ADVANCED TOW PLACEMENT OF COMPOSITE FUSELAGE STRUCTURE

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ABSTRACT

The Hercules NASA ACT program was established to demonstrate and validate the low cost potential of the automated tow placement process for fabrication of aircraft primary structures. The program is currently being conducted as a cooperative program in collaboration with the Boeing ATCAS Program. The Hercules advanced tow placement process has been in development since 1982 and was developed specifically for composite aircraft structures. The second generation machine, now in operation at Hercules, is a production-ready machine that uses a low cost prepreg tow material form to produce structures with laminate properties equivalent to prepreg tape layup.

Current program activities are focused on demonstration of the automated tow placement process for fabrication of subsonic transport aircraft fuselage crown quadrants. We are working with Boeing Commercial Aircraft and Douglas Aircraft during this phase of the program. The Douglas demonstration panel has co-cured skin/stringers, and the Boeing demonstration panel is an intricately bonded part with co-cured skin/stringers and co-bonded frames.

Other aircraft structures that have been evaluated for the automated tow placement process include engine nacelle components, fuselage pressure bulkheads, and fuselage tail cones. Because of the cylindrical shape of these structures, multiple parts can be fabricated on one tow placement tool, thus reducing the cost per pound of the finished part.

CONFERENCE

Ninth DoD/NASA/FAA Conference on Fibrous Composites in Structural Design, 4-7 November, 1991, Lake Tahoe, Nevada.

HERCULES ACT PROGRAM OBJECTIVE

Composite materials have demonstrated significant weight savings for aircraft structures with the added advantages of outstanding corrosion and fatigue damage resistance. Despite these advantages, the potential benefits of composite aircraft primary structures have been limited by the high cost of materials, labor intensive manufacturing processes, and inadequate technology in structural mechanics and materials science.

The objective of the Hercules ACT Program is to use an automated seven-axis tow placement machine in development of low cost manufacturing processes for efficient aircraft structural forms. Specifically, Hercules will demonstrate the advanced tow placement process for fabrication of subsonic transport aircraft fuselage structures.

HERCULES AUTOMATED TOW PLACEMENT

Hercules began the development of tow placement technology for the automated placement and in-process consolidation of ribbonized prepreg tow in 1980. In 1983, our first machine (FPM1) was operational and was used to manufacture flat panels, curved panels, and 360° cross sections, including stiffened and unstiffened skins.

Hercules tow placement process makes use of robotic machine technology to provide an automated fabrication process for high performance composite structures. The process involves the precise automated placement and in-process compaction of ribbonized prepreg tow. Multiple tows are laid down as a band, with band location and angle precisely controlled. Material cut and add features, incorporated into the process, provide high production rate potential, enhance design tailorability, and minimize material scrap.

Hercules has successfully demonstrated the capability to fabricate a wide variety of complex structures using this technology. Aircraft wing components, including ribs and spars, air inlet ducts, and fuselage structures, have been successfully tow placed.

Hercules currently has two operational tow placement machines. FPM1 is a six-axis machine that has the capability to manufacture structures with a 20-ft maximum length and 11-ft maximum swing diameter. Our new production-rated machine (FPM2 shown in Figure 1), which became operational in early 1990, is a seven-axis machine that has the capability to manufacture structures with a 33-ft length and 13-ft swing diameter.

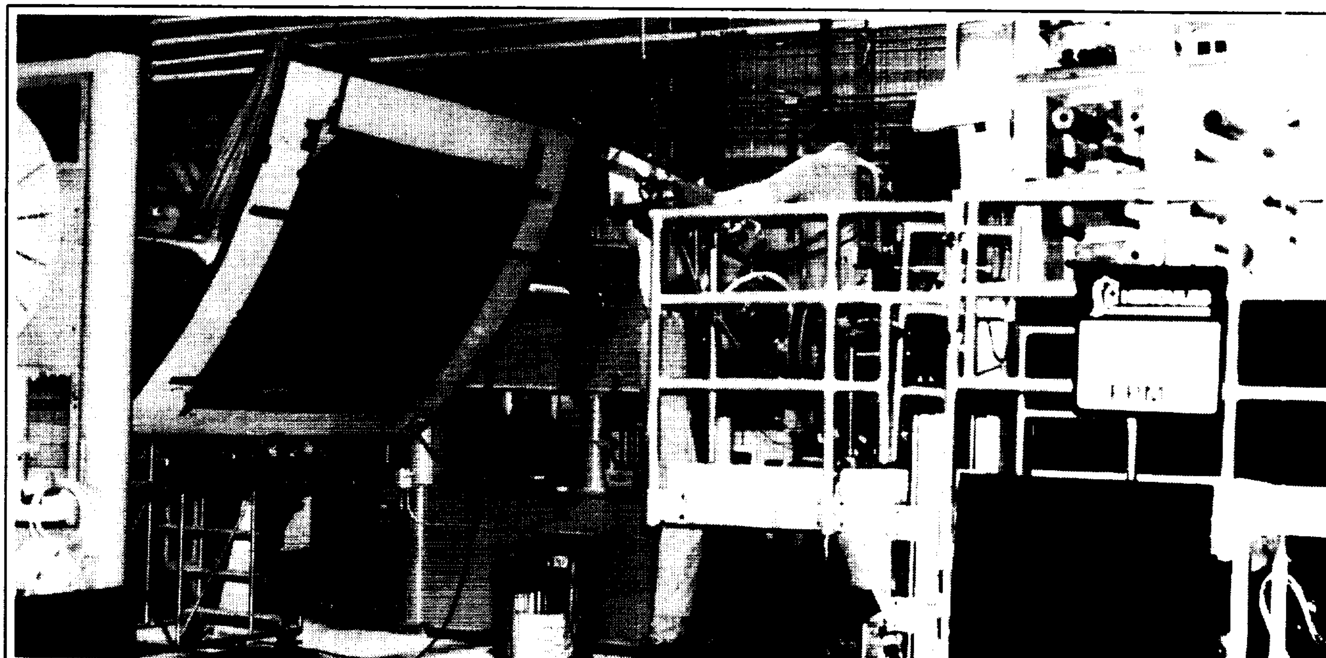

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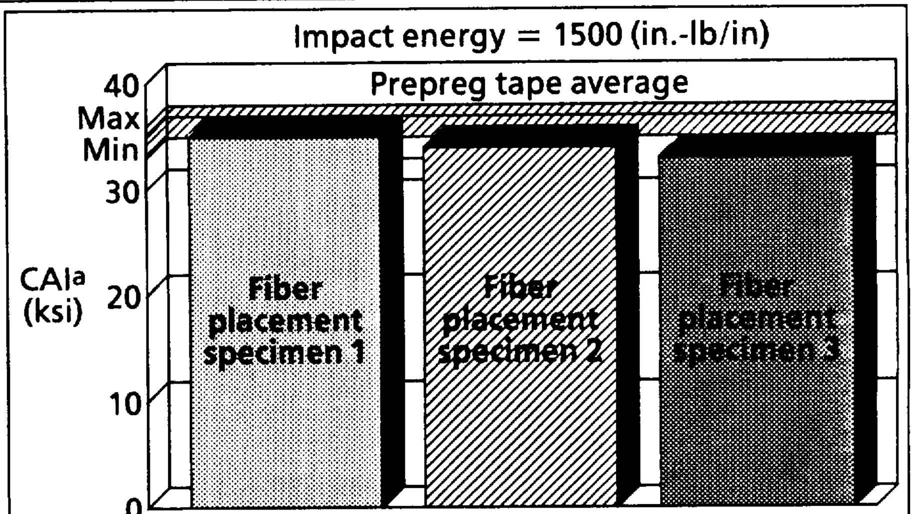
Figure 1. Hercules tow placement machine, FPM2

These machines use a prepreg tow material form that is projected to be approximately 20% lower in cost than prepreg tape. The tow-placed product is also comparable in performance to hand layup prepreg tape parts (Figure 2).

Hercules tow placement technology has continued to mature and improve during the past year. Various improvements have been made to the second generation machine (FPM2). Improvements have been made in our fiber placement delivery heads, machine control systems, and off-line programming. The fourth generation band cut/add (BCA)



a. Compression after impact tests

- Damage tolerant IM7/8551-7A towpreg demonstrated
- Fiber placement process CAI results demonstrate equal quality to prepreg layup process
- Concave surface, variable skin thickness, tapered cross section and thin ply laminates now possible with automated process

Figure 2. Compression-after-impact test data

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fiber placement delivery head was built; this head incorporates the successful features of the past heads plus some new innovative features to make it more production worthy. The key features of the fourth generation BCA head are the 32-tow, 4-1/4-in. bandwidth capability, the easy to remove components for quick servicing, and the synchronization of fiber lay down and band adding. The first Cure-On-The-Fly™ delivery head was also built. The Cure-On-The-Fly™ head is used in an on-line process for delivering thermoset prepreg tow requiring only a bagless oven cure, avoiding an autoclave cure cycle. In addition, the efficiency by which fiber path data are paged and manipulated was improved to decrease the computer time needed to generate control tables for the fiber placement machine. Also, the off-line programming computer is being upgraded. The IBM RS6000 Model 550 computer has been selected to replace the Apollo DN580.

HERCULES NASA ACT PROGRAM

In early 1990, the Hercules ACT Program was redirected from an isogrid stiffened fuselage structure to a more conventionally stiffened fuselage with hat section and blade stringers. The redirection process took several months to complete, but work was resumed in January 1991. The revised Hercules program was set up as a cooperative program between Hercules and the Boeing ATCAS Program. Hercules will fabricate test panels that are representative in design of crown, keel, and side quadrants of a Boeing Commercial transport aircraft. All panels will be fabricated using the automated tow placement process. In addition to providing designs, Boeing will test all panels fabricated for the Hercules ACT Program (Table 1).

Tow placement of the flat crown panels was completed in July and August 1991. Two 60-in. × 150-in. flat unstiffened 15-ply panels were tow placed and cured in July 1991 (Figure 3). These panels were delivered to Boeing and will be tested for uniaxial damage tolerance. One of the panels was a hybrid of fiberglass/ graphite and the other was an all

Fuselage Quadrant	Test Article	Undamaged Elements	Tension With Damage	Shear With Damage	Comp. With Damage	Bi-Tension With Damage	Comp/ Shear With Damage
Crown	Flat, unstiffened skin panels, 60 in. × 150 in.		2				
Crown	Flat, stiffened panels, 63 in. × 150 in.		1				
Crown	Curved, stiffened panels, 65 in. × 72 in.					1	
Keel	Flat, coupons, 5 in. × 7 in.				24		
Keel	Flat, stiffened panels, 30 in. × 44 in.				6		
Keel	Curved, stiffened panels, 30 in. × 44 in.						
Window belt	Tension coupons with thick taper, 12 in. × 12 in.	3	3				
Window belt	Curved panel with taper and cutout, 40 in. × 40 in.		1				
Window belt	Panel with double window frame 40 in. × 40 in.			1			

Table 1. Test matrix for Boeing/Hercules ACT Program integration

graphite panel. The hybrid panel consisted of 25% S2 glass and 75% AS4 fiber. Both the glass and graphite tows were impregnated with Fiberite 938 resin. The all graphite panel was tow placed with AS4 fiber impregnated with Fiberite 938 resin. The panels were cured using a 350°F and 100 psi cure cycle with a hold at 225°F. Bleeder release plies were applied to both sides of the panels to help allow volatiles to escape. Glass rovings were attached along the edge of the panels to also help the volatiles escape. Teflon film was placed over the panels that prevented resin from bleeding out, but still allowed air to escape through the glass rovings. A caul plate was placed over the panels and they were bagged and cured. Both panels looked good. Neither panel had a problem with trapped volatiles.

Tow placement of a 63-in. × 150-in. flat stiffened panel was also completed in July 1991 (Figure 4). The panel has five 16-ply hat stringers co-cured to the 15-ply skin. Both the panel skin and hat stringers are a hybrid material form consisting of 25% S2 glass and 75% AS4 graphite. The glass and graphite tows were impregnated with Fiberite 938 epoxy resin. The hat stringers for this panel are fabricated from a 16-ply panel that was tow placed on a large flat mandrel. The hat stringers will be kitted from this panel and hot drape formed in a machined aluminum forming tool. The cure process for this stiffened panel will use the inside mold line (IML) flex caul that has been used successfully at Hercules on other stiffened panels. The molded four-ply flex caul will be made from a machined REN 550 master model. The hat stringer cure mandrels will be machined metal tools. At the time of this paper, this panel had not been cured, but the skin panel and stringer panel had been bagged and stored in the freezer. We are waiting for delivery of the flex caul model and stringer forming tool.

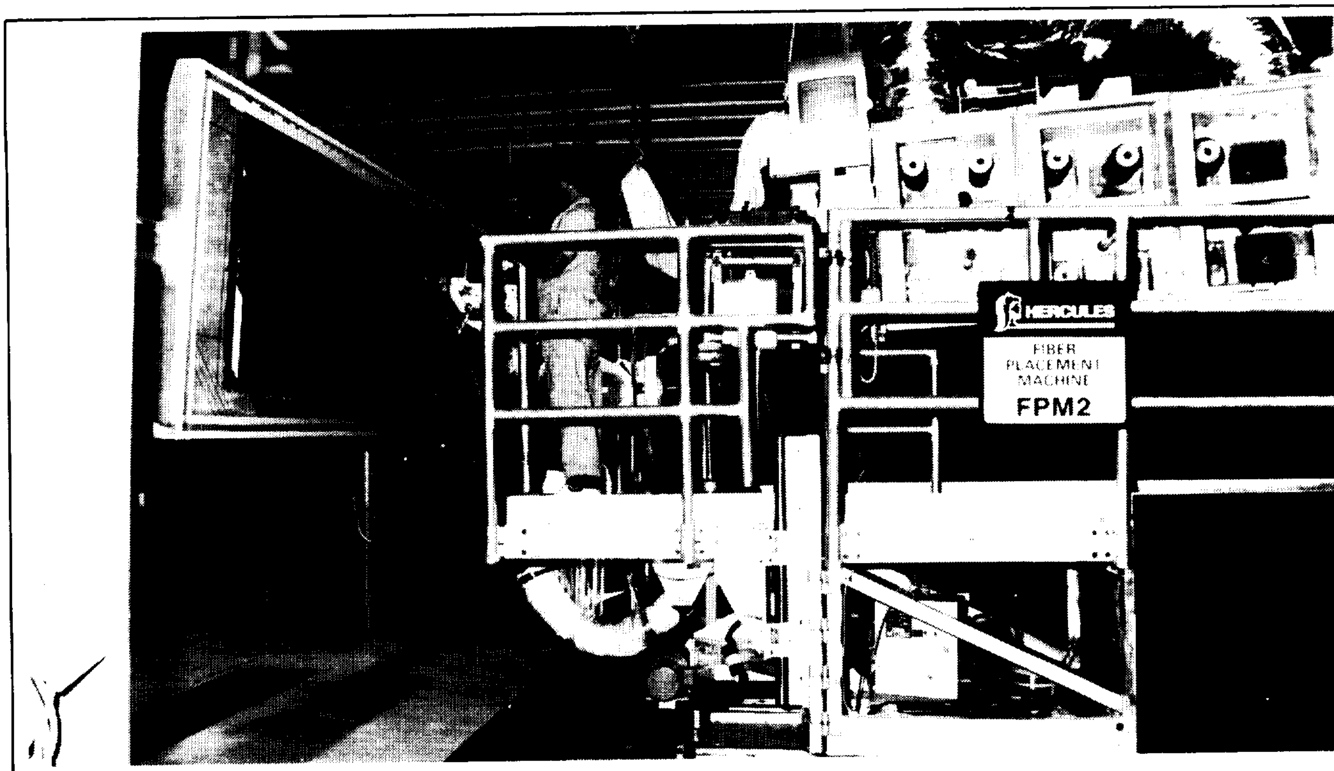

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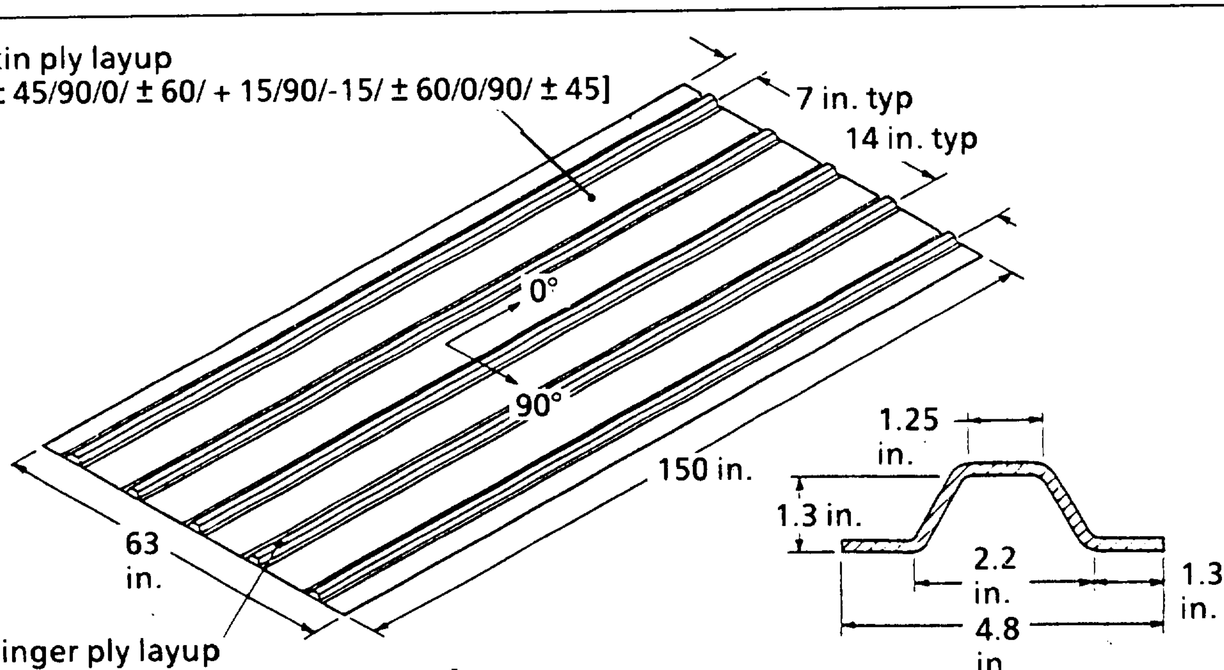
Figure 3. Hercules NASA ACT Program flat unstiffened panel



Material: 25% S2 glass/75% AS4/938

Repeat unit: 2 tows S2 glass
6 tows AS4

Figure 4. Hercules NASA ACT Program flat stiffened panel

The last item of the Hercules program representative of the fuselage crown section is a 65-in. × 72-in. curved panel with hat stringers. This panel will also have three J frames. The tow-placed skin and stringers will be co-cured and the RTM frames will be co-bonded. This panel will be fabricated in October 1991.

Fabrication of the fuselage keel and window belt structural test panels will be completed in 1992 and 1993.

HERCULES NASA ACT SUBCONTRACTS

Hercules advanced tow placement was selected for evaluation on other NASA ACT contracts. We currently have subcontracts from the Douglas ICAPS Program and Boeing ATCAS Program (Table 2). The Boeing ATCAS subcontracts are ongoing and include both tow placement of test panels and fabrication of tooling. The Douglas ICAPS subcontract was recently completed and we look forward to working with Douglas in Phase B if they continue their evaluation of tow placement.

Boeing ATCAS	Unstiffened flat panels (5 each) Stiffened flat panels (1 each) 3-ft × 5-ft curved stiffened panels (2 each) Tear strap panels (4 each) 7-ft × 10-ft curved stiffened panels (2 each) 10-ft × 12-in. oval mandrel 8-ft × 12-ft Invar cure mold
Douglas ICAPS	Stiffened skin panels

Table 2. Hercules ACT subcontracts

BOEING ATCAS SUBCONTRACTS

Several Boeing ATCAS subcontracts are ongoing at this time and two have recently been completed. The following paragraphs describe all Boeing ATCAS subcontracts to Hercules during 1991.

<u>Flat Unstiffened Panels</u> Five flat unstiffened coupon panels were tow placed in July 1991 under subcontract from the Boeing ATCAS program. Four of the panels were 40 in. × 132 in. and one panel was 60 in. × 150 in. The four 40-in. × 132-in. panels were for biaxial tension testing and the 60-in. × 150-in. panel was for hoop damage tolerance testing. Two of the biaxial tension panels were tow placed with a hybrid of S2 glass/938 resin and AS4-6K/938 resin. The other two biaxial panels were all graphite using AS4-6K/938 resin. One of the hybrid panels had hybrid material only in the 0°plies of the laminate. The 60-in. × 150-in. hoop damage tolerance panel was an all graphite AS4/938 panel. These panels were delivered to Boeing and test data are included in the Boeing ATCAS conference paper.

<u>Flat Stiffened Panel</u> A flat stiffened panel was tow placed in July 1991 under subcontract from the Boeing ATCAS Program. This panel is 63 in. × 150 in. and is stiffened by five hat stringers. The hat stringers are kitted from a large tow-placed panel and then hot drape formed. The skin and stringers will be co-cured using the Hercules IML flex caul and machined metal stringer cure mandrels. At the time of this paper, both the stringer panel and skin panel had been tow placed and stored in the freezer. We are waiting for delivery of tooling items required for cure.

<u>3-Ft × 5-FT Curved Stiffened Panel</u> Two 3-ft × 5-ft curved stiffened panels are being fabricated under subcontract from the Boeing ATCAS Program. Both panels have a radius

of 122 in. and are stiffened with three co-cured hat stringers and three co-bonded J frames. One of the panels is a hybrid of S2 glass/938 resin and AS4/938 resin. The other panel is an all graphite panel made with AS4/938. Both skin and stringers are made with tow-placed material. The skins were tow placed on a large 10-ft × 12-ft oval mandrel with a radius of 122 in. The stringer panel was tow placed on a large flat mandrel. Both panels will be cured on an 8-ft × 12-ft Invar outside mold line (OML) cure mold. The IML side tooling was designed by Boeing and enables the co-cure of skin/stringers and co-bond of the precured frames all in one autoclave cycle. At the time of this paper, the hybrid skin and stringer panels were tow placed and stored in the freezer awaiting delivery of the Invar cure mold. The all graphite panel was scheduled for tow placement in September 1991.

Tear Strap Panels We are expecting a subcontract in September for four tear strap panels. Three of the panels will be flat 30-in. × 100-in. panels. Two of these panels will have precured tear straps co-bonded to the skin with a layer of film adhesive. The other flat panel will use no film adhesive between tear straps and skin. The fourth tear strap panel will be a 65-in. × 72-in. curved skin tow placed on the 122-in. radius mandrel and cured in the Invar cure mold. It will have precured tear straps co-bonded to the skin with a layer of film adhesive. The subcontract for these panels will be finished before the November ACT conference.

7-Ft × 10-Ft Curved Stiffened Panel A subcontract for two 7-ft × 10-ft curved stiffened panels is expected in October. At the time of this paper, final design of these panels had not been defined. They will be scaled up from the 3-ft × 5-ft panel discussed in this paper. The tool approach will be the same as that used for the 3-ft × 5-ft. panels. An RFQ has not been received at this time, but is expected in September. Fabrication of these panels will be in October and November 1991.

10-Ft × 12-Ft Oval Mandrel A large 10-ft. × 12-ft tow placement mandrel (Figure 5) was fabricated in June 1991 under subcontract from the Boeing ATCAS Program. This mandrel has two sides in an oval configuration and each side has a radius of 122 in.The mandrel was made by rolling two aluminum plates to the 122-in. radius and welding the plates to an aluminum support structure. The mandrel shaft is a machined thick wall aluminum tube that was also welded to the support structure. This tool will be used for tow placement of the ATCAS 3-ft. × 5-ft panels and 7-ft × 10-in. panels.

8-Ft × 12-Ft Invar Cure Mold An 8-ft × 12-ft Invar cure mold (Figure 6) was fabricated in July and August 1991 under subcontract from the Boeing ATCAS Program. This concave cure mold has a 122-in. radius cure surface. The tool was fabricated by rolling a 0.750-in. thick plate of Invar 36 steel to the required 122-in. radius. Invar ribs (0.250-in. thick) were cut to size with a water jet and welded to the rolled plate. After welding the support structure, the tool was stress relieved and set up in a large three-axis machine for final machining of the 122-in. radius tool surface. Invar was selected for this tool because of coefficient of thermal expansion (CTE) concerns. Invar is a low CTE material. Because we are using this tool to co-bond a cured frame to an uncured skin, we did not want our cure tool to grow much at 350°F as this would cause a poor quality bond between the frame and skin. If co-bonding of the frames had not been a requirement, we would have selected a lower cost material such as aluminum for the cure mold.

DOUGLAS ICAPS SUBCONTRACT

The Hercules subcontract from the Douglas ICAPS program was recently completed. The objective of this contract was the fabrication of tow-placed panels that would be compared with identical panels made with the RTM process at Douglas. The automated tow placement (ATP) panels and RTM panels will be compared for structural performance and cost effectiveness.

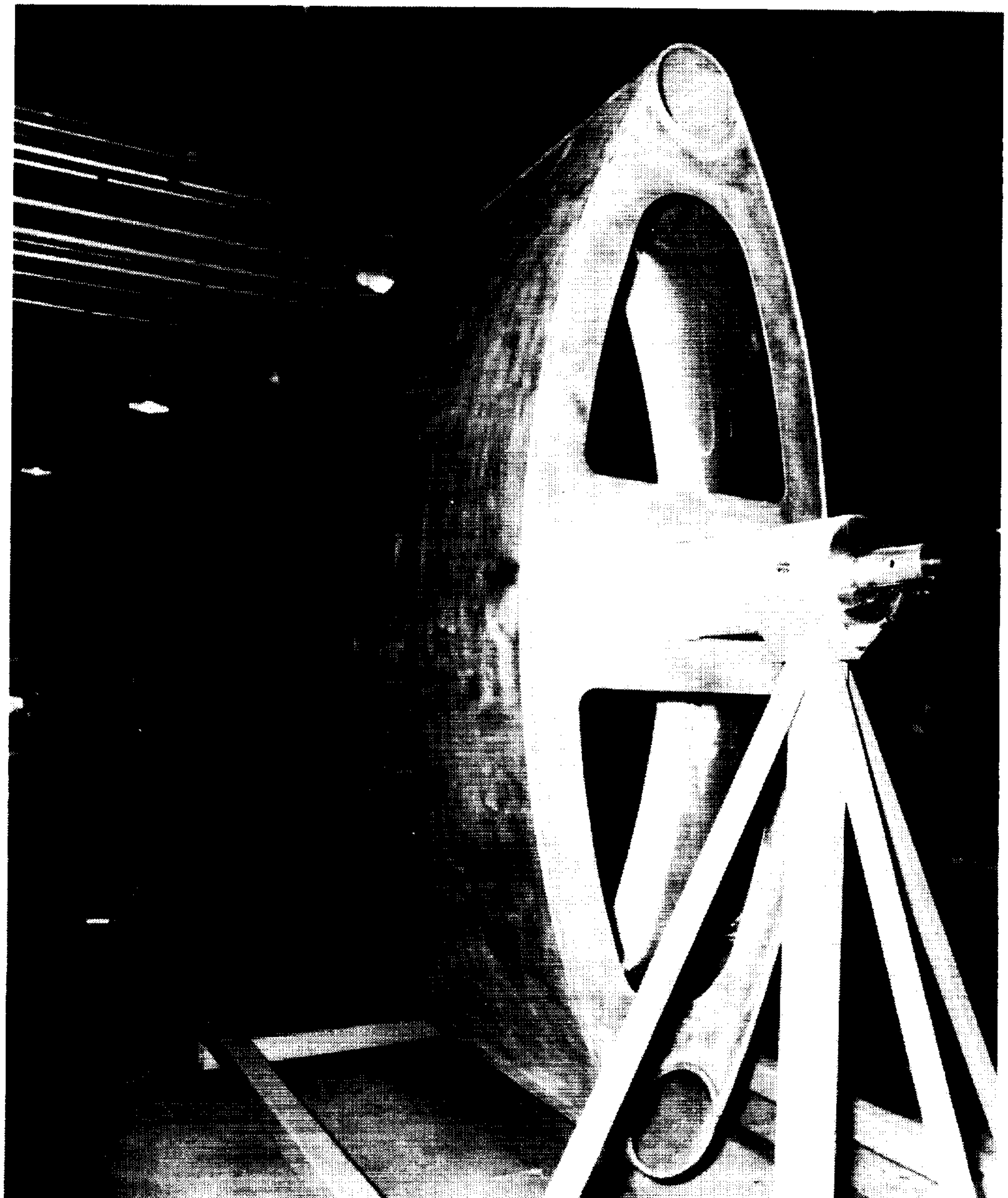


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Figure 5. Boeing ATCAS tow placement mandrel

The tooling concept for the ICAPS tow-placed panels was somewhat different than anything previously used at Hercules. Our objective was a low cost, low risk tool concept to achieve a skin to stringer co-cure. Surface smoothness was also a consideration in our tool concept selection. The stiffened test panels simulated aircraft fuselage skin so we wanted the outside mold line (OML) surface to be as smooth as possible. Some other objectives we wanted to achieve with our tool concept were a uniform skin thickness, close tolerance in spacing of the stringers, and net shape of the stringer achieved during the panel cure process. To accomplish these objectives, we used a low cost aluminum mandrel (Figure 7) to tow place the panel skin and transferred the skins to an aluminum OML mold for cure. The OML cure mold achieved the skin smoothness we wanted. The stringer spacing tolerance, uniform skin thickness, and net shape stringers were accomplished by using a molded caul sheet on the IML side of the panel during cure.

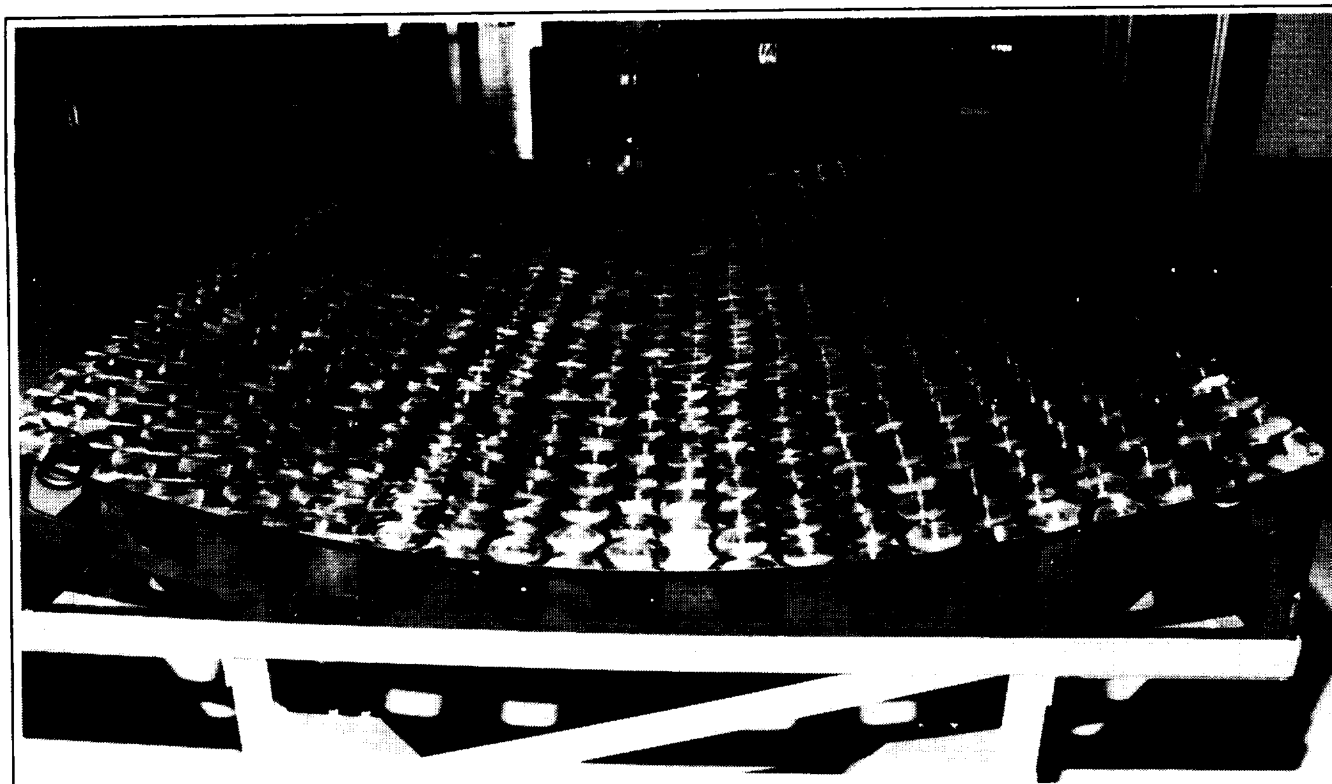

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Figure 6. Boeing ATCAS Invar Cure Mold

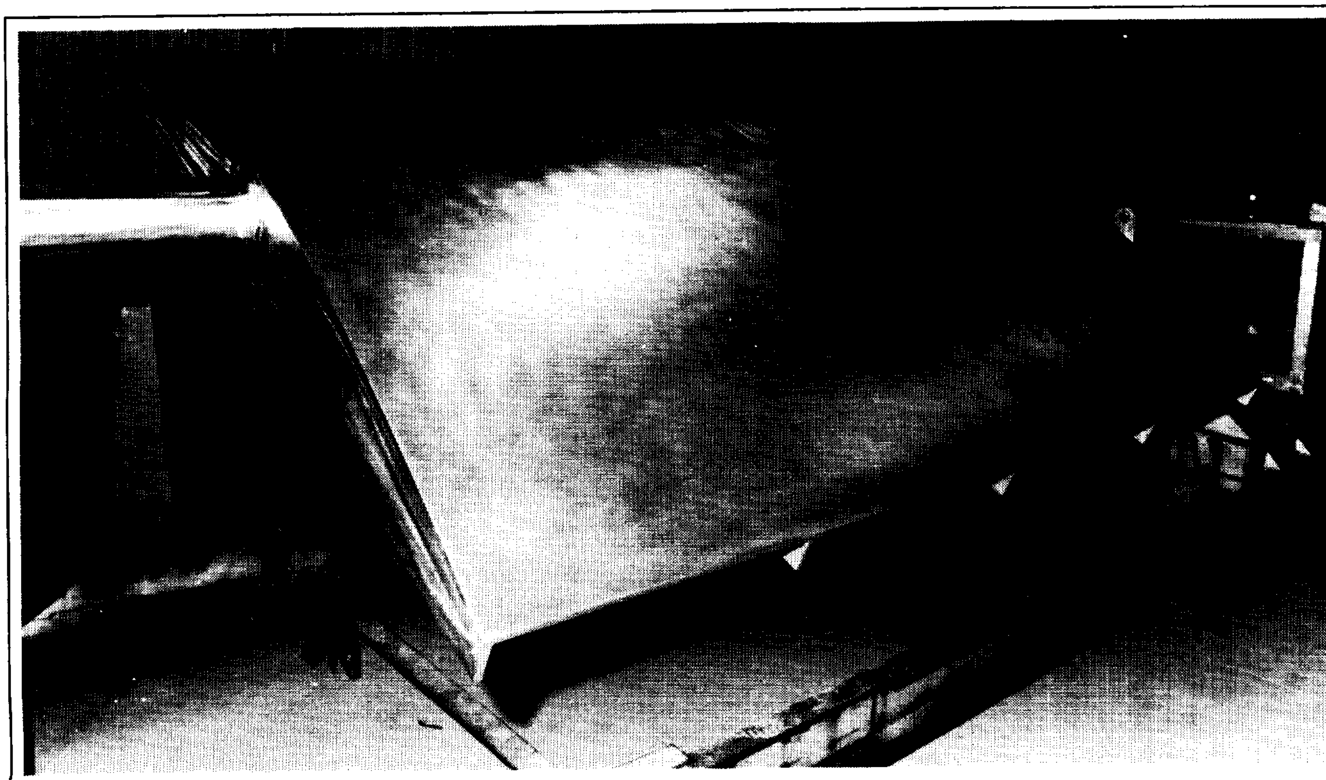

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Figure 7. Douglas ICAPS subcomponent panel tow placement mandrel

We used this tool concept on the flat element panels and the 118-in. radius subcomponent panels. The element panels were 21 in. × 36 in. and were stiffened with three J-stringers. The subcomponent panels were 48 in. × 60 in. and were stiffened with six J-stringers. The subcomponent panels also had three shear tee doublers that ran perpendicular to and under the stringers. The shear tee doublers were also co-cured to the panel skin.

The tooling concept was very successful for both the flat element panels and the large 118-in. radius subcomponent panels. The tooling was simple and easy to use and produced excellent quality panels.

The most innovative feature of our tool concept was the use of a four-ply molded flex caul on the IML side of the panel. The flex caul was laid up on a master model machined from monolithic graphite (Figure 8). Detail was machined into the model for stringer cavities and shear tee doublers. The flex caul was laid up on the model using tooling prepreg.

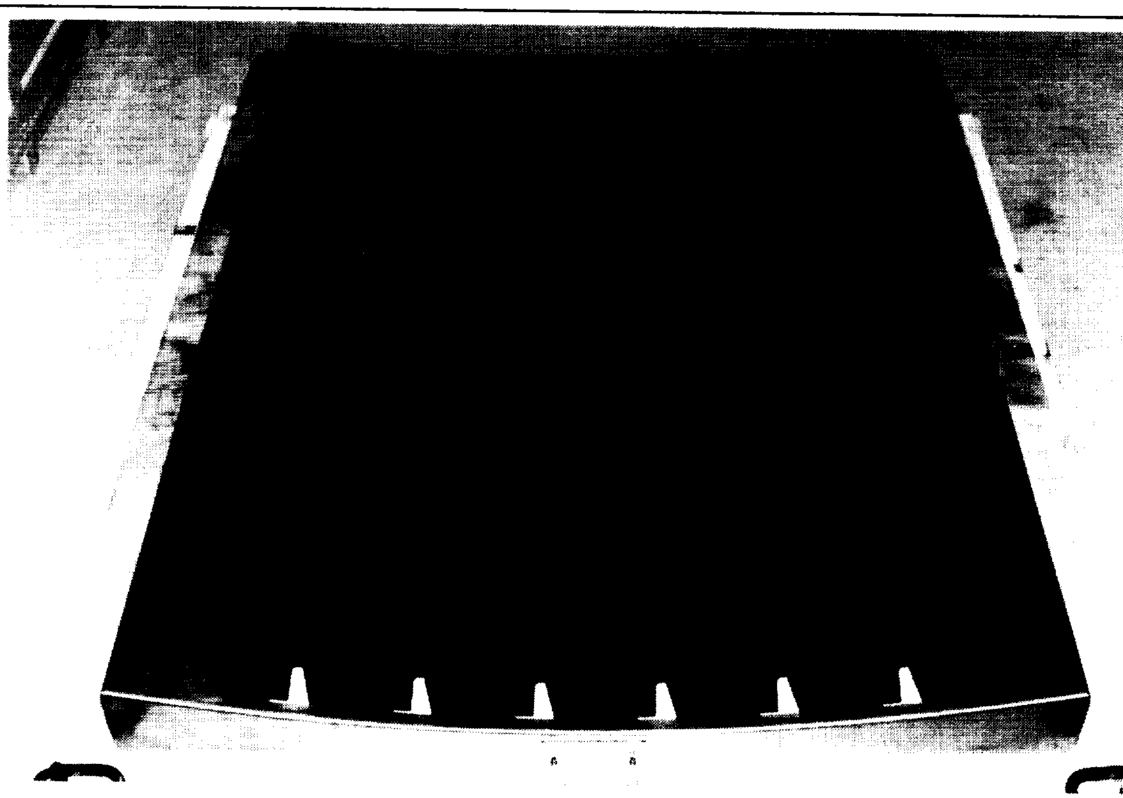

Figure 8. Douglas ICAPS subcomponent panel monolithic graphite flex caul mode

The close tolerance stringer spacing achieved on both the flat element panels (Figure 9) and the 118-in. radius subcomponent panels can be attributed to use of the molded IML caul. The flex caul also produced excellent quality stringers that were near net dimension after cure tool removal and required very little deburring or trimming.

The fabrication process used for the tow-placed ICAPS panels was simple, easy to duplicate, and proved to be very low risk. The 12-ply skin panels were tow placed on an aluminum mandrel and transferred to the OML cure mold. The panel skin was then aligned to reference marks on the OML mold. The shear tee doublers were located to the skin IML, again by aligning to marks on the tool. The hand laid up J-stringers were fitted with a machined metal stringer cure mandrel (Figure 10) and the stringer/cure mandrel assembly

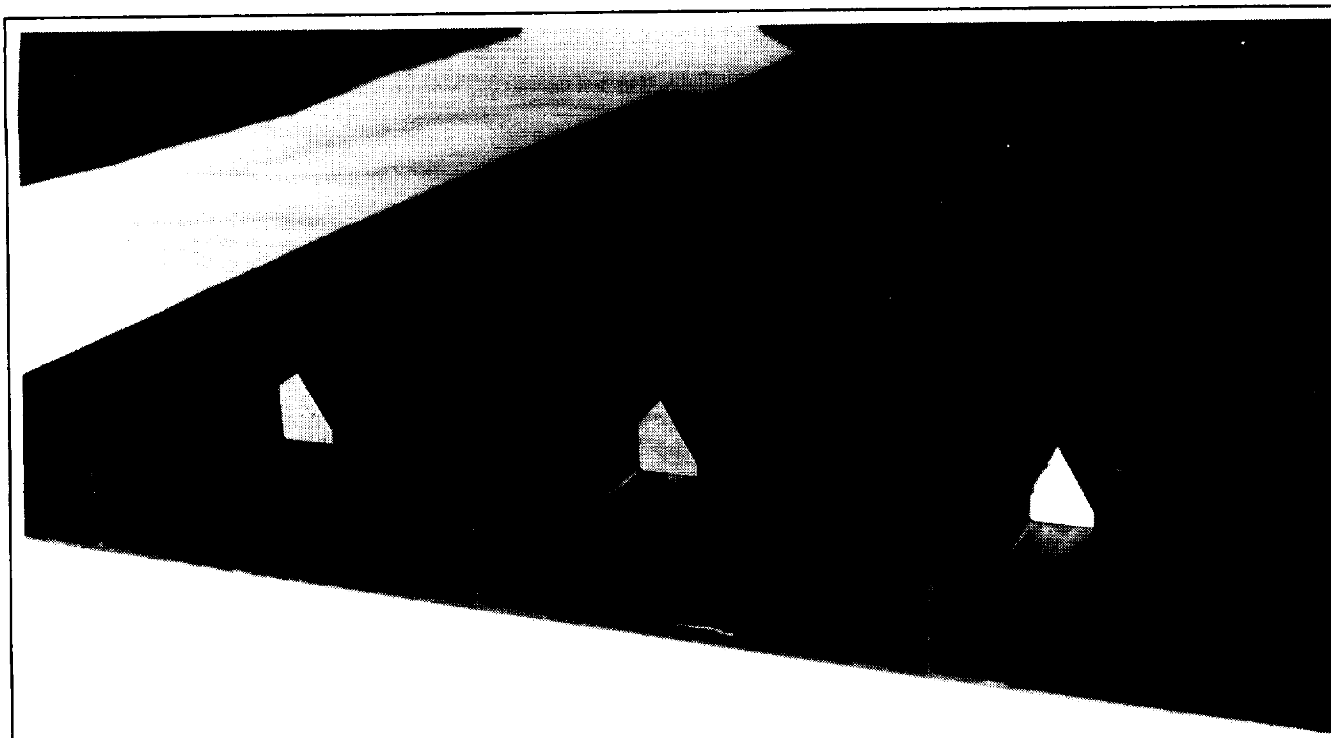

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Figure 9. Douglas ICAPS element panels flex caul

was positioned to the IML of the panel skin. Stringers were positioned using alignment marks on the tool. The molded graphite flex caul was then located over the skin/stringer assembly and pressed down to the skin IML. Pressing the flex caul down corrects any error in stringer position. The completed assembly was vacuum bagged and cured in the autoclave.

As the autoclave temperature increases and resin viscosity decreases, the autoclave pressure on the flex caul holds the stringers in proper position with a very close spacing dimensional tolerance.

After cure, the assembly was debagged and the tooling pieces were removed. The flex caul came off the panel with no problems. The stringer cure mandrels were removed by using T handles that screw into the sides of the cure mandrels. Removal of the stringer tools was not a problem. The panel was deburred and trimmed to net dimension (Figure 11).

Dimensional and ultrasonic inspections were performed on each panel. No problem areas were discovered during NDI and overall quality of the panels was excellent.

The process used in fabrication of these panels was unique in its simplicity and successfully accomplished all objectives of this program. The process takes advantage of the low cost potential of the automated tow placement process and combines it with a low risk assembly and cure process. We believe our process can be easily adapted to larger fuselage panels and see very few problems in this scale up.

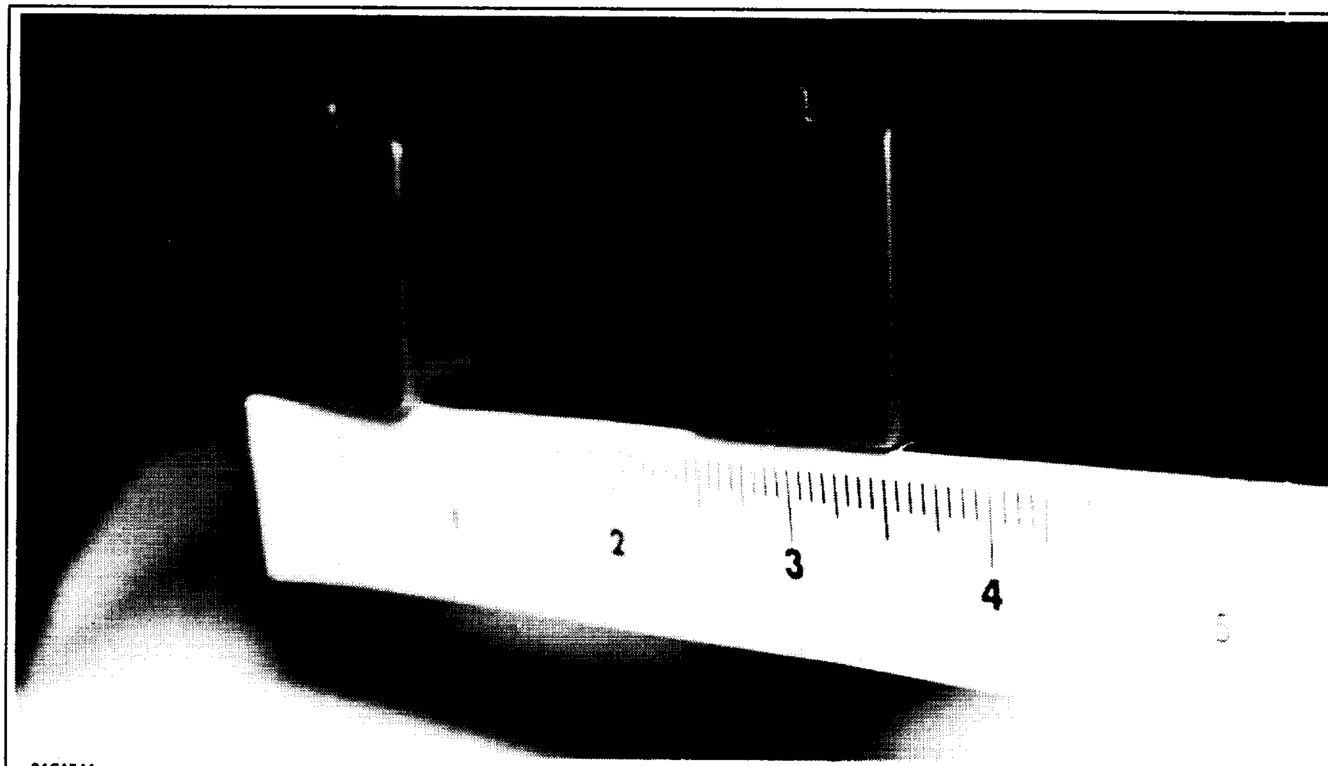

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Figure 10. Douglas ICAPS subcomponent panel stringer cure mandrel

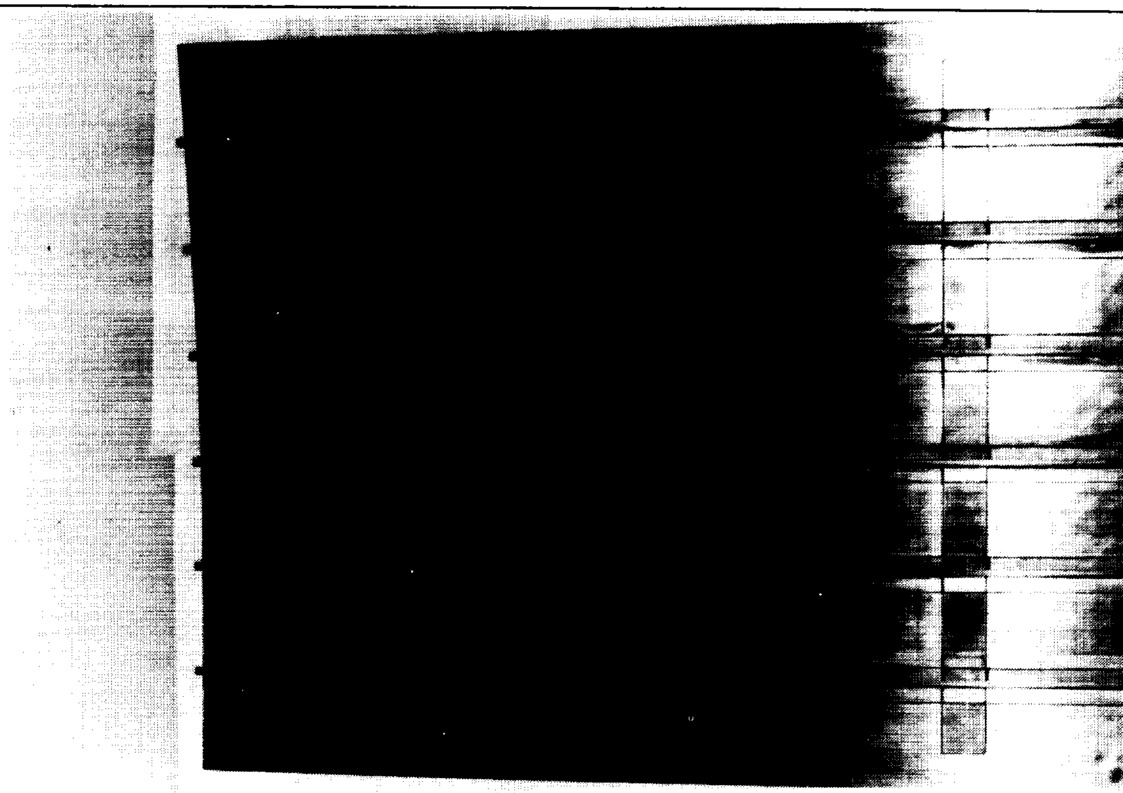

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Figure 11. Douglas ICAPS subcomponent panel