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COMPOSITES TECHNOLOGY FOR TRANSPORT PRIMARY STRUCTURE

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The ACT contract activity being performed by the McDonnell Douglas Corporation is divided into two separate activities: one effort by Douglas Aircraft in Long Beach, California with a focus on Transport Primary Wing and Fuselage Structure, and the other effort by McDonnell Aircraft in St. Louis, Missouri with a focus on Advanced Combat Aircraft Center Wing-Fuselage Structure. This presentation is on the Douglas Aircraft Transport Structure portion of the ACT program called ICAPS - Innovative Composite Aircraft Primary Structure. The McDonnell Aircraft portion of the ACT program will be presented by Mike Renieri in a presentation scheduled for tomorrow.

COMPOSITE APPLICATION GOALS

[redacted]

The Douglas Aircraft Company has a goal to have the wing technology readiness in hand in early 1993. It is anticipated that both a military and a civil application that require start of engineering development will occur during that year. Plans to initiate specific development design and tests have been identified.

The goal for a pressurized fuselage is to have the technology readiness in hand in early 1994 so that the preliminary designs can be finalized and start of engineering development can occur in early 1995. Douglas has targeted a specific vehicle, the MD-XX, to incorporate this technology.

START ENGINEERING DEVELOPMENT OF A WING BOX ON A SHORT-HAUL TRANSPORT IN 1993

START ENGINEERING DEVELOPMENT OF A PRESSURIZED FUSELAGE IN 1995

OBJECTIVE

There are several specific objectives in this program as well as the Douglas funded effort. First and foremost is cost savings. In the ACT May 1989 kickoff review meeting at NASA Langley Research Center, we had one chart on key barriers - one of which was "COST." We have attacked the major cost drivers as well as almost all of the other cost areas.

The weight savings on individual parts can be as much as 50% compared to metal, but on an overall assembly for primary structure the specific objective is to exceed 30%.

For a production program the objective is to have Development (non-recurring) and Production (recurring) costs to be equivalent to a metal system. This has been demonstrated on a few secondary composite structures already.

To achieve the weight savings we have to have a high strength after impact damage. Today to get that value we use toughened resin/high strength fibers which cost much more than the currently used material systems in secondary structures. Our objective is to use material systems that are less costly than today's, yet end up with a component that has high strength after damage as well as better tolerance to all types of impact.

COST SAVINGS OF 40% FROM STATE-OF-THE-ART COMPOSITES

WEIGHT SAVINGS OF 30% OF METAL ON ASSEMBLED STRUCTURE

DEVELOPMENT AND PRODUCTION COSTS EQUIVALENT TO METAL SYSTEM

DAMAGE TOLERANCE EQUIVALENT TO TOUGHENED RESIN/HIGH-STRENGTH FIBER MATERIAL SYSTEMS

ABILITY TO ANALYTICALLY PREDICT STRUCTURAL BEHAVIOR AND FAILURE

OVERALL FOCUS OF ICAPS

Evaluation in the mid-80's indicated that to make a cost breakthrough, a deviation from the current trend of fabrication had to be made. Douglas focused on the dry preform resin transfer concept. From early testing it was evident that a considerable improvement in the damage tolerance could be obtained, equivalent to the toughened resin high strength fiber prepregs just reaching the marketplace. These new systems were also higher in cost. The preliminary stitched preform concepts were sponsored by Douglas and were further evaluated under NASA contract in the late 80's to broaden the understanding. With the advent of the ACT program it was an opportunity to develop a more comprehensive evaluation program. While Douglas funds were developing the wing section using the new toughened resins, the NASA ICAPS program focused on the dry stitched preform concept. The stitching parameter development will be explained in the later presentation by Marvin Dow of NASA. All current stitching work is being accomplished by our old (but modified) Douglas sewing machine. A more versatile machine was needed to evaluate the speed-up of the stitching concept. After numerous equipment developer visits, a general specification was developed and the solicitation, proposal evaluation, and source selection process was accomplished. Several new resins are being evaluated that are more suitable for the RTM (pressure and/or vacuum) process. Tools for each process are fabricated for the subcomponent and testing is in progress. As test results are analyzed, the design/prediction methods are further evaluated. As the larger components are made, the cost projection analysis will be re-evaluated.

SIMPLE DESIGN
- ACCOMMODATES FABRICATION, INSPECTION, AND REPAIR

UNIQUE COMPOSITE MATERIAL
- STITCHED FABRIC PREFORMS AND RESIN TRANSFER MOLDING

PROCESSES AND TOOLING
- RTM AND ATP WITH POTENTIAL FOR USE ON LARGE INTEGRATED STRUCTURES

DEVELOPMENT TESTING
- DESIGN VALIDATION AND PERFORMANCE PREDICTION DATA

STRUCTURAL MECHANICS
- ENGINEERING FOUNDATION FOR FUTURE DESIGNS, PERFORMANCE PREDICTIONS, AND CERTIFICATION

PRIOR TO ACT PROGRAM

The selected baseline transport configuration used for the advanced technology related to subsonic transports in 1984 were the D3300 configuration for the wing and the MD-100 for the fuselage. The specific features addressed on the wing and fuselage would be utilized in a next generation new transport that would utilize organic composite structures. The composite joints and cutouts program under NASA contract used loads and design criteria from these baseline aircraft. These development contracts were awarded after the ACEE program and preceded the ACT program.

BASELINE STUDIES

- **ADVANCED DESIGN HIGH-ASPECT-RATIO WING**
- **DOUGLAS DEVELOPMENT PROGRAM**

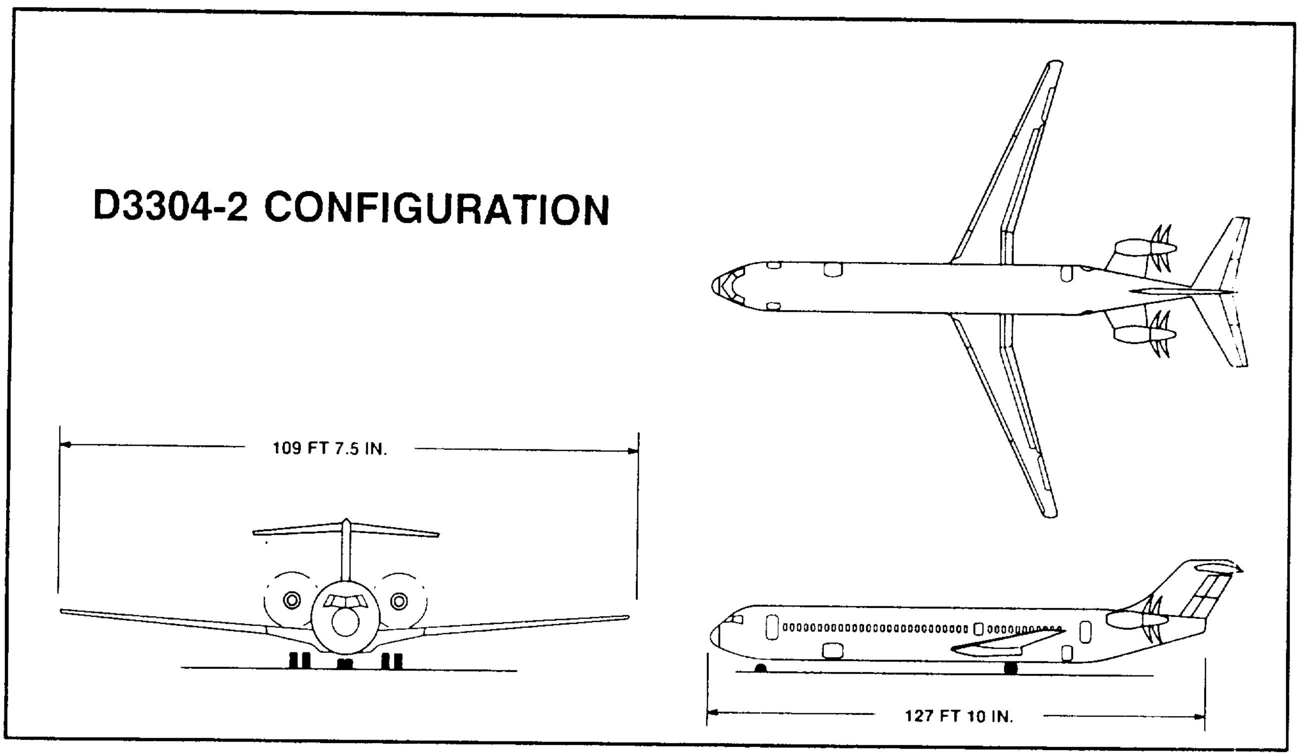
BASELINE DESIGN

- **LOW STRAIN CONCEPT**
- **BLADE-STIFFENED WING/J-STIFFENED FUSELAGE**
- **FEATURES**
  - **SKIN, BLADE LAYUP PATTERN IDENTICAL**
  - **REPAIRABLE**
- **DOUGLAS TOUGHENED RESIN WING BOX PROGRAM**

DEVELOPMENT

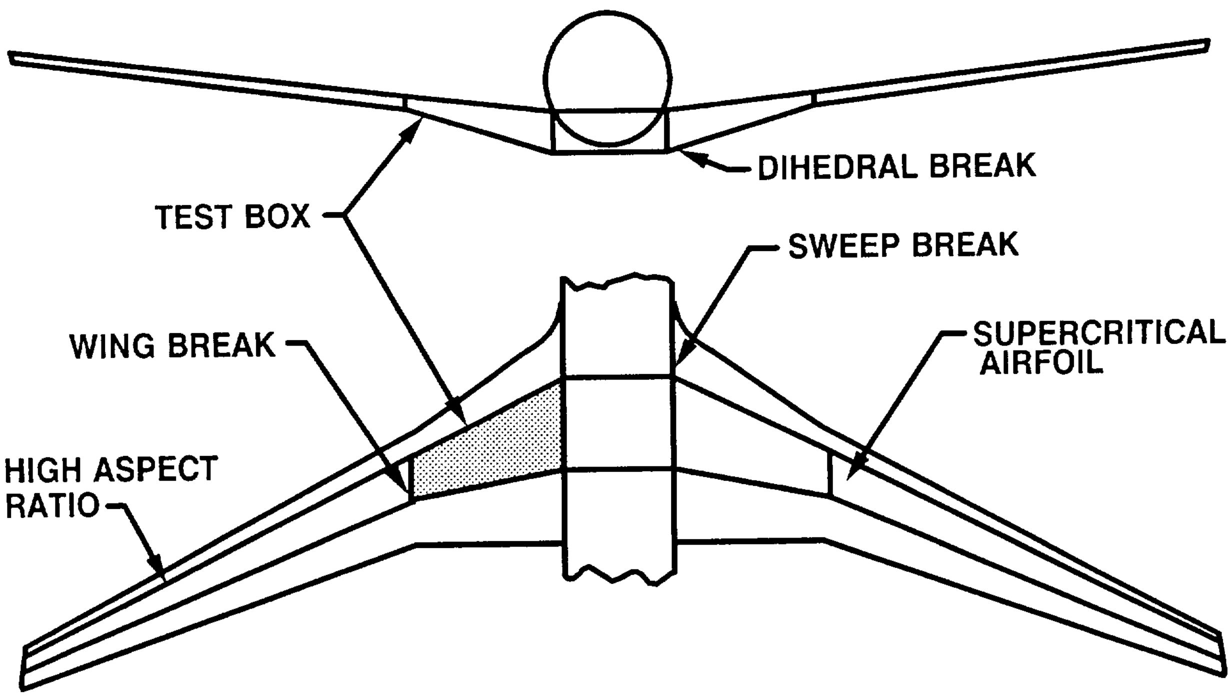
- **NASA JOINT AND CUTOUT CONTRACTS**
- **NASA PANEL FABRICATION CONTRACT**
- **DOUGLAS COMPONENT DEVELOPMENT**

The D3300 configuration was an intermediate range 200-passenger aircraft for which detailed wing loading and configuration data was generated. Today the Douglas Operating Plan refers to this aircraft as the MD-XX and is focusing on very high bypass ducted fan engines, but an unducted counter rotating system could still be a consideration.



BASELINE WING TEST BOX RELATIONSHIP

The test units for both Douglas and ICAPS Program is identified on the baseline wing plan form. The section is at the side of the body to the wing aerobreak, which is approximately twelve feet. For the baseline wing configuration used in this program the test units are full scale.



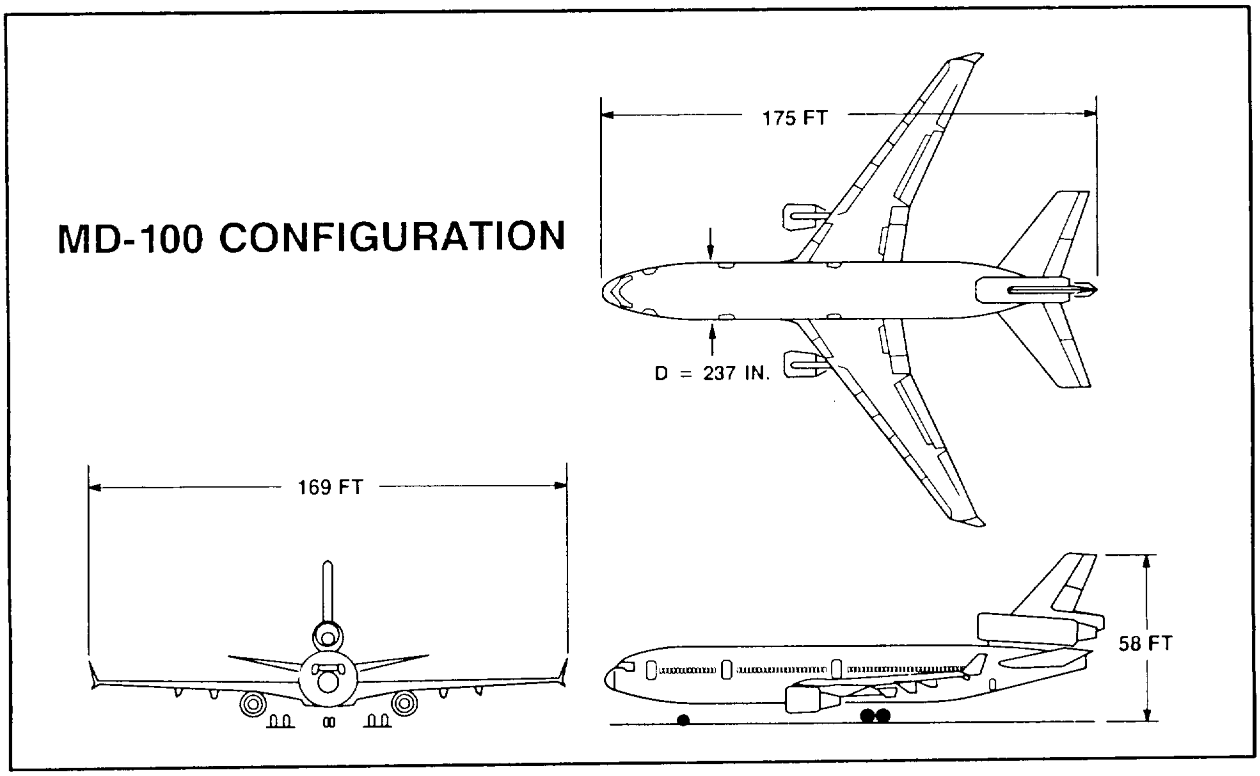
WING DESIGN CRITERIA

Wing loads and criteria are summarized. Shear and bending loadings are a maximum at the aerobreak station (outboard end of the test box) rather than at the root. This is because, even though root shear and bending moments are higher, this is offset by the much greater box dimensions at the root station. The design fuel pressures derive from the 9g crash condition. Minimum flexural and torsional stiffnesses are those required to meet dynamics and aileron effectiveness requirements.

COVER PANELS - MAXIMUM SPANWISE LOADING	N_x LB/IN. ULTIMATE [AVERAGED ACROSS BOX]	TENSION	23,200
		COMPRESSION	23,600
SPARS - MAXIMUM SHEAR FLOW	N_{xy} LB/IN. ULTIMATE [AVERAGED OVER SPAR DEPTH]		3,700
REQUIRED FLEXURAL STIFFNESS (ROOT)	(EI) 10^6 LB/IN.^{2}		261,300
REQUIRED SHEAR STIFFNESS (ROOT)	(GK) 10^6 LB/IN.^{2}		137,500
MAXIMUM FUEL PRESSURE	LB/IN.^{2} ULTIMATE	INNER WING	36.2
		OUTER WING	46.7

FUSELAGE BASELINE AIRCRAFT

The MD-100 configuration was a pre MD-11 configuration on which advanced structural configuration changes were evaluated. The NASA contract on fuselage cutouts and joints for composite structures used loads from this preliminary design. A considerable number of composite structural configurations were evaluated and the "J" stiffened panel was selected.



FUSELAGE DESIGN CRITERIA

The fuselage loadings given represent maximum forward fuselage conditions that occur at the front spar station. Hoop loading due to internal pressure differential are based on the 2.0 ultimate factor condition with no other loads present.

CONDITION		CROWN	SIDE	KEEL
MAXIMUM LONGITUDINAL TENSION LOADING	N_x LB/IN.	4,600	3,200	2,300
MAXIMUM LONGITUDINAL COMPRESSION LOADING	N_x LB/IN.	-1,700	-3,000	-2,100
MAXIMUM SHEAR FLOW	N_{xy} LB/IN.	800	1,500	1,000
MAXIMUM HOOP TENSION LOADING (PRESSURE = 9.1 PSI)	N_y LB/IN.	2,157 (AT 2p)		

ALL LOADS ARE ULTIMATE

EVOLUTION OF DESIGN STRAINS

The baseline composite wing is not based on a high strain concept since this is not an option because of stiffness and supportability constraints. A simple, easily producible and repairable design based on 4,000 strains was shown in an earlier NASA program to be weight-competitive on a damage tolerance basis with high strain concepts. Further reductions in design strain have been introduced to meet specific stiffness and repair criteria. The wing is designed to be repairable at any location by mechanically fastened patches.

HIGH STRAIN WING HAS HIGHER FABRICATION COMPLEXITY AND REPAIR LIMITATION

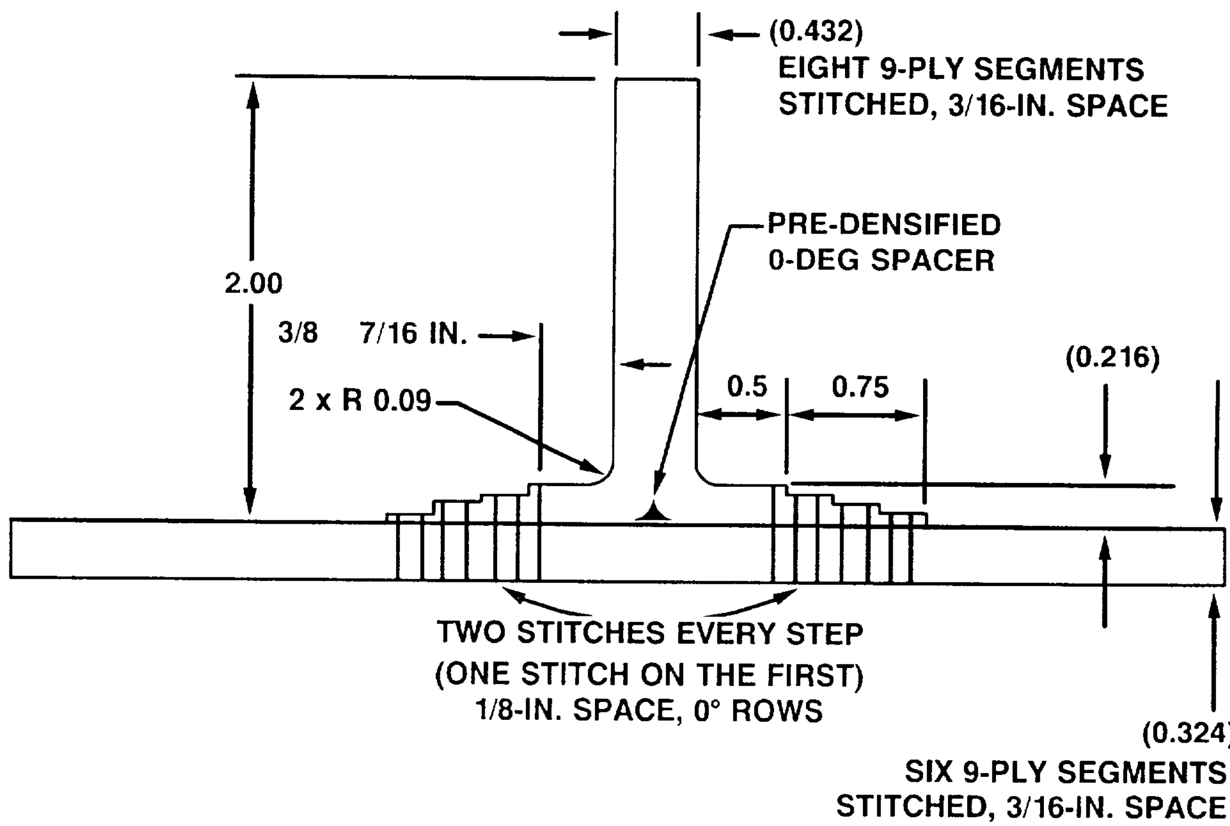
SELECTED HARD SKIN DESIGN LIMITED TO 4,500 μ STRAIN FOR DAMAGE TOLERANCE

STRAIN REDUCED IN PLACES TO 4,000 μ TO MEET STIFFNESS TARGETS

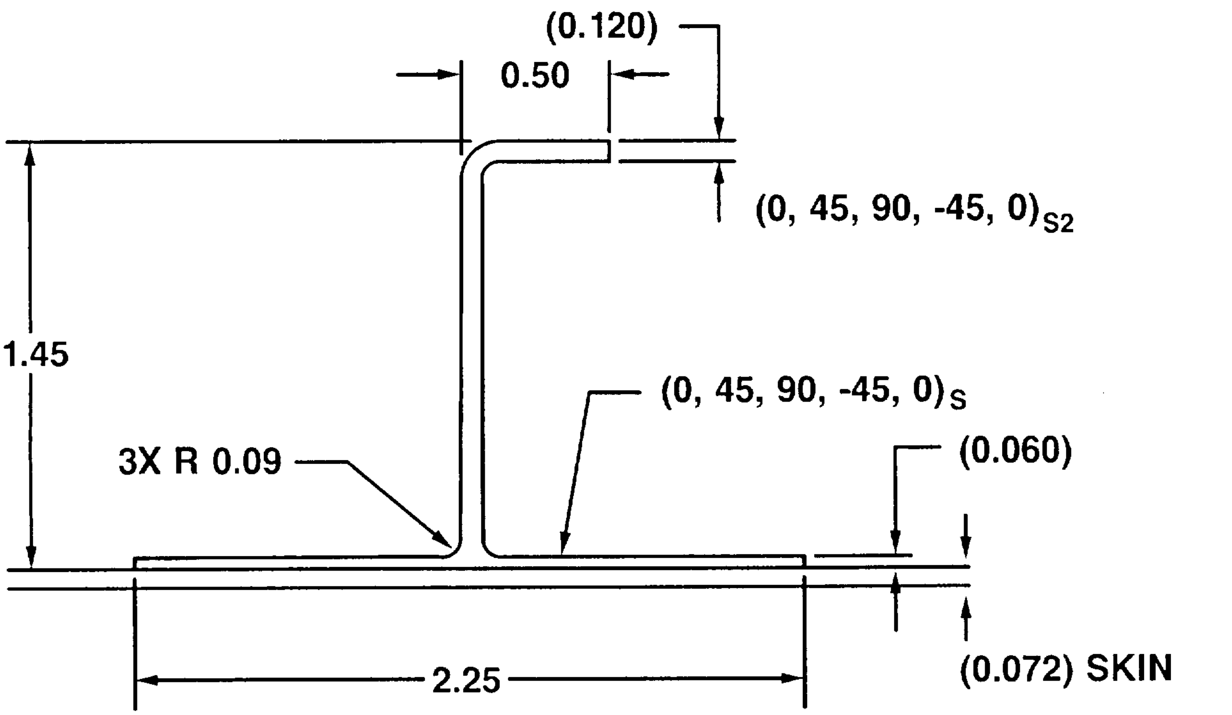
STRAIN FURTHER REDUCED TO 3,750 μ TO ALLOW BOLTED REPAIR PATCHES AT ANY LOCATION

WING STIFFENER DESIGN

From the many studies and development tests performed, the stiffener selected for the wing design being considered is a basic stitched preform 9-ply balanced pattern arrangement from which stiffener and skin stacks are made. In the cross section shown, the vertical blade is stitched, the skin stack is stiffened, and then the blade flanges are stitched to the skin. It will be possible to do most of this automatically after discussion with equipment manufacturers.

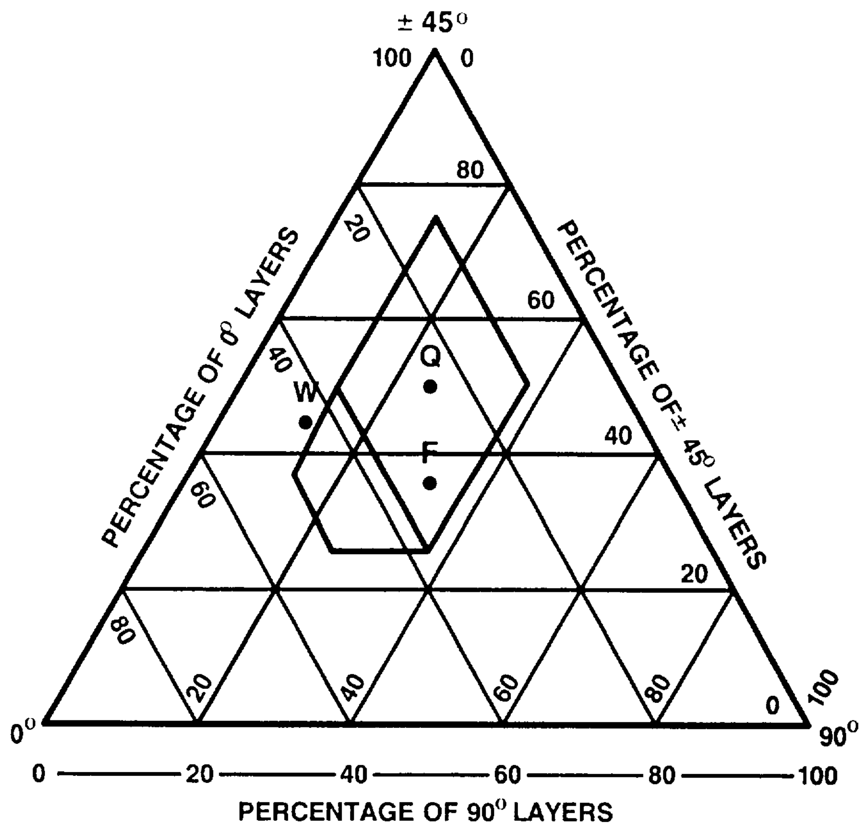


From the many studies and development tests performed prior to the ACT program, the stiffener selected for the fuselage design is a "J" configuration. These stiffeners will be dry stitched in the vertical stem and "J" cap, and then stitched to the fuselage skin.



REINFORCED LONGERON

A generalized design guideline in use for sometime at DAC constrains the percentage of fibers in each of the four directions (0, 90, +45, and -45) to fall between 12.5% and 37.5%. The fiber directions must be thoroughly interspersed to prevent the matrix from becoming the weak link in the laminate. These guidelines were set to allow good bolt load transfer behavior and did not necessarily apply to thin lightly loaded laminates or to laminates where no fasteners were required either in the original design or for repair. The chart extends the range slightly and permits, for example, the wing cover panels to increase the percentage of 0^{o} fibers to 44.4%. This was desirable in meeting stiffness requirements.



COST DRIVERS

Since the early 1980's, Douglas has been focusing on the cost issue of composite components in three specific areas: non-recurring, recurring and ownership. During the 1970's, when we were making sizable components under the NASA sponsored Aircraft Energy Efficiency program, the initial focus was weight savings. Their weight savings goals were achieved, but at what price? When cost estimates were made for production, it was clear that something different had to be done in order to make the transition into production. For example, on the DC-10 rudder program, by a few internal system changes, tool variations the projected recurring costs could be reduced by 30%. The major drivers are shown in the following charts.

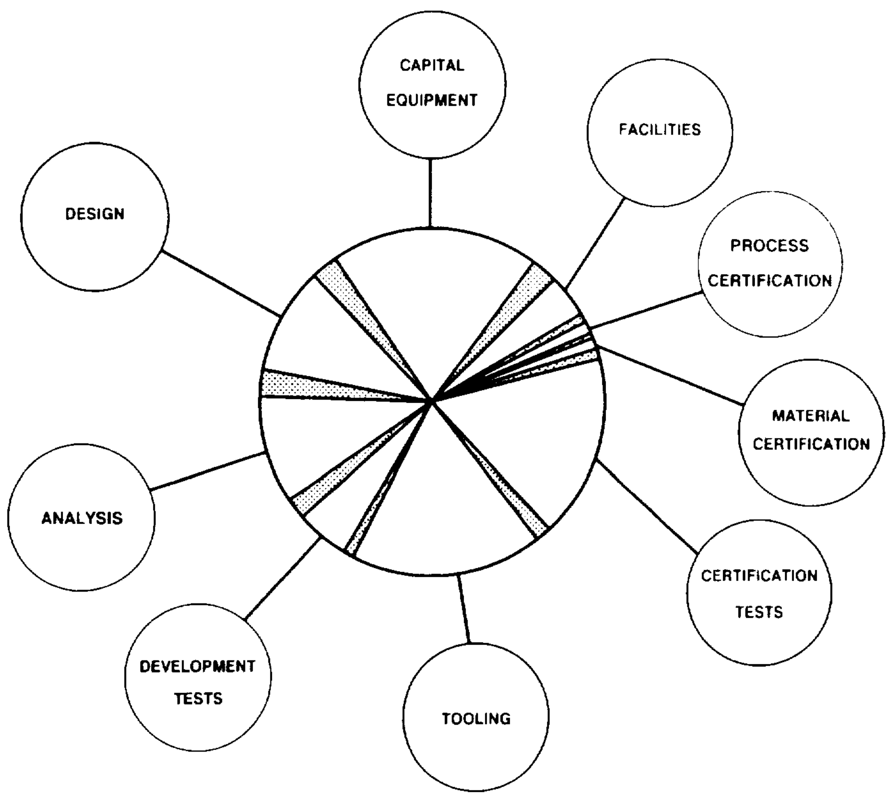
NONRECURRING

RECURRING

OWNERSHIP

COST DRIVERS - NON-RECURRING

For non-recurring costs, an investigation was made to determine the percentage range of the various items that make up the total cost to focus on, which were the major contributors. The background data was from a number of programs and a range of parts from small to full assemblies. Both commercial and military components were included. Large percentage variables were identified in tooling and capital equipment. Tooling related to the complexity of the part being considered and the capital equipment variable depended on how the cost was distributed to various programs or how many units were to be considered in the spread. In the ICAPS effort, heavy emphasis will be focused on simplified design to reduce tooling costs and define the fabrication process to not require high cost equipment items.



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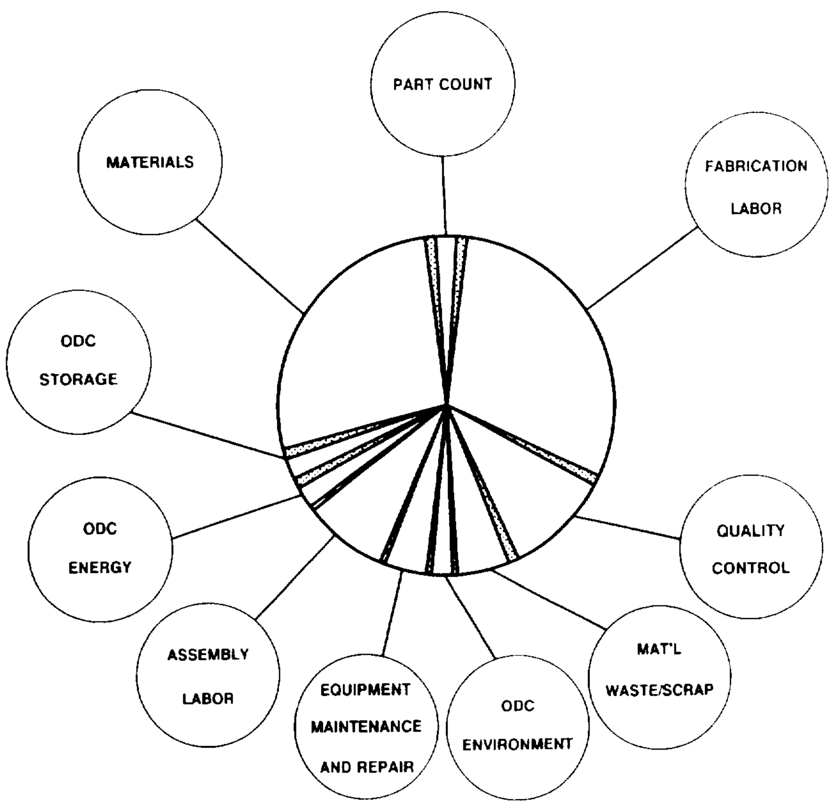
COST DRIVERS - RECURRING

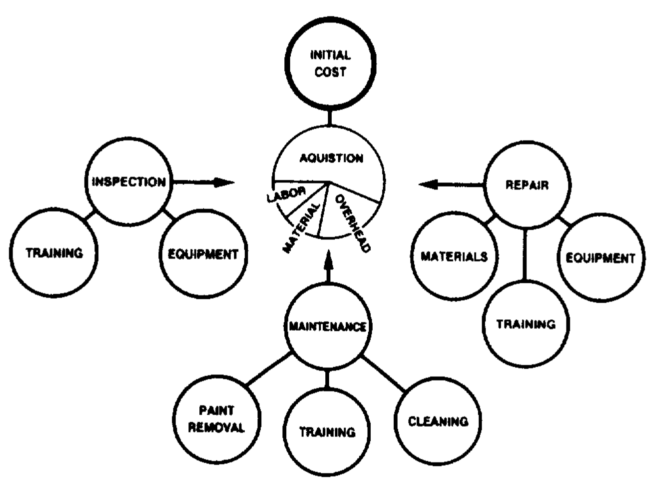
For recurring costs, the data show that there is a wide percentage range for the various elements from different data sources. It's clear that materials, fabrication, assembly, and quality control are the major cost drivers. On very small parts, the material cost is a high percentage in making the part. On a composite component made up of several parts, the material cost percentage is much lower. For ICAPS, the four major percentage areas are the ones on which the major focus is being addressed with significant reductions anticipated with the concept approach being taken. A majority of the other cost items will be reduced to some extent. As larger elements and subcomponents are fabricated, a specific set of percentages can be verified, and a cost relationship figure can be generated and compared to the state-of-the-art fabrication of the same component.



COST DRIVERS - OWNERSHIP

Although we have some carbon epoxy components flying on the DC-10 since June of 1976 and have accumulated over 55,000 hours on the high time units, we do not have a sufficient experience sample to draw specific conclusions at this time. Where we look at a transport that will have 40 or more years of service it's difficult to relate the inspection, maintenance, and repair history of only a few years.

In DOC data used by airlines, the cost of ownership in today's environment is approximately 50%. In ICAPS the major thrust is to develop the concept that would offer a 50% reduction in the cost of ownership for the composite components. As the percentage of composites increases, of the total operating weight empty there would be a significant effect to the operator DOC relationship. In the airlines DOC maintenance element, the structure represents half of this value utilizing composites that virtually eliminate corrosion and have a sigfant reduction in fatigue, there would be a further cost savings impact to the operator. On this figure we represent ownership as half and maintenance as the other half with regard to structure, and until we have more time to work with operators to develop cost impact trends, we will not connect the outside element to an operator cost pie chart.



SPECIFIC FOCUS OF ICAPS

This listing is what ICAPS is accomplishing to reduce the high cost drivers. A number of key parameters with respect to stitching have been investigated to optimize the process versus structural capability of the structure. Two new machines are being procured: one that will handle large widths for several processes and a computer controlled unit that will handle stiffener to skin stitching. The fabrication investigation covers two types of tools for RTM (resin transfer molding) in terms of vacuum or pressure impregnation. To compare processes for the fuselage, the Hercules advanced automated tow placement is being evaluated. New resins formulated for RTM are also being used. Of the thousand specimens tested, the data are being used for stitching parameter determination and structural mechanics methods improvement. As the larger components are fabricated, the cost data will be used to update the predictions that have been made to date. Each of these subjects is covered in further detail.

STITCHING DEVELOPMENT

STITCHING MACHINE PROCUREMENT

FABRICATION PROCESS TOOLS DEVELOPMENT AND RESINS

SUBCOMPONENT/COMPONENT TESTING

STRUCTURAL MECHANICS

COST DATA PROJECTIONS

POTENTIAL FOR STITCHING/RTM

Stitching has for a long time been considered to improve the through the thickness properties of laminated structure. When used with prepreg there was extensive fiber damage. The parts looked good, but the structural capabilities were degraded. With the development of unidirectional cloth with straight fibers, the probability of ply stacking and stitching was investigated. Structural testing showed substantial increase in damage tolerance capability with high residual strength approaching that of the toughened resins with high strength fibers.

Evaluations show that cost reductions could occur in many areas. Some are significant, others are not cost drivers but relate to facility requirements. As the design concepts were formulated, additional benefits were identified; i.e. near net shape stitched preforms, self-contained tool for RTM and cure, etc. With large high speed stitching equipment, scale-up to large aircraft structures is possible.

LARGE DAMAGE TOLERANCE INCREASE

LOW MATERIAL COST

LOW RECEIVING INSPECTION COST

LOW STORAGE COST

LITTLE AGING CONCERN

AUTOMATED NEAR NET SHAPE PREFORM

SELF-CONTAINED TOOL

LOW WORKPLACE ENVIRONMENTAL IMPACT

OPTIONAL FIBER PLY ORIENTATION

SCALE-UP CAPABILITY TO VERY LARGE STRUCTURE

STITCHING DEVELOPMENT

This is a listing of the various parameters that were considered and evaluated, and explained later as previously noted.

STITCH TYPE
- LOCK, CHAIN

STITCHING THREAD
- GLASS, KEVLAR

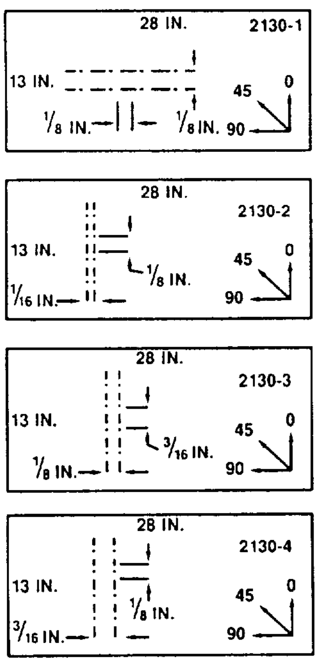
STITCHING PATTERN
- DENSITY AND DIRECTION

STITCHING TENSION
- NEAR NET SHAPE

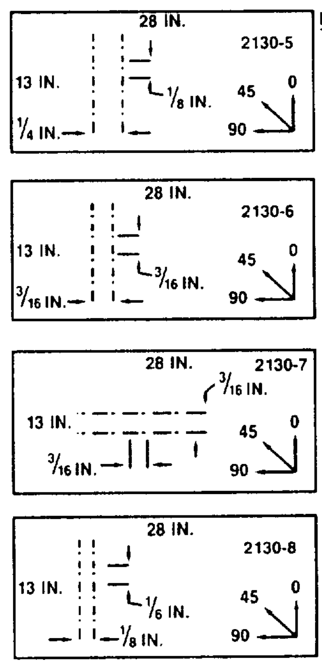
COUPON/SPECIMEN TESTING

FABRICATED 60 PANELS CUT INTO APPROXIMATELY 1,000 SPECIMENS FOR NASA TESTING

More than half of the tests planned in ICAPS are for stitching development. These are mostly done on quasi-isotropic laminates, which is close enough to practically used laminates in composition. One stitching parameter, whether stitch type, thread or pattern, is varied at a time. This slide shows the various stitch patterns chosen. Each panel was stitched accordingly, impregnated and cut into specimens. The goal of stitching development is to achieve the best balance of improved damage tolerance properties with minimum loss of basic tension, compression and stiffness properties.



PANEL	SPACING	STEP	DIRECTION
2130-1	1/8 IN.	1/8 IN.	90
2130-2	1/16 IN.	1/8 IN.	0
2130-3	1/8 IN.	3/16 IN.	0
2130-4	3/16 IN.	1/8 IN.	0



PANEL	SPACING	STEP	DIRECTION
2130-5	1/4 IN.	1/8 IN.	0
2130-6	3/16 IN.	3/16 IN.	0
2130-7	3/16 IN.	3/16 IN.	90
2130-8	1/8 IN.	1/6 IN.	0

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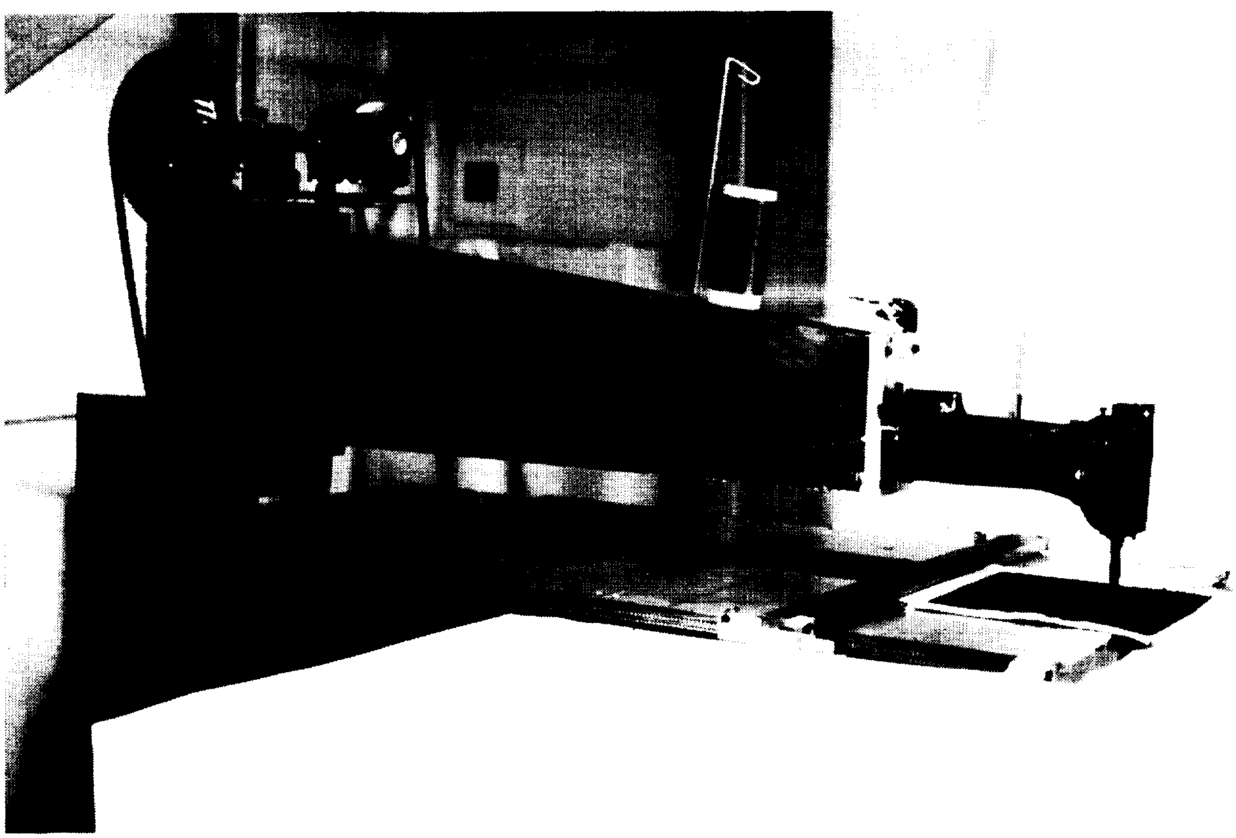
OF POOR QUALITY

ORIGINAL SINGLE NEEDLE STITCHING MACHINE

All heavy density stitching development to this date has been on the manual control single needle 5' long arm machine shown in this photograph. Adjustment of stitch step and tension on the thread is available. The material to be stitched is secured in a holding frame and an adjustable guide rail controls the spacing of stitched rows. This machine is located at and operated by Ketema, Anaheim, California (formerly Textile Products, Inc.).



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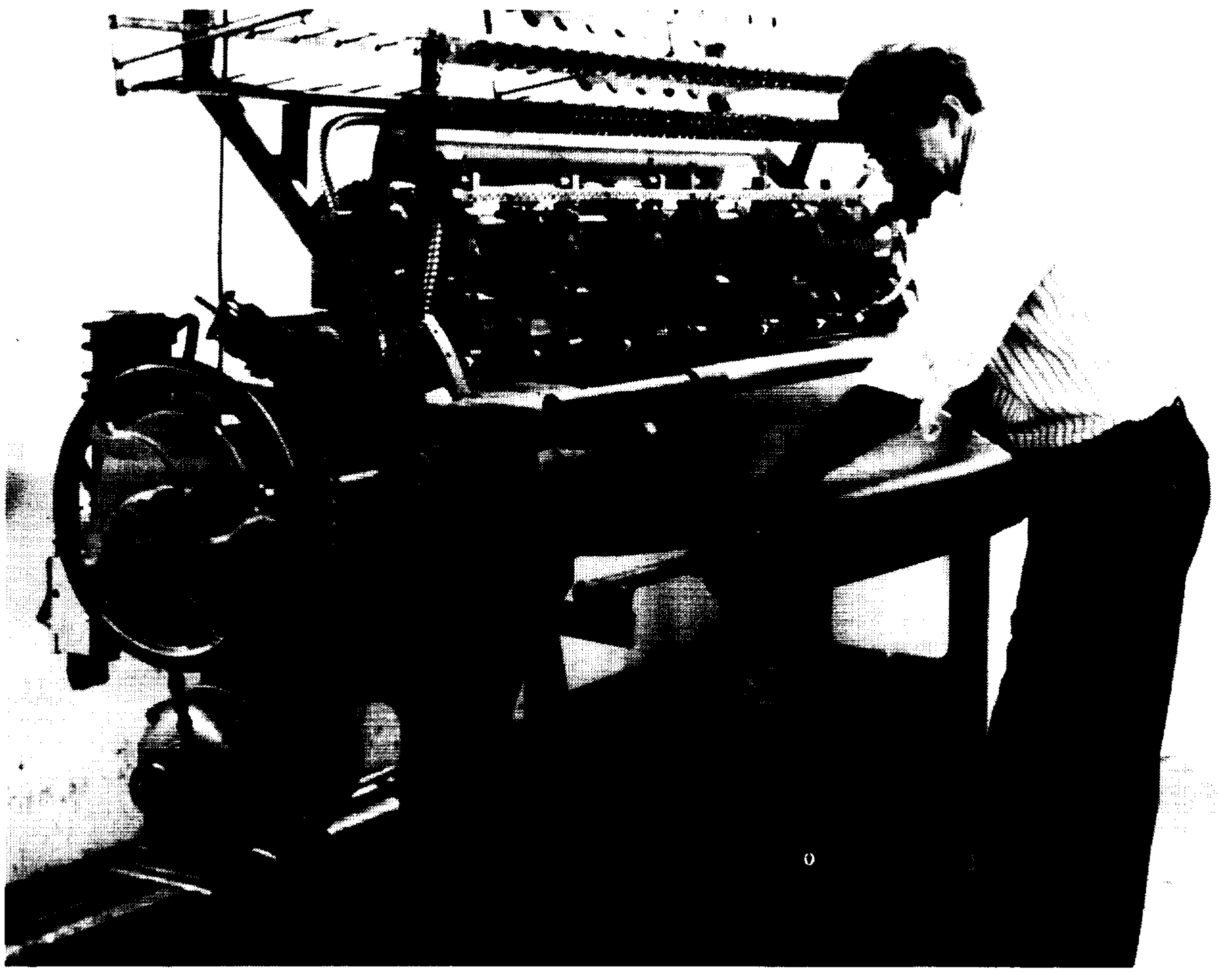
ORIGINAL MULTI-NEEDLE STITCHING MACHINE

Light density stitching has been accomplished on this multi-needle machine at Ketema. The machine is 60" wide with 1" needle spacing and maximum thickness stitching of 10 layers of uniwoven fabric. The equipment does not have multi-feed rolls so individual layers of material were cut, stacked, and then passed through the machine.



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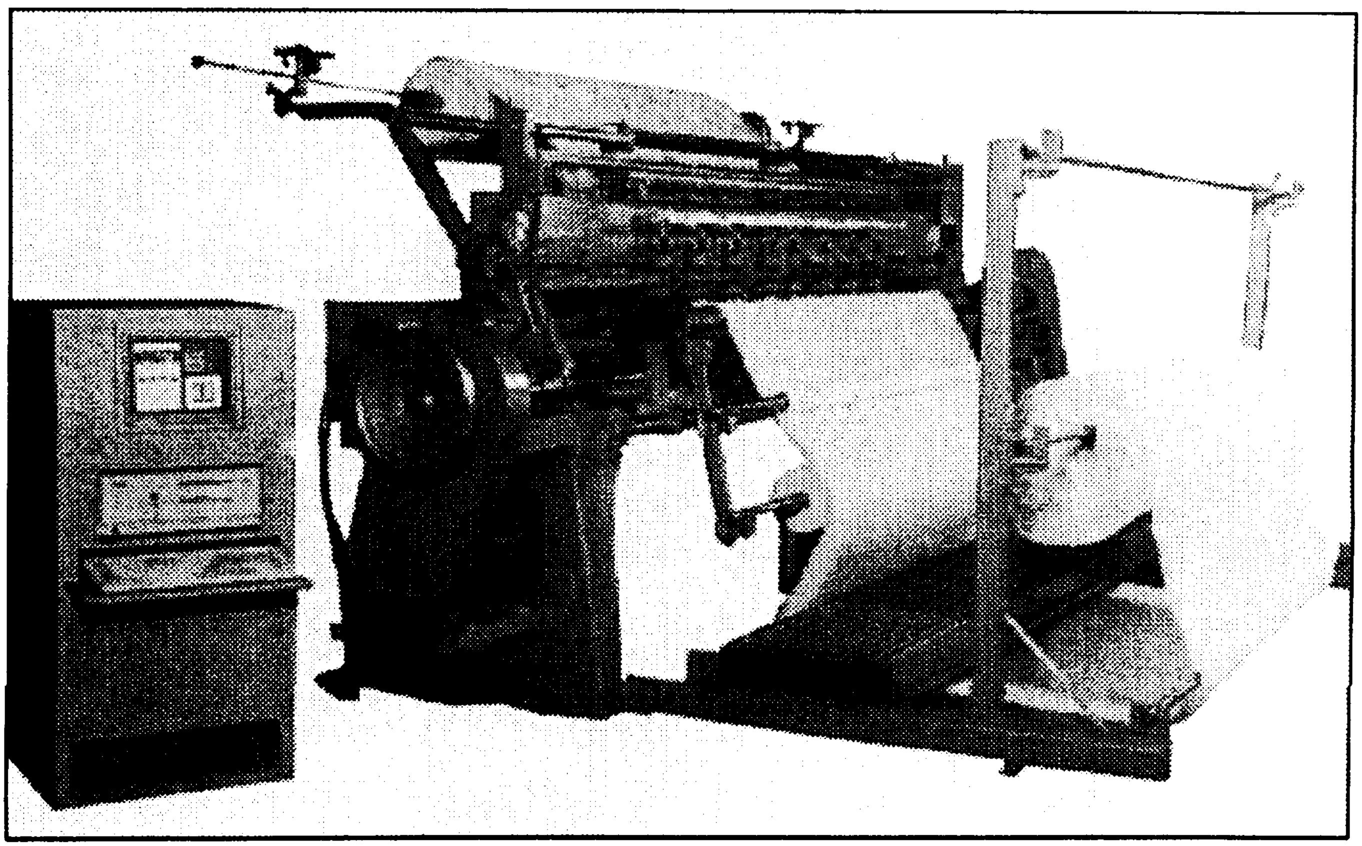
The stitching machine selection for this program is a Pathe machine that is being modified to have up to twelve unidirectional roll feed to lightly stitch the fuselage skins and a more unidirectional roll feed to lightly stitch the wing preforms. The wing basic plies will be stacked and stitched together by the basic pattern selected. This machine is in the process of being checked out by stitching some of the subcomponent parts at the machine manufacturers.

PATHE MULTI-NEEDLE STITCHING MACHINE



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BENEFITS OFFERED BY NEW STITCHING EQUIPMENT

The DAC ICAPS program features the automated stitching process to fabricate dry fiber near net shape stitched preforms. The development work completed to date to prove the structural benefits of the process (damage tolerance) has all been accomplished on a manual contour single needle long arm machine.

ICAPS will soon demonstrate the economic benefits of stitching that will become available with the new automated stitching equipment now being built for this project by Pathe.

This viewgraph shows

1. The description of the original machine, the computer control automated single needle machine, and the mechanical control multi-needle machines that are being purchased.
2. Identifies the assumed stitching speed for each machine. All machines are capable of operating at much higher rates. These rates are the assumed rates for a 1/4" thick preform and are conservative in all cases.
3. The estimated stitching efficiencies from observations on the original machine and from the experience of the automated machine builder.
4. Available penetration rate per minute is the assumed stitching rate times the efficiency factor times the number of needles.
5. The time to stitch one square foot with penetration density of 64 per square inch is the total penetrations per square inch ($64 \times 144 = 9216/ft^2$) divided by the penetrations per minute.
6. The time to stitch an 8'x12' uniform thickness panel is a multiple of step 5 above, times 96. Note that the current manual machine would require 24,576 minutes to stitch this skin where the new automated single needle machine would require 1248 minutes. This is a 95% reduction in time.

The multi-needle machine with 128 needles would require only 55 minutes to stitch this panel. This is a 95% reduction in time from the automated single needle machine.

The multi-needle machine with all 256 needles will require considerable testing before it can be considered for the application.

FABRICATION PROCESS FOR DEVELOPMENT AND RESINS

Two basic RTM processes and the automated tow placement process are being developed and demonstrated in the Douglas ICAPS program.

RTM

Vacuum impregnation and vacuum film in fusion are being developed as a method of fabrication for the Douglas wing effort. This method of RTM utilizes either liquid or film resins depending on the resin processing characteristics and final mechanical properties.

Pressure impregnation is being developed to fabricate composite fuselage skins and longerons. This method of fabrication will rely entirely on liquid resin systems and in-tool curing techniques.

AUTOMATED TOW PLACEMENT

Finally, the automated tow placement process of Hercules is being demonstrated under subcontract to fabricate the same fuselage skin and longerons components being done under pressure RTM.

Completion of a subcomponent cost and performance evaluation (end of Phase A) will depict which process or combination of processes will be used for continued development in Phase B.

FABRICATION PROCESS AND TOOL EVALUATION

VACUUM IMPREGNATION

FILM INFUSION

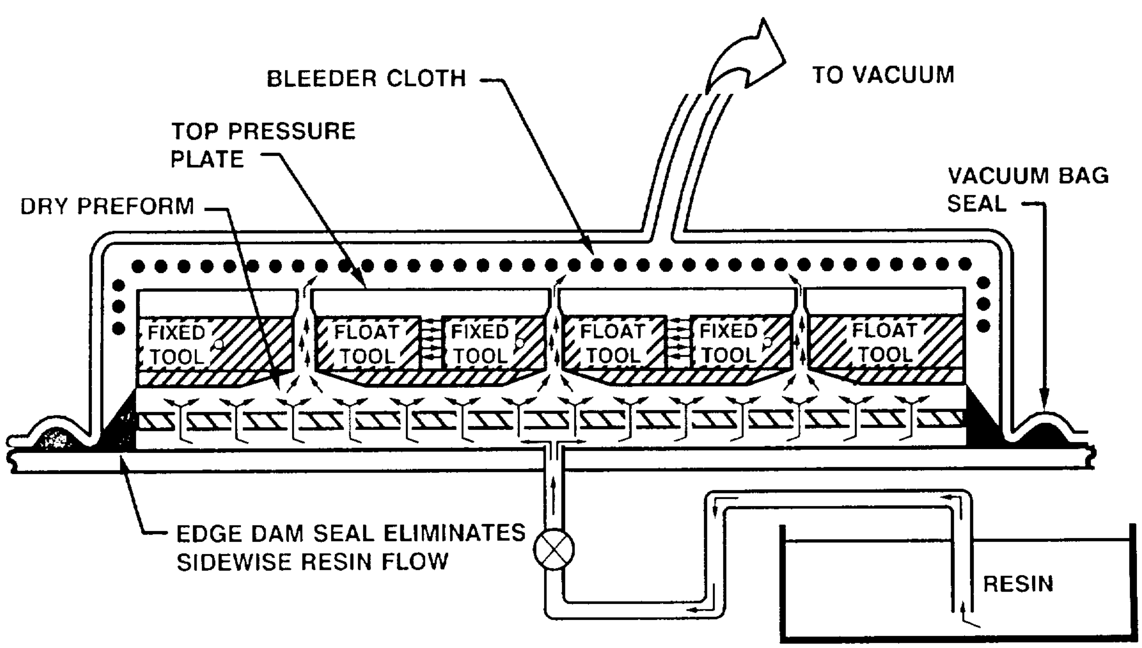
PRESSURE IMPREGNATION

AUTOMATED TOW PLACEMENT

VACUUM IMPREGNATION OF STIFFENED PANEL
LIQUID RESIN INFUSION

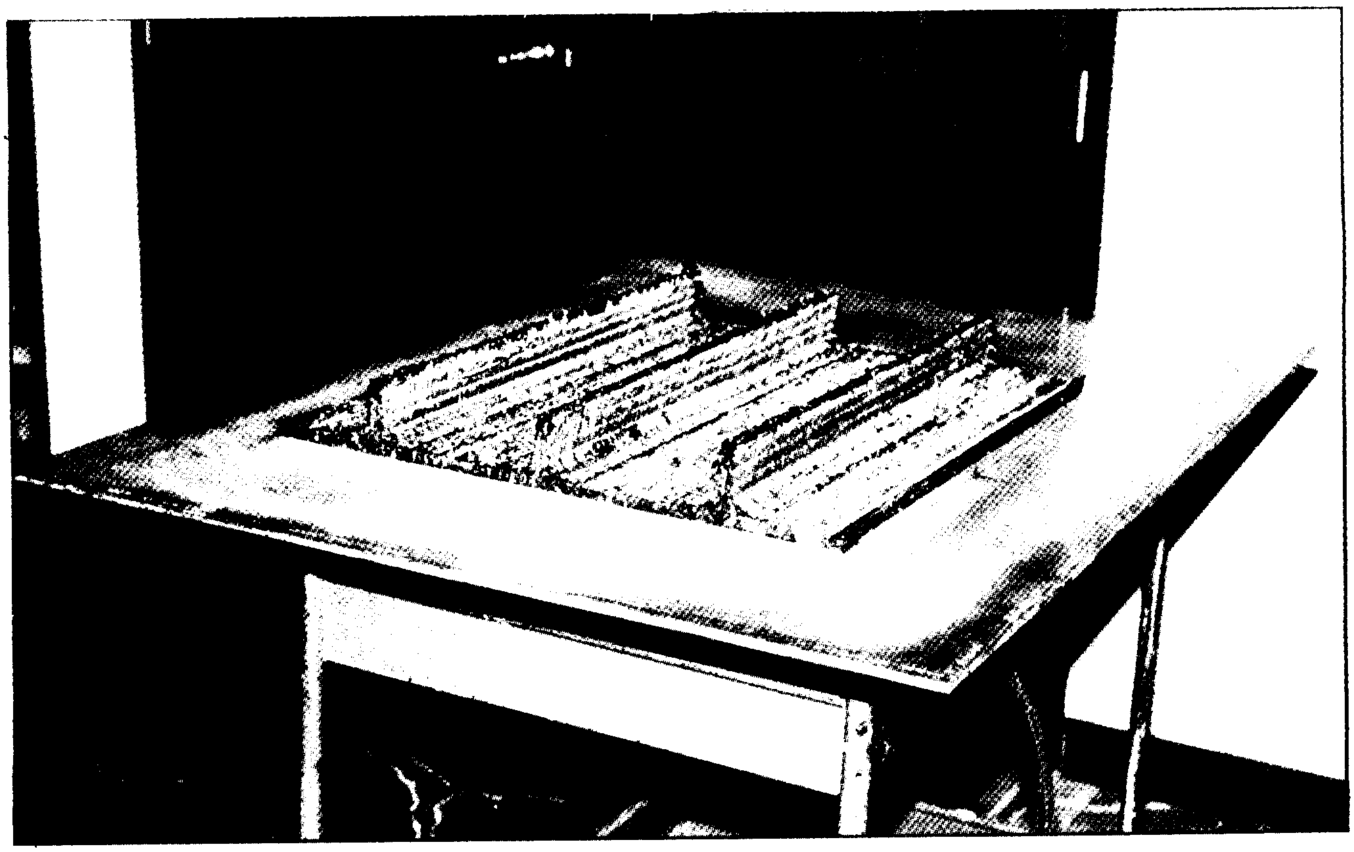
The complete process requires only vacuum source and either self heated tools or an oven.

Resin is mixed and degassed as required to remove trapped air. The tool is heated to desired temperature and vacuum is drawn on the system. The temperature varies for each resin system, for optimum impregnation and ranges from 150°F to 275°F. When the heat has stabilized, the valve is opened and the resin flows through the runners of a surface call plate, through holes in the runners that connect to the dry preform. The resin passes through the skin, up through the webs of the stiffeners, through holes in the upper pressure plate, and into the upper bleeder cloth. The temperature and resin gel time are coordinated so that the resin stops flowing and cures before it reaches the vacuum outlet line. Temperature may be raised, after resin gel, to a higher temperature to complete the cure cycle - all with only vacuum bag pressure.



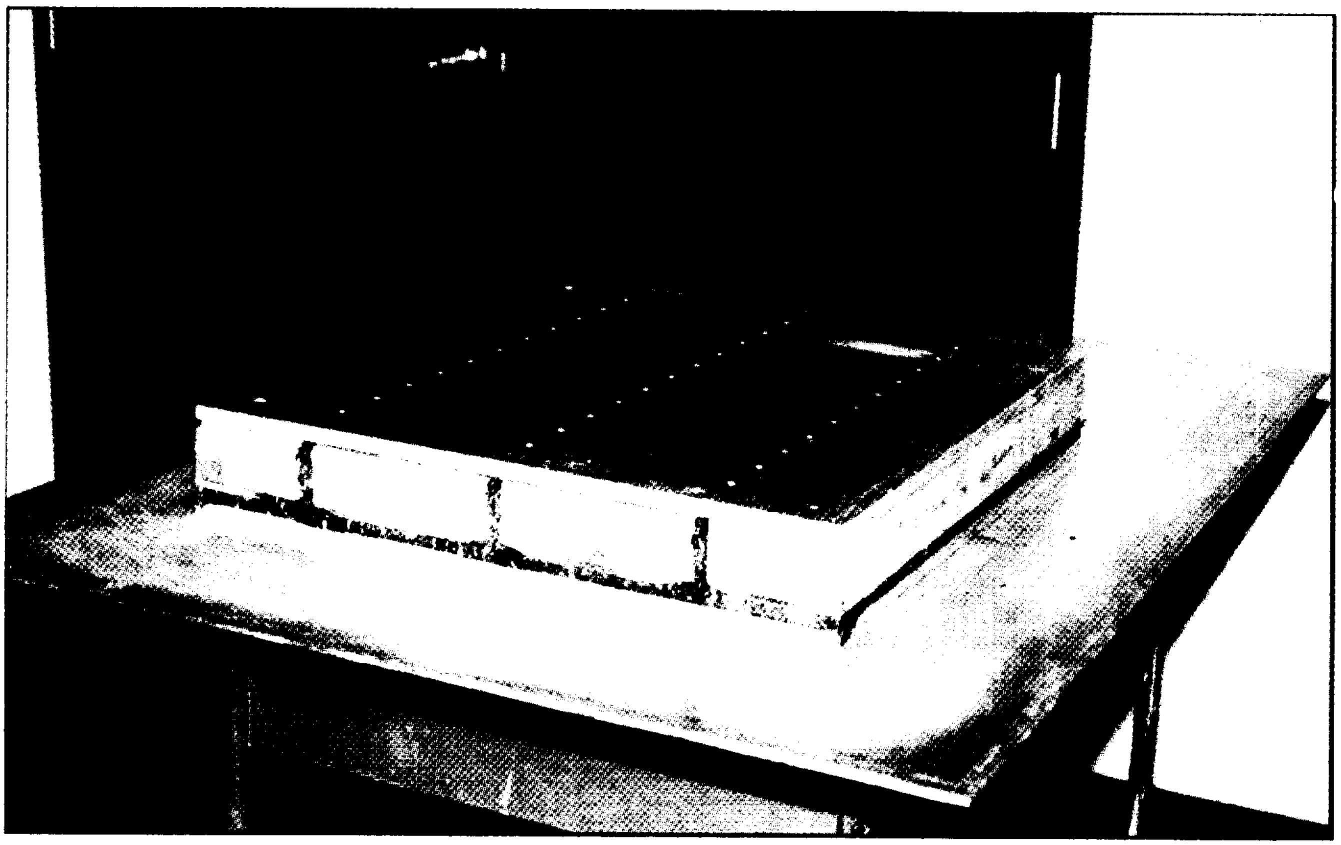
WING ELEMENT PREFORM

Douglas preforms are being developed with unidirectional graphite cloth being stitched into the three-dimensional shapes representing structural wing components. These structural shapes are then stitched directly to a stitched wing skin to give a complete wing skin assembly preform. This method of preforming has shown a great cost reduction in both layup and assembly of composite wing skins. Shown in this figure is a 3 blade stitched wing skin preform.



WING ELEMENT TOOLING
VACUUM IMPREGNATION

The tooling for vacuum impregnation of three blade stiffened wing elements consists of a set of machined aluminum blocks used to define the wing skin control with a set of matching flat tooling plates used to sandwich the preform/tooling blocks during impregnation. This entire assembly is then vacuum bagged while the resin is infused and cured in the preform.



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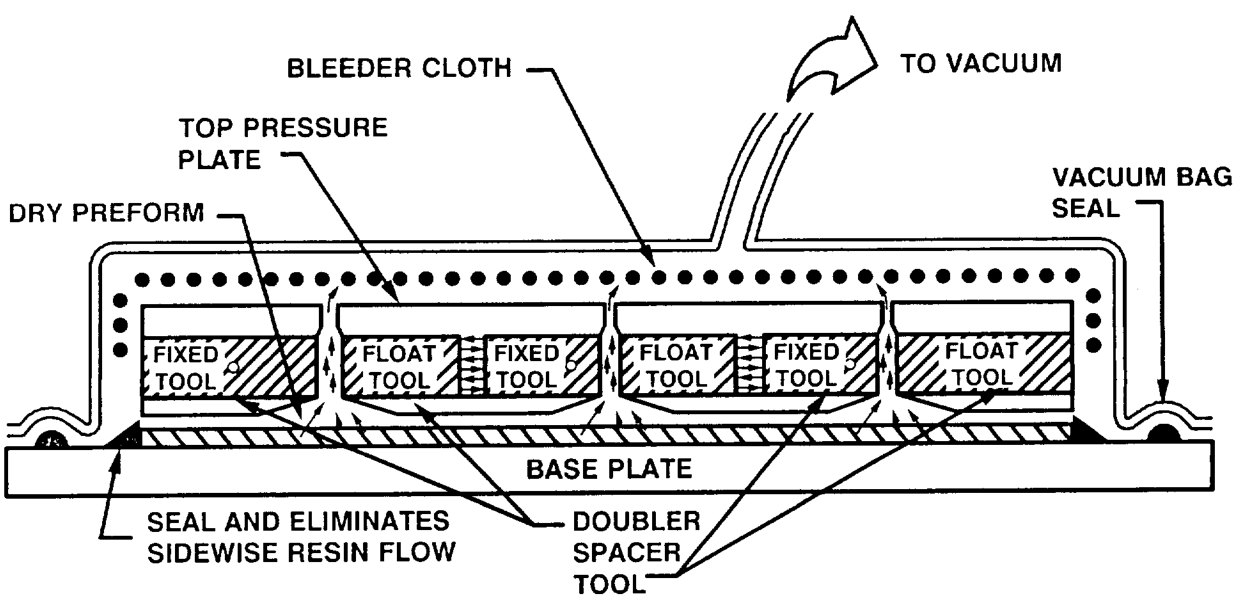
RESIN FILM INFUSION OF STIFFENED PANEL

The complete process requires only vacuum source and either self heated tool or an oven.

Resin film of desired amount is placed on the surface of the tool. The dry preform is placed on the resin, the upper tools located in place, and enclosed in a vacuum bag. Heat is applied. The resin viscosity thins and the resin flows upward through the skin, the webs of the stiffeners, through the outlet holes in the upper pressure plate, and into the bleeder cloth where it gels. The amount of resin, the temperature, and the gel time are coordinated so that the resin will stop flowing and cure before it reaches the vacuum outlet line. Temperature may be raised after resin gels to a higher temperature to complete the cure cycle - all with only vacuum bag pressure.



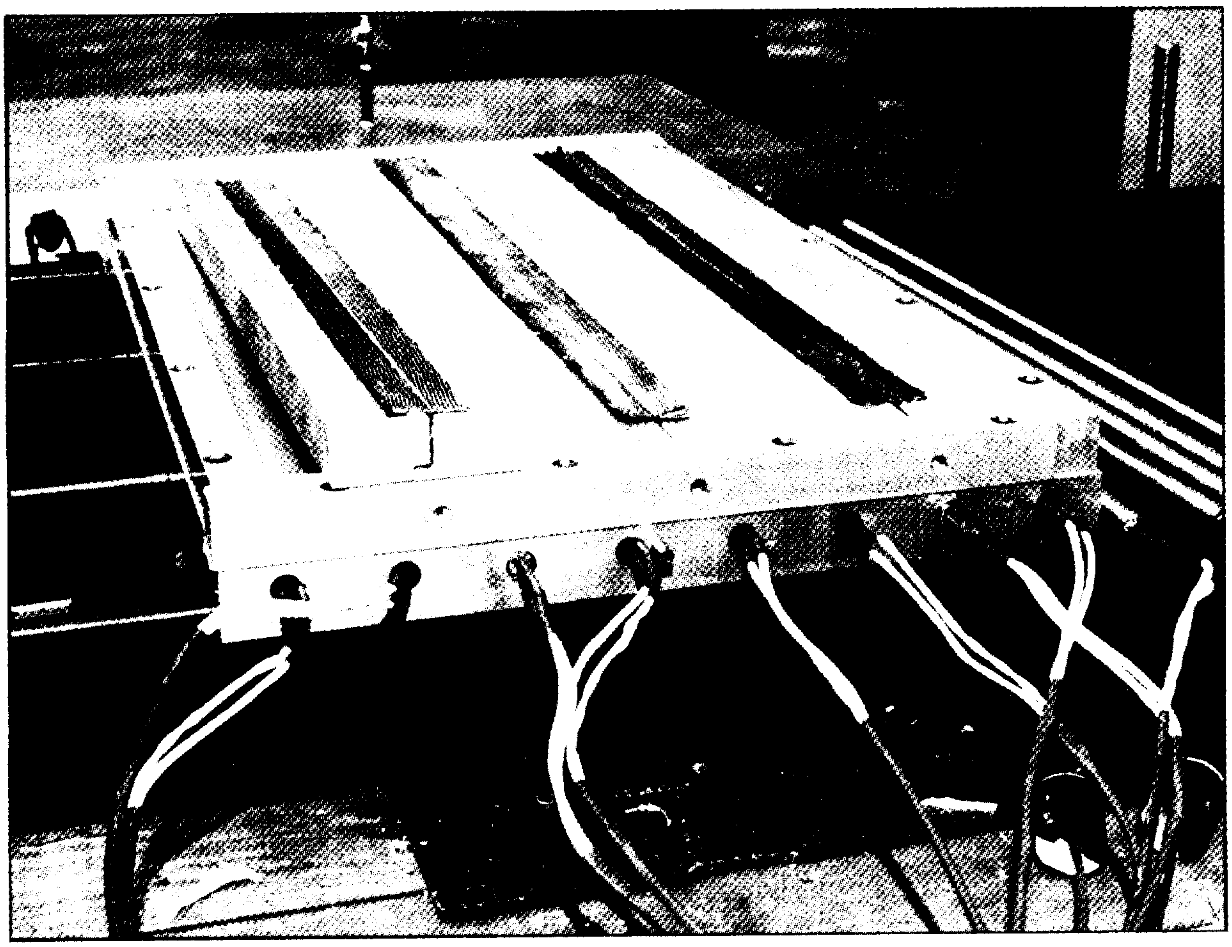
NEW RESIN EVALUATION

In the continuing Douglas evaluation of new resin there were a considerable number investigated that were in liquid form suitable for the ICAPS program. From the past fifteen months, the selection was narrowed to three or four which are in the ICAPS specimen/coupon evaluation process. The objective is to narrow down to one or two for the component fabrication early next year.

DOW CHEMICAL CO.	**TACTIX 695**
SHELL CHEMICAL CO.	**DRL 862**
CIBA-GEIGY CO.	**MATRIMID 5292 A/B (BMI)**
BRITISH PETROLEUM	**E-905L**
(OPEN)	

RTM FUSELAGE ELEMENT TOOLING

The pressure impregnation process is being developed for composite primary fuselage applications at Douglas Aircraft Company. This process is utilizing dry stitched preforms in combination with matched metal tooling and a positive displacement resin meter mis pump. The Douglas RTM fuselage element tool is shown in this slide.



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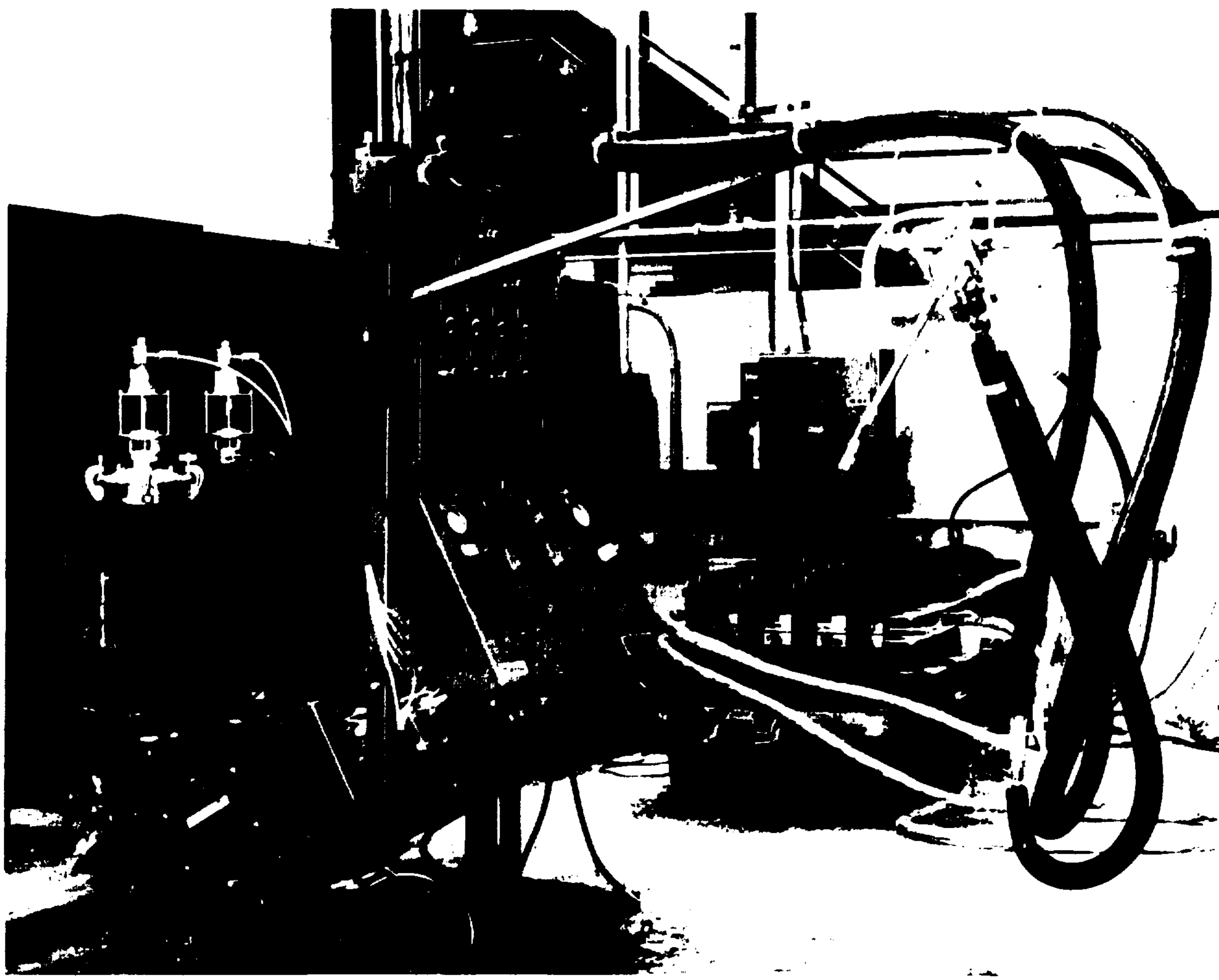
DAC RTM MACHINE

All the pressure RTM development being done at Douglas Aircraft is being done with a liquid control multi flow-4 machine. This machine can handle one or two component resins that require pre-heat temperatures of up to 175°F. This machine will be used extensively in the RTM fuselage sub-component work to be done at Douglas during the remainder of Phase A of the ICAPS program.



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PROCESS MODEL AND MONITOR

William & Mary College (W&MC) and Virginia Polytechnic Institute (VPI) are combining forces to create a process model and process monitoring system.

W&MC, under the direction of Dr. David Kranbuehl, has a FDEMS system that will record resin collation (as a preform is being impregnated along with resin viscosity and resin cure condition). A resin kinetics model is being developed to establish the relationship between DSC, viscosity, temperature, and time versus FDEMS measurement.

WILLIAM AND MARY COLLEGE
DR. DAVID KRANBUEHL

PROCESS MONITOR

FDEMS SYSTEM

- RESIN LOCATION
- RESIN VISCOSITY
- RESIN CURE CONDITION

RESIN KINETIC MODEL

- DSC VERSUS VISCOSITY VERSUS TIME VERSUS FDEMS RELATIONSHIPS
- CREATE RELATIONSHIP MODEL
- VERIFY MODEL PREDICTIONS

VPI is conducting a porosity study of preforms and resin flow rates with temperature/viscosity/gel time restraints. VPI, under the direction of Dr. Al Loos, will use their data alone with the W&MC data to construct a process cure model. The objective of this model is to assess a new design, predict if the RTM system will work, and if so, specify a curing time/temperature cycle.

VIRGINIA POLYTECHNIC INSTITUTE (VPI)
DR. AL LOOS

POROSITY STUDY OF PREFORMS

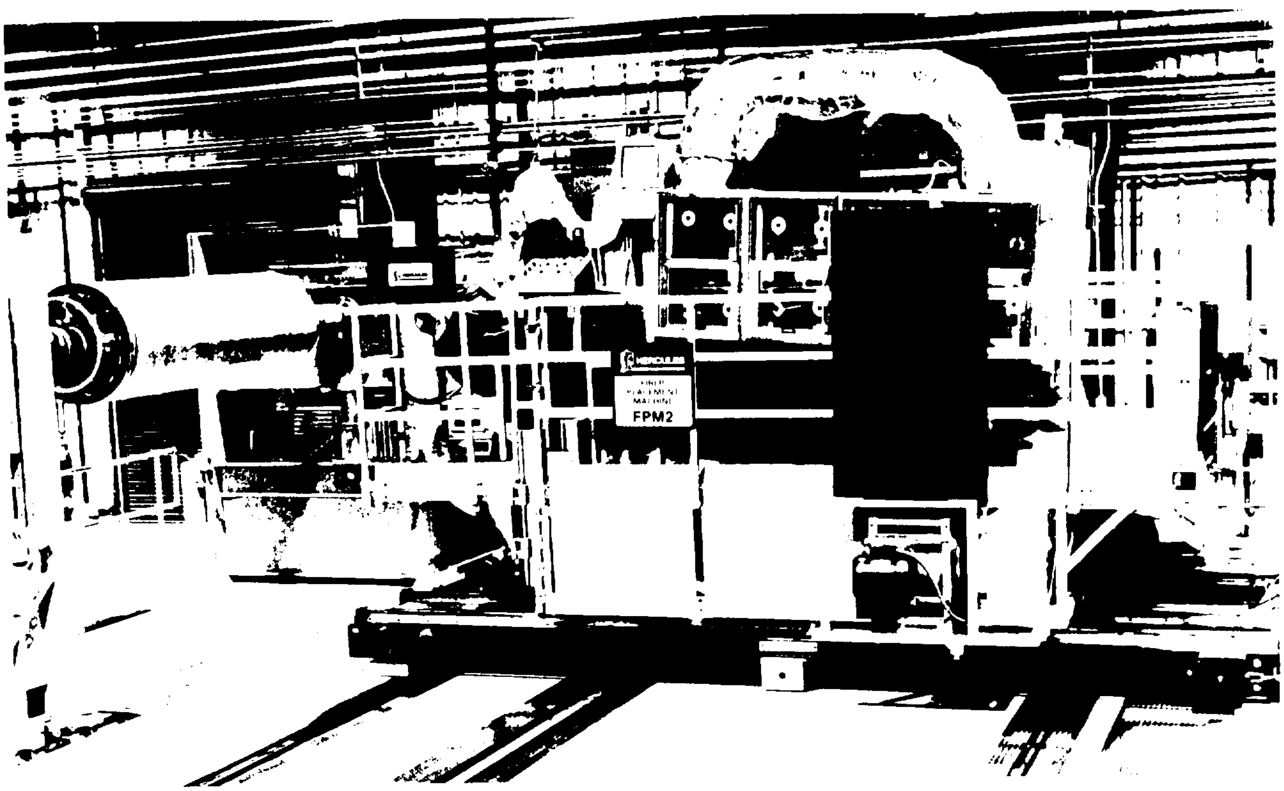
RESIN FLOW RATE
TEMPERATURE/VISCOSITY/GEL

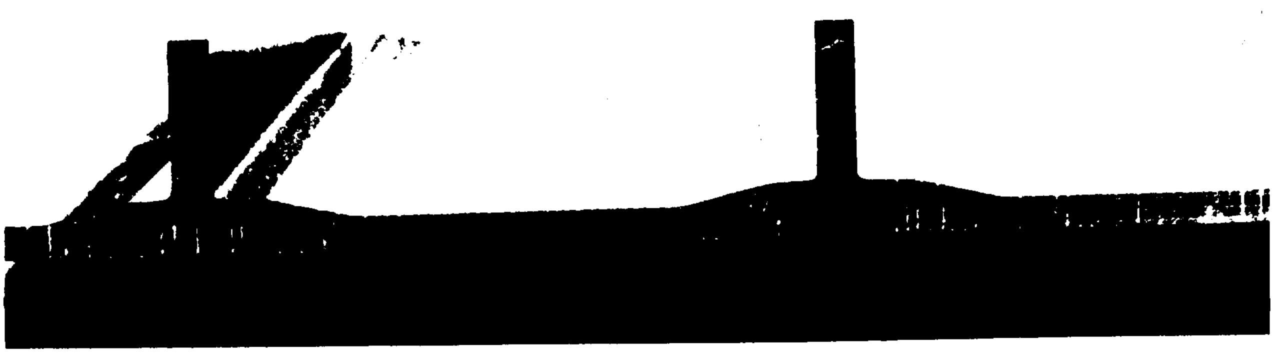
CREATE PROCESS PREDICTION CURE MODEL
- VPI AND WILLIAM AND MARY DATA

VERIFY MODEL PREDICTIONS

AUTOMATED FIBER TOW PLACEMENT

As part of the Douglas pressurized fuselage development, the automated fiber tow placement process is being evaluated in conjunction with the Douglas RTM fuselage effort. Hercules Inc. is fabricating element and subcomponent fuselage panels with their most advanced fiber placement machine in this Phase A effort. Shown below is a side view of the Hercules tow placement machine and a photo of the element panel fabricated earlier this year.





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DEVELOPMENT TESTING

This is a summary of the wing and fuselage test articles being fabricated. The majority of the elements (smaller sizes) are fabricated and in test. The sub-components (larger sizes) are in the fabrication process.

WING (TEST ARTICLES - 15 TOTAL)

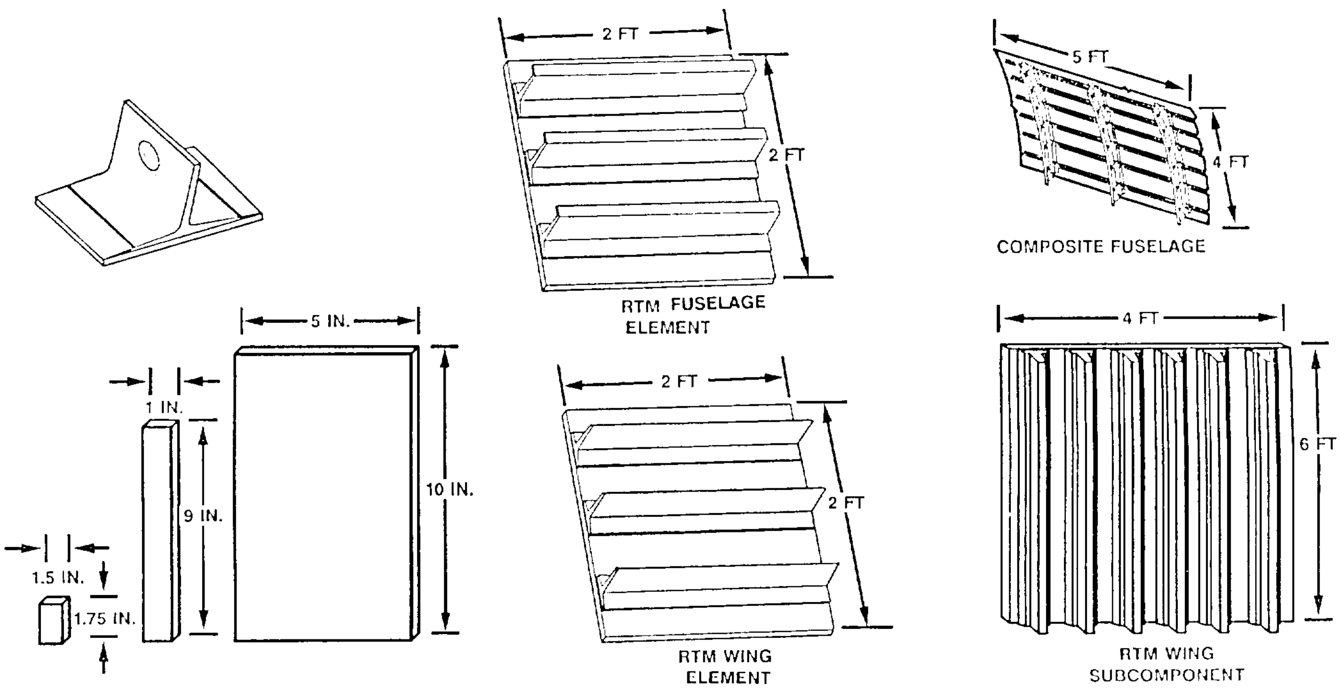
- **STRINGER PULLOFF**
- **THREE-BLADE STIFFENED PANELS (24 IN. X 21 IN.)**
- **SIX-BLADE STIFFENED PANELS (42 IN. X 60 IN.)**

FUSELAGE (TEST ARTICLES - 35 TOTAL)

- **LONGERON PULLOFF**
- **THREE J-STIFFENED PANELS (15 IN. X 21 IN.)**
- **SIX J-STIFFENED AND TWO-FRAME PANELS (48 IN. X 60 IN.)**

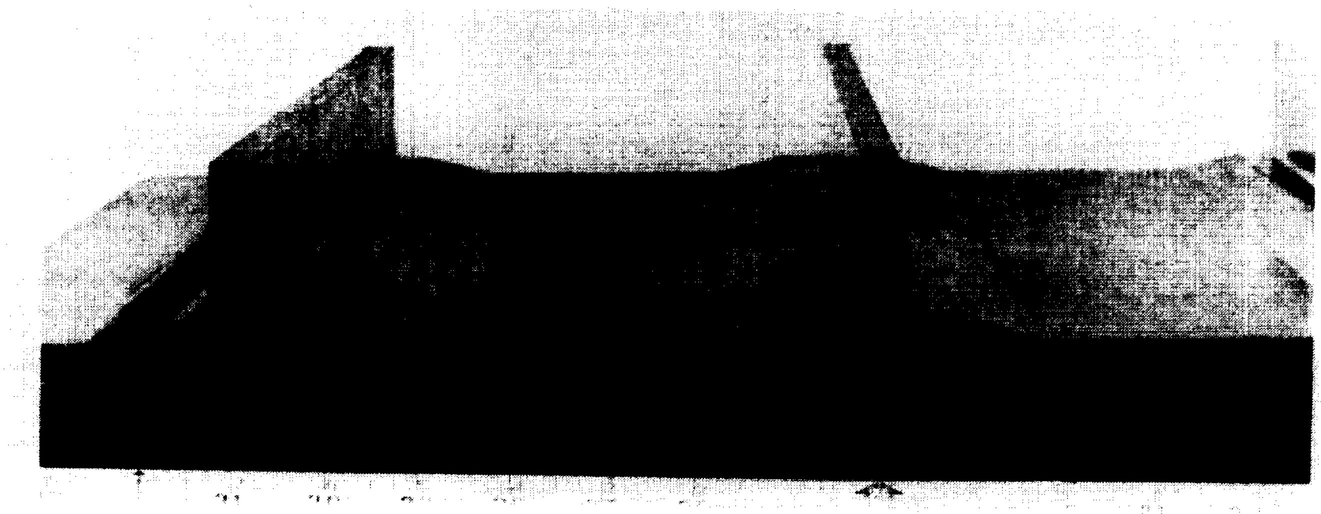
ELEMENT/SUBCOMPONENTS

This illustration shows the sizes of the various coupons, elements, and subcomponents. The coupons were of thick and thin sizes to do development work for both fuselage and wing structures. When the elements were designed, they specifically focused on the J-stiffened panels for the fuselage application and the thicker blade stiffened panels for the wing application. The subcomponents are scale-up of the element test articles that were sized to fit the existing testing fixtures.



THREE BLADE WING PANEL

This photograph shows one of the three blade stiffened (element) wing panels fabricated for compression development testing. Panels of this type as well as coupons and test specimens using the current state-of-the-art resin and intermediate strength fibers have shown that the dry stitch preform fabrication concept structure yields strength after damage equivalent to the newer toughened resins and high strength fibers. This can be accomplished at a much lower material and fabrication cost.



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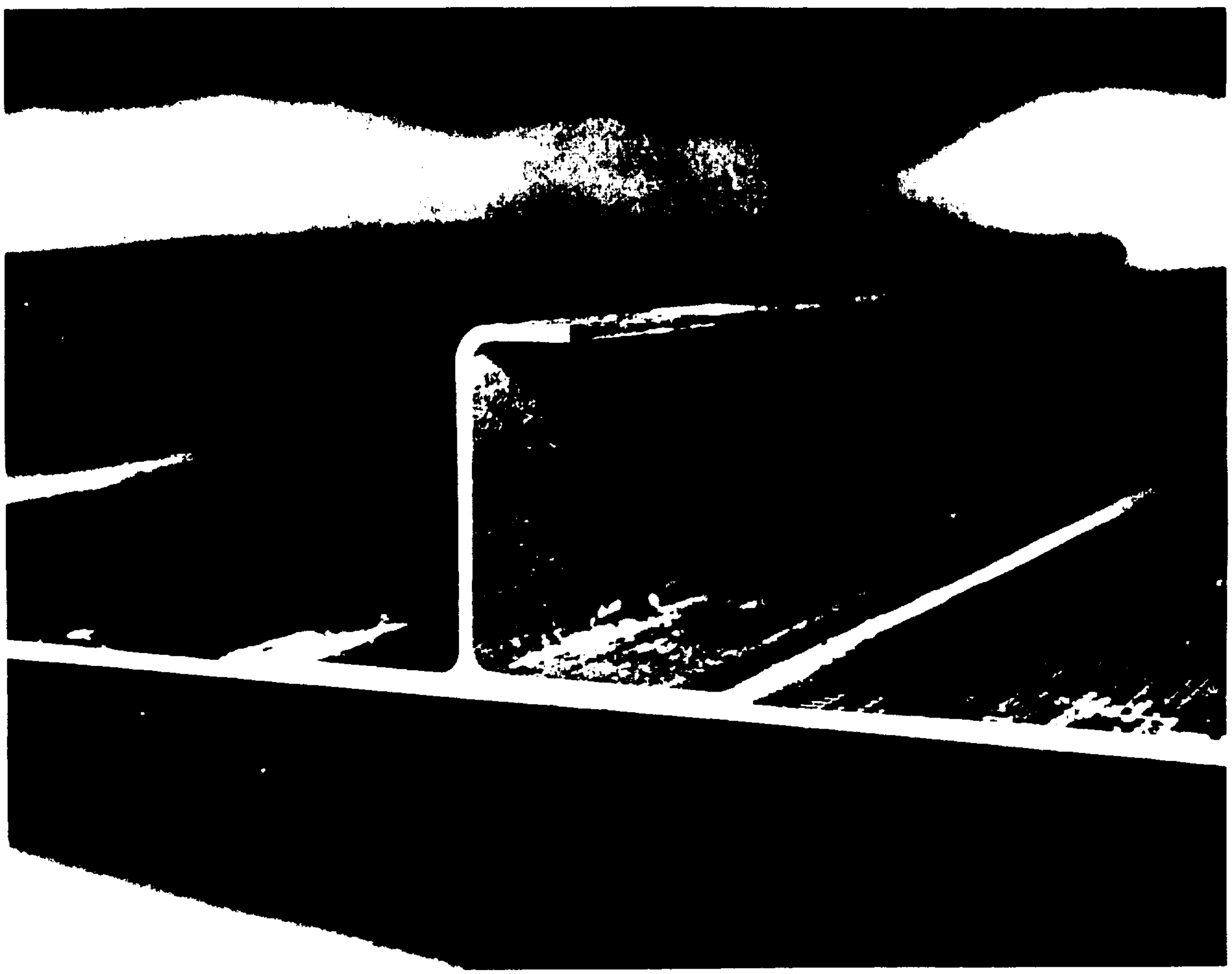
FUSELAGE "J" STIFFENED PANEL
RTM

This photo represents a three "J" stiffened fuselage element panel fabricated by the pressure RTM process.

FUSELAGE "J" STIFFENED PANEL
AUTOMATED TOW PLACEMENT

This is a cross section photo of a three "J" stiffened fuselage element panel fabricated with the automated two placement process under subcontract to Hercules.



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STRUCTURAL MECHANICS INVESTIGATION GOALS

As we introduce the innovative concept of Cost-Effective Resin Impregnated Stitched Preforms (CRISP), we need to investigate many new dimensions of composite structural mechanics. CRISP centers around two new approaches: stitching dry preforms and resin transfer molding (RTM in the general sense, including both vacuum and pressure processes). Both stitching and RTM alter the material properties to the extent that we need to modify the conventional laminate theory and composite design methodology. CRISP drastically improves composite damage tolerance performance under compression. Therefore we need to develop a new set of residual strength prediction tools for the design and application of stitched composites. There are more than a thousand tests at coupon, element, and subcomponent levels planned in ICAPS Phase A to validate our structural mechanics development.

MODIFIED LAMINATE THEORY FOR STITCHED MATERIAL

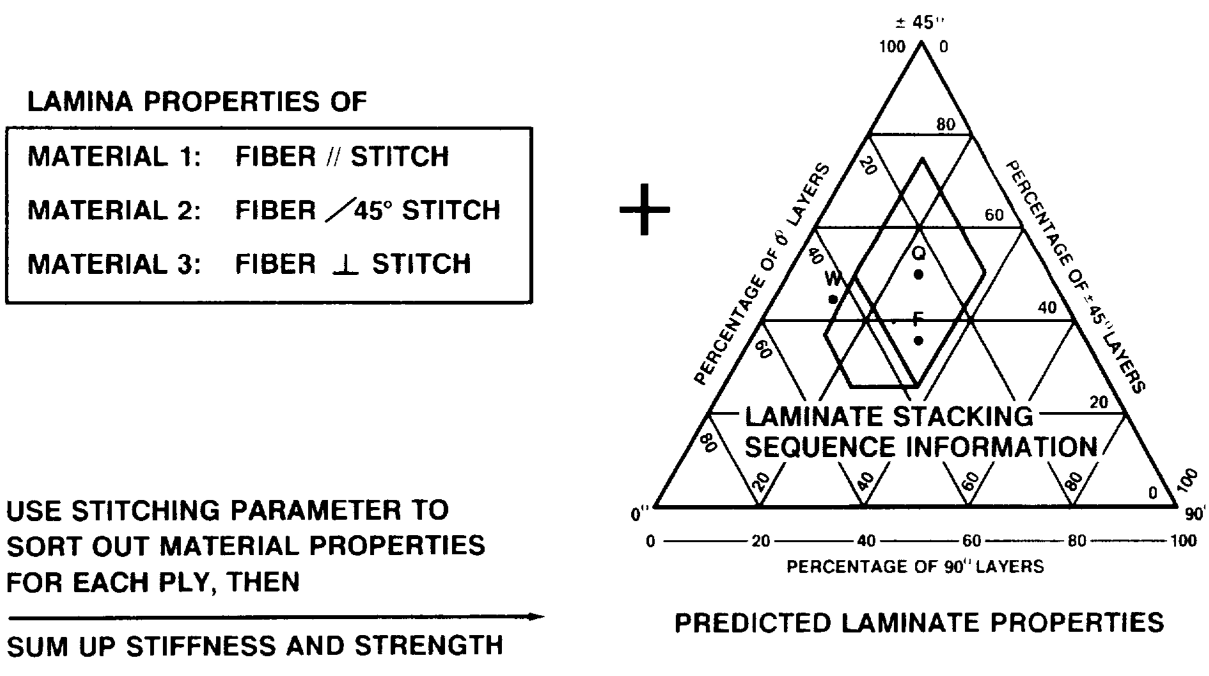
DESIGN METHODOLOGY WITH STITCHED LAMINATES

RESIDUAL STRENGTH PREDICTION

SUPPORTED BY MORE THAN 1,000 TESTS

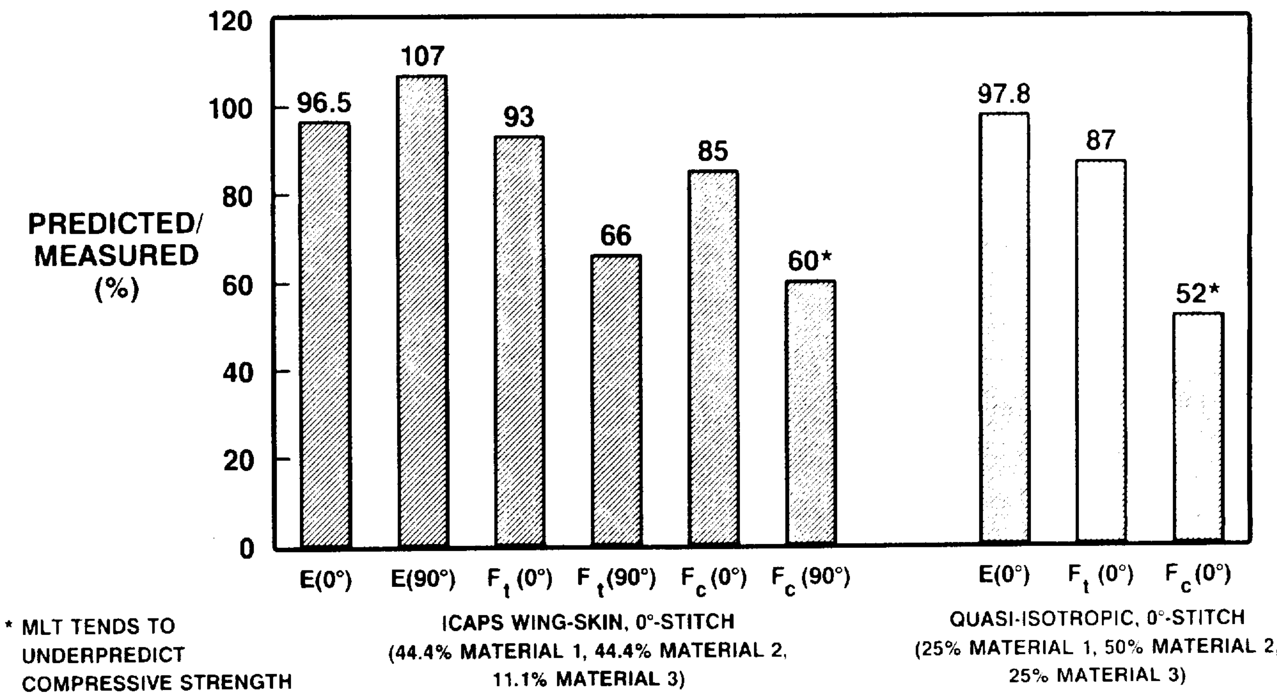
MODIFIED LAMINATE THEORY FOR STITCHED MATERIAL

Stitched laminates have greatly improved through-thickness strength, which leads to higher compression after impact (CAI) strength, and in many cases, higher effective compressive strength due to the suppression of brooming. We are in the process of further quantifying these benefits of stitching. As stitching helps CAI and compression performance, it alters other in-plane properties, and our most important finding is that this property change is non-uniform. Stitching disturbs the fibers perpendicular to stitch-line the most, therefore causing more strength reduction in that direction. Further, the property change is not uniform through the thickness either and the surface plies are affected more. This causes more strength reduction in thin laminates than in thick ones. In essence, stitched laminates are treated as if they were hybrid materials -- the plies having their fibers parallel, 45^{o} or perpendicular to the stitching lines, are modeled as different materials. Their strength and stiffness are added up using regular laminate theory.



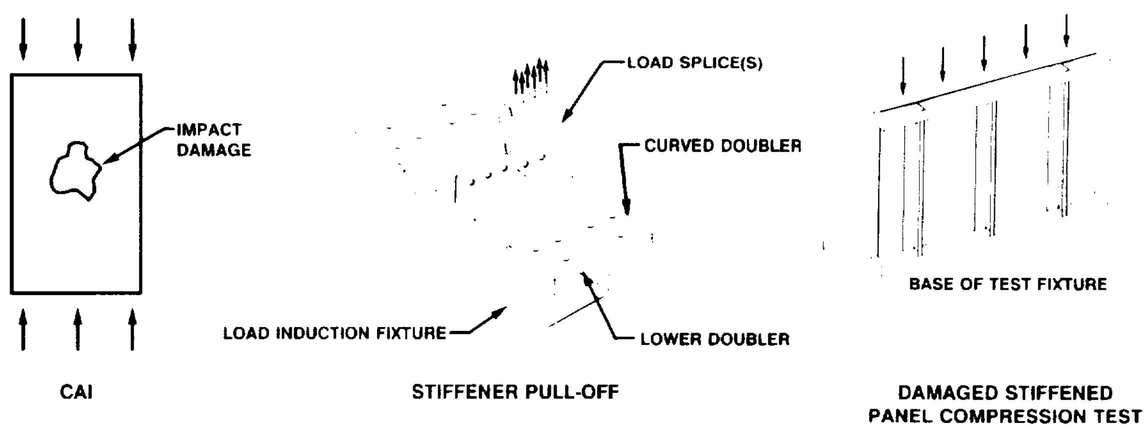
PREDICTION BY MODIFIED LAMINATE THEORY

The predictions shown in this slide are derived from a phenomenological theory modified for stitched laminates. Without any thickness correction factor, the model tends to under predict compression strength. A study is ongoing to determine if one extra factor is needed for the thickness effect. More tests are planned to study improved uniwoven material and thickness/stacking sequence combination effects.



RESIDUAL STRENGTH PREDICTION DEVELOPMENT

It is important to predict the ultimate strength (failure load) of damaged parts. Compression after impact (CAI) is probably the most common means of residual strength measure. However, large structures have redundant load paths built in them and do not lose the same percentage of strength with the same damage as the coupons. Also, most structures have stiffening members and stiffener-skin separation can be the failure mechanism. To estimate the ultimate strength of a stiffened part, this has to be accounted for in addition to buckling, crippling, and pure compressive failure. Stiffener pull-off tests will provide us with such strength data of stiffener-skin separation resistance for various material/process parts. We will use the CAI coupon and stiffener pull-off test results to establish impact damage modeling. Empirically matched "reduced stiffness and strength" parameters will be reduced and fed into finite element analyses. Element panel tests will be used to calibrate our prediction model parameters. The refined model will be used to predict the ultimate strength of damaged subcomponents.



ANALYSIS
- DAMAGE MODELING (REDUCED STIFFNESS AND STRENGTH)
- ULTIMATE STRENGTH PREDICTION ON DAMAGE PARTS (FINITE ELEMENT ANALYSIS WITH PARAMETERS OBTAINED FROM DAMAGE MODEL)

Since the ACT-ICAPS program has been initiated there have been several specific activities addressed to enhance the program results. Subcomponent fatigue testing will be accomplished prior to the Phase B components to determine if there are any issues that need to be addressed. Ply drop-off evaluation is being conducted to determine if the wing panel stacking sequence is acceptable. Validation of the spice joint is being made as well as thermal cycling of the stitched preform concept. Many components have over the years had varied compression failures related to the length between restraints called "brooming failure." This has been documented in numerous technical papers. A clarification of how stitching will affect these failure characteristics is being made. Additional damage tolerance tests are being conducted to cover additional impact force variables.

(DAC - NASA LANGLEY - UNIVERSITIES)

FATIGUE

PLY DROP-OFF CRITERIA

BOLTED JOINTS

THERMAL CYCLING

COMPRESSION FAILURE MODES

DAMAGE TOLERANCE

For the wing program there are three large scale wing box evaluations for comparison of cost. The wing box size is 8 foot root chord, 5 foot tip chord with a 12 foot section of span representing in size the side-of-body section of a DC-9-30 wing. The three cost analyses are on a metal, conventional composite, and ICAPS composite version.

CONVENTIONAL WING DESIGN - METAL

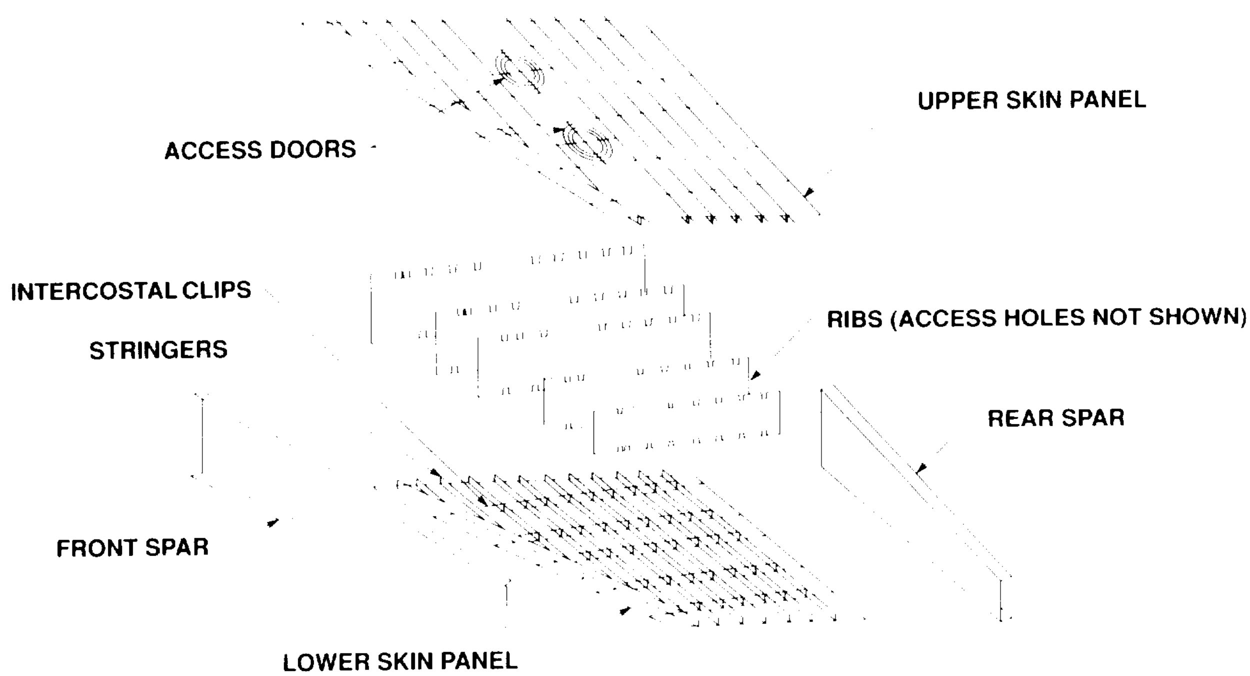
STATE-OF-THE-ART TOUGHENED RESIN WING - DOUGLAS

INNOVATIVE STITCHED DRY PREFORM WING DESIGN - ICAPS

STATE-OF-THE-ART COMPOSITE WING DESIGN

The Douglas composite wing program using toughened resin high strength fiber will consist of five ribs, two spars, and stiffened lower skins. The spars are typical spanwise "C" sections that will be mechanically fastened to the skins. Ribs will be flat with cutouts and stiffener. The cover skin thickness will taper by ply drip off and a blade stiffened cocured component. Rib shear clips will be secondarily bonded and fastened to the skins.

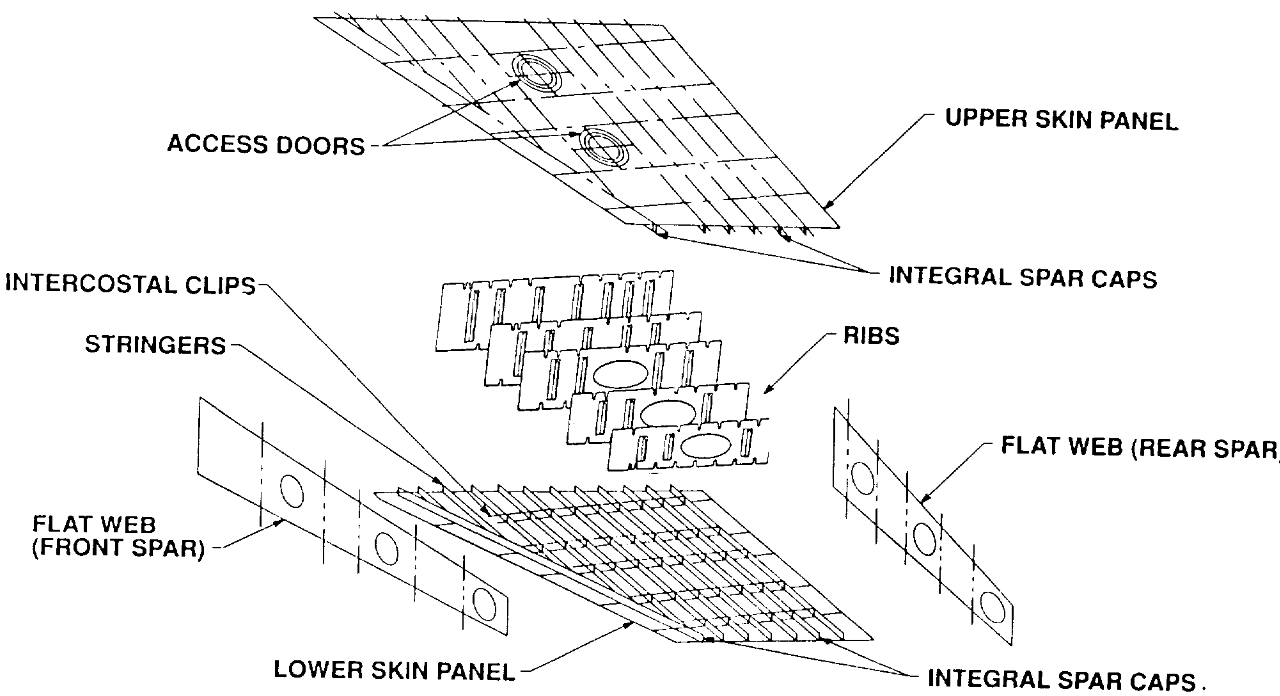
The component to be fabricated will have hand layup in many areas, but the cost model will search for and use the lowest cost fabrication concept (i.e. tape layup, filament/tow placement, etc.).



FABRICATION PROCESSES: AUTOMATED TAPE LAYUP (ATP)

ICAPS WING BOX ASSEMBLY

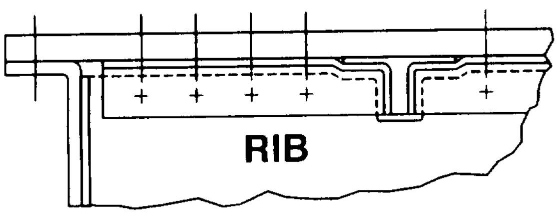
The ICAPS composite wing program will use dry stitched preform stiffened cover skins with stitched rib shear clips. Once again the ribs will be flat and nearly identical to the Douglas wing box ribs. The spars will be stiffened flat webs. The ribs and spar web will be mechanically fastened to the cover panels with shear fasteners with no tension fasteners through the cover skin. Savings in assembly and number are realized with this approach as well as future maintenance issues (i.e. fuel loads, etc.).



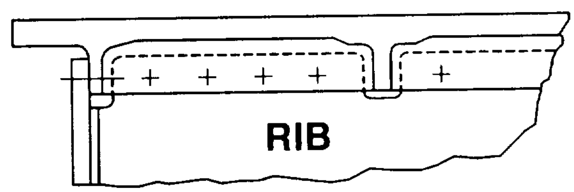
DESIGN DIFFERENCES

The significant difference between the state-of-the-art design and the ICAPS design is simplification and avoidance of problem issues that exist today. On the left there are mechanical fasteners joining the skin and spars that are in tension. A problem area develops when there are less than perfectly matched surfaces between the components. The ICAPS design avoids all fasteners through the cover skin as well as minimizing the number of fasteners. The ribs and spar webs are all stiffened flat members that are low cost minimum tool parts.

STATE-OF-THE-ART



ICAPS

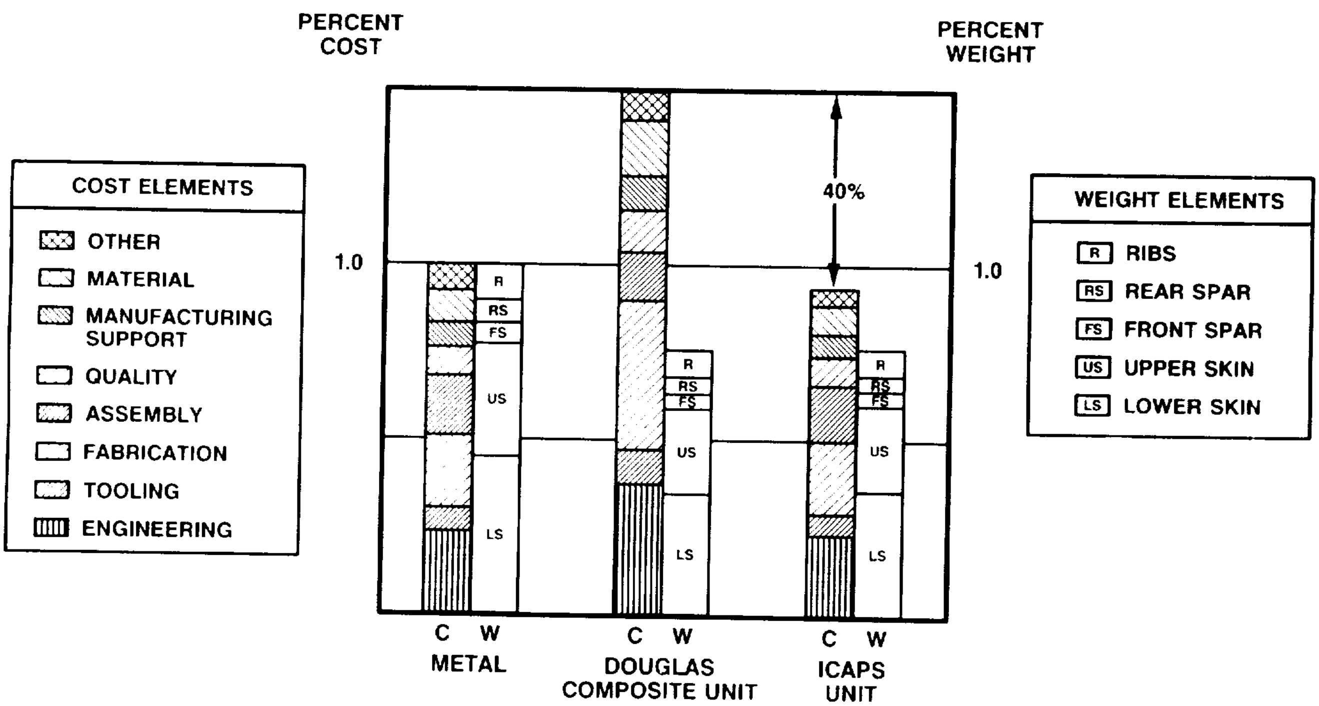


UNTAPERED STRINGER FLANGES
C-SECTION SPAR
SEPARATE RIB CLIPS
MANY SKIN BOLTS

TAPERED STRINGER FLANGES
INTEGRAL SPAR CAPS
INTEGRAL RIB CLIPS
STITCHING - FEW SKIN BOLTS

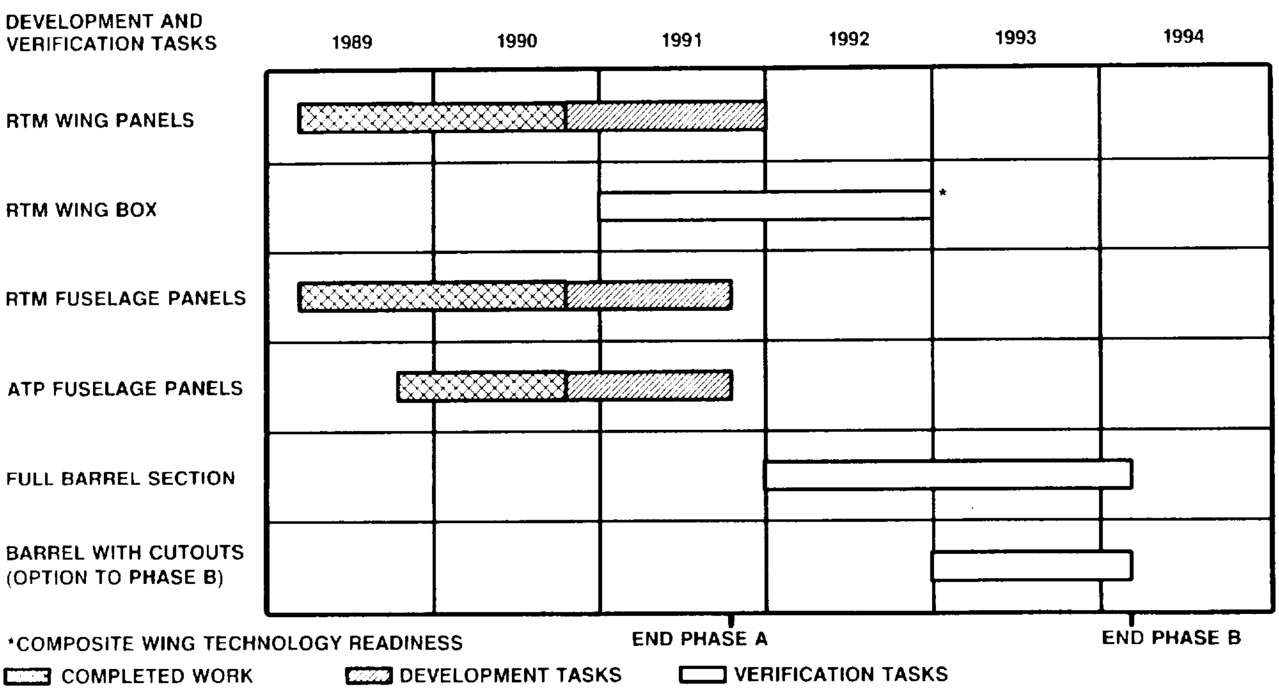
WING BOX COST DATA PROJECTION

The initial cost/weight projections for the three wing structural concepts are as shown. As additional data is generated from the elements, subcomponents and the two large scale box components, the analyses will be updated. The elements of cost data are listed as well as weight by component.



DEVELOPMENT AND VERIFICATION SCHEDULE FOR ICAPS

We are 19 months into the ICAPS program and have developed a considerable number of development tests focused at wing (thick laminate) and fuselage (thin laminate). Over the next year, we will be making and testing the large sub-component panels for both wing and RTM/tow placement fuselage panels. We will be initiating detail design on the RTM wing box so that the full box can be fabricated and structurally tested right after the Douglas wing box program. The full fuselage barrel design will depend on the selection evaluation of the RTM and tow placement test and cost data. The wing target dates are in agreement with the Douglas and ICAPS goals and objectives.



NOTE THIS SCHEDULE IS AN EXAMPLE. START AND END DATES ARE NOT NECESSARILY ACCURATE. HOWEVER, IT IS THE BIG PICTURE SCHEDULE I RECOMMEND.

PRODUCTION STITCHING PREFORM PROCESS

This slide presents a pictorial step-by-step production process to make near net shape stiffened wing skin like dry fiber preforms. The basic design uses a 9-ply repeat pattern layers of fabric.

The uni-woven fabric is purchased with major direction of reinforcement fibers at 0°, at 45° and at 90°. Nine rolls of this material are placed in a feed system, passed through the multi-needle stitching machine and rolled and stored for later use. Stitching is light density 1" apart parallel rolls.

The next step is to unroll one 9 ply stitched pre-ply and cut the doubler buildups required for the skin.

Six of the 9 ply stitched pre-ply rolls (54 total ply) are positioned on the feed system and pulled to the multi-needle position of the machine. Doublers are placed in position on the 54 ply area and then the entire skin and doublers are stitched together with the desired high density stitch pattern.

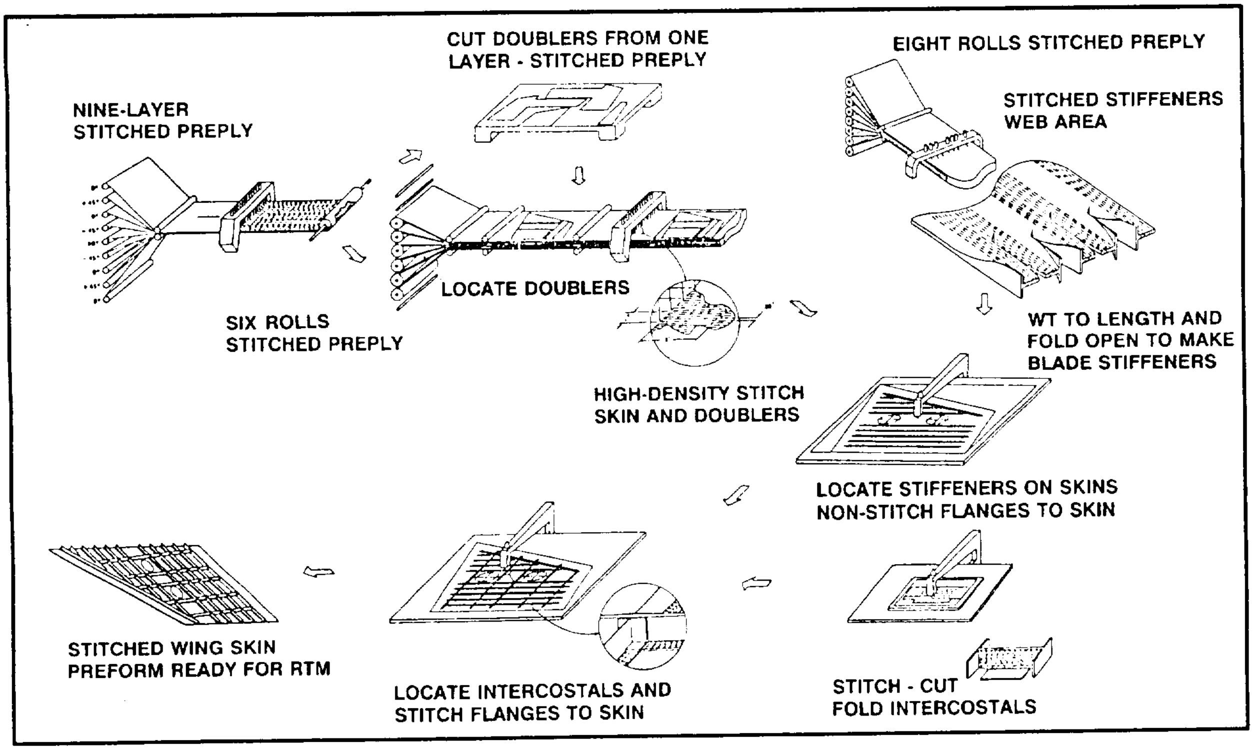
The stiffeners are made by stitching 8 nine ply stitched pre-ply material in areas of the web only for each stiffener. The stitched sections are then cut to allow the web and flanges to be folder right and left ready for installation on the stitched skin.

The stiffeners are properly located and the flanges are stitched to the skin using an automated single needle machine.

The intercostals are cut from two stitched pre-ply layers, stitched in the web area on a single needle machine and flanges are folded for stitching to the skin. The intercostals are then located on the skin/stiffener detail and stitched in the skin flange area.

The dry stitched preform is now out to near net size and is ready for the RTM impregnation and cure process.

PRODUCTION STITCHING PREFORM PROCESS



SUMMARY

The goals and objectives of ICAPS are still the primary focus of the on-going effort. There have been a considerable number of accomplishments that indicate progress is being made in attacking the high cost drivers. The stitching development has selected specific parameters. New resins are in evaluation for the RTM process and Hercules has done an excellent job in providing the development panels on tow placement for fuselage application. The equipment for the RTM process monitoring has been ordered so that shortly we'll be able to go from the laboratory effort to VPI/W&MC to the shop floor in fabrication of the large subcomponent.

We have specific application targets and feel very strongly that we can accomplish the cost breakthrough we need to make it happen.

ACCOMPLISHMENTS

- WING AND FUSELAGE SUBCOMPONENT DESIGNS
- DESIGN GUIDELINES FOR STITCHED/RTM COMPOSITES
- STITCHING AND ANALYSIS DEVELOPMENT TESTS 80% COMPLETE
- WING PANEL TOOLING DESIGNED
- FUSELAGE PANEL TOOLING COMPLETED
- ATP FUSELAGE PANELS FABRICATED
- HIGH-CAPACITY STITCHING MACHINES PURCHASED

TARGET OF OPPORTUNITY EXISTS FOR APPLICATION TO TRANSPORT STRUCTURE IN MID-1990

STITCHING DRY PREFORMS/RTM OFFERS BREAKTHROUGH IN AFFORDABLE MANUFACTURING

ICAPS PROGRAM PROVIDES ENABLING TECHNOLOGY