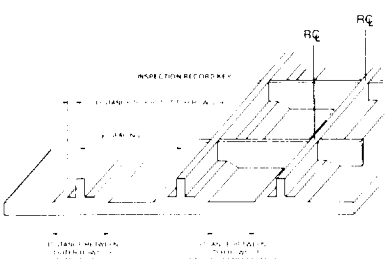
Douglas Wing - Stitching

The final result of this stitching process is a high quality preform (Figure 14) with the associated quality and cost aspects also shown in the figure.



FINISHED STIFFENED WING SKIN PREFORM

QUALITY



*BULK FACTOR ≤ 10% FOR ALL THICKNESS

PROGRAM QUALITY REQUIREMENTS

ITEM 1

S/N **DATE**

CHARACTERISTIC	VALUE	LEFT WEB		CENTER WEBS		RIGHT WEB		LEFT	RIGHT
℄ ℄ SPACING BETWEEN STIFFENERS	7.0								
		L	R	L	R	L	R		
DISTANCE TO FIRST STITCH ROW	0.37/ 0.44								
DISTANCE BETWEEN OUTER ROWS OF FLANGE STITCH	2.68/ 2.81								
DISTANCE BETWEEN OUTER ROWS OF STITCHING BETWEEN WEBS	4.19/ 4.32								
R℄ - R℄ SPACING BETWEEN RIB CLIPS	30.0								

PREFORM COST BREAKDOWN

OPERATION	TIME
• LDS 9 PLY MATERIAL 52″×120″ ON MULTI-NEEDLE MACHINE AT 120 RPM	2.7 HRS
• SET UP MULTI-NEEDLE MACHINE TO PERFORM HDS	4 HRS
• HDS 54 PLY SKIN 52″×88″ ON MULTI-NEEDLE AT 60 RPM (5 PASSES)	1.2 HRS
• HDS 72 PLY STIFFENER WEB AREA ON MULTI-NEEDLE MACHINE AT 60 RPM (5 PASSES)	1.2 HRS
• 90° LDS STIFFENER FLANGE AREA ON SINGLE NEEDLE MACHINE AT 400 RPM *	20 HRS
• 90° LDS INTERCOSTAL FLANGE AREA ON SINGLE NEEDLE MACHINE AT 400 RPM *	5 HRS
• HDS INTERCOSTAL CLIP WEB AREA ON SINGLE NEEDLE MACHINE AT 400 RPM	2 HRS
• CUT TAPER INTO STIFFENER FLANGE AREAS (6 STIFFENERS TOTAL)	4 HRS
• LDS ZIG-ZAG PATTERN FOR ATTACHING STIFFENER FLANGE TO SKIN AT 100 RPM *	8.2 HRS
• HDS STIFFENER FLANGE TO SKIN AT 100 RPM	8.4 HRS
• HDS INTERCOSTAL CLIP FLANGE TO SKIN, TOTAL FOR 21 CLIPS	1 HR
• SET UP SINGLE NEEDLE MACHINE	1 HR
TOTAL:	58.7 HRS

NOTE: * IDENTIFIES COSTLY ITEMS TO BE DESIGN REVIEWED FOR COST PURPOSES
LDS — LIGHT DENSITY STITCHING
HDS — HEAVY DENSITY STITCHING

Figure 14

CURRENT PROGRESS

Douglas Wing - Stitching

In developing the automated sewing equipment, a tremendous learning curve has been established. As shown in Figure 15A, an improvement of 50 percent has been realized in just fabricating three wing preforms. As the curve becomes more established the overall cost of preform fabrication will be substantially reduced. Figure 15B shows that learning curves were different for the many areas of preform fabrication. The area indicated in Figure 15B represents improvement in attachment of details of assembly stitching. Reasons for this improvement are predominantly related to improved work flow and refinement in stitching parameters.

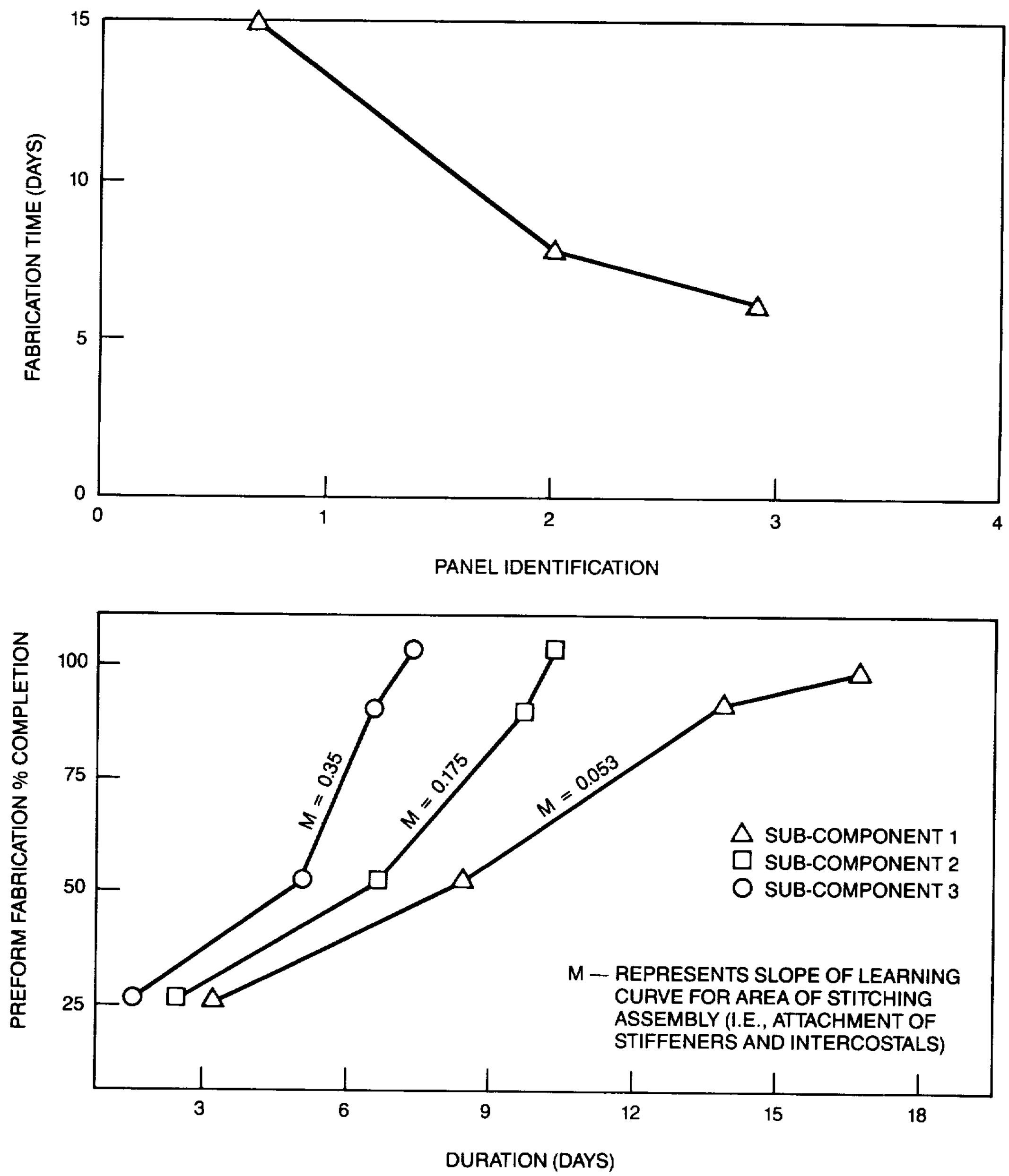


Figure 15

CURRENT PROGRESS

Douglas Wing - Fabrication

Upon completion of the preform fabrication, RTM fabrication was conducted using a resin film infusion autoclave curing process with a combination aluminum/graphite epoxy tooling approach. Figure 16 illustrates the tool layout as well as the first mandrel assembly within the preform.

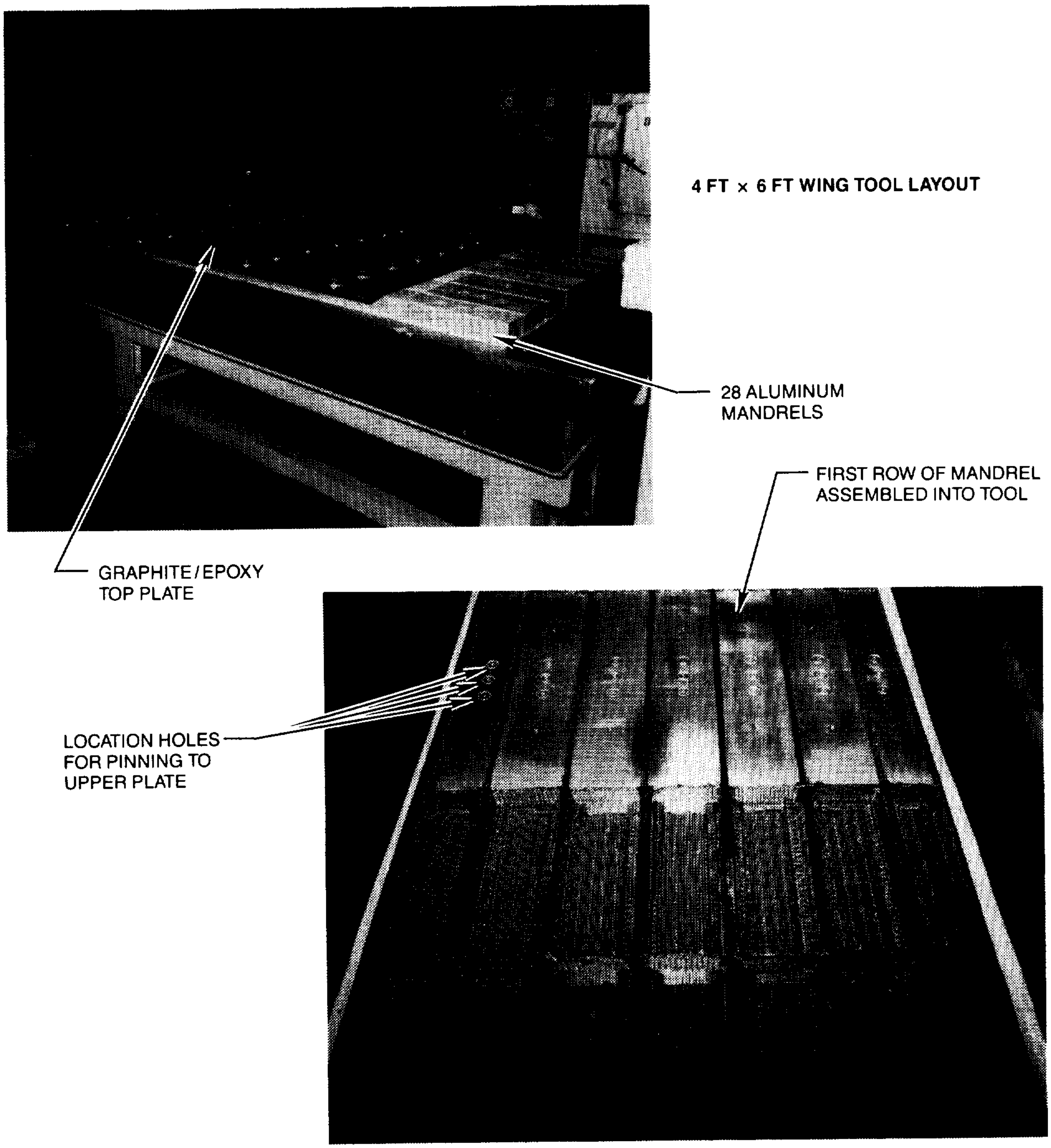
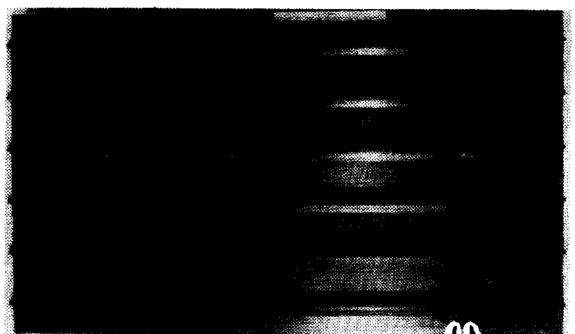
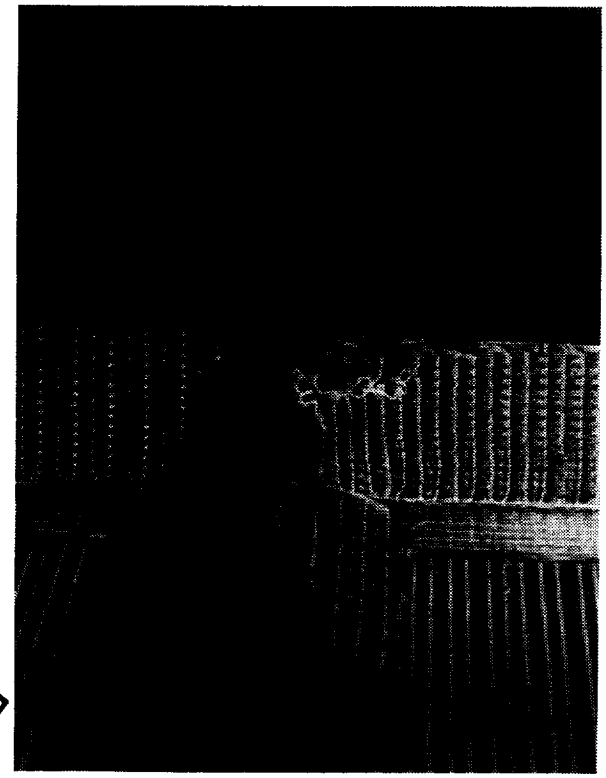


Figure 16

Douglas Wing - Fabrication

Shown below is the finished part with exploded views of the stiffener/clip intersections.





DIMENSIONAL ANALYSIS — FINISHED PART

THICKNESS	INCHES HIGH/LOW
SKIN	0.335/0.315
STIFFENER — PER STIFF.	0.465/0.451
RIB CLIP — PER ROW	0.129/0.123
RIB-CLIP ROW LOCATION/TOLERANCE	30.0/29.0

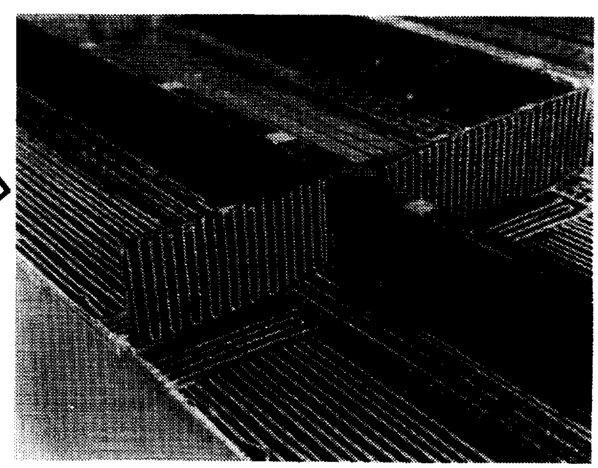


Figure 17

C-6.

CURRENT PROGRESS

Douglas Wing - Cost

Cost studies for the Douglas stitched/RTM wing process versus the automated tape layup (ATL) with hand layup reveal that the costs for the new process are approximately 50 percent less than conventional composites fabrication concepts.

RTM

Task	Hours
Preform fab	58
Trim preform	2
Tool clean/prep	16
Assemble tool	12
Bag part	4
Cure	9
Unbag	4
Trim	4
Total hours:	109

ATL/Hand Layup

Task	Skin	Stringers	Clips
ATL	14	7	
Hand layup (cut/collate/debulk)	4	40	100
Tool prep	16		
Assemble tool	12		
Bag	5		
Cure	4		
Unbag	1		
Trim part	4		
	60	47	100
Total:	207 hours		

Figure 18

CURRENT STATUS

Douglas Fuselage - Stitching

The Douglas fabrication plan for stitching 4- by 5-foot 126-inch radius fuselage panels is illustrated in Figure 19. In this process, the 12-ply skins are light density stitched (LDS) to provide stabilization for handling (Figure 19A). The 20-ply stiffeners are (LDS) stitched in 10-ply segments, stacked to make 20-ply stiffeners and heavy density stitched in the web area (Figure 19B). The stiffeners are then formed similarly to that of wing stiffeners (see Figure 9); then stitched to a flat skin in the specified locations. Once the stitched preform is complete, the skin can be draped to the required 126-inch radius with no skin wrinkling or buckling.

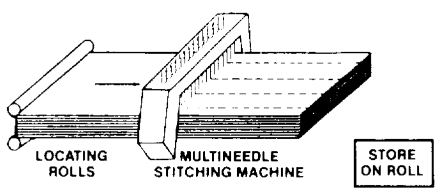


FIGURE 19a LIGHT DENSITY STABILIZATION STITCHING

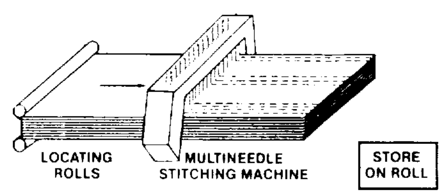


FIGURE 19b HEAVY DENSITY STITCHING OF LONGERON WEB AREAS

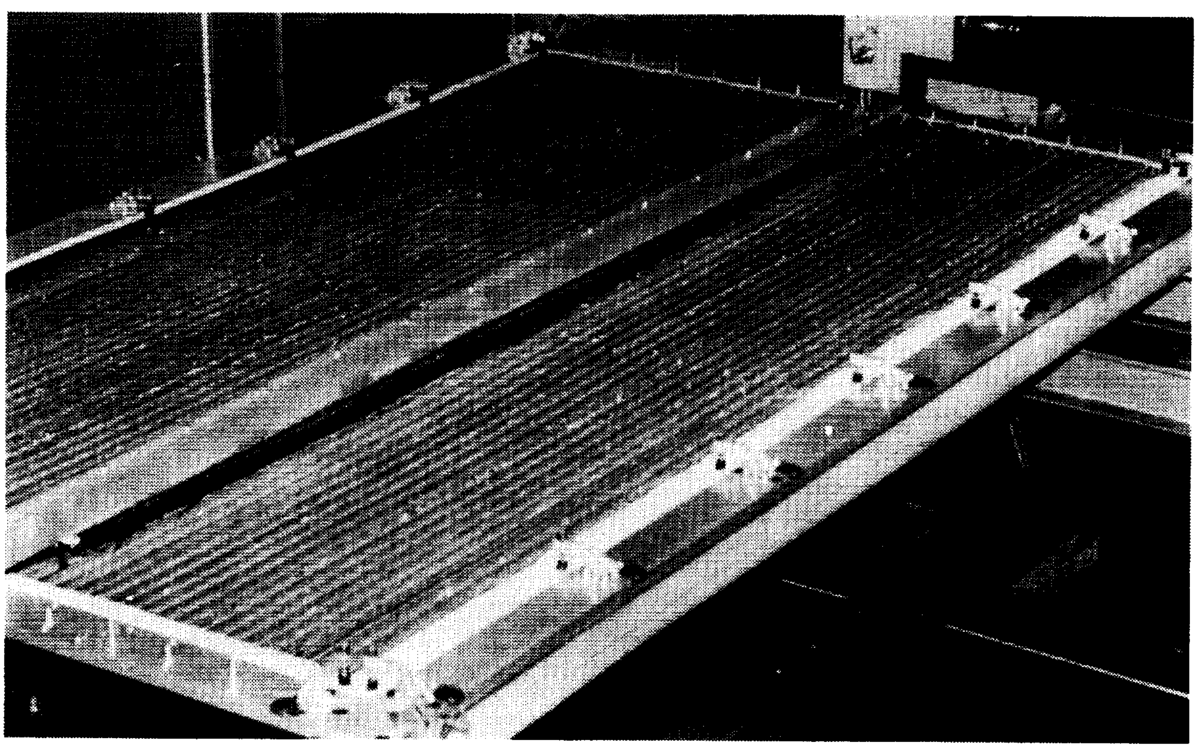


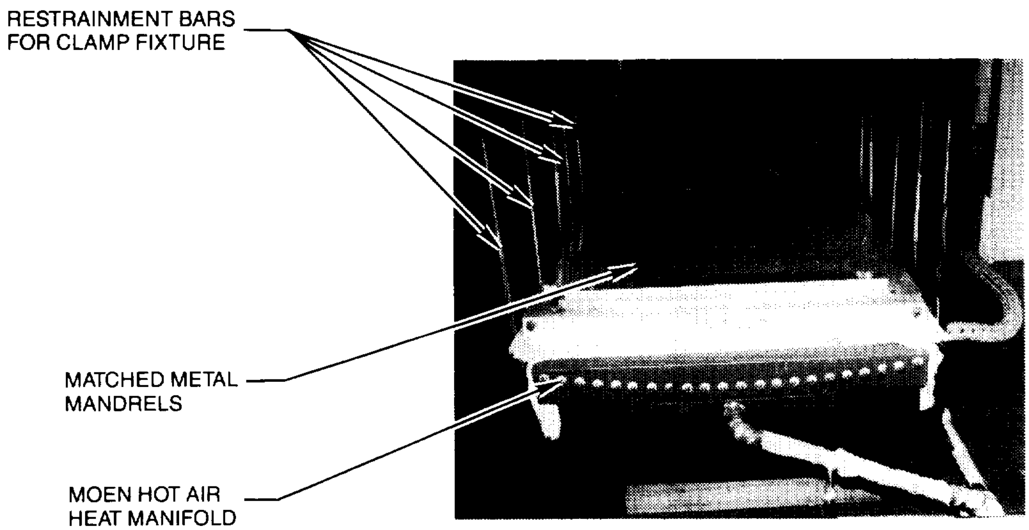
FIGURE 19c FUSELAGE ASSEMBLY STITCHING ON SINGLE NEEDLE MACHINE

Figure 19

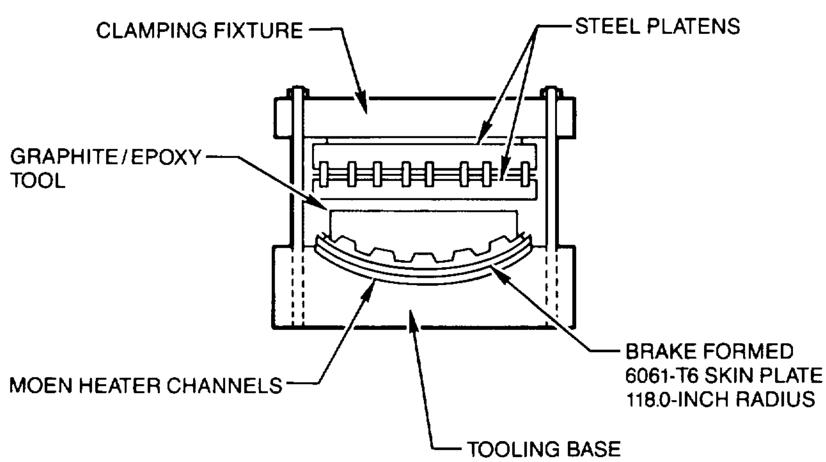
CURRENT STATUS

Douglas Fuselage - Tooling

Douglas has devised two tooling methods for making fuselage panels using the pressure RTM fabrication process. In the first approach, a complete matched metal tool is assembled in pieces as shown below in Figure 20A. The second approach was to use a one piece cavity tool with mandrels, providing definition for the stiffeners, Figure 20B.



MATCHED METAL TOOL CONCEPT
SHOWN PARTIALLY ASSEMBLED



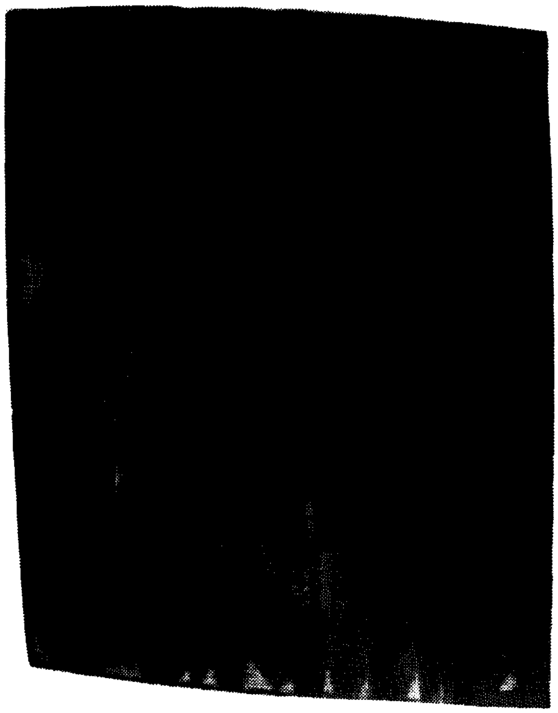
GRAPHITE TOOL CONCEPT

Figure 20

CURRENT STATUS

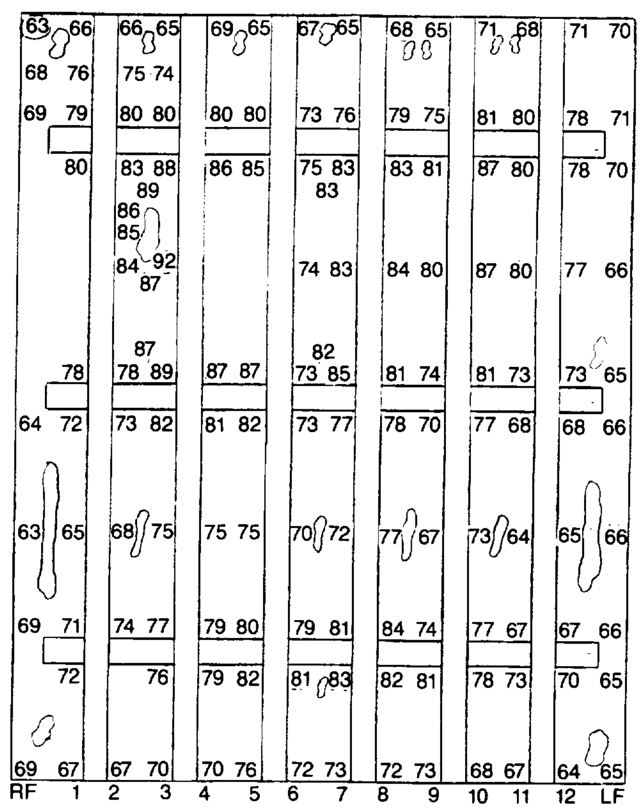
Douglas Fuselage - Fabrication

Prior to fabrication of the RTM fuselage panels, a series of tool proof parts were fabricated to verify process procedures and tooling tolerances. Results of the first tool proof part revealed numerous dry spots due to tooling tolerance mismatches. Shown below (Figure 21) is the first tool proof part with the associated dimensions. A skin thickness of 0.072 inches was the design target.



TOOL PROOF PART

TOOL PROOF SKIN



LOCATION OF DRY SPOTS WITH
PART DIMENSIONS IN 1/1,000 OF AN INCH

Figure 21

CURRENT STATUS

Douglas Fuselage - Fabrication

A closer examination of the tooling tolerance mismatches reveals interesting information on the effect of bulk factor, clamp pressure, porosity, permeability, and hydrostatic resin pressure. In tool proof part #1, the bulk factor was 8.3 percent greater than the tool design value (materials with a .0065 per ply thickness were used instead of a .006 per ply thickness material). This resulted in a decrease in porosity, thus causing resin not to flow in the areas of decreased permeability. Shown below is a graph of compaction pressure versus porosity. If one follows the porosity curve generated for this preform down to the compaction pressure necessary for design goals, the midpoint porosity for that preform tool combination is established. In this case, it is $\simeq 0.475$. Also shown on the graph are the tool design limits for porosity based upon ± 0.006 per ply tool tolerances. Combination of these curves gives a visual aid in helping determine that the desired porosity range $0.428 < \phi < 0.510$ was too close to the porosity midpoint for the tool proof part thus causing tooling tolerance mismatches to become very sensitive on flow profiles.

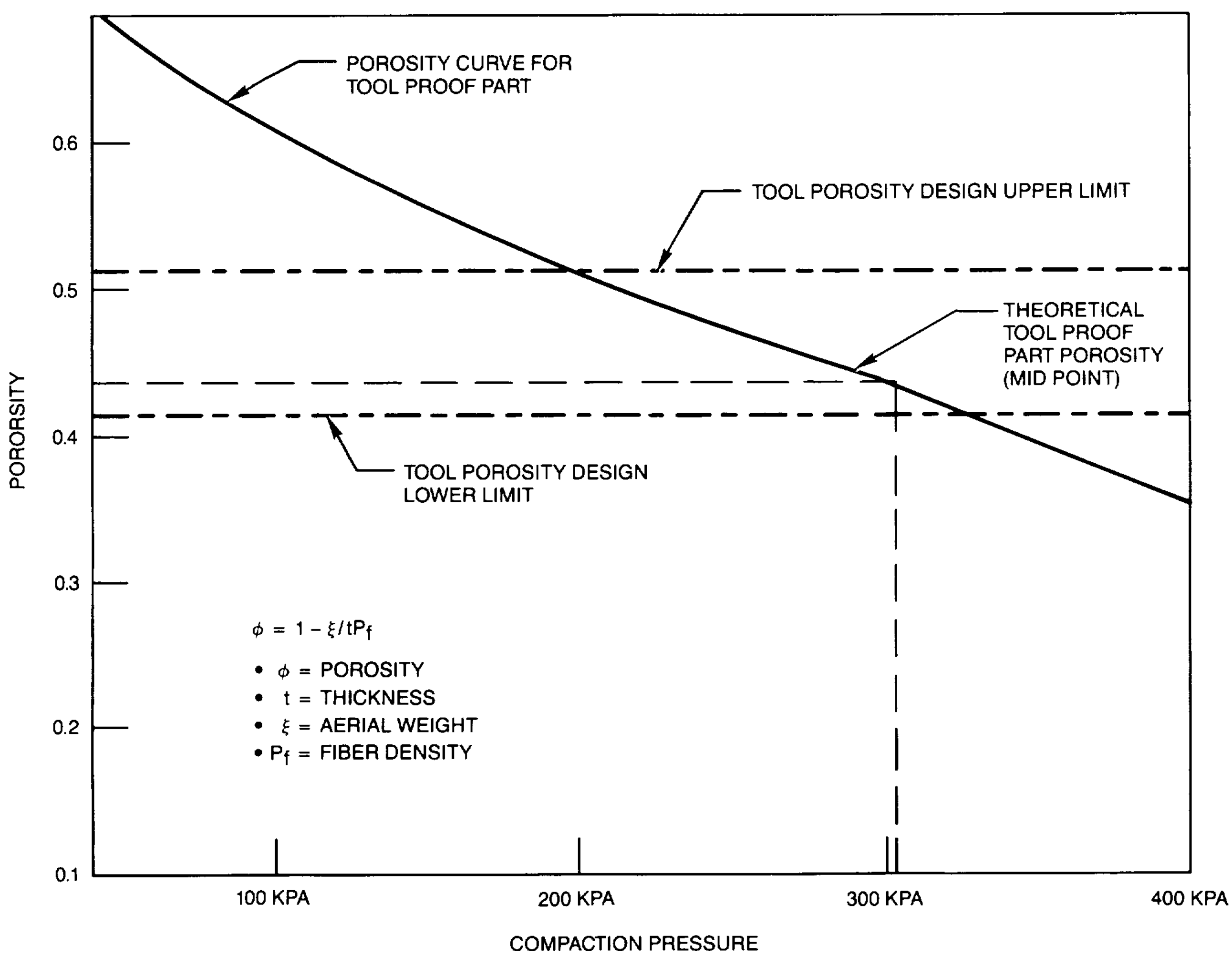


Figure 22

Douglas Fuselage - Fabrication

A detailed look at permeability sensitivity (P_s) is seen below.

$$P_s \alpha \frac{HydrostaticResin}{Permeability}$$

This graph indicates the tool design P_s is 12.5 (at midpoint). The upper and lower bounds at tool tolerances of $\pm$.006 inches yield a P_s boundary from 8 and 37.5. (Notice the significant change in -.006 inches versus +.006 inches. This indicates flow is three times harder at -.006 than at +.006.) This information provides a boundary in which the tool designer can expect resin to flow easily, unimpeded. Once the tooling limits are set, a designer should verify that the preform actually being used fits the design criteria. Shown here is the average $P_s = 30$ for the tool proof part (based on per ply thickness of .0065). In this case, the tool proof part P_s was at a lower extreme of the tooling tolerance limit. The actual upper and lower flow permeabilities in this part are 5.4 and 200. One can easily see this far exceeds the tool design. From this information a tool design for any part can be made accurately if the data is available.

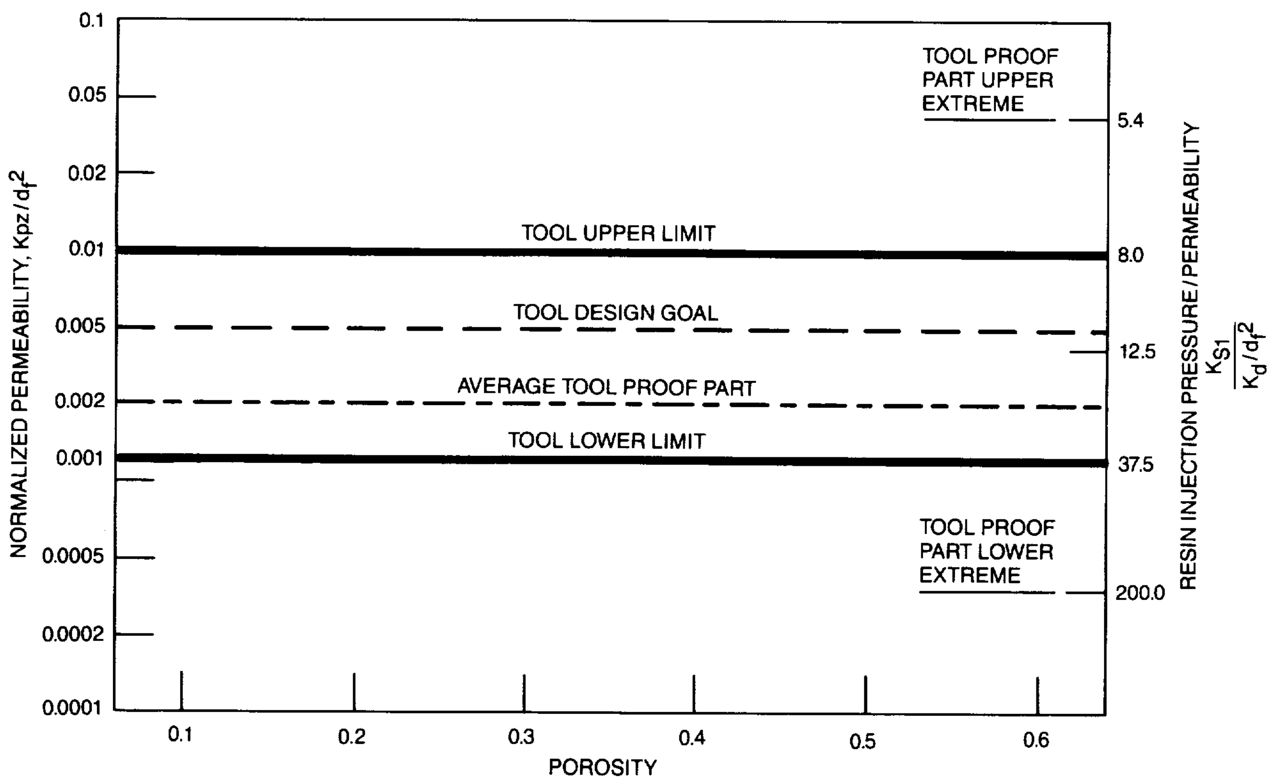
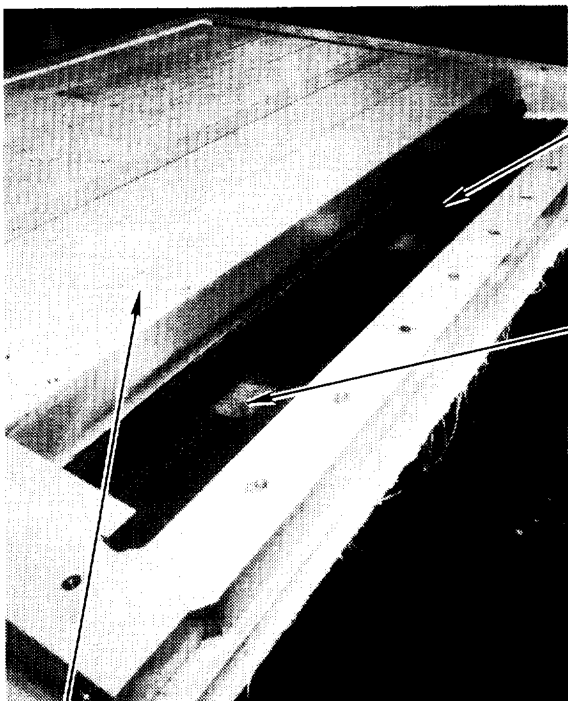


Figure 23

CURRENT PROGRESS

Douglas Fuselage - Fabrication

With the tooling tolerances brought into specification, the fabrication of three 4- by 5-foot 126-inch radius fuselage panels proceeded without incident. Figures 24 and 25 are a series of photos showing the tool assembly, injection, and disassembly process.



MATCHED METAL TOOL FINAL ASSEMBLY

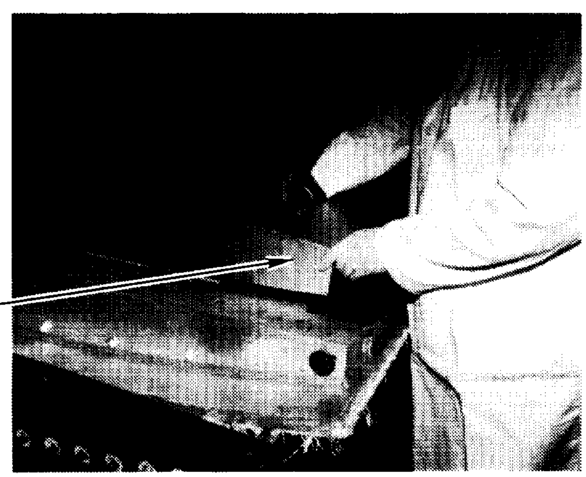
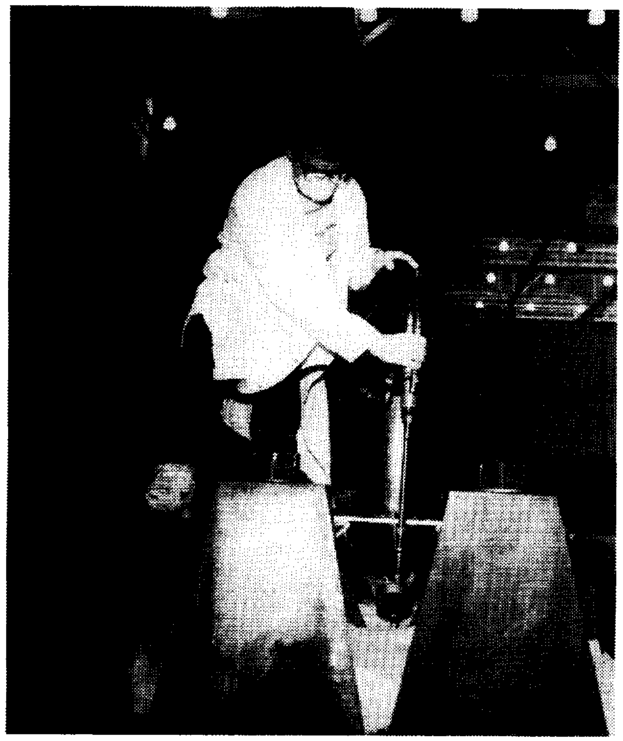


Figure 24

CURRENT PROGRESS

Douglas Fuselage - Fabrication

Shown below is the injection and tool disassembly process.



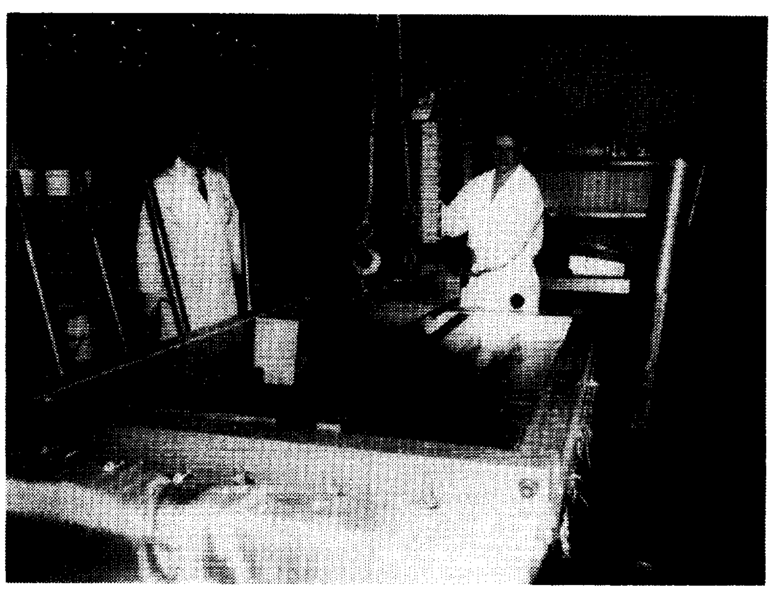


Figure 25

CURRENT PROGRESS

Illustrated below are the completed RTM fuselage panels.

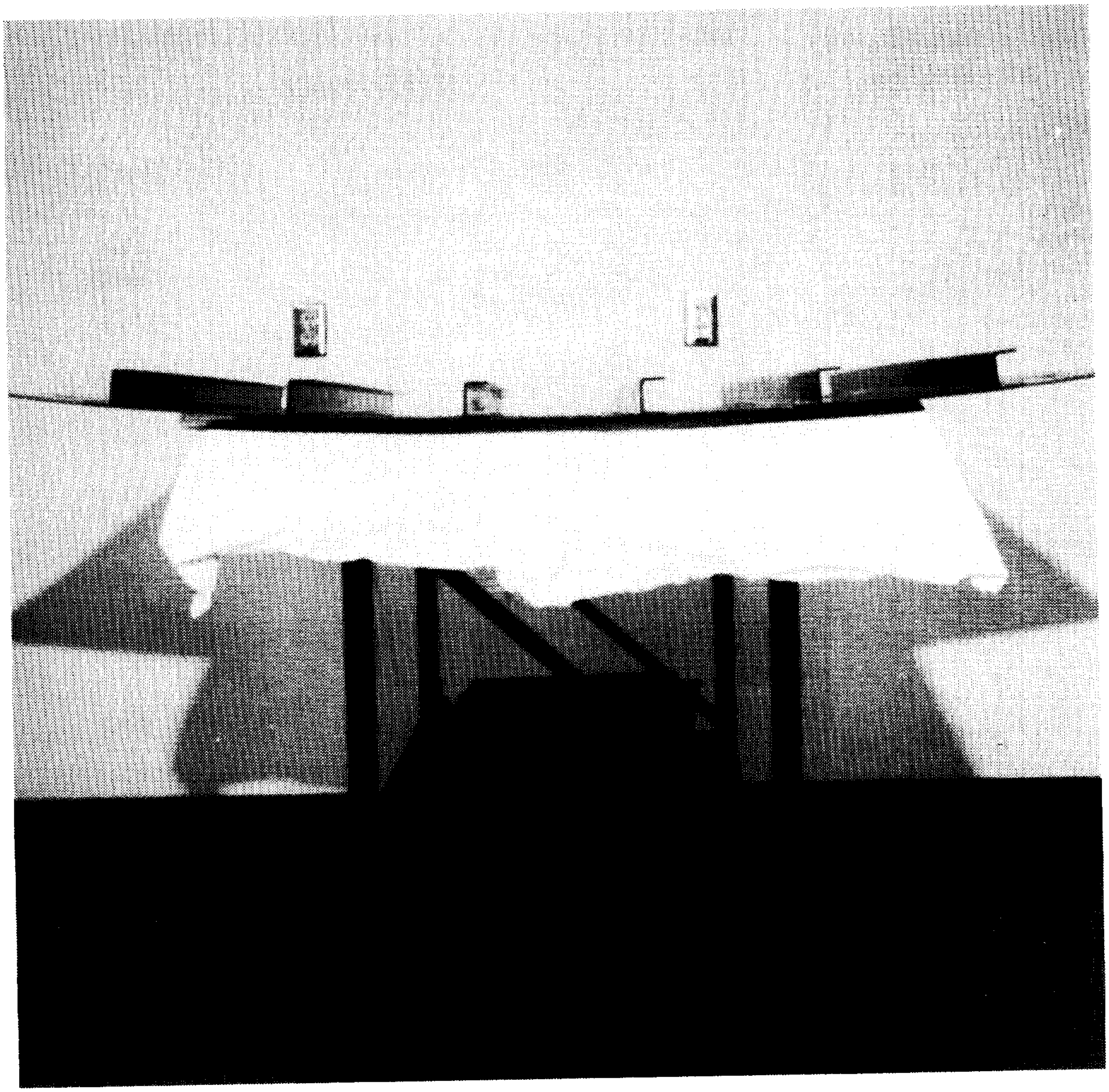


Figure 26

CURRENT STATUS

Douglas Fuselage - Cost Studies

RTM Fuselage

Task	Hours
Preform fab	8.0
Trim preform	8.0
Tool clean/prep	2.0
Assemble tool	24.0*
Resin inject/cure	12.0
Disassemble tool	8.0
Trim	8.0

Total:	88.0

*Multi-piece tooling provides excessive costs.

ATP Fuselage

Task	Hours
Fiber placement of skin	
• set-up	4.09
• machine	8.40
Stringers - hand layup	
• 4.5 hrs x 2 men x 6 parts	54.00
Shear tee doubler	
• 5 min/doubler x (3) x 1 man	.25
Panel assembly	
• 4 hrs x 2 men	8.00
Panel cure	
• 4 hrs x 2 men	8.00
• autoclave process time	8.00
Final trim	
• 4 hrs x 2 men	8.00

Total:	82.77
Process	8.00

	90.77

Note: Total is per panel. NDI and QA is not included.

Figure 27

CONCLUSIONS

RTM Wing Development

- RTM/stitching goals were achieved
- High quality preforms have been fabricated using automated stitching equipment
- Learning curve on utilizing automated sewing equipment is very short (result of mature textile technology)
- RTM fabrication process for complex stiffened wing structure works well
- A reduction of 50% in touch labor of RTM versus state-of-the-art composite fabrication process was realized during this phase of program
- Scale-up to large wing structure is possible

RTM Fuselage

- RTM/stitching goals were achieved
- High quality preforms have been fabricated using automated stitching equipment
- RTM fabrication processes for complex stiffened fuselage structure have been successfully developed
- Tool design requires a thorough understanding of process modeling, preform porosity and permeability
- Costs of RTM versus ATP are extremely competitive
- Scale-up to large fuselage structure requires extensive tooling development