



LIQUID RESIN

The Journey Towards Future Aircraft Structures

A Whitepaper by Composite Integration

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April 2025

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INTRODUCTION.

Traditionally, the gold standard for creating the highest quality composite material has been prepreg—cured under pressure in an autoclave. However, this is no longer the only method. For some time, Resin Transfer Moulding (RTM) has delivered comparable quality. Now, Resin Infusion (RI) also achieves this standard and can offer weight reduction. This represents a significant technical and economic step forward.

The science, engineering, and art involved in composites manufacture has always posed significant challenges. It is often highlighted in academic lectures that composites are unique; the material is created simultaneously with the component, along with the properties determining the technical and physical performance of the part.

Most are well aware of the manufacturing challenges associated with composites, which need no further elaboration here. Alongside these challenges is the critical decision of choosing the manufacturing method to optimise cost, quality, and production rate.

Navigating the complexity of various composite manufacturing processes and their nuanced variants requires considerable and broad industrial experience. Traditionally, the method for quick and low-cost production has been hand laminating; however, unless performed by the finest artisan laminators—custom competition surfboards are a prime example—the quality suffers. Hand-laminated boat hulls, once considered adequate, face challenges as they age; early in a boat's life, the inevitable void content might not be problematic, but it can later lead to osmosis, a condition where voids absorb moisture and then rupture. On the other end of the spectrum, where quality is essential, prepreg consolidated and cured in an autoclave has been a default solution. While this addresses the quality concern, it is slow and costly, with raw materials priced 2-3 times higher than the equivalent dry fibre and liquid resin. F1 racing, America's Cup yachting, and aerospace are notable fields where this material has proven highly appropriate and successful.

This paper explores how and why liquid composite moulding has now become a viable method for manufacturing aerospace structures.

“Now Resin Infusion can deliver the same quality, and can reduce weight”.

A BROADER PERSPECTIVE.

It is worth taking a moment to reflect on the current landscape. The aerospace industry is facing unprecedented technological challenges alongside exciting opportunities. The demand for conventional commercial aircraft remains exceptionally high, coupled with a rapidly growing interest in novel electric vertical take-off and landing (eVTOL) aircraft. This significant demand is juxtaposed against the pressing need to design, construct, and operate aircraft that substantially reduce environmental impact.

When Airbus developed the A320 in the 1980s, the focus was primarily on performance over ease of assembly. The initial business model was predicated on the sale of 400 units—a target that has been vastly exceeded. To date, Airbus has delivered over 10,000 A320s, with a current order backlog of more than 6,000 units, and a total order backlog close to 9,000 aircraft of various types as of Q3 2024. To meet this anticipated demand, the company will need to produce approximately 100 single-aisle assembly sets per month. Meanwhile, Vertical Aerospace—a leading UK eVTOL startup nearing its first manned test flights—anticipates even higher production volumes, estimating a monthly output of 300 aircraft.



Figure 1

Future single aisle aircraft such as the A320 family are requiring enormous ship rate sets to fulfil current orders.

It is crucial to pinpoint where significant efficiency gains can be realised in commercial aircraft production. Two primary factors—engine efficiency and wing design—play pivotal roles.

Longer wings with reduced drag are notably advantageous and are optimally manufactured using composites rather than aluminium, saving weight. Composite wings, as seen in the A350, A400M, and Boeing Dreamliner, have made considerable progress in this area. However, traditional manufacturing methods for these components, such as autoclaved prepreg, are excessively slow, costly, and energy-intensive, rendering them impractical for fulfilling future orders.

To meet the demands of large-scale production efficiently and sustainably, applying the appropriate composite technology is essential. Preformed fibre packs with very short Takt times, which can be moulded at high rates using either Resin Infusion or Resin Transfer Moulding, present the only viable solutions to this challenge. This approach aligns with the ambitious environmental targets set by the Global Aviation Group—The Air Transport Action Group, which is committed to achieving net-zero carbon emissions by 2050. Traditional autoclave methods are untenable due to their slow production rates and high energy consumption.

Liquid resin processes for aerospace structures are viable and fit for purpose. The challenge lies in adopting the correct methodology to ensure effectiveness. The industry has not yet reached a consensus on the optimal processing parameters, unlike the confidence gained from decades of refining prepreg processes. Regardless of the manufacturing options available, future aircraft structures production methods must meet the following criteria:

- Very high-rate manufacture.
- Laminates of exceptional quality.
- Low cost.
- Reduced manufacturing energy costs.
- Enhanced operational efficiency and a more sustainable whole life model.

HOW ARE THESE REQUIREMENTS RESOLVED?

Typically, when customer demands call for rapid, cost-effective, and high-quality delivery, the clichéd response suggests only two can be satisfied. However, all these criteria must be met, compounded by ambitious net-zero targets. Can this be achieved?

Liquid resin moulding processes, specifically Resin Transfer Moulding and Resin Infusion, contribute significantly to reducing costs, increasing productivity, and lowering energy consumption while maintaining exceptional quality.

Success with these methods is contingent upon a deep, practical, and readily applicable understanding of the process science, followed by the development of hardware and software that apply these process parameters effectively to the parts in question. Precision and control are crucial, a challenge given that both processes sometimes carry a legacy of being perceived as non-scientific. Developing the right understanding is a journey.

“Success with these methods is only achieved through a deep, practical and readily applicable understanding of the process science”

This journey to manufacturing aerospace quality composites usually involves the following crucial steps:

- Understand the material.
- Understand the process variables.
- Conduct sufficient real-world trials.
- Evaluate and apply the trial data and experience.
- Define the process.
- Design the machine and clarify how the experience gained is applied.
- Make the part.
- Evaluate the part for quality, rate, cost, and energy cost.

When each of these steps has been carried out and often repeated, success will follow.

A SCIENTIFIC BUT VERY PRACTICAL HEAD IS NEEDED...

The fundamental elements of liquid composite moulding are not always well understood, often sparking ongoing debate within technical forums about resin pressures during Resin Infusion. Double bagging and the role of semi-permeable membranes remain topics of discussion. Moreover, significant research is still required to industrialise and simplify fabric permeability measurements, making them more accessible to composites engineers on the ground.

Composite Integration adopts a practical and data-driven approach in optimising process methodologies. This expertise stems from countless mouldings and test laminates manufactured at Composite Integration almost daily. This work is conducted both independently and in collaboration with our customers on their projects. With extensive cross-sector manufacturing experience, this breadth is particularly useful as specific sectors encounter unique challenges. For instance, very thick infusions common in the wind sector become advantageous for thicker marine appendages. Composite Integration has consistently been a reliable source of knowledge, positioned to provide customers with authoritative guidance.

In many ways, measuring success can be straightforward, focusing on key factors such as fibre volume fraction and void content. Achieving these metrics at a reasonable cost, rate, and low energy footprint is now readily achievable. There are also several other important quality indicators, such as resin cure and fibre waviness, which are not significantly impacted by the Resin Infusion or Resin Transfer Moulding process parameters. Generally, the key process considerations are grouped under the following headings:

- Resin rheology.
- Process temperature.
- Fabric permeability.
- Vacuum and pressure integrity.
- Tooling strategies & design.
- Dry fibre preforming.
- Control of volatiles in the resin and fibre.

There has historically been a significant academic and sometimes commercial effort to understand and characterise fabric permeability and thickness during processing. Interestingly, this is often the domain of universities and specialist labs. Industrially accessible, accurate, and straightforward measurement tools for fabric permeability and thickness at different process pressures remain elusive. Fundamentally, both parameters are essential, and Composite Integration has designed and built this measurement capability in-house. Ply thickness can be quickly measured, whether wet or dry, under different pressures defined by the process in question. Similarly, measuring fabric permeability is becoming part of a standard Composite Integration routine. This is crucial, given that there are mechanically desirable fabric forms that provide excellent properties but are very challenging to infuse or inject with liquid resins. Objective data on this aspect of fabric performance is essential.

Through thickness, permeability can be measured at precise fibre fractions, various thicknesses, and elevated temperatures, with data comparing well with published values.

Figure 2

Composite Integration in-house fabric thickness compression rig. Enabling very accurate ply thickness measurements wet or dry at realistic processing pressures.

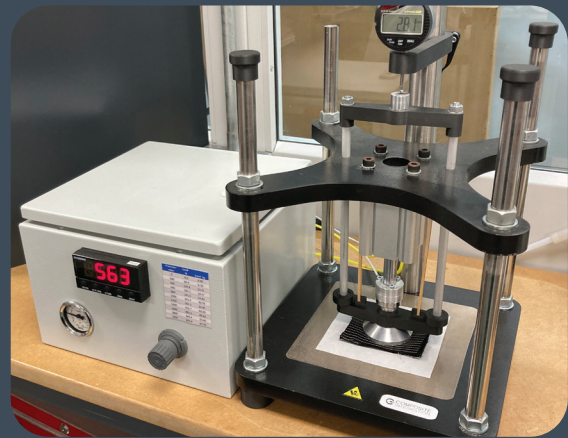


Figure 3

The through thickness permeability rig at Composite Integration – giving the ability to turn around quick and accurate results for very precisely specified fibre fractions. The rig works with laminates up to 50mm thick, so real world laminates with various fibre orientations can be tested.



In addition, it is crucial to ensure that resin systems are thoroughly de-gassed and free from bubbles, a process that is now objectively measured at Composite Integration. Recent developments have significantly improved this area of our research. Studies conducted in our labs have demonstrated a strong correlation between the extent of resin degassing and the resulting laminate quality. The capability, now an optional feature on CIJECT

machines, provides a critical 'go/no-go' capability for the process.

Extensive observational studies have been conducted to understand resin behaviour at lower pressures (Figure 4 & 5). These studies have informed the development of a numerical output, now available as an optional feature on many CIJECT machines, with data measured in near real time, using a chemical analysis sensor.

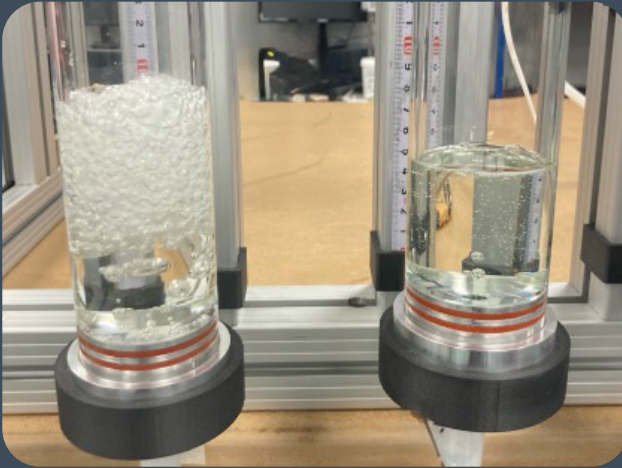


Figure 4

Plenty of work has been carried out to observe what happens to resin at lower pressures. The bubbles can be quantified.

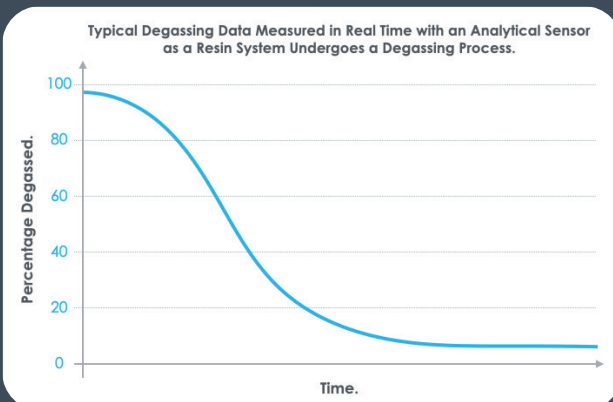


Figure 5

The type of numerical output from analytical sensors now available.

However, while many of these parameters are well understood and controlled, the most critical factor remains the process pressure. In Resin Transfer Moulding, this directly impacts the rate and fibre alignment; similarly, in Resin Infusion, the pressure at which resin is delivered into the laminate significantly affects the fibre fraction and void content. If the incoming resin pressure is too low, the infusion process is slow and likely to introduce voids.

Conversely, if the pressure is too high, it can compromise the fibre fraction. The chart in Figure 6 provides a comprehensive summary of the desired outcomes and underpins the precision required in the resin delivery hardware and software during Resin Infusion.

This approach has been refined over several years through hundreds of laboratory and collaborative industrial studies. Figure 7 & 8 overleaf illustrates the typical nature of this work.

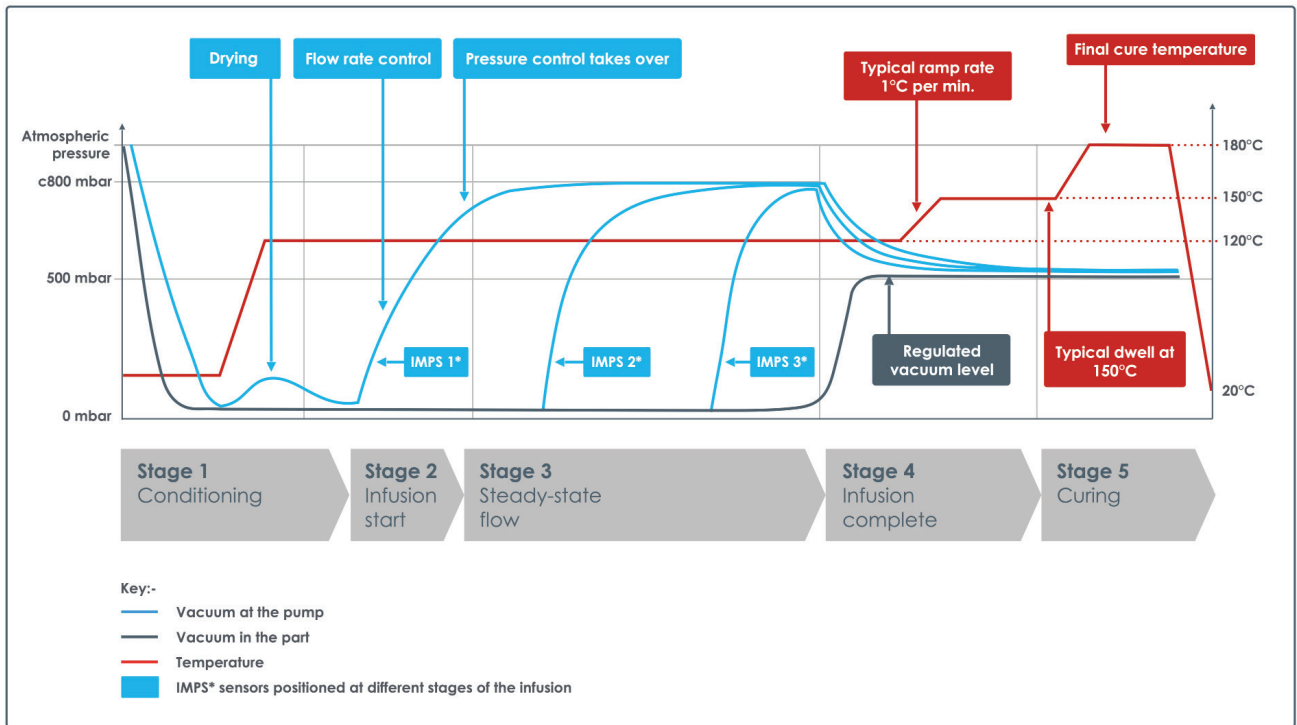


Figure 6 The Composite Integration Resin Infusion process parameter model – verified with hundreds of infusions in all sectors. From light aerospace parts, to the largest wind blades.

Figure 7
Typical resin infusion process
pressure profile study pressures.



Figure 8
Resin Infusion process pressure vs.
laminate thickness.



APPLYING AND AUTOMATING THE PROCESS SCIENCE.

With a confident grasp of all the key processing parameters—achieved largely through meticulous practical experimentation—success in Resin Transfer Moulding and Resin Infusion is attainable. Multi-axial laminates with fibre fractions close to 60% and negligible void content are among the key qualities achievable with both small and large parts.

Armed with this knowledge and competent practical capabilities, transitioning from the laboratory environment to the demonstrator and production settings can be effectively facilitated by automating the process through user-friendly hardware and software. In this regard, our CIJECT machines play a pivotal role in introducing hardware and software solutions to numerous successful aerospace R&D programmes and production environments. By applying significant effort to refine the process variants of both Resin Transfer Moulding and Resin Infusion, and integrating this control into the machines, quality and production rates are nearly guaranteed. This level of excellence is evident not only in the aerospace sector but also in others, including wind and marine industries.

A key aspect that is often overlooked is the ease of use of these machines. Substantial effort has been invested to ensure that the complex operations are managed by software, with simple process stop/start buttons and precise pressure control within a few millibars, delivering high-quality results and minimising operator errors. Easily programmable process steps enables high levels of automation, demonstrably reducing part-to-part variation. This makes a significant difference in industries where the challenges are substantial.



Figure 9

Typical multi-axial resin infused carbon with high fibre fractions and virtually negligible void content pressures.



Figure 10

A typical large scale liquid resin infusion machine for aerospace applications capable of either Resin Infusion or Resin Transfer Moulding.

RESIN TRANSFER MOULDING.

There is still work to be done to industrialise certain aspects of liquid composites moulding. In terms of Resin Transfer Moulding, the primary challenge relates to the rate of production. With Resin Infusion, the challenge also concerns rate, but crucially, it extends to achieving repeatable quality.

There have been notable historical successes in aerospace Resin Transfer Moulding. For several decades, aircraft of various sizes and roles have utilised Resin Transfer Moulded propellers. It might have been argued in the past that more traditional compression moulded prepreg was technically more suitable. However, propellers crafted with precision dry preforms over foam cores, and frequently over-braided, have proven incredibly successful. With hundreds of thousands of flying hours, applications like these demonstrate the excellent fitness for purpose of Resin Transfer Moulding for critical flying components. It is through the application of robust processing principles, derived from proficient resin handling machines, that these components continue to evolve in performance and viability against the criteria already presented in this paper. Dowty Propellers—a part of the GE group—has long been recognised for their prolific, high-quality examples of commercial aircraft propeller systems (see Figure 11).

Figure 11

An excellent example of aerospace Resin Transfer Moulding – in this particular case a Dowty turbo prop from a light regional aircraft. Today's challenge is to improve on rate and consistency.



The new challenge, however, lies in achieving much higher rates of Resin Transfer Moulding. This is driven by the recent surge in demand for a very large number of eVTOL propeller blades and other smaller components in matched closed moulds. Not only is a sound grasp of the process science required, but success also demands a level of automation in mould handling as well as resin injection control and management.

Composite Integration has delivered several manufacturing cells to address these needs. There is a significant demand for this technology in other sectors, including the wind sector. Manufacturing cells that deliver sophisticated preformed parts with multiple metallic and foam inserts in isothermal automated tooling are currently in production, producing multiple mouldings every hour. Often employing a non-vented injection strategy, resin management is carefully refined to optimise for rate, quality, and fibre fraction. Figure 12 illustrates a general arrangement for this type of high-rate RTM cell.

Figure 12

A typical high-rate RTM work cell capable of multiple, sophisticated high fibre fraction mouldings every hour, designed by Composite Integration.

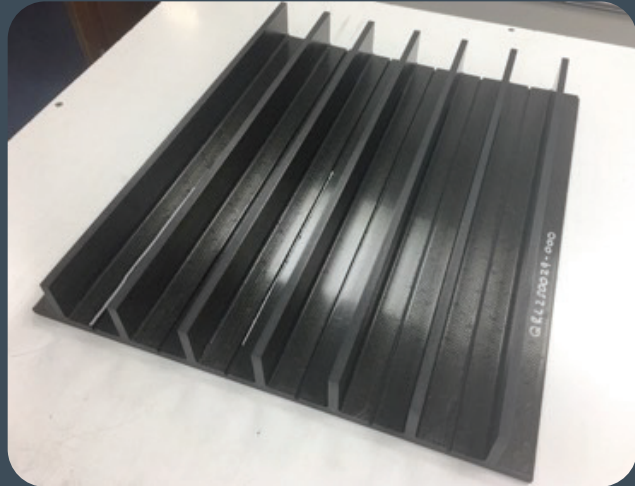


In addition to this example, the 17-metre C-Spar for the Airbus Wing of Tomorrow programme, manufactured by GKN, represents a significant development in RTM processing. Fabricated using RTM in Invar tooling, this component is logistically remarkable for its sophisticated, multipart metallic tooling and exceptional component quality. The spar incorporates both multi-axial and dry fibre placement options. The CIJECT machine, illustrated in Figure 10, is quite typical of the resin handling equipment used for projects of this magnitude. It is capable of injecting single-component resin systems and two-component (2k) systems while ensuring:

- Part injection at 6 bar.
- Flow & pressure management, creating a process envelope.
- Ratio verification for 2k systems.
- Precise management of resin temperature.
- Logging of resin ageing.
- Implementation of preventative strategies for potential issues.
- Remote monitoring and data acquisition/analysis.

Figure 13

A mechanical test component made from multi-axial carbon with skin and rib detail, typical of structures for future wing and aerospace surface mouldings.



RESIN INFUSION.

In 2015, Composite Integration commenced a program of work with Safran Nacelles as part of the ProPound project, funded by Innovate UK. This ongoing technical programme also involved Nottingham University, Manchester University, and Broetje Automation, running in two phases until 2022. The project had several technical objectives aimed at enhancing the production capabilities at reduced costs for nacelle-type parts. In partnership with Safran Nacelles, extensive work was undertaken to define the key manufacturing processing parameters for aerospace-quality composites manufactured by Resin Infusion. From the outset, it was apparent that there was a lack of precise definition in the process parameters for the infusion of high-temperature, low-viscosity single-component resin systems. Typically, the fibre systems were reasonably conventional, employing a variety of carbon multi-axial materials with lightning strike protection, yet further refinement with these materials was necessary.

During this project, it became evident that successful Resin Infusion with typical aerospace laminates could be quite sensitive. Key factors such as adequate fibre pack drying and resin degassing became measurable and critical to success. However, the resin pressure regimes during the infusion and curing processes needed meticulous control. The chart in Figure 8 provides a clear summary of the necessary requirements. The definition of pressure parameters was the result of extensive experimentation, allowing for the reliable and repeatable manufacture of laminates with fibre fractions close to 60% by volume and negligible void content.

Dynamic process control is closely coupled with the specific design of the infusion consumables. This careful alignment of infusion design and integration with the infusion machine control methodology, results in predictable and repeatable high quality outcomes. It has been demonstrably possible to produce laminates of the required quality without the need for double bags or semi-permeable membranes. While membranes play a role in certain strategic aspects of resin infusion, double bags are not necessary for achieving high fibre fractions or vacuum security.

The result of this highly successful partnership is twofold. Safran Nacelles, as a partner

and customer, now has a robust infusion process for manufacturing flying parts cost-effectively. Composite Integration embeds these parameters into CIJECT machines.

For over a decade, a CIJECT has been capable of controlling an infusion with closed-loop feedback - a technology known as “Direct Infusion” - and these parameters have been further refined to deliver the control required for such parts. Pressure control is typically within a few millibars of the set value during infusion, the extent of resin degassing is well-established, and importantly, much of this process ‘heavy lifting’ is managed by software, making the machines user-friendly and simplifying the operators’ tasks.

The process envelope is comprehensively tracked, controlled, and logged, meeting all key requirements for consistency, quality, production rate, and energy efficiency.



Figure 14

A nacelle type demonstrator about to be successfully infused. Here the entire process has been defined and implemented.



Figure 15

Safran Nacelles, where significant progress has been made in enabling liquid resins to compete in every respect with autoclaved prepreg. The work was carried out under the ProPound project. (Image copyright Safran Nacelles)

Following on from this work, other successful parts have been manufactured by Resin Infusion. The thrust reverser outside skin for a business jet, shown in Figure 16, is made from a multi-axial carbon and dry lightning strike protection material, using Hexcel RTM6 resin.

The nuanced development of the Resin Infusion variant used to produce this part has demonstrated that several benefits are possible.

- The layup operation is simpler than with prepreg.
- Weight saving of 5% over the prepreg.
- A 60% reduction in carbon footprint.
- Aerospace-grade laminate quality.

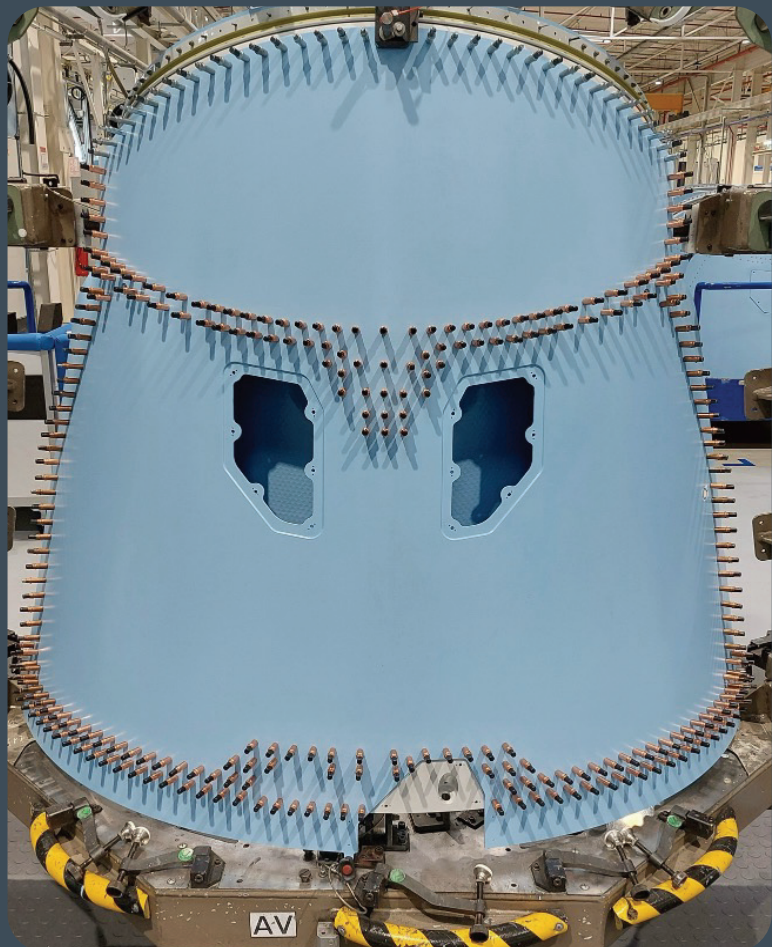
These achievements were realised without a complex infusion setup; no double bags, no overlaps of plies, or semi-permeable membranes were used. However, a clear infusion strategy, specific use of custom infusion consumables, and precise control of the key infusion parameters were crucial to producing a part of this quality. By producing a prototype external skin of the business jet reverser, we were able to prove the viability of Resin Infusion as a premium alternative to pre-preg.

This component has captured and demonstrated the possibilities for future aerospace structures outlined at the beginning of this paper—there are improvements across all these factors.

Liquid resin processes now certainly compete with those manufactured in autoclaves. While Resin Transfer Moulding has been competitive in quality for some time, its rate of production is now well established. Resin Infusion is also now competitive in this sector, perhaps establishing it as the new gold standard.

Figure 16

Outside skin of a business jet thrust reverser, made from multi-axial carbon and dry lightning strike protection material, using Hexcel RTM6 resin. Made by Resin Infusion.



WHAT'S NEXT.

Much of the deep and practical process understanding gained at Composite Integration has been embedded into machines that have served numerous aerospace customers successfully. The capability to produce aerospace-quality composites robustly and reliably has advanced significantly, resulting in a greatly enhanced understanding compared to just a few years ago. As the aerospace sector evolves, our integration of cutting-edge technologies addresses current demands and anticipates future challenges.

Having demonstrated that Liquid Moulding of aerospace grade composites can meet the quality of autoclave/prepreg parts, it is also prudent to note the energy saving and production flexibility that moving from large autoclaves to distributed, self heated, in-situ tooling can bring. Autoclaves can be a significant production bottleneck, demanding extensive logistics to operate at scale as well as lost energy from the heat/cool cycle necessary for loading and unloading.

Where challenges persist, Composite Integration remains invested and committed. We continue to innovate in areas such as enhanced degassing measurement and the development of industrial-scale permeability tools. With the growing need for advanced resin systems, such as 2K resins, the precision of mix verification from our CIJECT machines will play a crucial role in meeting these challenges.

Looking ahead, Composite Integration is dedicated to fully embedding liquid resin processes, driving the aerospace industry towards higher production rates, maintained quality, reduced costs, and support for future Net Zero objectives.

As we navigate the complexities of aerospace manufacturing, Composite Integration remains at the forefront of technological advancements. Our commitment to research, development, and customer collaboration enables us to meet the evolving demands of the industry.

We partner with customers at nearly all stages, from almost the earliest Technology Readiness Levels (TRLs). Utilising advanced facilities and comprehensive material science expertise, we drive projects from initial concept to full-scale production. Committed to setting tomorrow's benchmarks today, we invite you to join us in shaping a more efficient, sustainable, and innovative future in aerospace.

WHAT'S NEXT?

To explore how our technologies can improve your operations and get you ready for the future of aerospace manufacturing, please reach out to Tim Searle directly.

[Get In Touch](#)

