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**RESIN TRANSFER MOLDING
for
ADVANCED COMPOSITE
PRIMARY AIRCRAFT STRUCTURES**

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INTRODUCTION

Resin Transfer Molding (RTM) has been identified by Douglas Aircraft Company (DAC) and industry to be one of the promising processes being developed today which can break the cost barrier of implementing composite primary structures into a commercial aircraft production environment. The following paper will discuss the RTM process developments and scale-up plans Douglas Aircraft will be conducting under the NASA ACT Contract.

PROCESS DESCRIPTIONS

Resin Transfer Molding at Douglas Aircraft consists of two distinct methods of resin impregnation: 1.) Vacuum infusion and 2.) Pressure injection.

Figure 1 below describes the two forms of vacuum resin infusion being developed at Douglas. First is resin film infusion, in which a resin (film) is placed on the tool, the preform is placed over the resin, the entire assembly is vacuum bagged and oven cured according to the proper cure cycle for that resin system. The second form of infusion is liquid resin infusion. In this method, instead of placing the resin film on the tool, a porous distribution manifold is placed on the tool to allow the liquid resin to infuse the preform. As with the film infusion method, the entire assembly is vacuum bagged at 30 in mercury and cured at 350 degrees in an oven. (Note: Hard tooling can and often is used in place of vacuum bag.)

PROCESS DEVELOPMENT VACUUM IMPREGNATION

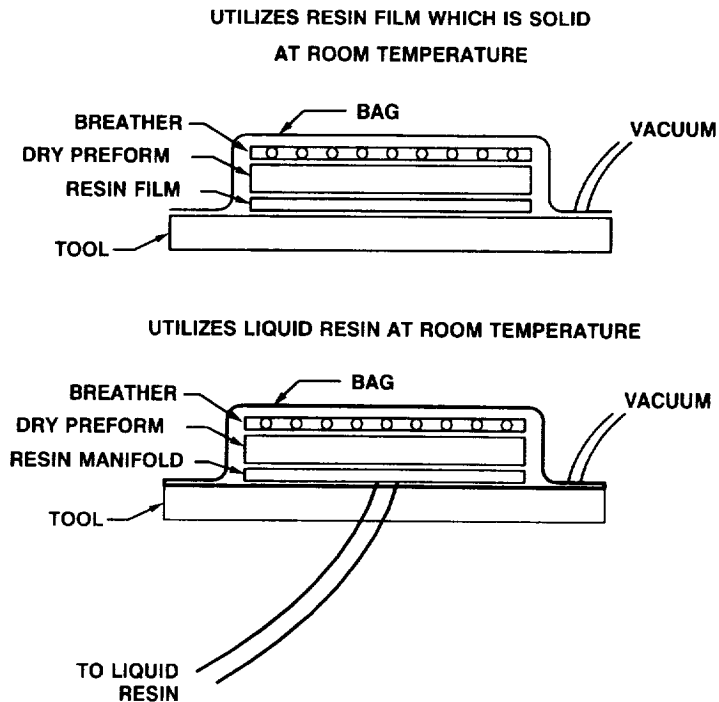


Figure 1

PROCESS DESCRIPTIONS

The second form of Resin Transfer Molding is pressure injection. As described in Figure 2 below, this process transfers liquid resins through a mix chamber into a compacted stitched preform contained within a matched metal tool. The tooling for this process is usually self-heated and requires some type of press or restraining fixture.

In the Douglas RTM development, the resin injection port is located at the center of the part allowing resin to flow directly into the preform, while venting occurs at locations deemed necessary by preform geometry (resin pressure of 40 psi is desirable). In the case of flat panels, venting usually occurs at each corner.

This type of process is currently being implemented into many automobile prototype manufacturing facilities.

PRESSURE IMPREGNATION

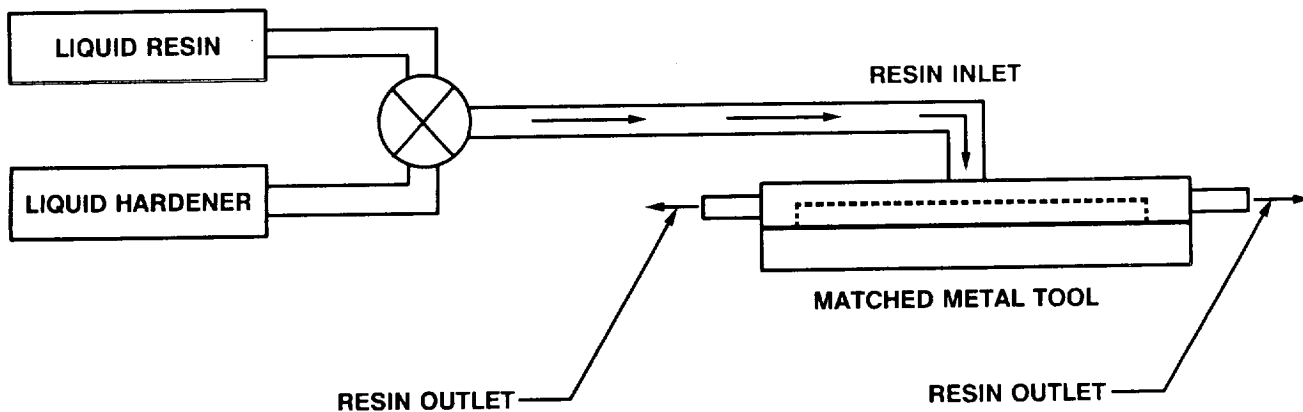


Figure 2

PROCESS OBJECTIVES

The objectives of Douglas' RTM development is to 1.) Exploit the benefits of RTM to maximum potential, 2.) Become cost competitive. Below is a list of the primary benefits RTM offers as a process (Figure 3).

RTM/STITCHING BENEFITS

LOW-COST MATERIAL SYSTEM (WITH PREMIUM DAMAGE TOLERANCE)
REDUCED ASSEMBLY COSTS (DUE TO STITCHING)
SHORTER PROCESS CYCLES
BUILT-IN QUALITY (REDUCED QUALITY INSPECTION COSTS)
GREATER CONTROL OF DIMENSIONAL ACCURACY
REDUCED FABRICATION COSTS (CUTTING, LAY-UP, PROCESSING)
INHERENT STRUCTURAL QUALITY

Figure 3

PROCESS OBJECTIVES

If all benefits of the RTM process are realized, significant advances can be made in the application of composite primary structure to commercial aircraft. Those benefits of most importance in leading to application are primarily cost related. Figure 4 below compares the Douglas funded 8' x 12' wing box fabricated with conventional materials and methods versus the NASA funded 8' x 12' wing box to be made by RTM. If full advantage of the stitching process can be realized, (stitching rib clips to skin) a cost savings of 48% is projected over the conventional box being fabricated by Douglas.

During wing box fabrication, detailed data will be compiled on material and labor costs. This data will provide a direct comparison between conventional and advanced composites fabrication. Obviously, a major issue is the cost of composite wing structure versus the cost of conventional aluminum construction. Attempts are underway to define aluminum costs at the wing box level. Another approach will involve wing cost models to project composite wing box costs to full scale wing structures.

RECURRING COSTS FOR 8 X 12 TEST BOX

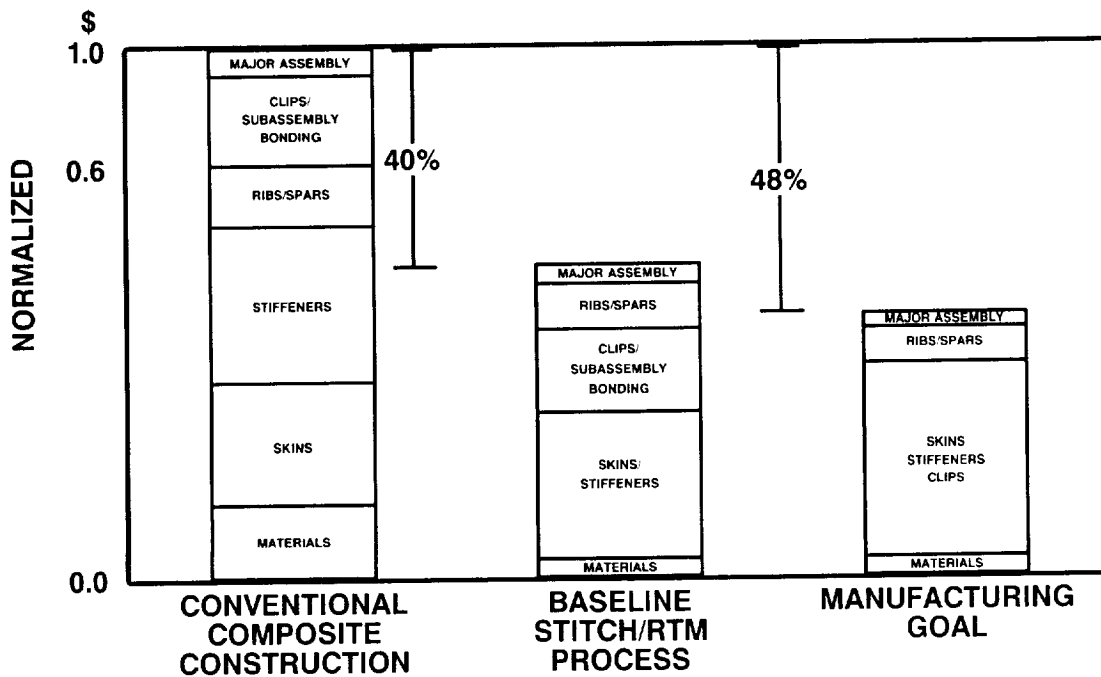


Figure 4

**MANUFACTURING DEVELOPMENT
for
COMPOSITE PRIMARY WING STRUCTURES**

WING SUB-SCALE TOOLING DEVELOPMENT Effect of Preform

In developing a manufacturing strategy for the Douglas wing effort, it became clear that vacuum infusion with heavy density stitched preforms was a natural for this structure. The heavy density stitching gives the damage tolerance needed as well as the compaction necessary to utilize the vacuum impregnation minimum pressure process. Below in Figure 5, compaction studies run at Douglas indicate that the stitched preform gives 92% of what full compaction would be for 60% fiber volume. The real benefit of this is that the tooling for the structure can be greatly simplified. In fact, tooling is basically used for part volume definition only since no compaction or movement is required.

WING ELEMENT TOOLING DEVELOPMENT EFFECT OF HEAVY DENSITY STITCHING ON TOOLING DEVELOPMENT

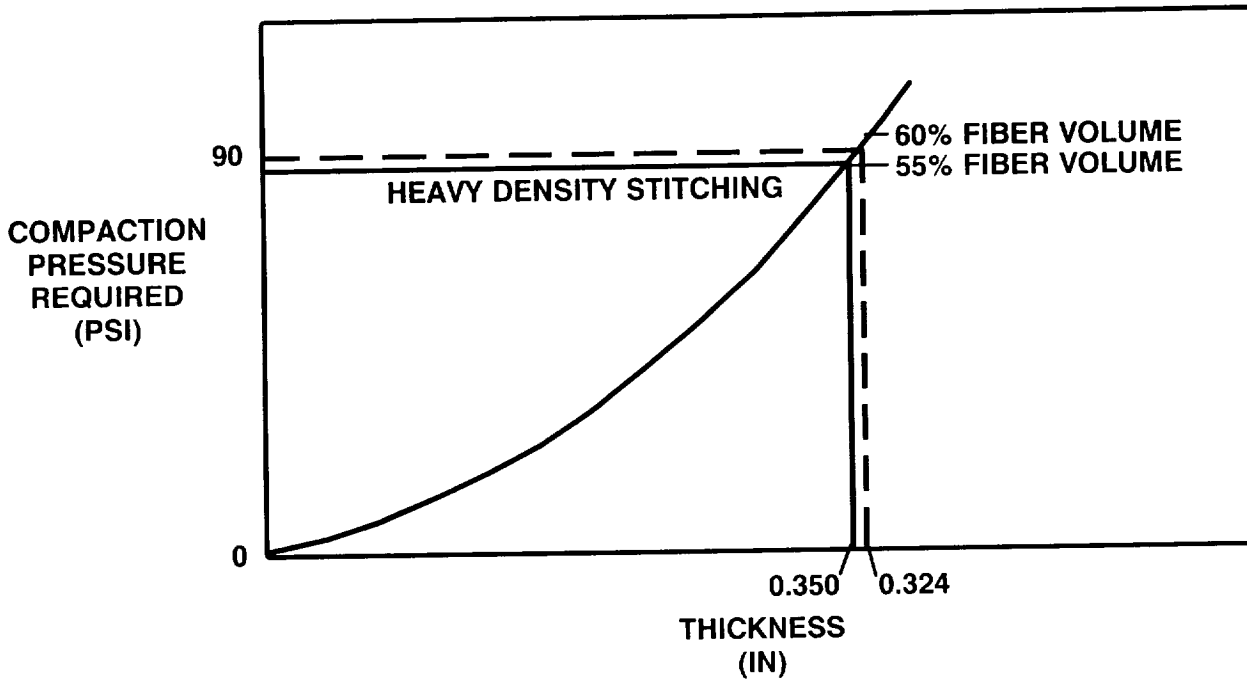


Figure 5

WING SUB-SCALE TOOLING DEVELOPMENT Tool/Process Definition

Douglas tooling for three stringer element wing panels is currently set up for both film resin infusion and liquid resin infusion. In Figure 6, on the left is a schematic of the film infusion tooling. As with the flat panel tool, the resin film is first placed on the tool, the preform and mandrels are then placed on the resin, and the entire assembly is bagged and cured according to the proper resin cure cycle. (Note: The current method of processing with 3501-6 film resins requires the use of an autoclave to insure proper wet-out.) In Figure 6 (right), the liquid vacuum infusion method is illustrated. In this case, the resin film is replaced with a porous distribution manifold that allows the liquid resin to uniformly permeate the preform. Once resin infusion is complete, the entire assembly is allowed to cure under vacuum bag pressure and oven heat only. (It should be noted that this tooling currently uses rubber expansion for compaction between stiffeners. In future tooling, this will not be necessary. Also, rigidized periphery tooling can be used in place of vacuum bag to hold tolerances of preform.)

WING ELEMENT TOOLING DEVELOPMENT

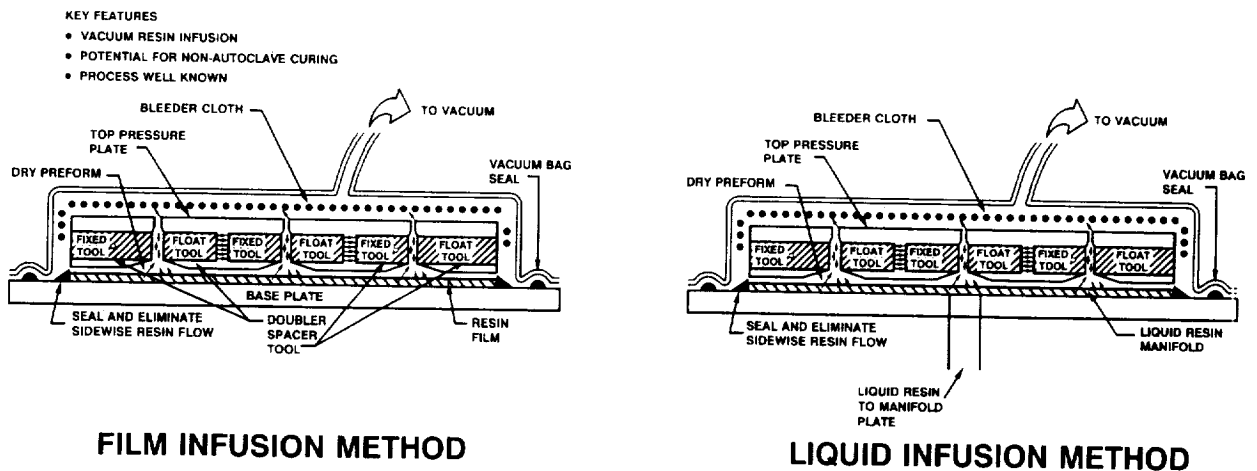


Figure 6

WING SUB-SCALE TOOLING DEVELOPMENT
Douglas Wing Vacuum Infusion Tool

Below in Figure 7 are photos of the preforms and tooling for wing element work. On the upper left is a heavy density stitched 3 blade wing element preform ready for resin infusion. Below to the right is the matched metal aluminum tooling assembled on the preform before vacuum bagging the assembly.

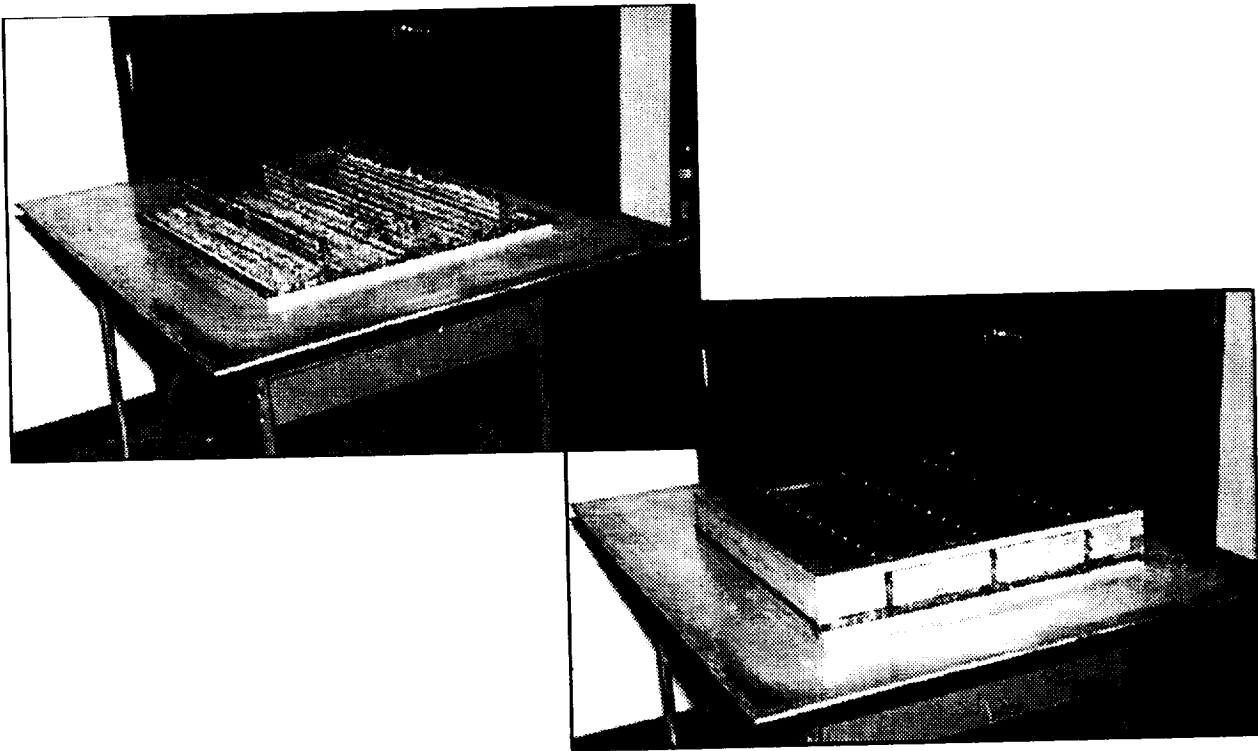


Figure 7

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WING SCALE-UP TOOLING DEVELOPMENT

In scale-up of the vacuum infusion process, Douglas will select between liquid and film resin infusion. To date, the infusion process performs better with liquid resins rather than the film resins. However from a tooling scale-up perspective, the film resins are preferable. To utilize a film resin, it appears that a viscosity profile should be maintained well below 250 centipoise at 250 degrees F or below for between one and two hours.

In using such a film resin, the vacuum infusion tooling and process have a significant advantage in that both are currently well defined for scale-up. The primary development necessary is in selecting tool materials that satisfy classical tooling concerns (i.e., coefficient of thermal expansion, thermal mass/weight and cost.) The three Douglas concepts evaluated are shown in Figure 8. In evaluating each concept, expansion control for scale-up and cost were driving factors. The tooling concept selected by Douglas is the aluminum/graphite combination. While this aluminum/graphite concept is approximately 14% more costly than the all aluminum tool, the benefits in tooling tolerance control and scale-up outweigh the small cost penalties.

TOOLING CONCEPTS EVALUATED

VACUUM IMPREGNATION OF WING SCALE-UP ISSUES (SUBCOMPONENT)

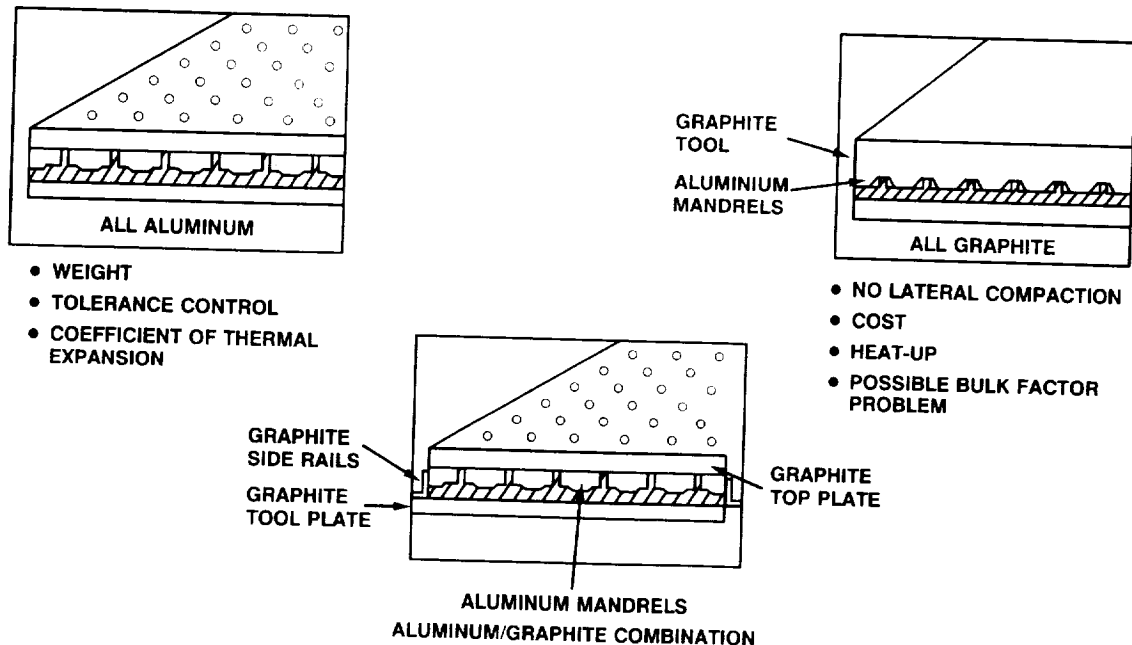
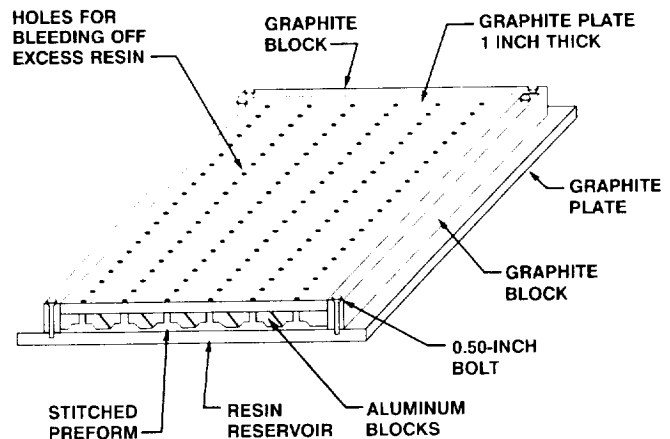
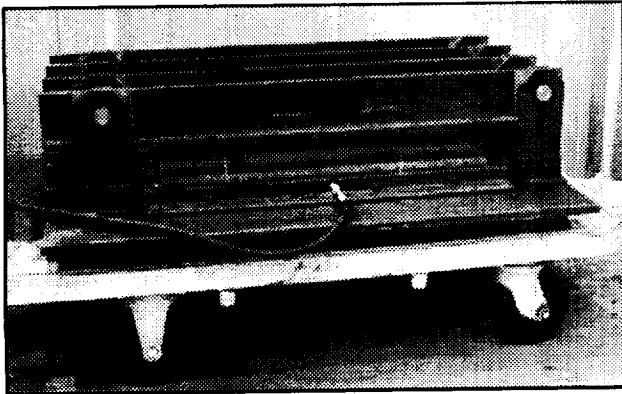


Figure 8

WING SCALE-UP TOOLING DEVELOPMENT

Shown to the right in Figure 9 is the tooling concept that will be used to fabricate 4' x 6' wing skin panels. This concept is a combination of graphite tooling plates with aluminum mandrels. This was chosen over an all aluminum tool because the graphite/epoxy tooling plate is better able to control tolerances, maintain resin bleed holes in proper location, and allow for possible integration of stitched rib to skin clips in future development. (Note: Resin bleed holes will consist of steel bushings potted into the graphite tooling plate to maintain hole dimensions and prevent excessive wear.) This aluminum/graphite tool once assembled is then placed in a restraining fixture as shown below on the left. A compaction pressure of 20-30 psi can be applied with a pressure bladder restraining fixture to squeeze excess resin out and insure a quality surface finish.

WING SUBCOMPONENT TOOLING CONCEPT AND PROCESS DEFINITION



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Figure 9

**MANUFACTURING DEVELOPMENT
for
COMPOSITE PRESSURIZED FUSELAGE STRUCTURES**

FUSELAGE SUB-SCALE TOOLING DEVELOPMENTS Effect of Preform

In developing the pressure injection RTM process for thin fuselage structures, two critical points to tool design need to be considered up front. First is matched metal tooling needed for compaction pressures required to yield 60% fiber volume or the final desired thickness. (Compaction is needed due to the fact this preform is not heavily stitched.) In Figure 10, the chart on the left shows that approximately 48 psi is required to give the appropriate compaction pressure. This pressure becomes important when designing for tool rigidity and when pressurizing the tool with resin during fabrication. Another piece of information found on the chart is bulk factor. A 0.01 inch bulk factor is inherent in the preform. While this bulk seems small, in scale-up (i.e., multiple longerons) it does become additive causing tolerance problems for tooling. To circumvent these problems, the bulk factor must be accounted for in tooling. Figure 10 to the right illustrates both types of matched metal tooling being looked at by Douglas. First is a clamp/fit fixture used to eliminate bulk factor problem before assembly into a matched metal tool frame. The second tooling concept is a sidewall compaction matched metal tool that allows bulk factor and compacts after the tool is closed.

FUSELAGE ELEMENT TOOLING DEVELOPMENT EFFECT OF PREFORM ON TOOLING DESIGN BULK FACTOR

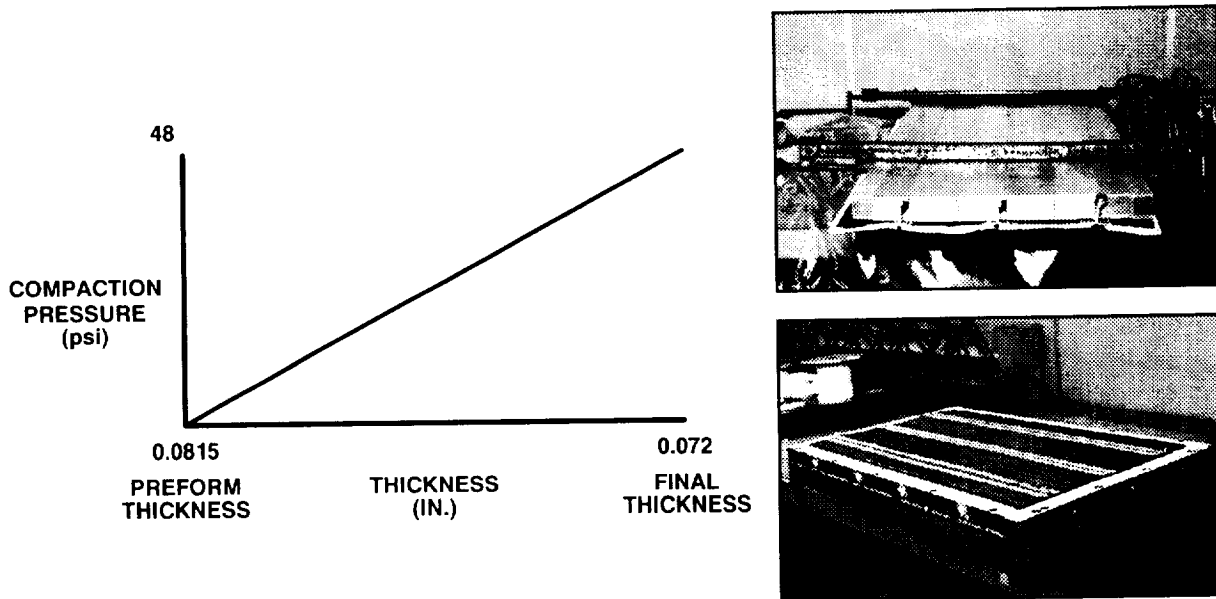


Figure 10

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FUSELAGE SUB-SCALE TOOLING DEVELOPMENT Effect of Preform

Another reason matched metal tooling is required for fuselage structure has to do with flexibility of the preform. Since the thickness of each "J" section longeron is only 0.072 inches, the preform will not maintain its required shape and orientation. In Figure 11 (left), preform flexibility is illustrated. Figure 11 to the right, shows the matched metal tool required to shape the longerons properly.

FUSELAGE ELEMENT TOOLING DEVELOPMENT EFFECT OF PREFORM ON TOOLING DESIGN

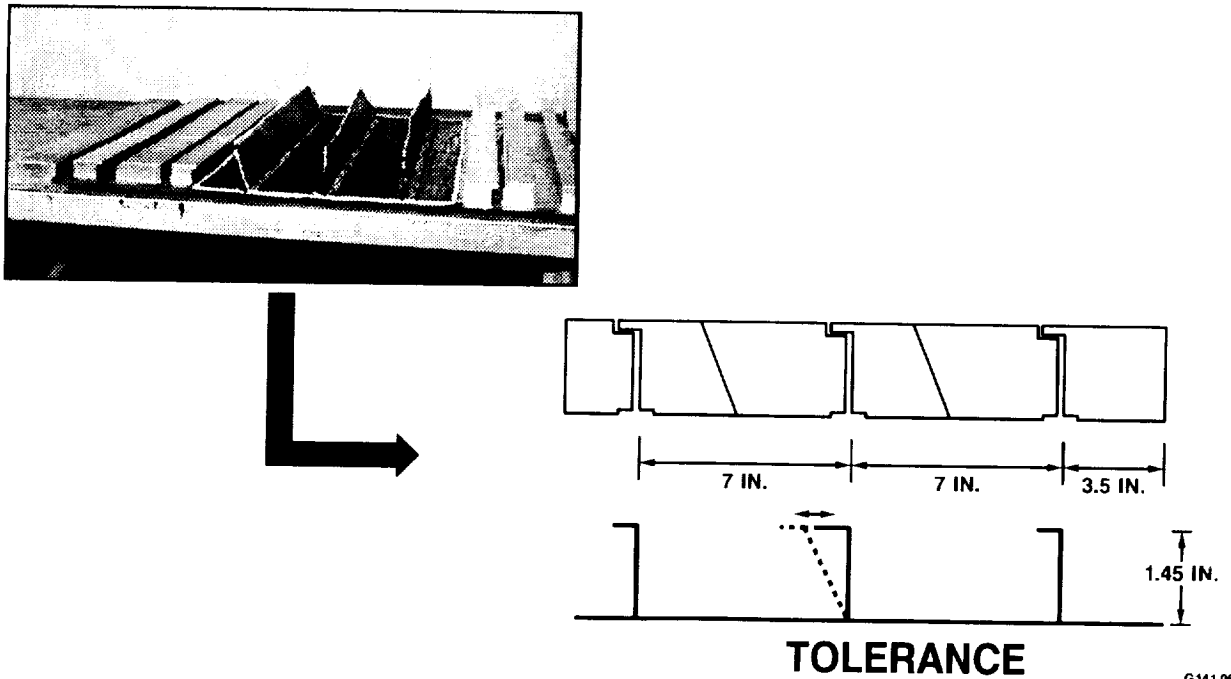


Figure 11

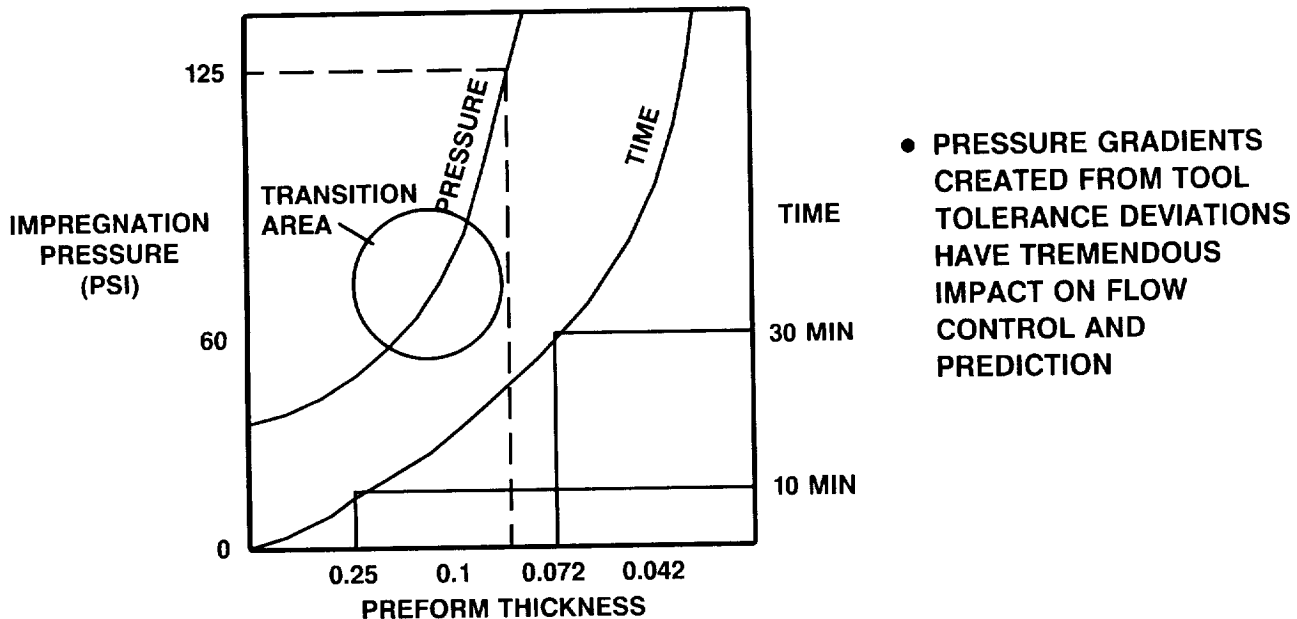
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FUSELAGE SUB-SCALE TOOLING DEVELOPMENTS Effect of Tooling Tolerances

In progressing from flat panels to stiffened structures, various unforeseen problems were encountered. While it was already known that resin injection pressures for thin preform were extremely high (125 psi), the effect of tooling tolerance had not yet been discovered. Figure 12 below, indicates that the resin pressure required to permeate a preform appears to follow some exponential form for very thin laminates. In examining the graph, note that as the thickness of the preform decreases, significant increase in the amount of pressure required to permeate the preform occurs. This result, translated to tool design, says that if tooling mandrel tolerances (for matched metal tools) are not extremely close, the resin flow profile expected may not occur. The resin will follow the path of least resistance to the exit vent, thus resulting in a part that is not fully impregnated. (This has only been found to present a problem in thin structures.)

FUSELAGE ELEMENT TOOLING DEVELOPMENT

EFFECT OF PREFORM AND TOOL TOLERANCES ON PROCESSING THIN STRUCTURES



* 3 BY 3 FOOT PREFORM SIZE

Figure 12

FUSELAGE SUB-SCALE TOOLING DEVELOPMENT Douglas Fuselage RTM Tool

In developing the tooling for the sub-scale fuselage structure, strict attention was given to tool tolerances. All mating surfaces in the horizontal plane of the tool were blanchard ground to $\pm .005$ inch to aid in regulating resin injection pressures. This tool is constructed of aluminum, with self-heated calrod heaters and is clamped between I-beams to apply compaction pressure. The fabrication process is simply to inject resin into the skin at the center of the tool until resin appears at the corners, then inject the stiffeners until resin appears at the opposite vent at the other end of the tool. Resin pressure is maintained at 40 psi while the part is cured. See Figure 13 below.

FUSELAGE ELEMENT TOOLING DEVELOPMENT ELEMENT TOOLING CONCEPT

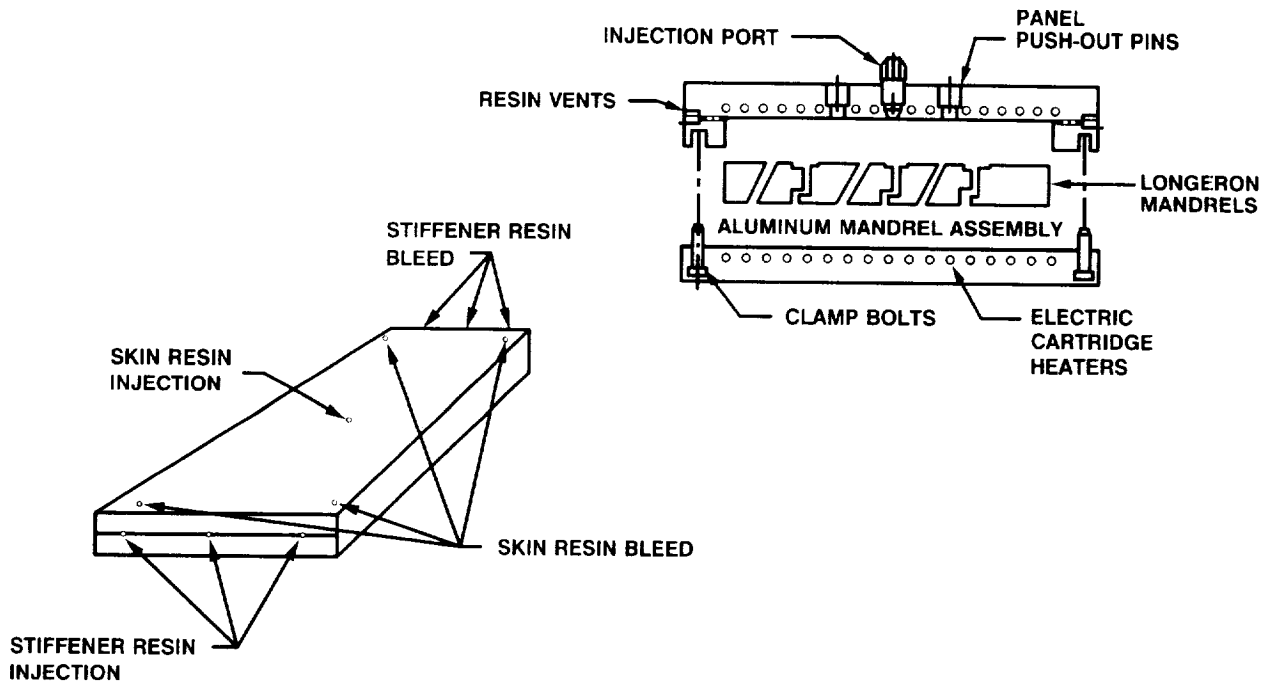


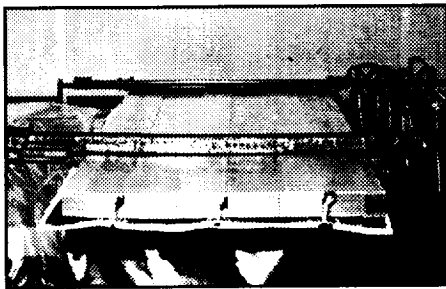
Figure 13

FUSELAGE SUB-SCALE TOOLING DEVELOPMENT

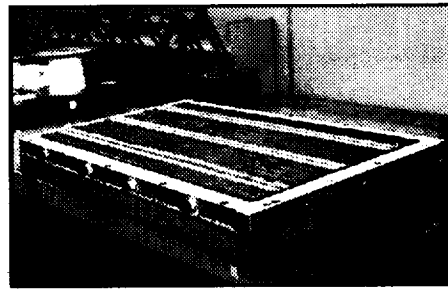
Figure 14 below shows the Douglas fuselage tool in various stages of fabrication. The upper left photo is a view of the clamp/fit tooling used to insert the preform and mandrel assembly into the matched metal self-heated containment tool shown on the upper right. Below is the entire tool assembly with heaters ready for final clamping from the pressure bladder restraining fixture.

FUSELAGE ELEMENT TOOLING DEVELOPMENT

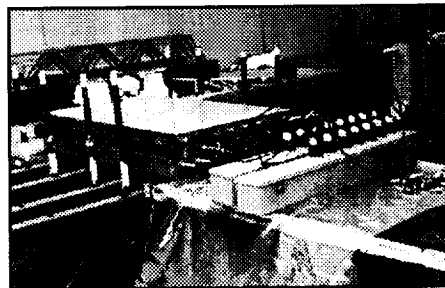
ELEMENT TOOLING



MANDREL ASSEMBLY



TOOL/MANDREL INTEGRATION



TOOL ASSEMBLY

Figure 14

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FUSELAGE SCALE-UP TOOLING DEVELOPMENT

Major drivers in tooling scale-up development for fuselage as related to cost include tolerance control, tool heating and press/restraining fixture. In addressing these issues, numerous tool concepts were evaluated at Douglas. The best two are shown below in Figure 15. On the right of Figure 15 is a scaled-up version of the sub-scale fuselage tooling with minor modifications. These include use of flexible caul in place of a hard upper tool (to ease tool assembly), use of hot air convection heat system in place of calrod heaters (due to cost), and use of a dedicated restraining press with stainless steel inflatable pressure bladders (due to cost of large press). Below to the left is an alternate concept consisting of a one piece carbon/epoxy tool which is being considered to replace the mandrel concept if matched tool tolerances continue to be a problem in the resin injection cycle. (Note: A careful cost/performance study of the RTM composite fuselage panels will be done with duplicate panels being made by the Automated Tow placement process at Hercules. Data from this study will determine the manufacturing approach for Phase B fuselage development.)

PRESSURE IMPREGNATION OF FUSELAGE TOOLING CONCEPTS

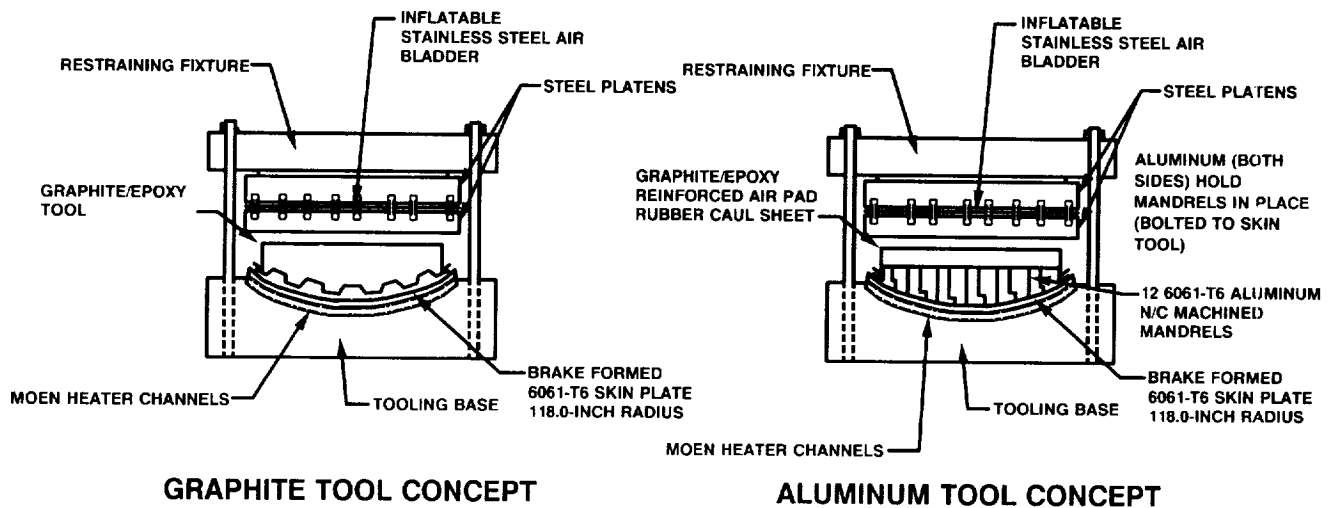


Figure 15

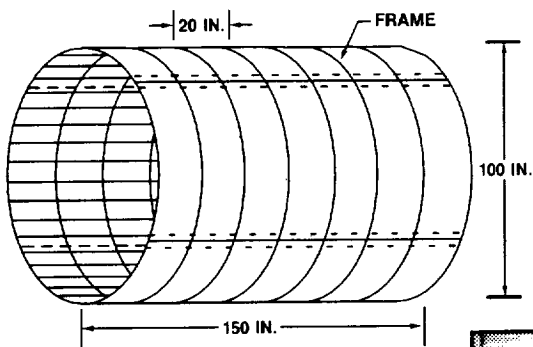
PRODUCTION UTILIZATION NEEDS
Tooling Scale-up to Production

In developing the tooling for the fuselage, it is clear that the OMI tool surface and tool base are from a design perspective common for any tool concept Douglas may have. For this reason, an existing fuselage tool built under previous NASA contract will be modified to fit the RTM process being developed. Shown in Figure 16 is the size fuselage to be manufactured in Phase B and the existing tools to be used for the fuselage. This lower tool (similar to the tool base in Figure 15) will be used with the best concept for the upper tool portion and modified to include as much automation and heavy tool handling capability as possible.

Primary focus to date on fuselage has been the RTM fabrication development for fuselage quarter panel skins with "J" stiffener longerons. Therefore, to date, manufacturing development of other fuselage elements (clips, frames, floor beams, etc..) has not been addressed in detail.

PHASE B FUSELAGE DEVELOPMENT

FUSELAGE BARREL



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Figure 16

PRODUCTION UTILIZATION NEEDS In Line Process Monitoring

Process monitoring must ultimately become an integral part of the RTM process if it is to go to production. For this reason in line process monitoring with process modeling is part of a continuous Douglas funded improvement program and part of the NASA ACT program.

Figure 17 below illustrates the work being done under NASA contract with William and Mary College and Virginia Polytechnic and State University (VPI). In Figure 17 (above left) are the sensors being used by William and Mary College to generate kinetic relationships for various RTM resins. Below left are kinetic relationships for the Dow Tactix 138 resin. Figure 17 to the right represents permeability studies on stitched fabrics being done at VPI to begin modeling the RTM process. Shown in this chart are permeabilities for 54 ply wing skin lay-ups and 12 ply fuselage lay-ups.

PROCESS MONITOR / MODEL DEVELOPMENT

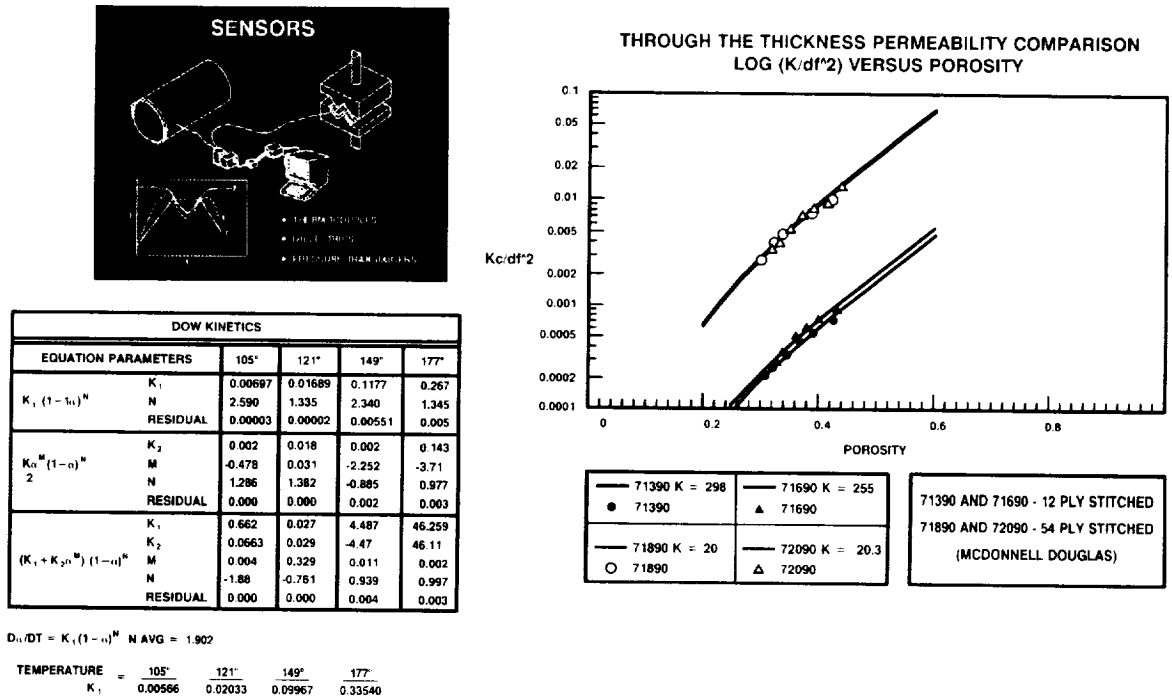


Figure 17

PRODUCTION UTILIZATION NEEDS Future Factory

In looking forward, a futuristic factory must be envisioned that is equipped to handle the uniqueness of RTM fabrication concepts. At Douglas, we envision a close tie with major resin suppliers that will equip us with the capability of handling large quantities of liquid and film resins. In Figure 18 below, the resin storage is located within the building foundation for space conservation and system delivery purposes. Douglas also envisions 1.) the use of standard automated handling equipment to move preforms from automated stitching machines to the tools, 2.) state-of-the-art resin film laying equipment to calendar out resin on the tools, and 3.) hydraulically controlled tools with in line process control to supply complete process control from a central control point.

PRODUCTION NEEDS ADVANCED FACTORY CONCEPT

KEY FEATURES

- IN-GROUND RESIN STORAGE
- HYDRAULIC-CONTROLLED VACUUM-TIGHT TOOL CAVITIES
- COMPLETE AUTOMATED CONTROL OF STITCHING AND CURE OPERATIONS

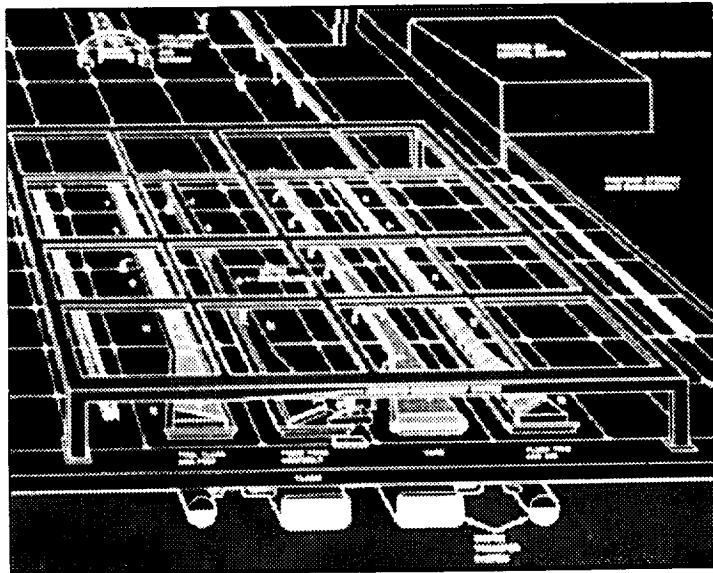


Figure 18

CONCLUSIONS

1. Thru-thickness vacuum infusion process well suited for large wing structures
2. Projected cost savings of 48% for RTM composite wing over conventional technology composite wing
3. Resins currently acceptable for vacuum infusion not meeting 3501-6 mechanical property standards
4. Resin requirements:
 - a. Film form resin desirable
 - b. Less than 100 centipoise resin viscosity
 - c. Less than 250 degrees F resin infusion temperature
 - d. Resin infusion time of 1 hour or more
 - e. Resin capable of oven cure under vacuum bag desirable
 - f. 3501-6 composite laminate properties desirable
5. Scale-up tooling costs for pressure RTM is cause for concern
6. Tooling and preform integration critical to success of pressure RTM
7. Fuselage cost/performance comparisons of Automated Tow Placement versus pressure RTM are key to design/manufacture of full scale Phase B fuselage barrels
8. Advanced RTM factory will require multi-industry participation to succeed