# Large Scale Composite Manufacturing for Heavy Lift Launch Vehicles

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## ABSTRACT

Risk reduction for the large scale composite manufacturing is an important goal to produce light weight components for heavy lift launch vehicles. NASA and an industry team successfully employed a building block approach using low-cost Automated Tape Layup (ATL) of autoclave and Out-of –Autoclave (OoA) prepregs. Several large, curved sandwich panels were fabricated at HITCO Carbon Composites. The aluminum honeycomb core sandwich panels are segments of a 1/16th arc from a 10m cylindrical barrel. Lessons learned highlight the manufacturing challenges required to produce light weight composite structures such as fairings for heavy lift launch vehicles.

## 1. INTRODUCTION

Automation for composites have demonstrated significant potential to enable production of large aircraft and launch vehicles. Automated composite manufacturing is attractive because of the reduced operating costs they offer through increased production rates enabled by reliable and repeatable fabrication processes. The initial investment in the machine may be expensive, but when long term producibility as well as reliability comes into play, the benefits largely outweigh the financial upfront impacts. In an effort to provide a comparison of automated fabrication methods, a study was conceived wherein a comparison of industry leading autoclave and Out-of-Autoclave (OoA) composites were fabricated using state of the art automated processes.

Evaluation of processing and mechanical properties needed to be established to show the differences between Cytec's IM7/977-3 (autoclave prepreg) & T40-800Bb/5320-1 (out-of-autoclave prepreg) unidirectional tape material. Autoclaves are required to cure standard aerospace composites due to the need for ply compaction at high pressures (275790 -551580 Newton / meter^2) while OoA material systems are cured using moderate temperature, vacuum (711.2 mmHg at Sea Level), and ambient pressure. The objective for this program was to compare two composite materials. This evaluation examined material and machine interaction and their efficiencies through destructive and non destructive evaluations. The advantage of the IM7/977-3 is that it is an industry proven material and selected for use on many flight platforms. One advantage for OoA materials such as T40-800B/5320-1 is the lower processing costs associated with OoA materials. Another advantage is the use of lower cost tooling and as shown recently in efforts through DARPA, lower cured composite residual stresses. These efforts can be seen in technical papers written by Gail Hahn and Gary Bond of The Boeing Company referenced below. These advantages are weighed against their disadvantages. Today, the third generation OoA prepregs typically have a 14-21 day shoplife. Whereas, autoclave systems have 30-45 day shoplife. Shoplife is defined as the time prepreg can be processed into low-void composites without a degradation in material properties and performance. Therefore, the use of Automated Tape Laying (ATL) is proposed to shorten the time period composite parts are manufactured and within the shoplife of the prepreg, especially for these third generation OoA prepregs with shortened shoplife.

Current material developments have shown that the third generation OoA curing composites such as 5320-1 have mechanical properties nearly equivalent to those of state of the art autoclave cured composites when fabricated within their shoplife limits, as seen in *Non-Autoclave (Prepreg) Manufacturing Technology for Primary Aerospace Structures* by Gail Hahn and Gary Bond. OoA composites are becoming more attractive to aerospace designers as they look to apply these materials on production vehicles rather than just prototypes as structural properties will not have to be sacrificed and they can utilize the cost benefits gained from OoA composite manufacturing.

The purpose of this manufacturing technology program is to develop the fundamental processing parameters for the ATL manufacturing of autoclave and OoA composite materials for aerospace structural applications. Figure 1 is an image of the MAG-IAS Low Rail Charger utilized in our tape placement process.

**Figure 1. MAG-IAS Low Rail Charger Tape Placement Head**

HITCO utilized its extensive knowledge of automation experience of MAG-IAS in conjunction with Cytec Engineering Materials to assist in the process trails and fabrication of each NASA test article. The machine on which these efforts were conducted is the MAG-IAS Charger. Process trials were conducted at HITCO's Gardena, California facility. HITCO is a unique facility in that they have substantial experience with automation and have facilities large enough to cure large composite structures. NASA performed surveys of several US facilities and HITCO was unique in having the combination of substantial automation and cure facilities that are >4.57m wide to cure these parts.

The MAG-IAS Charger is equipped with 7 axis of motion and is primarily suited for flat and mild contoured structures with varied laminate thickness, contour, and build up areas. Products can be laid up to near net configurations with the application of ATL head pressures which results in a significantly reduced material waste percentage (as low as 5%). The MAG Charger tape laying systems automatically and independently control a 15.24 centimeters band of composite prepreg material. Inherent to automated fabrication methods are the sensitivity to manufacturing flaws. Gaps and overlaps are minimized as the machine precisely lays interior or exterior contoured boundaries. One of the main attributes of the MAG Charger is the unique tape placement delivery head. The Charger supports superior compaction on core and tight radii contour surface features by having adjustable head pressure which can accommodate light weight core. These features are critical to the successful performance of NASA Space Launch Systems (SLS) barrel sections since they contain light-weight aluminum cores that would normally not withstand ATL head pressures. However, the MAG Charger has adjustable head pressures enabling the application of ATL tape on top of NASA aluminum sandwich core materials.

## 2. BACKGROUND/PROBLEM STATEMENT

The NASA Advanced Composite Technology (ACT) Project was tasked by NASA's Exploration Technology Demonstration Program (ETDP) to demonstrate and mature composite structural concepts to technology readiness level (TRL) 6. TRL 6 is defined as the performance demonstration of a system, subsystem, or prototype in a relevant environment. As part of this development process, the ACT team has fabricated a series of flat and curved panels using both autoclave and out-of-autoclave materials. The primary objective of this effort is to understand and document manufacturing scale-up issues and automated processes used for large panel fabrication represenatative of the barrel section of a large scale (10 meter diameter) fairing. This knowledge will provide the Exploration Technology Demonstration Program a basis of work for future large-scale composite fabrication efforts.

Autoclave cured composites are the predominate method for producing large scale aircraft and launch vehicle components due to the ability to achieve high ply compaction at high pressure (413,685 - 689,475 Newton / meter^2). Compaction and pressure allows for predictable material properties to be obtained from the materials. The addition of compaction and pressure allows for the predictability of the material properties to be obtained from the material on a repeatable basis. Candidates for large structure fabrication include NASA Launch Vehicles which has up to a 10 meter diameter stage sections. Current launch vehicle composite components are at a maximum of 5.48 meters in diameter.

Large scale automated processing of autoclave/OoA materials are the future for large structure fabrication due to the fabrication processes which are gained when utilizing these material systems along with tape placement. With advancements in automation and aerospace grade materials, the aerospace industry is beginning to “break new ground” in what is possible for large structure processing. Manufacturing costs associated with non-recurring and recurring costs of hand lay fabrication are avoided resulting in quality laminates at reduced cost. In addition to materials, automated technology is also leading the future of large structure fabrication. Traditionally, aerospace quality laminates were limited in size due to material out life and complexity. Due to this, many designs are scrapped and/or redesigned to be built in multiple sections in order to be cured in more nominally sized autoclaves. This project utilized Cytec's IM7/977-3 & T40-800Bb/5320-1 unidirectional tape material to achieve these tasks.

## 3. OBJECTIVE

The objective of this program was to develop processing parameters and protocols for automated tape laying (ATL) for autoclave and OoA composite materials for launch vehicle applications. Objectives were divided into separate panel fabrications. HITCO was to fabricate panels in accordance with the NASA provided drawings and the guidelines established in the approved Manufacturing Plans. This effort was intended to demonstrate and then mature the manufacturing techniques required to fabricate very large composite flight hardware and as such HITCO fabricated all panels using an Automated Tape Laying (ATL) machine and 15.24 centimeters wide pre-preg tape. The panels that were fabricated are listed below.

- **8000CMDP Panel, Curved 1/16th Segment, Autoclave, Sandwich**
  8 Ply IM7/977-3 Face Sheets and 2.54 centimeters Al core, $[45,90,-45,0]_s$ Layup

- **MTP-6001 Panel, Curved 1/16th Segment, Autoclave, Sandwich**
  6 Ply IM7/977-3 Face Sheets and 4.13 centimeters Al core, $[60,-60,0]_s$ Layup

- **MTP-6003 Panel, Curved 1/16th Segment, Autoclave, Sandwich**
  6 Ply IM7/977-3 Face Sheets and 2.86 centimeters Al core, $[60,-60,0]_s$ Layup

- **8010CMDP Panel, Curved 1/16th Segment, Out-of-Autoclave, Sandwich**
  8 Ply T40-800B/5320-1 Face Sheets and 2.54 centimeters Al core, $[45,90,-45,0]_s$ Layup

- **MTP-6010 Panel, Curved 1/16th Segment, Out-of-Autoclave, Sandwich**
  6 Ply T40-800B/5320-1 Face Sheets and 2.86 centimeters Al core, $[60,-60,0]_s$ Layup

- **MTP-6000 Panel, Curved 1/16th Segment, Autoclave, Sandwich**
  6 Ply IM7/977-3 Face Sheets and 2.86 centimeters Al core, $[60,-60,0]_s$ Layup

## 4. PROJECT TRAINING

HITCO began by fabricating pathfinder scaled replicas of the full size panel. These pathfinders, shown in Figure 2 consisted of the full scale ply stack with 60.96 centimeters width, and 60.96 centimeters length segments. The goal was to identify potential problems and manufacturing issues that may occur during the full scale part fabrication with a view towards establishing more mature work instructions for the 1/16 arc-segment test panels. Several risk-mitigating processes were developed after identifying several potential issues. These concerns included application and material handling of core splice, core application and crushing, and ply stacking.

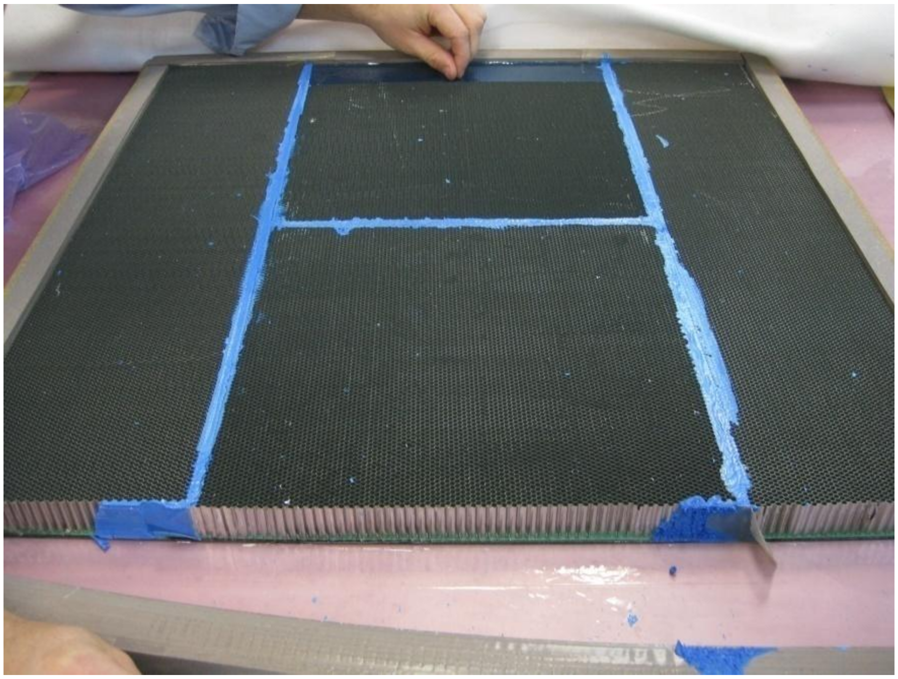


**Figure 2. Pathfinder Development**

Demonstration or pathfinder panels were fabricated with the supervision of NASA engineering personnel. Once these panels were complete, the fabricated specimens were sent to NASA for further testing and validation regarding laminate quality. HITCO's next step consisted of a step by step process commencing with the ATL of flat witness panels to focus on material and machine process parameters such as overlap and gap control, material orientation control, and ply placement. Once the range of fundamental machine operating parameters were established, the complexity of tape placement increased from flat to a curved laminate.

ATL is a well established production process that has been adopted by numerous military and commercial programs. It links the engineering model to automated fabrication, improves fiber orientation, repeatability on large complex geometries, reduced touch labor, and reduced scrap. Legacy military and commercial programs have seen benefits from tape placement using epoxy resin based materials. HITCO's machine: the MAG-IAS Charger utilizing 15.24 centimeters tape was the manufacturing system used for both autoclave and OoA prepregs as shown in Figure 3.

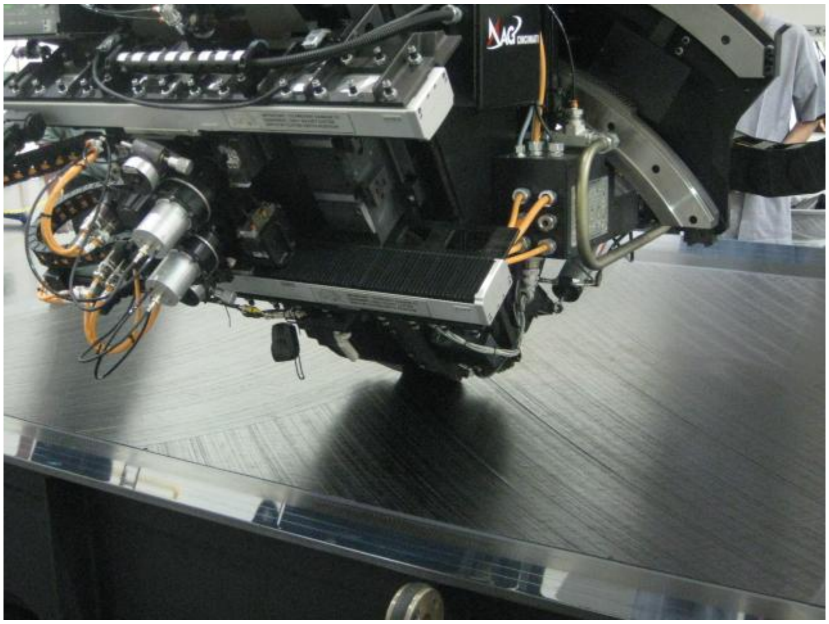
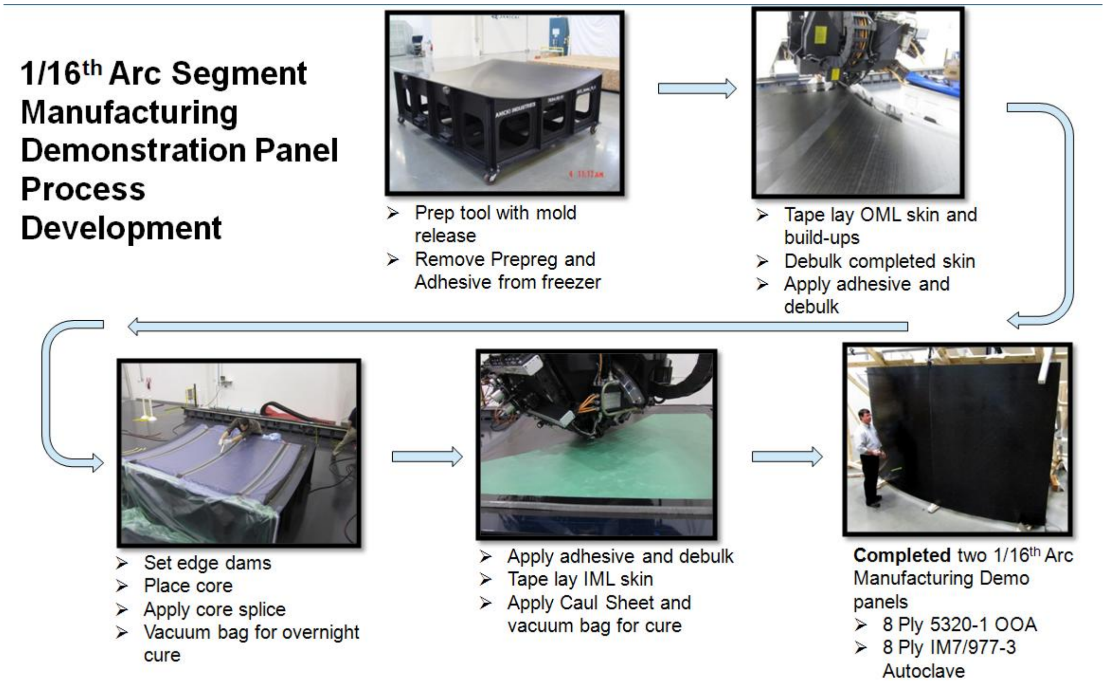


**Figure 3. ATL Head Placing Material**

The fabrication process of the six 1/16th Arc Segment panels began once the pathfinder panels were complete. The 1/16th arc segment manufacturing demonstration panel process development can be seen in Figure 4. It represents the fabrication process of the 1/16th arc segment panel for all six panels.



**1/16th Arc Segment Manufacturing Demonstration Panel Process Development**

- Prep tool with mold release
- Remove Prepreg and Adhesive from freezer

- Tape lay OML skin and build-ups
- Debulk completed skin
- Apply adhesive and debulk

- Set edge dams
- Place core
- Apply core splice
- Vacuum bag for overnight cure

- Apply adhesive and debulk
- Tape lay IML skin
- Apply Caul Sheet and vacuum bag for cure

**Completed** two 1/16th Arc Manufacturing Demo panels

- 8 Ply 5320-1 OOA
- 8 Ply IM7/977-3 Autoclave

**Figure 4. Manufacturing Demonstration Process**

# 5. PART MANUFACTURING

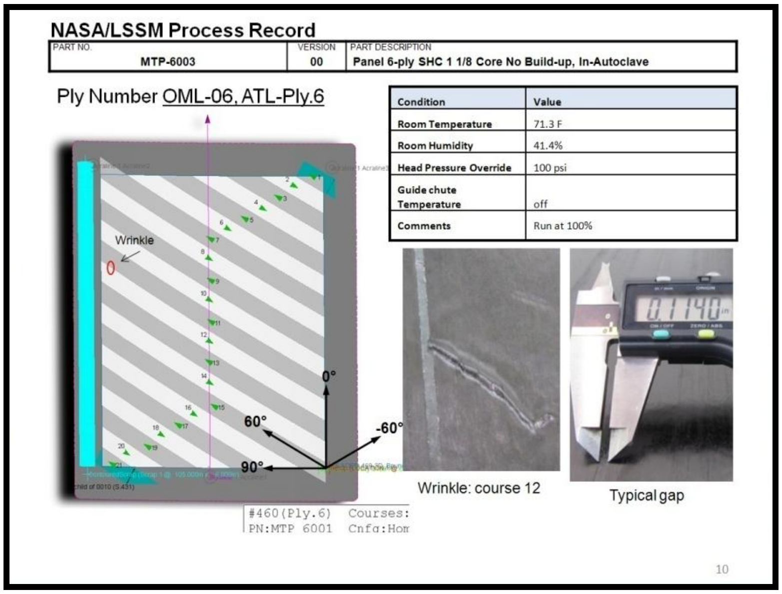
The general preparation stage for all panels was generally consistent. The materials were drawn from the freezer to allow adequate thaw time prior to tape laying. The tool was prepared by removing and dirt and debris with an acetone wipe. This was repeated until all debris was removed from the tool surface. The tool was then sealed using Chemlease™ composite tool sealer. After the application of the composite sealer, a release agent, 700-NC Frekote was applied to the tool. This process was repeated for each panel build. Each panel consisted of either IM7/977-3 or T40-800Bb/5320-1 six inch-wide tape. The panel consisted of a 6-8 ply face sheet ply stack with ply build ups depending on the design of the panel. These build ups were to mimic the buildup section which would be required for joints, and mounting hardware. The ply stack varied as well from $[60,-60, 0]_s$ for the 6 ply panels to $[45,90,-45,0]_s$ for the 8ply panels as used throughout the panel top and bottom face sheets. Dimensions of this panel are approximately 1.98 m x 2.44 m. Areas of interest included the ply build ups which represent the flange attachment points of anticipated real life parts which are at both ends of the panel.

**Materials –** The demonstration panels were fabricated using either Cytec's IM7/977-3 or T40-800B/5320-1 prepreg tape, 15.24 centimeters wide for ATL processing. The FAW for each system was 145 gsm. Film adhesive to help bond base laminate to core were either Cytec's FM 300M or FM 309-1M on a random mat glass scrim. Core was a combination of perforated 49.6 and 97.6 $kg/m^3$, 2.54 centimeters to 4.14 centimeters aluminum 0.32 centimeter 0.0007P 5052 expanded honeycomb. The heavier core was placed beneath the build ups for added strength at the curved ends of some of the panels. Core splice consisted of Hysol 9396.6MD two part epoxy adhesive.

**Tooling and Equipment –** Fabrication was performed on HITCO's Charger Low Rail ATL. Test articles were laid up on a Janicki Industries 2.28 m x 2.74 m composite tool. Once the plies were laid and inspection performed, the panel was final bagged for cure per material supplier's recommendations. Cure profiles and cure recipes were per NASA's requirements and were over seen by HITCO engineering personnel.

# 6. RESULTS

Panel fabrication began by combining NASA part drawings/requirements and digital machine model/parameters into MAG ATL programming software. This software generated the Numerical Control (NC) program for the MAG ATL to fabricate the panels. Once the NC program was complete, a simulation of the layup was performed to confirm the accuracy of the programming. Prior to initiating the fabrication process, HITCO established a working manufacturing plan which laid out operating parameters, material requirements, and machine processing parameters including pressure and temperature settings. This granted HITCO and NASA the flexibility to make adjustments on the fly to hone in on more detailed operating parameters and track changes and adjustments real time. During fabrication, flaws from ATL tape, adhesive, core or core splice were captured with digital photography to later test the effect of defects in the laminate found during normal processing. Shown below in Figure 5 is an example of the data recording slides which were put together to help track and evaluate defects in the manufacturing process.



**NASA/LSSM Process Record**

| PART NO. | VERSION | PART DESCRIPTION |
|---|---|---|
| MTP-6003 | 00 | Panel 6-ply SHC 1 1/8 Core No Build-up, In-Autoclave |

Ply Number OML-06, ATL-Ply.6

| Condition | Value |
|---|---|
| Room Temperature | 71.3 F |
| Room Humidity | 41.4% |
| Head Pressure Override | 100 psi |
| Guide chute Temperature | off |
| Comments | Run at 100% |

```
#460(Ply.6)  Courses:
PN:MTP 6001  Cnfg:Hom
```

Wrinkle: course 12

Typical gap

Figure 5. Manufacturing Process Record

Fabrication began with the loading of the material as well as the ATL program in to the Charger ATL. Prior to running the program, the tools location must be determined by the tape layer. This process includes locating tooling positions in X, Y, and Z coordinates which give the tools surface a localized position in 3D space which the ATL can reference. Once the tooling positions were located off locating tooling pins, the ATL was able to reference the tools x, y, and z positions and determine the height of the tooling surface. The manufacturing process record based each flaw based on this relative positioning technique. Once located the surface was located and recorded the fabrication process of the panel was able to begin. The tool consisted of a 1/16th section from the 10 m diameter barrel. The tool was fabricated by Janicki Industries in Sedro-Woolley, Wa. The tool was constructed utilizing carbon composite material and consisted of a female tool configuration.

Panel fabrication began with the application of the Outer Mold Line (OML) carbon epoxy ply. No tackifier was used in the application of the first ply. Tackifiers are chemical compounds used in formulating adhesives to increase the tack, the stickiness of the surface of the adhesive. Though the tool surface was slick due to the release coat applied, the material was still able to be applied with an increase of the platen temperature on the ATL. The material, when subjected to moderate heat, becomes tacky and helps secure the material to the tool. For the first ply application the ATL head heating platen temperate was increased from ambient room temperature (~21 °C) to 26.6 °C. Once the first ply was placed, it was checked for quality requirements.

An issue which was encountered during the tape laying of the first ply was inconsistencies in the laps and gaps, as well as the starts and stops. This was determined to be the result of the machine not being properly harmonized with the prepreg roll material. The roll required adjusting on the ATL machine so that the laps/gaps were minimized. Adjustment of the 15.24 centimeter prepreg role is accomplished through set screws which center the ~16.8 kilogram ATL prepreg roll properly. After the first ply was placed, the remainder of the full coverage plies went down with relative ease.

A few issues occurred when trying to place the short course build up plies. When trying to place the short plies the material had minor issues releasing from the backing paper, and occasionally resulted in a wrinkled ply, which had to be removed and replaced. Subsequent to the lower face sheet laminate was placed, the charge was compacted at ambient pressure and temperature. Following the compaction, Cytec's film adhesive was trimmed to size to cover the complete lower charge, and vacuum compacted to the surface (debulk) for a period of 20 minutes. When the lower charge was compacted, the core consisting of 49.6 and 97.6 kg/m$^3$ core was trimmed to size and placed onto the surface. The core was compacted onto the film adhesive to keep the material in place for the next stages in the fabrication process.

As soon as the core was secured, the core splice application began. For the core splice, Hysol's EA9396.6MD epoxy adhesive was used with the help of a Semco pneumatic injector. The adhesive was loaded into the gun and injected in between the gaps of the core shown in Figure 6. The manufacturing team practiced the core splice on several training panels in order to gauge the quantities needed and the timing of movement of the Semco injector. Once the splices were filled with adhesive, silicone and brass strips were used to cover the seams and to prevent the core splice from oozing into the neighboring honeycomb core cells. If the core splice material did leach into or below the core, it could possibly lead to indications which would be found during NDI, disbonds, or even picking the core up off the laminate. The use of brass strip and silicone rubber was determined to mitigate the aforementioned risk. The panel was then vacuum bagged over night to allow the core splice to cure to manufacturing specifications.

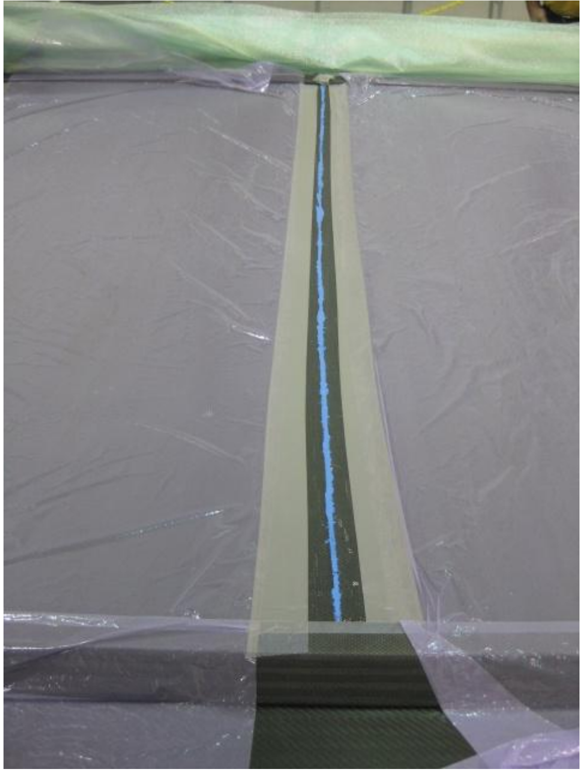


**Figure 6. Core Splice**

Next the consumable materials which were used for the core splice were removed and any low spots found in the Hysol adhesive that could result in low spots in the laminate were repaired by first sanding the affected area to give an ideal bonding surface, then filled using additional Hysol 9396.6MD or the appropriate Cytec film adhesive. During this time, the cores integrity was verified and if there was any deformation of the core cells, they were repaired with the use of tweezers. This reformed any depressions that might have become visible as a low spot or depression during lamination after cure. When the core splice was completed the above core layer of film adhesive was trimmed to size and was applied and compacted onto the core surface. After the film adhesive had 20 minutes under compaction to insure that all air had been removed from the core, the bag was removed and the above (bag-side) core laminate began.

For the inner mold line (IML) core laminate, a separate ATL NC program file was created using the same ply strucuture as the OML. The bagging materials were removed after debulking the adhesive on top of the core. Now, preparation for the IML laminate could begin. Due to design of the panel and the function of the program it was necessary to fabricate a run off path which the ATL would be able to use to run off the edge of the part without crushing the light weight core. A window frame was created around the periphery with scrap strips of core. This core was taped into place which kept it from moving once the ATL head transition from the core surface to window frame core surface.

Once complete, the compaction pressure was adjusted to compensate with tape laying over light weight core. The addition of too much compactor pressure could damage the core and crush cells. The IML core plies were applied with 172,368 - 344,737 Newton / meter^2 head pressure. The first ply had no issue tacking to the film adhesive as the film adhesive had mild surface tack. The remaining plies saw similar issues to that of the OML core (tool-side) plies. There were issues with the material securing itself to the ply and issues of ply wrinkling and fiber distortion occurred for both the autoclave and OoA prepreg tapes. The panel was completed and final bag begun. The panel’s final bag procedure closely followed Cytec’s recommended bagging diagram to ensure laminate quality. After the curved panel was completed, HITCO switched to the flat vacuum table and began fabricating witness panels. One flat panel was a solid laminate 0.91 m x 0.91 m flat panel used to validate the 1/16th panel cure cycle and a 0.91 m x 0.91 m cored sandwich panel which included NDI defects.

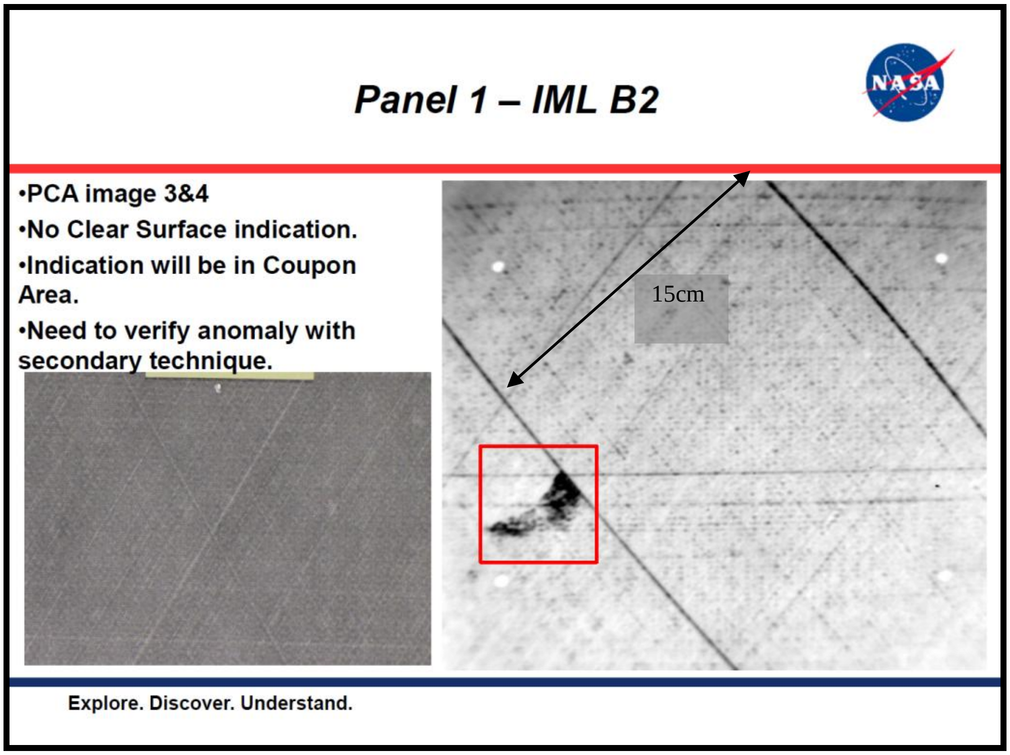
Once the panels were final bagged and ready for cure, they were transferred to the autoclave where they followed the material suppliers cure cycle. However, NASA modified these cures by introducing a slow temperature ramp up to 176 °C. The ramp rates were kept as tight as possible to simulate the expected cure of even larger scale sections of the sandwich barrel section of a 10m diameter fairing. After the cure, the panels were removed from the autoclave and their cure bags were removed. The panels were checked for any damage that may have occurred during cure. The panels were removed from the tool as seen in Figure 7.

**Figure 7. Part Detool**

## Non-Destructive Evaluation (NDE)

The panels were then positioned for thermography non-destructive testing (NDT). Thermography uses a thermally sensitive camera which produces an infrared image of the scanned section after the part surface received a large flash of light from a quartz bulb. An example of this processing is shown in Figure 8. The camera measures how long the heat energy takes to leave the surface, and is able to locate disbonds, material flaws, and foreign objects. After examining both the IML and OML surfaces of the panel, the panels were sectioned for photomicrographs, acid digestion testing, and mechanical testing. All the NDE data captured the defects in the as fabricated state for each layer. A template was created to provide NASA the opportunity to determine the effect of defects. While the state of the art has not matured to the point where precured defects are translated into postcure performance in a deterministic manner, the data and records have been captured for future researchers as the technology of defect recognition maturates along the digital thread to reduce cycle time, increase performance and enhance affordability.

Non-destructive evaluation of the panels included visual inspection and thermography.



Panel 1 – IML B2

- PCA image 3&4
- No Clear Surface indication.
- Indication will be in Coupon Area.
- Need to verify anomaly with secondary technique.

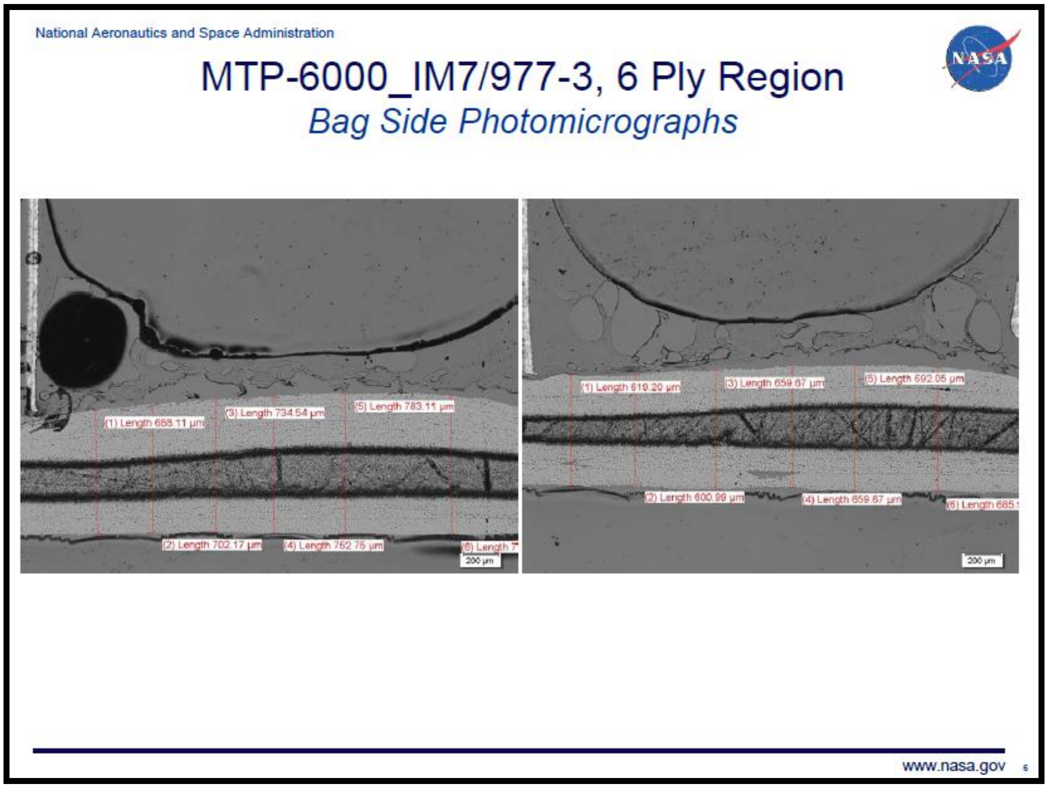
Explore. Discover. Understand.

**Figure 8. NDE Imaging**

**Error! Reference source not found.**8 provides preliminary results of thermography evaluations.

### Destructive Testing

Photomicrograph coupons were taken from select areas of interest from each panel. A section was taken to evaluate areas based on part geometry (ply drops, build ups, etc). Photomicrograph specimens were mounted and polished in accordance with best practices for preparation of composite specimens. These images showed the ply to ply compaction within each panel as well as provided imaging for percentage void count. In both material platforms, the resulting panels were relativity void free. Photomicrograph results are shown in Figure 9.



National Aeronautics and Space Administration

MTP-6000_IM7/977-3, 6 Ply Region

*Bag Side Photomicrographs*

**Figure 9. Photomicrographs**

## 7. CONCLUSION

The progress which aerospace industries are achieving through the use of automatic tape laying as and OoA material is growing rapidly. Material out life is extended to 21 days and beyond. Mechanical and physical property improvements are competitive with autoclave materials. These advancements in manufacturability will open the door for future products of much greater size than those that exist today. With the addition of ATL, the removal of the human factor is more prevalent which increases both accuracy, as well as net material lay down productivity. The largest advantage to the use of automation is the increased material lay down rate. Conventional hand layup ranges between 0.68 to 1.13 kg per hr whereas in large monolithic panels the material lay down rates range are greater than 2.27 kg. In larger lightly contoured parts the lay down rates can be on the order of 4.5 to 6.8 kg per hour. With further advances in material and machine synchronization, the realm for what is achievable grows significantly.

Automated Tape Placement over honeycomb structures is a convincingly robust process. Optimization of Cytec Engineered Materials (CEM) unidirectional tape for ATL is needed to add predictable and credible understanding to add to this convincingly robust process. Further development with regards to impregnation levels and material backing paper issues OOA materials need refinement to really make it a viable solution.

## 8. ACKNOWLEDGEMENTS

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