1 VACUUM INFUSION OF LARGE PRECISION STRUCTURES

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Keywords*: flow modelling, vacuum infusion, large structures*

ABSTRACT

The construction of large precision structures from composite materials poses many problems and this paper will focus on the fabrication process. At DRAO we are actively researching the potential to build large (15m to 18m aperture) single piece yet very precise radio telescopes from carbon fibre composites. Because of their size, only out of autoclave processes were considered. This paper will discuss the vacuum infusion process, the accompanying flow modelling, and how this process is working for the fabrication of large single piece radio telescope reflectors.

One primary reflector for a 15m offset telescope consists of about 200 m^2 of area. In order to reach the desired ~200 micron RMS (root mean square) surface accuracy a lot of things must be done very carefully such as placement of the structural fibres, choice of resin, accuracy of the mold, and of course the overall structural design. Such a structure represents a significant cost in both time and materials, and as a consequence no mistakes can be made during the resin injection or vacuum infusion process. Extensive use was made of both flow modelling software and test panels. Initially small rectangular permeability test panels were made to obtain characteristic values for the flow modelling software. A manifold design was developed using this flow modelling software, and then a series of large scale test panels (of increasing size) were built to refine the flow model. Finally, once the flow model had been tweaked to accurately reflect the outcome of the large test panels, the full scale infusion was performed.

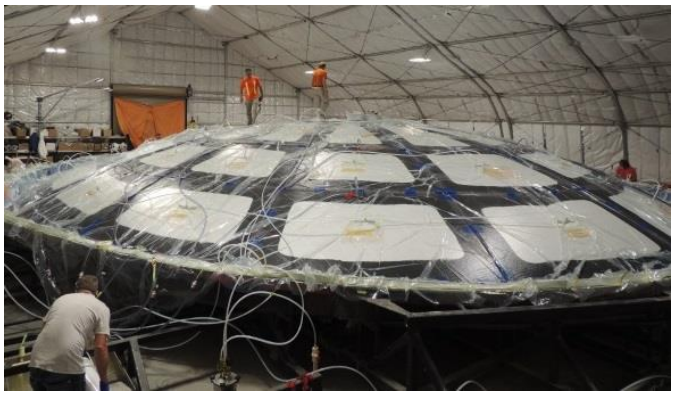


Figure 1: Vacuum infusion of a 15 metre radio telescope, just 12 minutes into a 2 hour infusion.

1 INTRODUCTION

At the Dominion Radio Astrophysical Observatory in Penticton we have been building composite radio telescope prototypes for more than 10 years. The goal is to develop a high performance but less expensive radio telescope suitable for production in numbers sufficient for use in one of the new array instruments. These instruments do not consist of single large reflectors as was the case in the past, but instead use dozens to hundreds and even thousands of smaller reflectors all working together, each collecting data that is then *correlated* with a very powerful computer, into a single high resolution radio image. Because these array instruments require hundreds of identical reflectors, it appears likely that molded composite structures could offer an advantage both in cost and in performance. This is true because the composite molding process allows the fabrication of near-identical parts using less skilled labour. Further, exploitation of the properties of composite materials leads to additional cost savings and performance gains. This is not just the utilization of the high specific strength and stiffness of the composite material (and the non-isotropy), but also the integration of many (typically metal) components from the older design into a few composite parts.

We have decided to take full advantage of the composite material and the available fabrication processes and build a radically different telescope. Our design uses a single piece rim supported primary and secondary reflector. The design also uses offset optics to eliminate blockage, diffraction effects, and scattering of radio energy from the secondary support legs. Figure 2 shows the Dish Verification Antenna 1 (DVA-1), completed in 2015. System tests show that this telescope has a very high performance [1]. This remarkable performance is a result of the net sum of the reflector surface accuracy, the single piece reflector surfaces, the shaped offset Gregorian optics, and the very low noise L band receiver (1 to 2 GHz). Furthermore the carbon composite telescope has a much higher thermal stability than any metal telescope which allows for more high precision observing time.

Current work centers on moving up in frequency from L band to Q band (33 to 50 GHz) and beyond. A second reflector of much higher surface accuracy and a much higher performance reflective surface has been fabricated. This paper will discuss the fabrication process used for this second (DVA-2) reflector.

Figure 2: The DVA-1 single piece carbon composite radio telescope.

2 FABRICATION PROCESS

2.1 Vacuum Infusion versus Prepreg

The prepreg process is still the first choice for most aerospace projects, but various "Out of Autoclave" (OOA) processes are gaining ground primarily because of manufacturing cost reductions. In our case we have chosen Vacuum Infusion as the preferred OOA method of fabrication because the composite material properties met the requirements and it satisfied the practical fabrication constraints imposed by the sheer size of the part. The prepreg process was not chosen principally because of the impossible size of the required autoclave, and also because the added cost of the material (and labour) was not sufficiently offset by the small improvement in material properties.

2.2 The Vacuum Infusion Process

The Vacuum Infusion Process (VIP) is one of a family of processes known under a variety of acronyms such as VARTM (Vacuum Assisted Resin Transfer Molding), and VIM (Vacuum Injection Molding). The main distinguishing feature with VIP is that it uses only vacuum to draw the resin into the part. Other methods such as VARTM can also use pressure at some stage in the process especially if the part has a semi-rigid backside mold. We use the VIP process exclusively because it suits our fabrication methodology with only a simple vacuum bag to hold the fabric against the mold.

2.3 Limitations on the VIP Process

With only atmospheric pressure acting as a motive force to push the resin into the part, there is clearly a physical limit to the height of the part which in practical terms is about 6m. A single piece radio reflector would have to be pretty large in diameter before the height of the part approached 6m. Depending on the focal ratio, this limit restricts one to a single piece reflector of about 45m in diameter; not a size we are likely to build anytime soon. In terms of the maximum area of the part, there are no real limits. The author has infused parts as large as 600m^2, and larger parts than that have been built by others. There are only the logistics to consider: the practical aspects of getting very large quantities of resin into the part on rather short time scales, amongst others.

One of the primary limitations on the VIP process concerns the problem of "wetting out" the part. High strength and stiffness composite material has very closely packed fibres (especially carbon fibre), and is hard to get the resin into (hard to wet-out). Another way to say this is that high strength and high stiffness composites have low porosity and (usually) low permeability. Thus we have competing requirements; to facilitate fibre wet-out we need higher porosity and higher permeability, but for high strength and for high stiffness we want the opposite. Clearly a compromise between these competing requirements must be found for each project.

3 FLOW MODELLING

For the design of resin and vacuum manifolds for the VIP and other similar processes including RTM, software such as Polyworx [2] is available. Polyworx, a combined Finite Element/Control Volume software package takes the guesswork out of resin and vacuum manifold design. Programs such as this also let one explore alternate manifold schemes without incurring the cost in time and materials necessary to do the same job experimentally.

3.1 The DVA-2 Main Reflector Manifold Design

Figure 3 is an image of the DVA-2 manifold design. The 6 red lines on each quadrant represent the external resin feed lines. For this infusion we decided to split up the resin into 4 stations, two on each side of the centerline. This minimizes external feed line length and the resistance to flow inherent in long feed lines, but increases the

complexity of mixing and distributing resin to 4 filling stations instead of 1. Another factor was the use of epoxy resin which has a highly volume dependent exotherm, so splitting the resin into 4 shallow trays was a simple way to keep the resin cool and extend the gel time. The resin manifold under the vacuum bag is represented by the green radial and tangential lines which divide the surface up into something similar to a trapezoid (except the horizontal edges are curved). At the center of each trapezoid is a vacuum port. Along the top edge of the lower vertical flange there is also a vacuum line, and there is a final vacuum at the center-top of the part. This vacuum must remain open for the entire infusion time. On the dish surface there are 3 rows of 12 vacuum ports plus one at the centre for a total of 37 ports plus 12 more around the top of the outer flange giving a grand total of 49 vacuum ports.

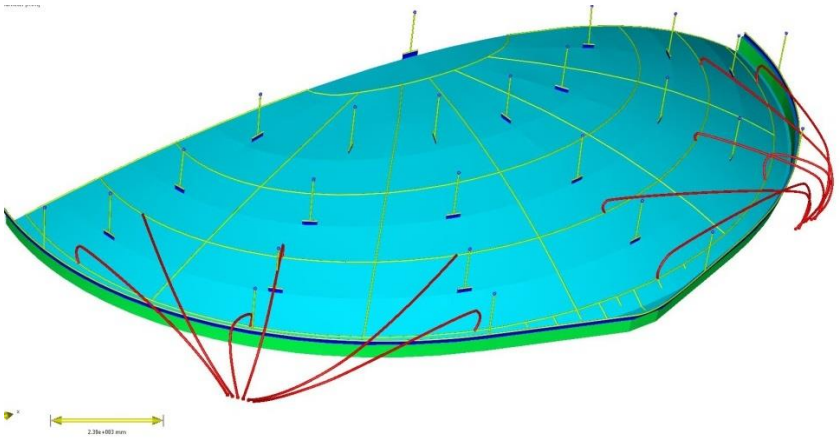


Figure 3: The DVA-2 resin and vacuum manifold design (one half of symmetric part shown).

3.2 Discussion of Manifold Design

This manifold represents the best of several manifolds developed for the infusion of large single piece reflectors here at DRAO. The primary advantages of this design centre on "robustness". What is meant by robustness in this context is the ability of the manifold to correctly deliver the resin into the part in the required manner (i.e. within the time constraint, evenly, and without leaving any dry areas), while at the same time being tolerant of local variability in panel average permeability and porosity, as well as fabrication error such as exact manifold placement. On top of all that, it is important for a good manifold design to allow some redundancy, such that a single plugged external or internal feed line or vacuum line does not jeopardize the entire infusion. This may be a tall order, but it is one that this manifold delivers. On the negative side are the number of vacuum ports, 49 a big number considering that each one represents a through-bag penetration which could easily be the site of a vacuum leak (although a vacuum leak at a vacuum port is less serious than one at a resin port), not to mention the extra work required to install them all. The alternative designs, while having fewer vacuum ports and bag penetrations, had other flaws such as a lack of redundancy and/or required very precise manifold placement in order to work properly, and hence they were ultimately rejected.

3.3 Infusion Sequence

Figure 4 shows two frames from the flow modelling software illustrating the predicted fill pattern at 3 minutes and at 55 minutes. Interestingly one can see that the flow rate is quite non-linear with 311 litres of resin consumed after just three minutes, while 892 litres were consumed after 55 minutes. The importance of being aware of this non-

linear resin consumption is all too evident, as failure to allow for this will at the very least substantially increase the overall infusion time (if you get the feed valves closed before the feeds suck air), or ruin the part if you don't get the valves closed. The cell structure of the manifold is clear, with each cell or zone filling from its perimeter in towards the vacuum port at its center. Colours in the plots represent time, red being the most recently filled, blue the oldest. If the cell edges (the feed lines) are not in exactly the correct position on the part, the cell will still fill, and within some tolerance, the vacuum port at the centre will still draw the resin fronts together leaving no dry spot. It is important though to get the timing right, so that the top central feed patch (an ellipse in this case) fills last. In this way any gasses, the result of resin curing under the bag, or any trapped air, will still have an escape path out of the part. In order to keep the overall infusion time down to the minimum value, it is also important to have all the resin fronts reach their perspective vacuum ports at about the same time (this will also save resin).

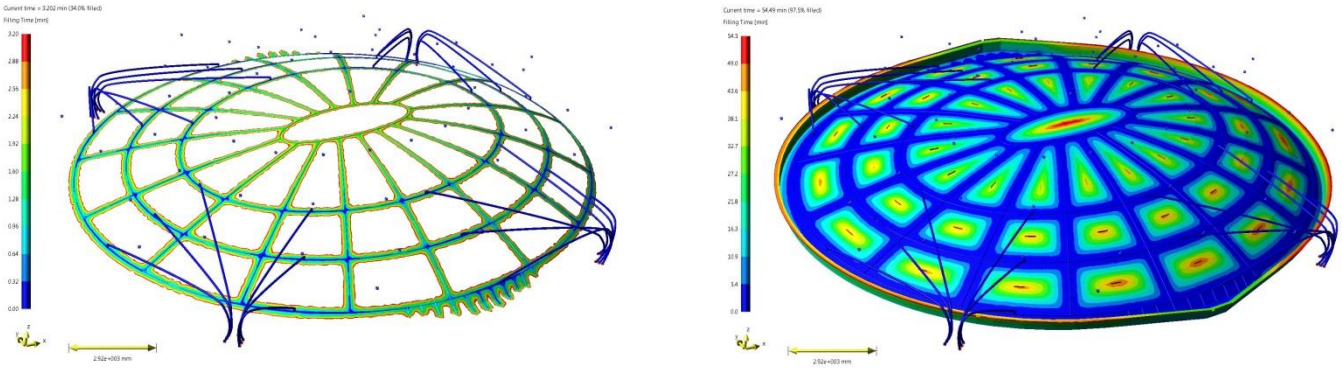


Figure 4: Vacuum Infusion model: LHS 3min after valve opening, RHS 55min after valve opening.

3.4 Small Scale Panel Testing

It is necessary to determine the laminate properties, permeability, and porosity, for each orthogonal direction and for each different layup in the part in order to model the flow using a program such as Polyworx [2]. There has been a large body of work done on fluid flow in permeable membranes as it relates to RTM and VIP over the last 25 or so years. Papers such as [3] and [4] describe the 1-D and radial flow methods. We use the line-feed, 1-D flow method to determine permeability. Resin flow under these conditions is described using the integrated 1-D form of Darcy`s equation (1):

$$x(t)^2 = 2t\Delta PK/(\eta\phi) \qquad (1)$$

where x is the flow front position as a function of time, t is time, ΔP is the pressure difference across the part, K is the permeability, η is the resin viscosity, and ϕ is the porosity of the laminate. Using an experimental setup like the one pictured in figure 5, the flow front position is recorded as a function of time. Since we are using Polyworx in its "2.5D" mode (shell elements only, but the effects of gravity and part shape modelled correctly), only in-plane through-thickness-averaged properties are required. If a plot is made of the square of the flow front position versus time, a straight line plot should result with the slope equal to the remaining terms in equation (1) and because all the quantities are known except K, then it is simple enough to solve for K. If this plot is not a straight line, then there is some problem with the test panel. Usually near the beginning and the end of the infusion of the test panel, the flow characteristics are not properly described by equation (1), which manifests itself as a non-linear curve. The solution is to establish a best fit straight line through those terms in the middle of the test run that do exhibit the desired linear behaviour.

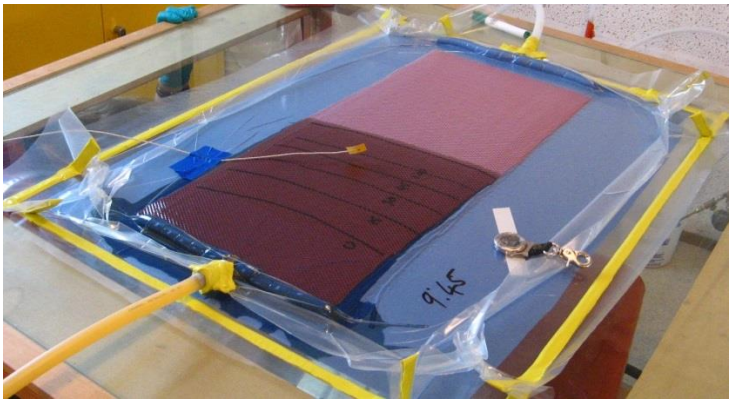


Figure 5: A typical permeability test panel setup.

There is one other term in the equation (1) that we usually don't know before the permeability test, and that is the porosity ϕ. The simplest way to determine porosity is to trim and weigh the completed panel after the resin has cured and compare this weight with the constituent weights of the fabrics or other reinforcements that make up the panel. The ratio of the constituent weights over the panel weight gives the volume fraction V_f, where the porosity ϕ is related to the volume fraction by:

$$\phi = 1 - V_f \tag{2}$$

Besides measuring the permeability and porosity, the small scale test panel is useful for qualitative examination of the flow characteristics of the proposed laminate. With the glass table shown in figure 5, the flow characteristics and through-thickness wet-out of the laminate can be examined.

3.5 Large Scale Test Panels

Once the material properties and qualitative flow characteristics have been established with the small scale test panels, the flow modeling proceeds as per section 3.1-3.3. If the part were small enough, one would test the flow model using the full scale part, but in our case, the part is too large to risk. Instead we did large scale testing. Usually the manifold design can be broken down into similar or identical units, in which case it is only necessary to test one unit or cell or a set of cells that best represent the whole. In our case a radial "pie" section from the center to the rim is all that is needed. Figure 6 shows the configuration of the test infusion. The test section chosen includes an area of the rim which had a slightly more complex manifold design (in figure 4 it is at about the 5 o: clock position). This test section is a good representation of the whole part. It has the same total height, and it has all the same features such as the 5 zones from the lower rim up to a piece of the central elliptical zone. In fact, because of the size of the lower zones or cells we did truncate the pie section, making the lower part of the radial edges parallel (this can be seen in figure 6). This modification to the main infusion model necessitated modelling the test panel separately so that we could directly compare the results from the large scale test with the model. Figure 7 shows a comparison between the flow model on the left and the actual test part infusion on the right. Clearly the resin fill pattern is essentially the same as the model. The results from this large scale test showed us a couple of important things. First, the general scheme of filling the part with rectangular edge-feed panels with a central vacuum does work with our laminate, and within the geometric accuracy that is possible with our

construction techniques. Second, the infusion time with the epoxy we have decided to use was quite a bit longer than modelled, in fact almost twice as long. This was most likely because this resin's viscosity increases markedly during its gel-time. A special non-isothermal reactive software model would take care of this. Alternatively, just knowing the difference between modelled and actual fill times on a test panel (that was large enough to represent the full scale part with sufficient accuracy), was all we needed to complete the job successfully.

Figure 6: Large scale test part on primary reflector mold. LHS flow model, RHS test part setup.

The large test panel is also a good practice run for your fabrication crew. It allows them to go through all the necessary steps for a large scale infusion project without risking the main part on the first go. Not only that, but in laying up the part you go through a trial run of laying down the laminates, flow medium, vacuum bag, etc., and you can check every step of the construction and infusion process.

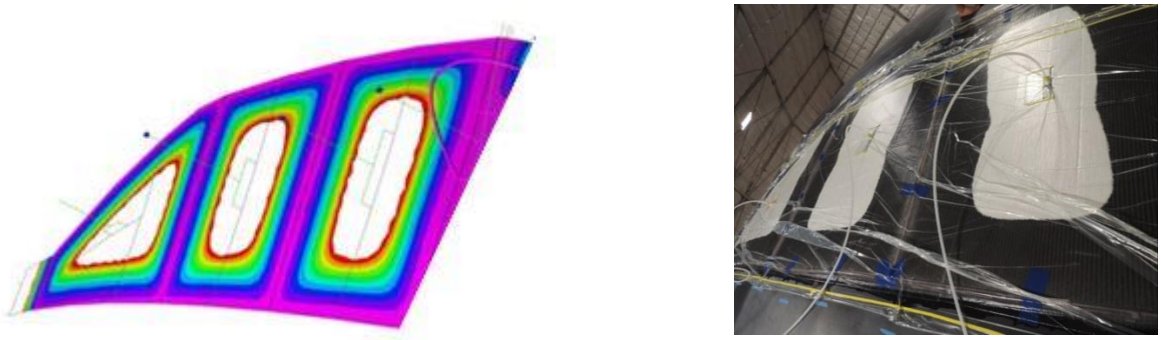


Figure 7: Large scale test part LHS flow model, RHS test infusion where black areas are wet-out.

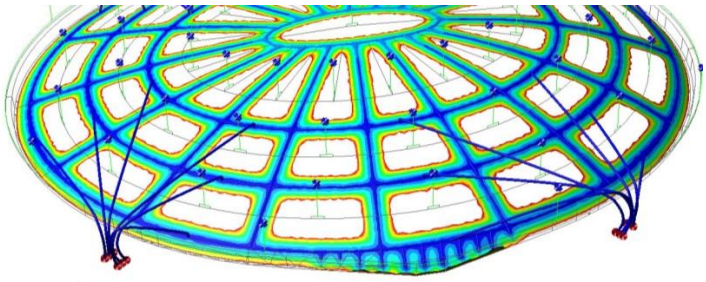
4 DVA-2 INFUSION

After extensive flow modelling and fabrication of test panels the actual part infusion went smoothly which of course was the goal. The crew was made up of the usual combination of well-trained infusion veterans and newcomers. All benefitted from an early morning briefing and dry run. In a production scenario, a resin mixing pump would be a better solution, but for this prototype mixing was done with drill mixers in roughly 15 litre quantities. The mixed resin was then poured into each of the four shallow resin trays that look somewhat like large paint roller trays (designed to keep the resin cool and to maintain sufficient resin depth over the feed inlets). As mentioned earlier, the important thing here is to mix enough resin to satisfy the immediate resin consumption and allow enough time

to mix the next batch before running out. Figure 8 shows one of the four resin delivery trays and resin mixing station.

Figure 8: Resin feed tray and mixing station (one of 4).

After the first ten minutes or so, the resin flow rate tapers off and the emphasis generally shifts to watching the resin fill pattern on the part and looking for vacuum leaks. Of course vacuum checks are done before the infusion and leak down rates and absolute vacuum levels are checked and the infusion not started until those values are well within range. Still, there are often a couple of small leaks which show up as either a bubble trail, or sometimes as an area where the part fill pattern starts to deviate from the modelled pattern. These leaks are typically around feed line bag penetrations, but could also be pin holes in the vacuum bag. Depending on the size of the part, a team of one or more crew members should be spending their time watching the infusion and repairing leaks if they occur. As noted earlier, the actual fill time of the large scale test part was found to be longer than predicted. This increase in fill time was corroborated by the infusion of the full scale part, but this difference doesn't manifest itself right away because the resin viscosity takes time to increase. Figure 9 shows a comparison between the flow model and the actual infusion at a point 12 minutes into the infusion. What should be reasonably clear is that the model and actual fill patterns are very similar as is the fill percentage. Over time, the actual fill percentage lagged behind that predicted by the model. This difference meant an adjustment in the gel time by a change to a slower hardener (as evidenced by the behavior of the large scale test panel), a simple change if done before the infusion, but a failed part otherwise.



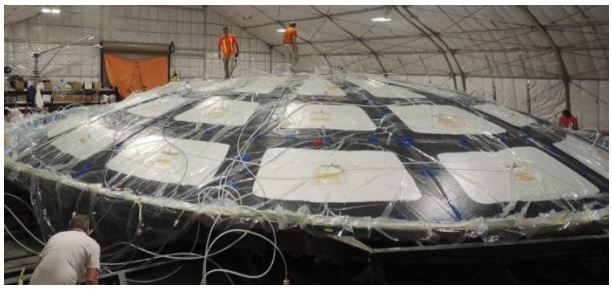


Figure 9: Full dish infusion at 12 minutes, LHS, model, RHS actual part.

Figure 10 shows the part near the end of the infusion. One hour has gone by since the valves were first opened and according to the flow model the part should be filled, yet there are still white "islands" around the vacuum ports. Only a few percent of the part remains to be filled, and it is now, near the end of the infusion, that the resin viscosity increase really makes itself felt. From this point until valves closed took almost one extra hour, and this is of course the critical hour when all of the modelling, testing, and preparations pay off. Also it is important to keep an eye on

the part, checking to make sure there are no vacuum leaks developing (i.e. because of feed lines pulling off from resin weight in the line, or from the exotherm as the resin starts to heat up). Also one needs to watch the resin levels in the resin trays, as air getting into the feed lines at any point will degrade the part. And lastly, if your manifold design is not the best, you could have excessive amounts of resin being drawn out of the part and into some of the resin traps. Plenty of parts have been ruined because of vacuum loss long after the infusion when resin traps fill with resin and block the vacuum or worse (i.e. resin getting sucked into the vacuum pump).

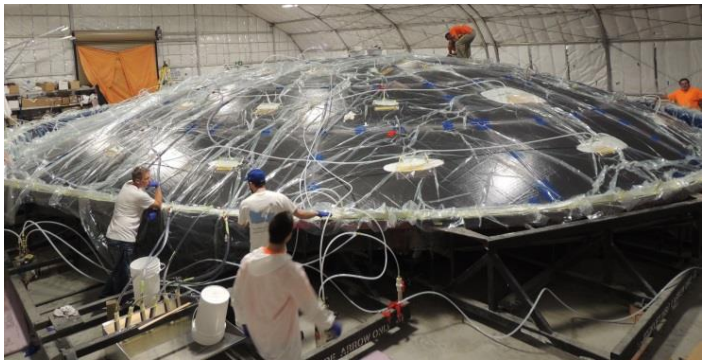


Figure 10: Sixty minutes into the infusion.

5 CONCLUSIONS

The VIP process has shown itself to be a very capable process for the manufacture of large composite structures. The practical maximum height is about 6m, but there are no real limits on horizontal size. The part quality and material properties are high, almost as high as for a pre-preg structure, but the setup and equipment costs can be kept quite low. The VIP process is very useful both for the fabrication of prototype parts, and with suitable modifications, for volume production.

The DVA-1 showed that it was possible to meet design specifications and build a 15m single piece composite reflector with world class performance. Surface measurements of the DVA-2 have not yet been made, but it is expected that this second reflector, through modifications in design, materials, and process, will meet the new design target for a surface accuracy approaching 200 microns RMS.

6 REFERENCES

[1] L. B.G. Knee, L. A. Baker, et-al "System performance testing of the DVA1 radio telescope". *Proc. Of SPIE*, Edinburgh, Vol 9906, 2016

[2] A. Koorevaar. "Simulation of Liquid Injection Molding", www.polyworx.com , 2002

[3] R.S. Parnas and A. J. Salem. "A Comparison of the Unidirectional and Radial In-Plane Flow of Fluids through Woven Composite Reinforcements". *Polymer Composites*, Vol. 14, No. 5, October 1993

[4] A. Hammami. "Permeability Assessment for the Vacuum Infusion Molding Process". *Proceedings of ICCM 13*, Beijing, 1059, 2001