

SELECTION AND VALIDATION OF A MINIMUM-COST COLD WATER PIPE MATERIAL, CONFIGURATION, AND FABRICATION METHOD FOR OCEAN THERMAL ENERGY CONVERSION (OTEC) SYSTEMS

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ABSTRACT

Ocean Thermal Energy Conversion (OTEC) can exploit natural temperature gradients in the oceans to generate secure baseload electricity free from global warming emissions, as well as fresh water. The #1 acknowledged challenge of constructing an OTEC plant is the Cold Water Pipe (CWP), which draws cold water from the ocean depths up to the surface, to serve as the coolant for the OTEC Rankine cycle. For a commercial-scale plant, the CWP is not only 1000m in length, but also is on the order of 10m in diameter.

This paper describes work done recently developing the advanced fiber composite CWP for Lockheed Martin's (LM) emerging OTEC line of business. The work started with deciding on the minimum-cost CWP architecture, materials, and fabrication process, adopting an overall approach of building an integral CWP down into the water directly from the floating OTEC platform. It then proceeded to a small-scale Proof-of-Principles validation of the innovative fabrication process. More recently, key elements of the process and apparatus have been successfully validated at a 4m/13 ft. diameter scale suitable for a future OTEC Pilot Plant. The validations have included assembly of sandwich core rings from hollow pre-pultruded "planks," accurate machine-based dispensing of overlapping strips of thick fiberglass fabric to form the lengthwise-continuous face sheets, and stepwise resin infusion/cure of 4m diameter workpieces, successfully obtaining a non-discernable knitline between successive infusions.

1. INTRODUCTION

1.1 Ocean Thermal Energy Conversion and its Cold Water Pipe

Development of OTEC systems (Figure 1) is underway at LM and elsewhere to meet worldwide needs for clean secure baseload electric power and potable water (Ref. 1). Its #1 acknowledged challenge is its huge Cold Water Pipe (Fig. 2) which must be 1000m (3300 ft.) long and is 10m (33 ft.) in diameter for a commercial plant. The principal load drivers (Fig. 3) are net external pressure (it is a suction pipe) and bending fatigue (from wave-induced pitching of the platform). Other key requirements include 30-year life, resistance to high pressures at depth, a slightly negative buoyancy, and minimum cost. An important additional (and dominant) requirement is

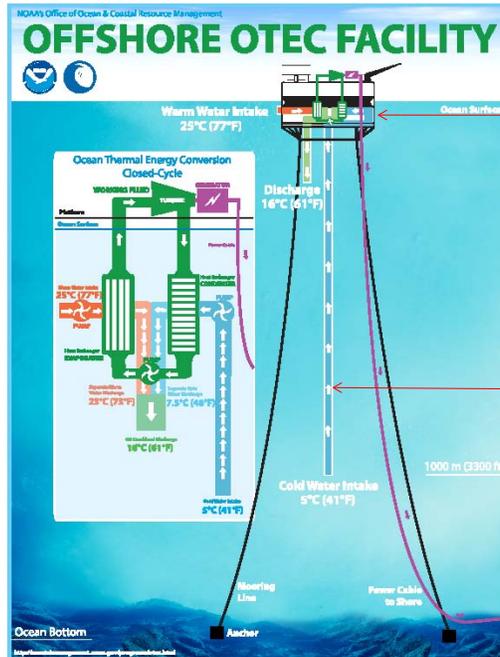
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Reference: Proceedings of SAMPE 2012, Baltimore, MD, May 2012. (This paper was awarded 2nd prize in the SAMPE Outstanding Paper Contest.)

minimization of the deployment risk for this huge pipe, and maximizing its structural durability since for thermodynamic reasons there is only one CWP for an OTEC plant. Minimizing recurring cost is especially important since OTEC is mostly a commercial undertaking.

In the OTEC Rankine cycle, warm surface water boils the ammonia working fluid, and cold water from the depths condenses the ammonia vapor back to liquid.

A floating platform is generally the preferred configuration, to minimize the total length of the Cold Water Pipe



Heat exchangers, turbines, pumps, and generators are above and just under the surface

The Cold Water Pipe extends down to the cold water layer located at 1000m depth, and carries the cold water to the surface

<http://coastalmanagement.noaa.gov/programs/otec.html>

Figure 1. An OTEC plant and its major components

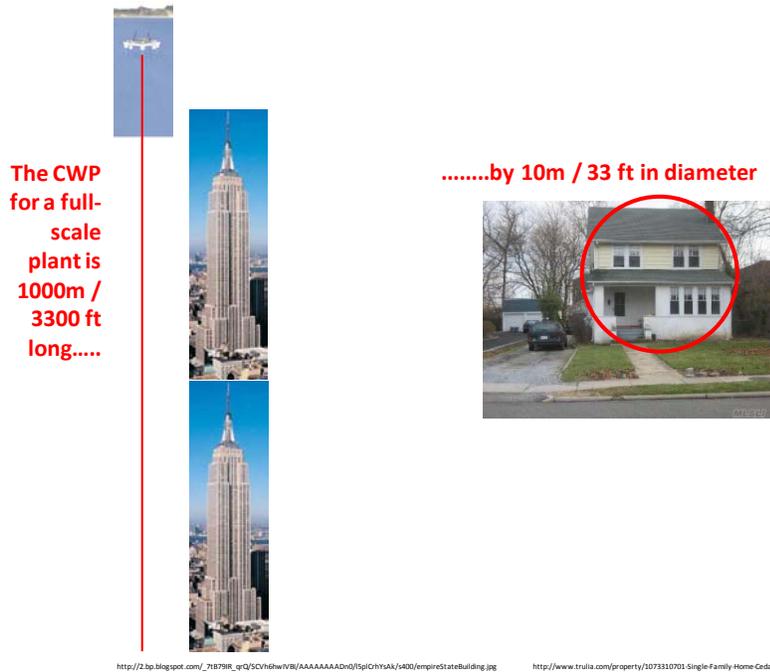


Figure 2. The Cold Water Pipe is (literally) the single biggest challenge of OTEC.

CWP must survive:	System-level origin	Analysis status
Bending fatigue*	Wave-driven platform motions	OK
Net external pressure*	Internal suction from pumps	OK
Localized external pressure *	Grippers and bushings	OK
Axial strain	Clump weight	OK
Static bending	Currents	OK
High water pressure*	1000m length	OK
Seawater corrosion*	30 years immersed	Material heritage OK

*Principal design and material drivers

Figure 3. Cold Water Pipe Structural Requirements with analysis status

1.2 Scope of this paper

This paper starts with the system-level requirements for the Cold Water Pipe, and addresses how the specific configuration, materials, and fabrication/tooling method were selected as the minimum-cost solution (Fig. 4) that meets these requirements. A Proof-of-Principles demonstration, described elsewhere, was undertaken successfully to prove out these and other key elements of the approach at small (0.5 m, 19 in. diameter) scale.

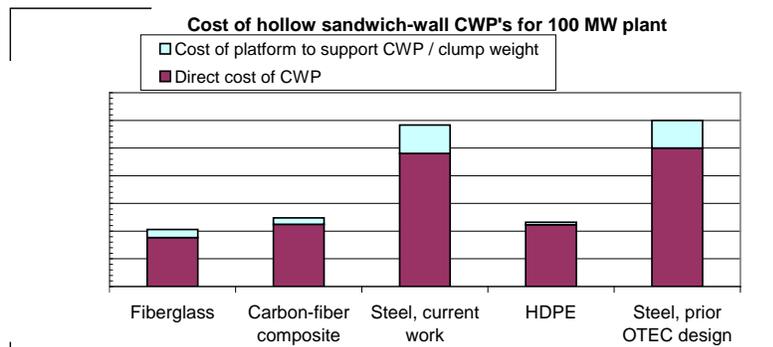
The main focus of this paper is to describe the subsequent scale-up, specifically the validations of key elements of the approach that were undertaken and accomplished at the 4m (13 ft.) diameter pipe scale that is necessary for an OTEC Pilot Plant. These validations have included fabrication of the hollow sandwich core that is assembled from pultruded “planks,” and design, fabrication, and performance testing of both the fabric dispensing apparatus and the molding region. The paper contains many photographs illustrating the work.

1.3 For further details

This paper is an overview of the work done. Many further details can be found in the Final Technical Report for the US Dept. of Energy program that supported the work, available at the following URL:

<http://www.osti.gov/bridge/servlets/purl/1024183/1024183.pdf>

Primary basis for selecting the current CWP materials: Recurring cost (materials and fabrication labor) of a minimum-cost design of a 10m CWP for 100 MW plants, in materials not **eliminated by technical show-stoppers**



Requirements met:	Fiberglass	Carbon-fiber composite	Steel	HDPE
External pressure	Yes	Yes	Yes	Yes
WIM cyclic strain	Yes	Yes	No	Yes
WIM axial buckling	Yes	Yes	Yes	Yes
VIV cyclic strain (without strakes)	Yes	Yes	No	Yes
Streaming and clump weight axial	Yes	Yes	Yes	Yes
Platform rotation	Yes	Yes	Yes	Yes
Manufacturable in low-cost configuration	Yes	Yes	Yes	No

Fiberglass and carbon-fiber composite are the two surviving candidates. They have similar net costs and can be fabricated by the same methods. Fiberglass was chosen to simplify galvanic corrosion issues and to avoid near-term supply issues in the carbon fiber marketplace.

Figure 4. Primary basis for selecting the current CWP materials

2. COLD WATER PIPE ARCHITECTURE, MATERIALS, SIZING, AND FABRICATION/TOOLING METHODS

To meet the requirements on net external pressure, local pressure at depth, and net buoyancy the pipe architecture is a sandwich with a hollow pultruded core (Fig. 5). The core is fabricated from discrete “planks” assembled into discrete “core rings”, but the face sheets are longitudinally continuous strips running continuously down the length of the CWP. Adjacent strips of fabric are joined by distributed overlap splices to make the face sheets circumferentially continuous. Structurally, this architecture forms an integral one-piece CWP with no joints in the main load-bearing face sheets, thereby maximizing durability and reliability.

Construction: Sandwich wall with hollow vented core

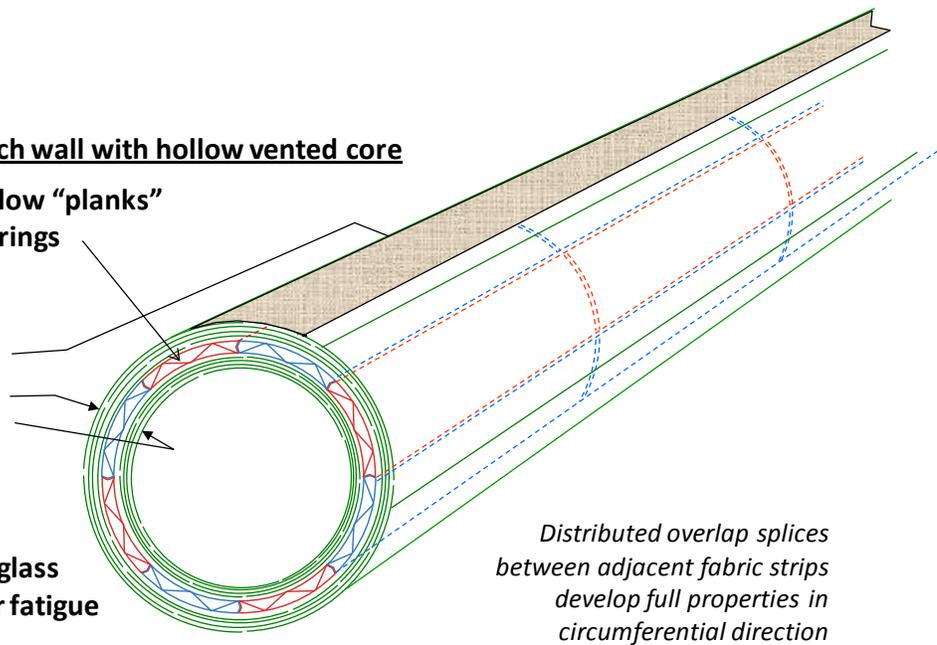
- Core: Pultruded hollow “planks”
- assembled into core rings

- Face sheets: Longitudinally continuous fabric strips, applied over assembled core rings

Materials

- Low-cost X-Strand¹ glass fibers having superior fatigue resistance
- Derakane 8084² toughened vinyl ester resin matrix having very little water absorption

1. Product of Owens Corning Technical Fabrics
2. Product of Ashland Chemicals



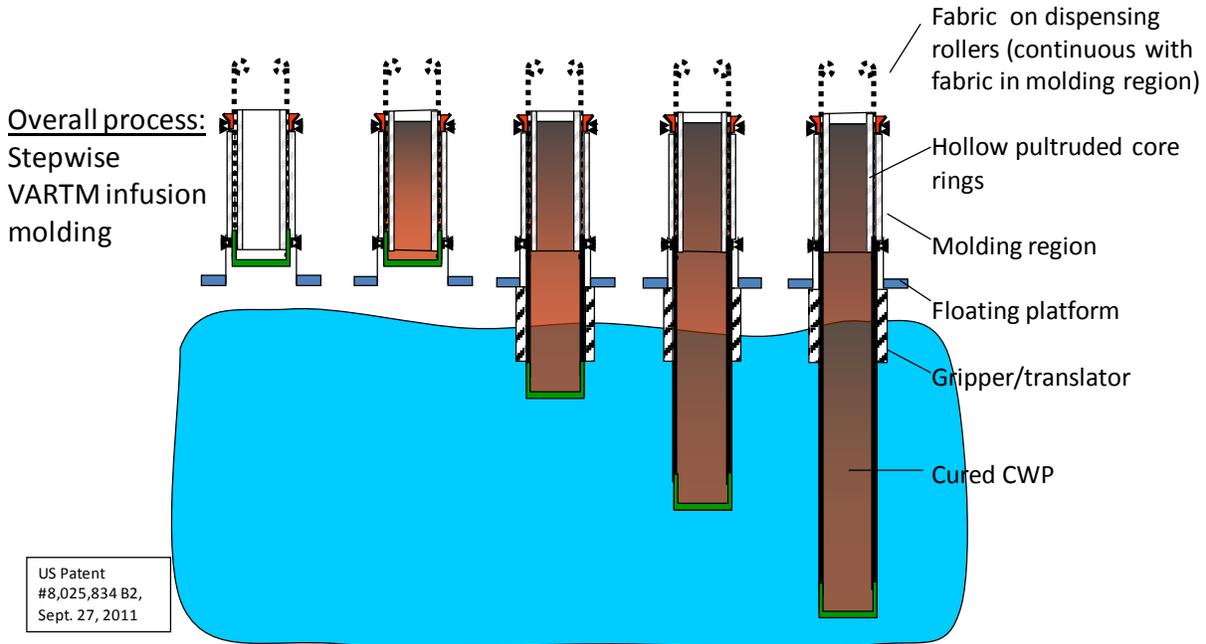
Integral one-piece CWP with no joints in the main load-bearing face sheets maximizes durability and reliability

Figure 5. Advanced fiber composite CWP architecture

Equations representing all of the quantifiable requirements were put into a preliminary design optimization program, which then automatically selected the minimum-cost core configuration, panel thicknesses, and fiber orientation distribution. It is these costs that are compared in Figure 4 as the basis for selecting the minimum-cost solution.

To minimize deployment risk, the CWP is fabricated in steps directly from the OTEC platform, vertically down into the water (Fig. 6). This eliminates the very-large-scale handling, assembly, and upending processes that have been the bane of a number of previous attempts to construct

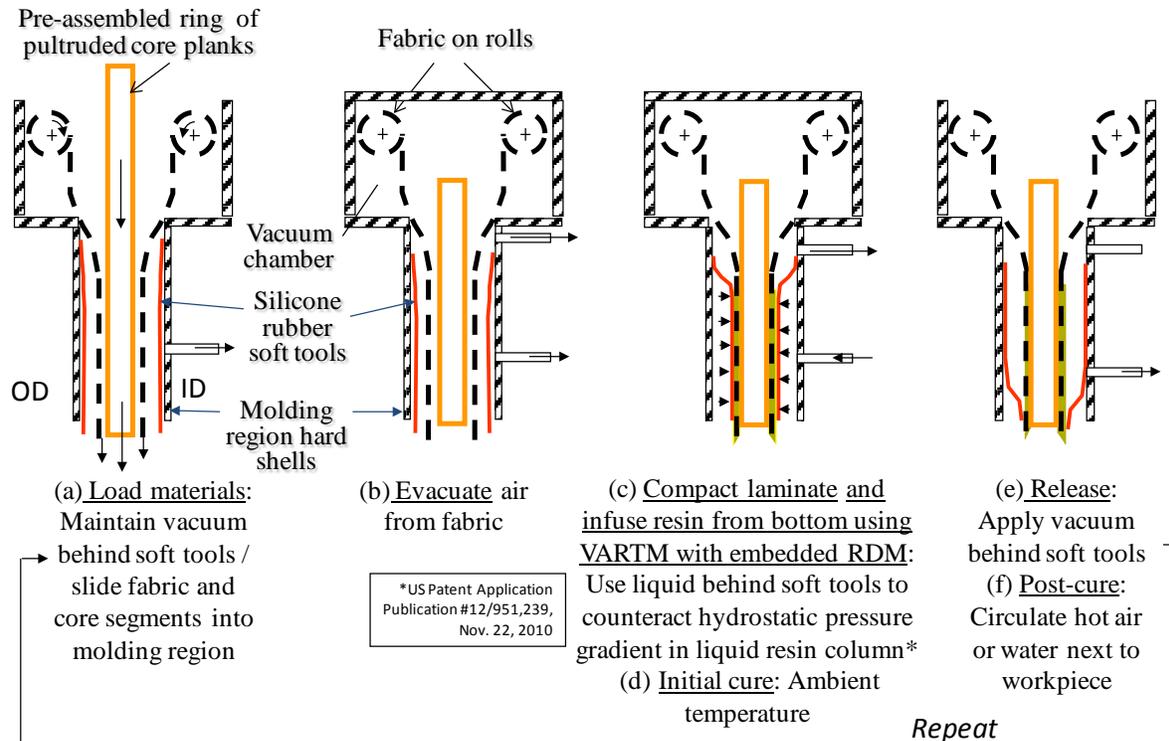
OTEC plants. During each step, only a local portion of the CWP is infused with resin, but the fabric is continuous from step to step, forming the essentially one-piece CWP without structural joints, maximizing durability.



Fabrication off of the platform eliminates major deployment challenges, enables integral fabrication of huge pipe, reduces transportation costs

Figure 6. High-level fabrication strategy – Manufacture the CWP directly off the floating platform

The selected fabrication process is stepwise infusion molding (VARTM), with the resin being infused into a local portion of the dispensed face sheet fabric at any one time. Figure 7 provides a concept-level illustration of the key operations in the infusion process. In (a), the fabric for the next infusion step (along with the corresponding core) is drawn down into the molding region by the vertical motion of the gripper on the already-cured portion of the CWP. The soft tools are pulled back against the hard shells by vacuum during this operation. In (b), the vacuum chamber surrounding the fabric rolls is sealed and vacuum is pulled, evacuating the air from all of the fabric and compacting the fabric onto the core.



Stepwise VARTM process enables fabrication of a 10m diameter, 1000-m long one-piece CWP

Figure 7. CWP processing steps using VARTM (Cross-section through left side of apparatus)

In (c), liquid is introduced behind the soft tools to compensate for what will be a hydrostatic pressure gradient in the liquid resin when it is infused. This enables VARTM of very large vertical steps, much taller than the roughly 5 m (15 ft.) that is the usual limit with VARTM. This is the key to being able to fabricate a 1000 m CWP in a reasonable number of steps. The catalyzed resin is introduced from the bottom of the dry fabric, and the infusion is stopped when the resin reaches the proper height. The resin is allowed to cure at room temperature, (d).

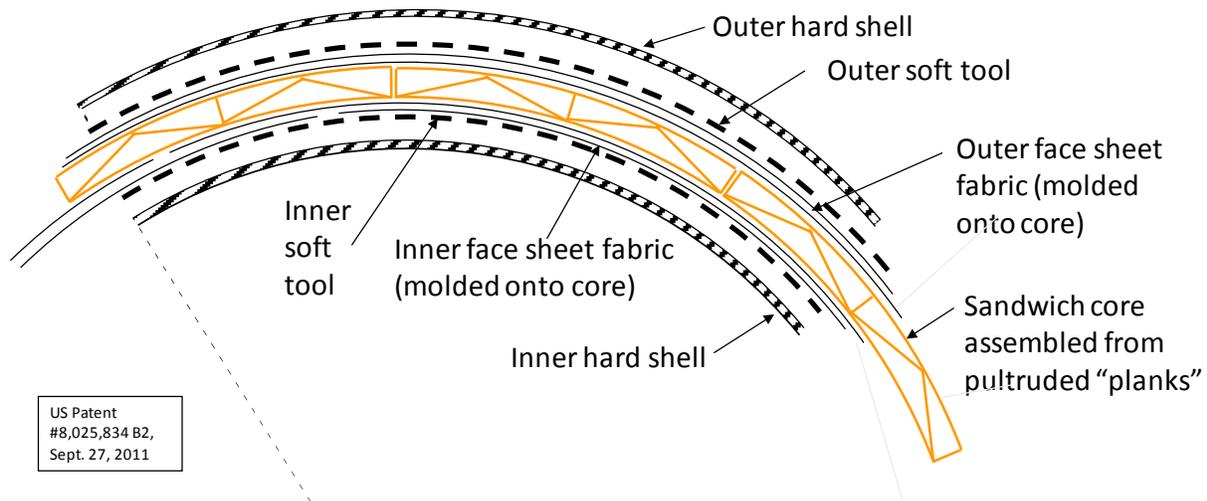
Finally, in (e) the vacuum on the workpiece is released and vacuum is applied behind the soft tools, to pull them away from the workpiece. If necessary, hot air or hot water is then circulated in order to post-cure the workpiece and confer maximum seawater corrosion resistance.

To make a full-length 1000 m long CWP, this process is repeated for a total of roughly 175 steps at roughly 5.7 m (19 ft.) per step.

Figure 8 illustrates the tooling concept. Since the cured portion of the CWP must move downward within the molding region, it is very advantageous to be able to have the resin containment surfaces move away radially from the workpiece on both the inside and the outside. This is done by having the resin containment surfaces be conformable “soft tools” (re-usable silicone rubber vacuum bags). The hard shells support the apparatus and also form the

containers and pressure reaction surfaces against which vacuum or pressure react in order to manipulate the soft tools during various phases of operation.

Since the resin containment surfaces are soft, some element is needed to actually define the shape of the workpiece, and this is done by the rigid cylindrical core that is assembled from pre-fabricated planks as part of the CWP manufacturing process.



- Outer and inner soft tools pull away from workpiece to allow axial insertion of new workpiece material (core and fabric), then press towards workpiece during molding operations.
- Outer and inner soft tools present smooth faces to part during cure, then release easily
- Outer and inner hard shells become containers which allow fill behind soft tools with a liquid, enabling VARTM of very tall workpieces.

Figure 8. Tooling concept: Use pre-fabricated pultruded sandwich core as a “flyaway tool” that defines the shape of the workpiece. Silicone “soft tools” (re-usable vacuum bags) compact the face sheet fabric against the outside and inside of the core.

3. DESIGN OF THE LARGE-SCALE COLD WATER PIPE FABRICATION APPARATUS

Under the US Dept. of Energy’s “Advanced Water Power Program” (AWPP) which is advancing the technology for renewable energy from the oceans, the concepts proven out at the Proof-of-Principles stage were implemented into a large-scale apparatus design. This design is summarized in the solid model illustration at the left of Figure 9, key elements of which (Figure 9, right) were then validated under the DoE program. Design of each of the validated elements is more fully described in the sections that follow.

Design configuration of large scale apparatus

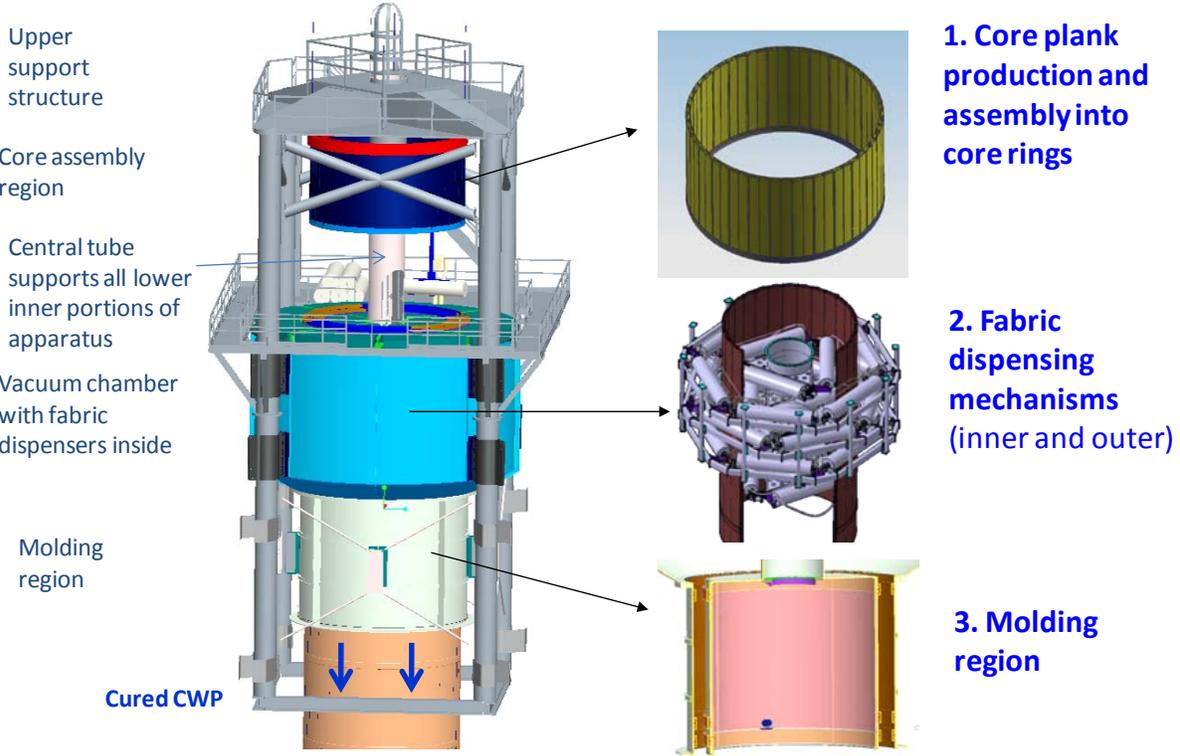


Figure 9. Major apparatus elements selected for validation at 4m CWP scale under the DoE program

4. VALIDATION AT THE 4M/13FT. DIAMETER SCALE

The most critical elements of the design and fabrication process have recently been validated at the 4m (13ft.) diameter scale needed for LM's future OTEC Pilot Plant. These elements include (1) production (in a factory) of the hollow pultruded core planks, and Core Assembly (Figure 9, upper right) which takes place above the vacuum chamber; (2) accurate machine-based Fabric Dispensing from a series of fabric rolls (Figure 9 middle right); and (3) the stepwise infusion molding process (Figure 9 lower right) which takes place inside the Molding Region. The remainder of this paper describes these validations.

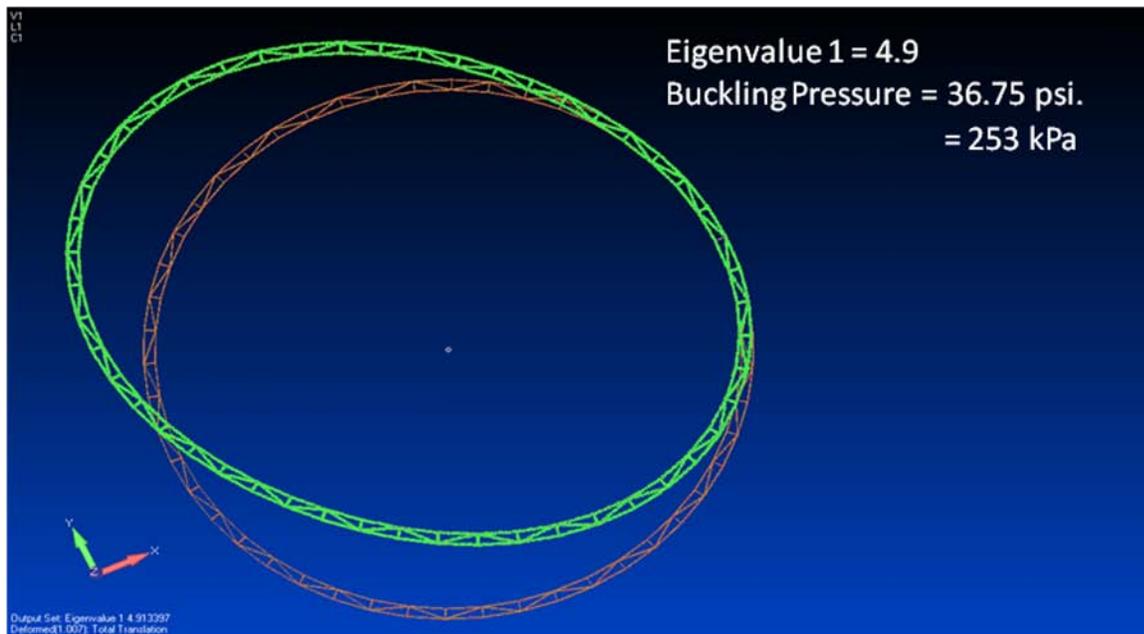
4.1 Core plank production and assembly into core rings

The core of the CWP performs two major functions: (1) In service, it is the structural core of the sandwich-wall pipe, conferring buckling resistance under external pressure (and bending) loadings. (2) During fabrication, it serves as the element that defines the shape of the CWP, allowing the rest of the fabrication apparatus to consist of "soft tooling" which then can be moved radially inward and outward by air pressure and vacuum as appropriate during the various phases of each fabrication step.

4.1.1 Materials and configuration

The core of the sandwich-wall CWP utilizes the same basic materials as the face sheets (fiberglass laminate with vinyl ester resin) in order to gain their durability under long-term seawater exposure, and durability at the high pressures experienced at depth. The core is hollow in order to gain a good overall section thickness to confer adequate buckling resistance of the sandwich, while minimizing the materials cost, mass, and wet weight of the CWP. By venting the bottom of the interior of the hollow core to seawater and ensuring that the hollow spaces are continuous from bottom to top, the local seawater pressure inside the core equals the local external seawater pressure, eliminating what would otherwise be an insurmountable net pressure difference that would crush the core.

The triangular shape of the core cells confers good buckling resistance (Figure 10) under the negative net internal pressure that is unavoidable when the CWP pumps are located on the OTEC platform. Other heritage hollow-core shapes, such as the trapezoidal core developed by LM for fiber composite highway bridges, collapse easily under net external pressure (at least, they do on the computer) because the quadrilaterals form “mechanisms.”



Sandwich architecture with triangular core cell design survives external pressure loadings with a large Margin-of-Safety

Doug Hillson

Figure 10. One key analysis -- External pressure buckling

The core is fabricated as constant cross-section “planks” (Fig. 11) by pultrusion, in this work by Glasforms, Inc. For the Pilot-Plant scale CWP, these planks are about 89 mm (3.5 in.) thick and about 508 mm (20 in.) in width. The main structural fabric in the planks utilizes the same fiber and fiber orientation distribution as the CWP face sheets, in order to avoid any mismatch stresses

that would otherwise occur due to differences in elastic constants between core and face sheets. The planks use a vinyl ester resin similar in its seawater resistance to the Ashland 8084 resin used in the face sheets, but better optimized for the pultrusion process.

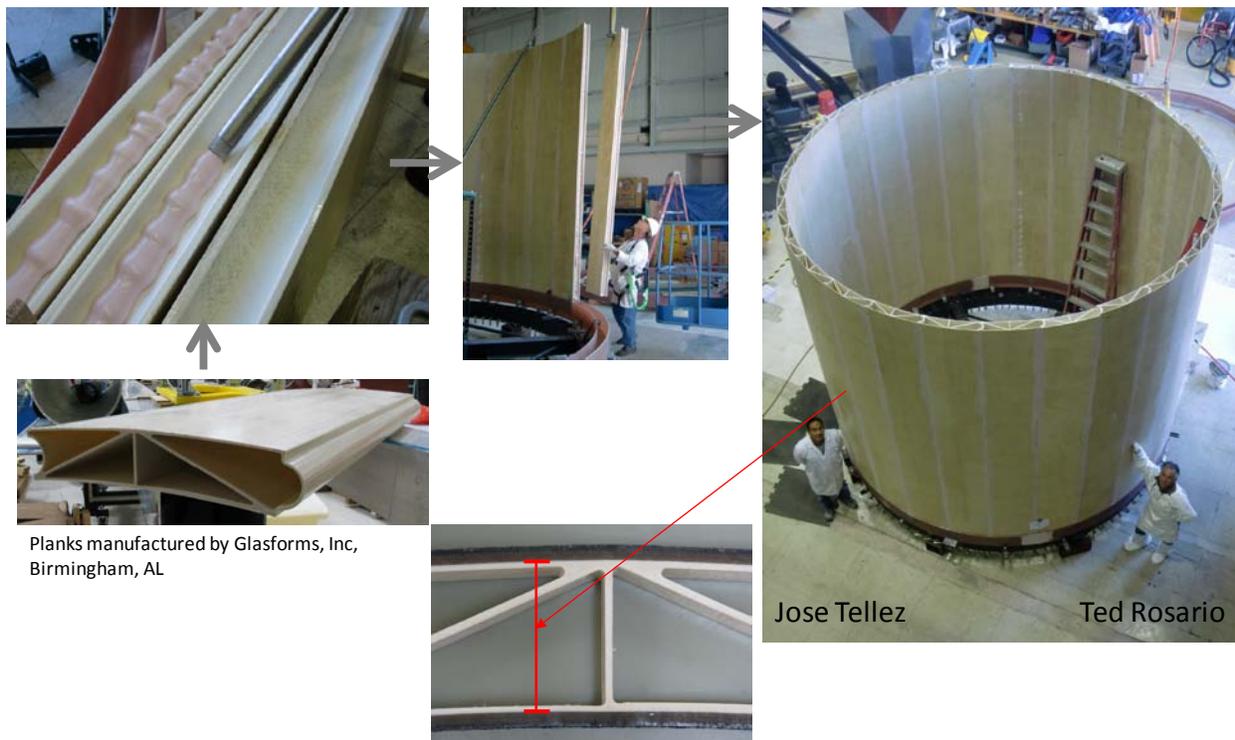


Figure 11. Core plank production and assembly into core rings -- First assembled core ring

4.1.2 Assembly into core rings

The planks include tongue-in-groove features along their edges in order to enable joining them together by simple adhesive bonding into complete core rings, using a thick putty adhesive dispensed from commercial equipment designed for such adhesives. Dispensing of the adhesive proved very straightforward, as did handling and assembly of the large planks in a vertical orientation. The hollow shape of the core planks kept them very straight, and there were no difficulties mating adjacent planks together. Even popping the last few tongue-in-groove planks into place was a simple operation, despite skeptics who thought otherwise. Photos from these operations as well as one completely assembled core ring are shown in Fig. 11, which also (center bottom) illustrates the pultruded core surrounded by inner and outer face sheets as in the full CWP.

Diameter measurements on the workpiece shown in Fig. 11 showed that the diameter was accurate to within ± 6 mm (± 0.25 in) over the 4m (13 ft.) size. This accuracy is more than adequate for the subsequent CWP fabrication process, see below.

Accordingly, the core plank production and assembly processes are deemed to have been validated at this large scale.

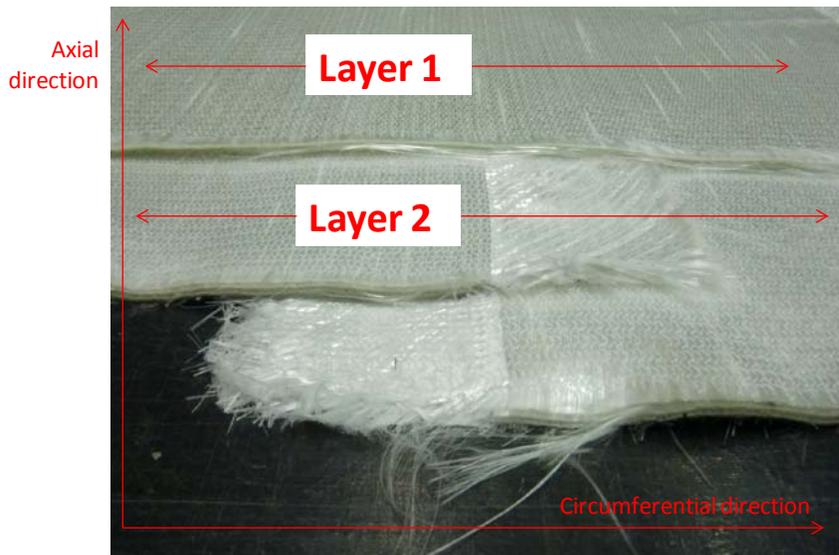
4.2 Fabric architecture, fabric production, and dispensing process

As was illustrated in the concept sketches, in the CWP fabrication process the fabric starts out as large rolls of fabric positioned above the molding region. Fabric is pulled off of the rolls and onto the CWP core as the CWP is moved down by the gripper in between fabrication steps. As it is pulled into place, it must form the overlap splices which, after resin infusion, make each face sheet into the structural equivalent of a face sheet that has circumferentially-continuous fibers.

4.2.1 Face sheet fabric architecture and production validation

The face sheet fabric is dispensed as thick “preform” layers from a set of rollers (seen in Figure 9) located below the Core Assembly Region, above the Molding Region, and inside the vacuum chamber. Each preform layer of fabric must be dispensed from a separate group of rollers, and to minimize apparatus complexity and height, the Pilot Plant face sheets have been divided into only two preform layers (Figure 12). Each preform layer is about 3 mm (0.120 in.) thick, and is fabricated by standard stitching assembly from three layers of 1 mm (0.040 in.) thick face sheet fabric produced on standard non-crimp stitching equipment. The fabric was manufactured by Owens Corning Technical Fabrics.

- Each face sheet is divided into two major layers (preforms) of stitch-assembled face sheet fabric
- Within each layer, the individual fabric rolls are joined by overlap splices.
- Fabric is continuous in the lengthwise direction, except for occasional distributed local overlap splices required for fabric roll replenishment during manufacturing of the full CWP.



Fabric details for 4m CWP

- 6 rolls at <100” (2540 mm) wide each cover the circumference of the CWP
- Each preform layer is 0.120” (3.05 mm) thick
- Preform fabric was stitch-assembled by Owens Corning from 3 plies of custom stitched X-Strand fabric
- 0’s are left out of the last 3” (76 mm.) along each edge
- 75% 0’s (axial)
- Balance 90’s and 45’s

- Architecture creates generous overlap splices for carrying the circumferential loads
- Splices in each major layer are reinforced by continuous fabric in other major layer
- By leaving out the zeros in the overlap splices, the thickness increase at the splices is minimized

Figure 12. Face sheet fabric architecture

4.2.2 Splices between adjacent rolls of preform fabric

Within each preform layer, the individual fabric rolls are joined by overlap splices. The scheme is illustrated in Figure 12. The axial direction of the CWP is defined as the 0 direction. The minimum-cost solution described in Figure 4 has 75% 0 degree fibers with the balance being divided between 90 degree fibers (circumferential) and +/- 45's. Since the splices bear load predominantly in the circumferential direction, there is no gain by having an overlap of 0's within the splices, and eliminating the double layer of 0's eliminates what would otherwise be a substantially increased local thickness. A 152 mm (6 in.) overlap splice is thereby created by leaving out the 0 degree fibers in the outer 76 mm (3 in.) on each edge of the fabric. Splices in each preform layer are reinforced by the continuous fabric in the other preform layer, as shown in Fig. 12. Figure 13 shows a test specimen made with this configuration, and the additional thickness at the splice is barely discernible, and of no practical consequence.

Fabric is continuous in the lengthwise direction, except for occasional distributed local overlap splices required for fabric roll replenishment during manufacturing of the full CWP.

4.2.3 Validation of fabric overlap splice strength

Figure 13 shows results from a local buckling test (done by Makai Ocean Engineering under a US Navy program) on a sample of Pilot-Plant sized CWP, run primarily to validate the model used to design the CWP for adequate buckling behavior under the forces that will be present locally at grippers and bushings in the overall design. In the test, both face sheets, including a splice in each one, were loaded by radial compression of the outer face sheet while constraining the ends to move only in the radial direction. This puts the face sheets in circumferential compression. The specimen failed away from the splices, which held the required loads. This test thereby provides an early validation of the overlap splice fabric architecture.

*Local pressure buckling test on section of 4m CWP
(Dominant loading on face sheets is circumferential compression)*



The specimen failed away from the splices. The splices held the required loads.

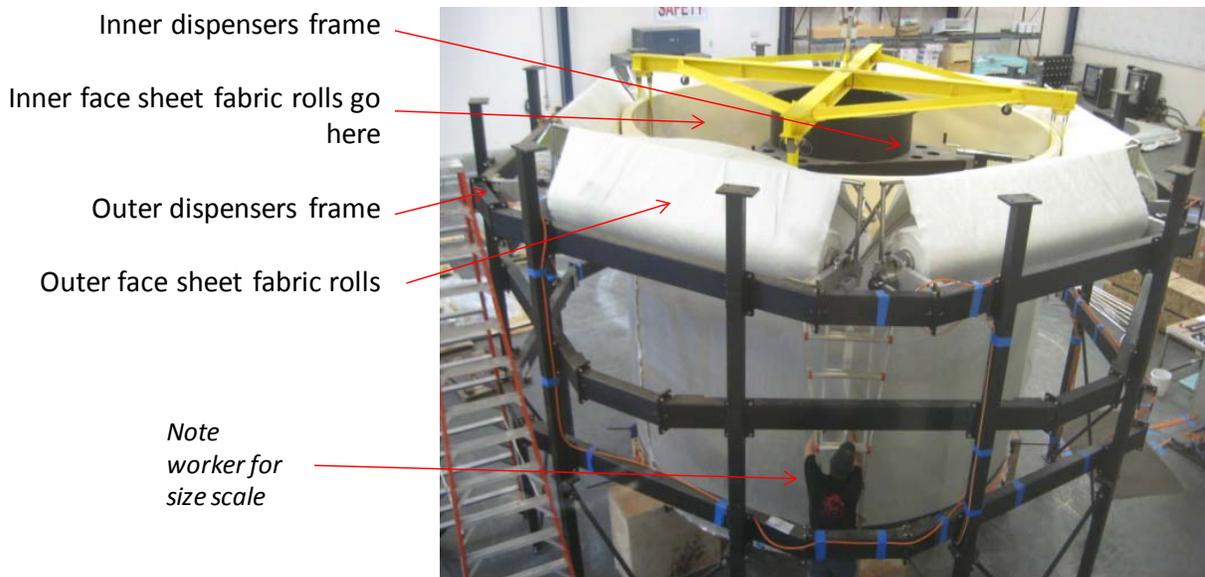
Makai Ocean Engg.

Figure 13. Validation of fabric overlap splice strength

4.2.4 Fabric dispensing process and its validation

4.2.4.1 Fabric dispensing apparatus

Figure 14 shows the outside of the fabric dispensing apparatus at 4m (13 ft.) diameter scale, set up for validation of outer face sheet dispensing. The overall support structure is a set of axial posts spanned by circumferential beams to which the fabric dispensing mechanisms are attached. To minimize costs, only one group of six fabric roll mechanisms was fabricated, and they were used at different times to test both the inner and outer dispensing behaviors. The mechanisms contain a servomotor at one end, which can maintain constant tension in the fabric over a wide range in externally imposed payout velocities (as in a gripper pulling the CWP down at an arbitrary speed). The servomotors can apply braking when the fabric is stationary, to maintain tension in the dispensed fabric.



Detailed design and fabrication of apparatus by
Janicki Industries, Sedro-Woolley, WA

Janicki Industries photo

Figure 14. Fabric dispensing apparatus (during validation of outer face sheet dispensing)

A key part of the dispensing apparatus on both outside and inside are the curved guides (see Figure 15) which change the path of the fabric from a flat plane emerging from the fabric rolls, to a cylindrical plane adjacent to the CWP core. The shapes of these guides were specially designed in order to spread the fabric turning forces over the entire width of the fabric, eliminating what could otherwise be wrinkling or other damage of the fabric.



Janicki Industries photo

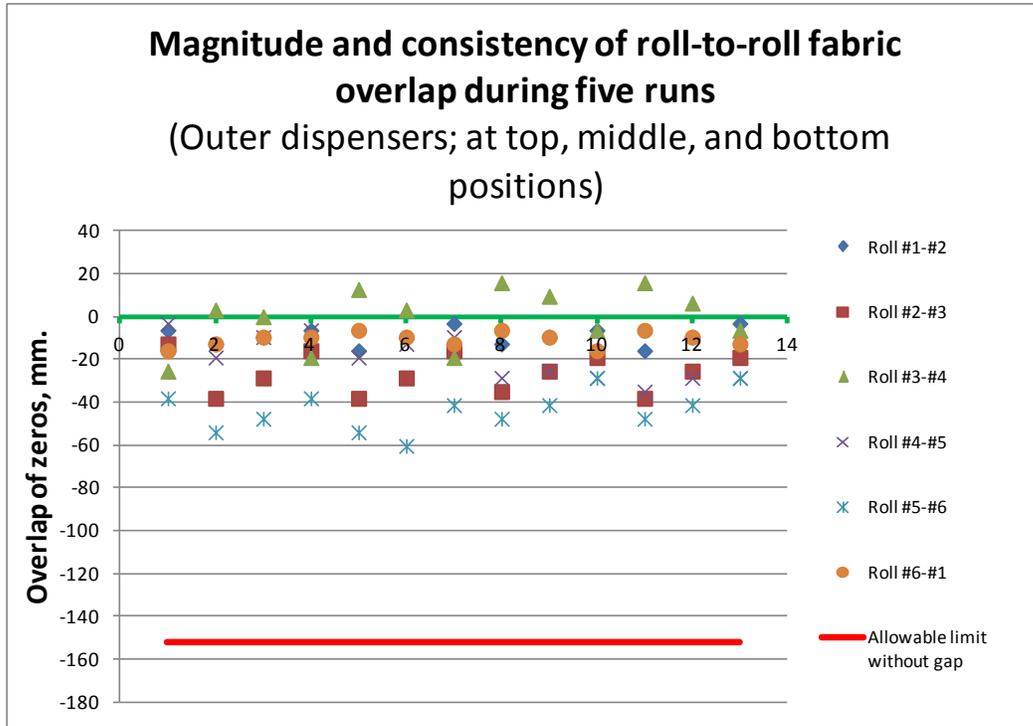
Figure 15. Outer fabric dispensing, with formation of typical overlap splice

4.2.4.2 Formation of overlap splices

Figure 15 shows formation of a typical overlap splice. The outer fabric servomotors (at one end of each roll) and non-driven bearing housing (at the other end of each roll) are seen at the top, and the outer fabric guides are seen at mid-height in the photo. The overlap splice formed by these two rolls as they come together on the core is seen in the lower half of the photo.

4.2.4.3 Validation of fabric dispensing accuracy

To validate the fabric dispensing accuracy in this limited-height workspace, fabric was pulled off of the six fabric rolls (outer rolls in this case) by vertical movement of the core to which the bottoms of the six fabric ends were attached. The overlap of the zeros was measured, with 0.00 being defined as having the edges of the 0's in the two adjacent rolls be just adjacent to each other, as was shown in Figure 12. A positive overlap means the 0's are overlapping, and a negative overlap means there is a gap between the zeros. A negative overlap of 152 mm (6 in.) (red line) would be the point at which the two strips of fabric are no longer in contact. As can be seen from the results in Fig. 16, the accuracy of the process is such that the deviation from perfect positioning is a small fraction of the deviation at which the two pieces of fabric would no longer have an overlap. Accordingly, the fabric architecture, production, and dispensing process have been validated at this large scale.



- The apparatus forms consistent overlap splices, well within required tolerances.
- The fabric dispensing apparatus is validated.

Figure 16. Validation of fabric dispensing accuracy

4.3 Stepwise infusion molding process

If there is a “heart” of the CWP fabrication apparatus, it is the Molding Region. Here is where the resin is infused using the VARTM process, into the fabric that has previously been placed and compacted against the core. Because the top of each infusion step must be structurally continuous with the bottom of the next, particular attention has been paid to the details that control the quality of the “knitline” that forms between them. Advantage is taken of the fact that infusion of exactly the same geometry is performed repeatedly during CWP fabrication, to design the vacuum bags and resin distribution lines as re-usable elements instead of the usual expendable process materials.

4.3.1 Molding Region apparatus elements and subsystems

Figure 17 shows a solid model of the molding region, calling out its key major subsystems. The large grey cylindrical surfaces are the inner and outer hard shells which form the structure of the molding region, and also form reaction surfaces enabling pressure or vacuum to be applied to the inner and outer soft tools. Towards the bottom are the inner and outer Re-Usable Resin Distribution Lines (RURDL) which will be described subsequently. At the very bottom are double inflatable seals, which allow pulling vacuum on the fabric section being infused and

processed, while that fabric is attached to the cured CWP previously processed. Toward the top are inner and outer centering rings which both position the not-yet-cured portion of the workpiece properly in the apparatus, and help separate various regions that are under different gas pressures.

Figure 18 provides an indication of the size scale at which this work has been done to date. This molding region (after vertical extension) is intended to be used in the future Pilot Plant.

Figures 19 and 20 show photos of some of the elements of the Molding Region, including the inflatable lower seals, the inner and outer soft tools installed on their respective hard shells, the inflatable upper centering rings and seals, the Re-usable Resin Distribution Line (RURDL), and the video camera ports with LED lighting inside the apparatus, for monitoring of the flow front height during infusion.

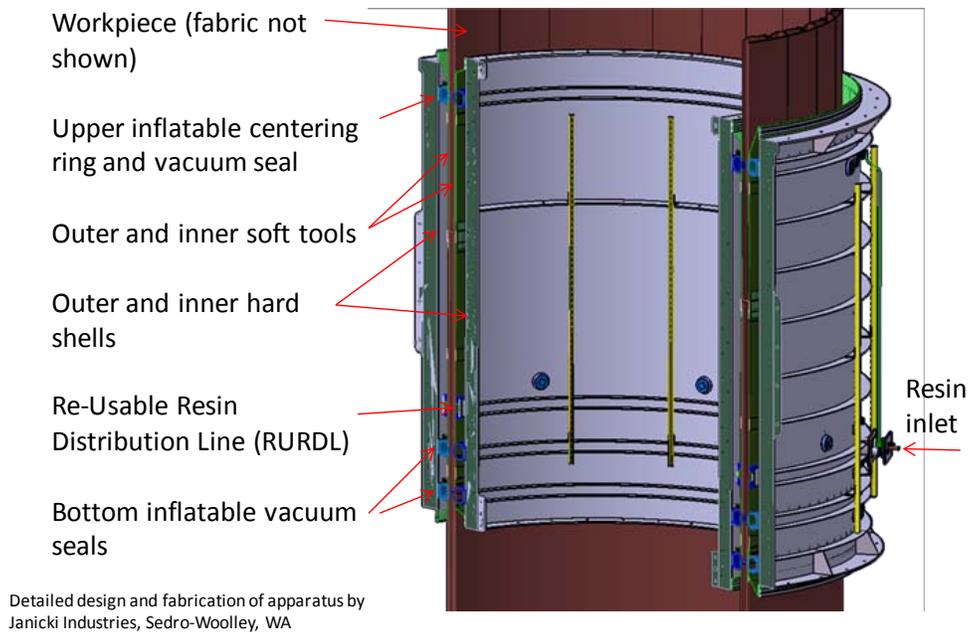
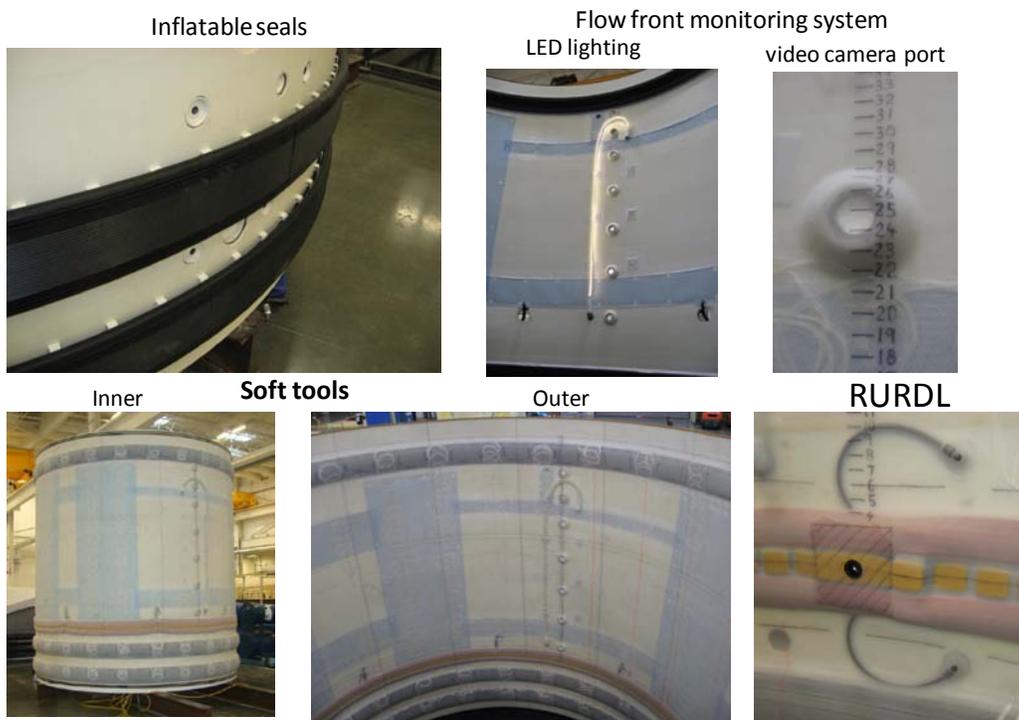


Figure 17. Stepwise infusion molding process -- Molding Region apparatus elements and subsystems



(Nat Shankar, Matt Ascari, Alan Miller, Ted Rosario)

Figure 18. Molding region in LMSSC B/132, Sunnyvale



Janicki Industries photos

Figure 19. Some elements of the Molding Region

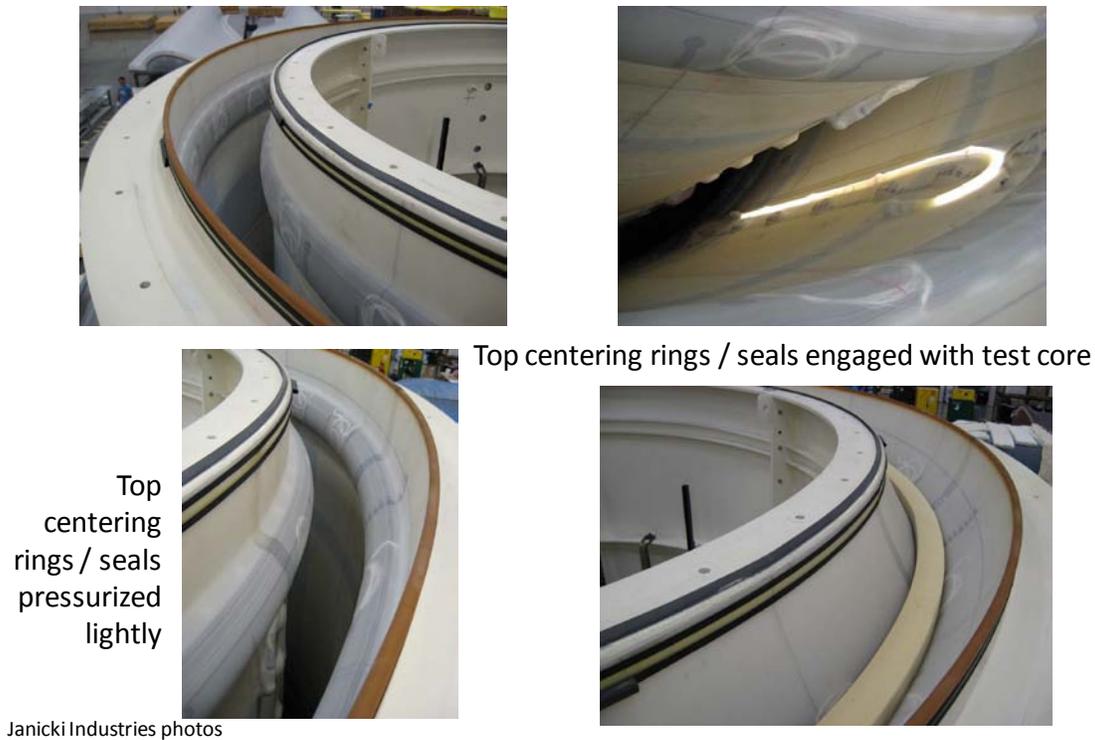


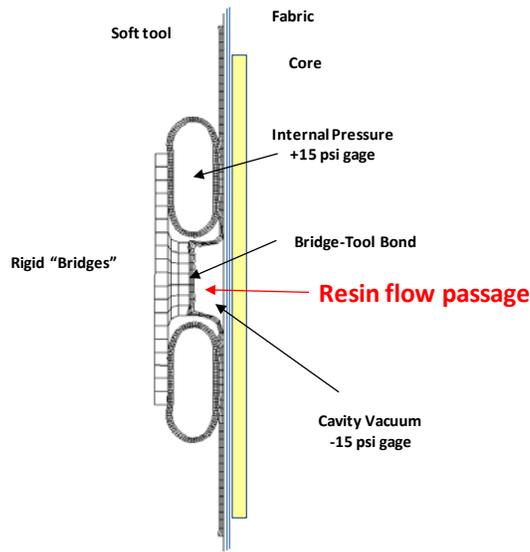
Figure 20. Apparatus assembled and soft tools drawn back by vacuum

4.3.1.1 Re-usable Resin Distribution Line (RURDL)

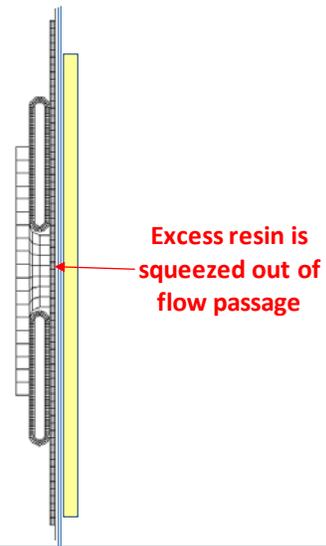
As mentioned above, in “ordinary” VARTM the RDL is expendable, and must be installed during bagging before every infusion and stripped away from the workpiece after cure. Such operations would be burdensome when repeated perhaps 175 times for fabrication of a 1000m CWP using steps that are 5.7 m (19 ft.) long. Figure 21 shows the Re-usable Resin Distribution Line (RURDL) that was invented to solve this problem. There are an inner RURDL and an outer RURDL.

Each RURDL operates by pulling a local portion of its soft tool away from the workpiece, thereby forming a temporary resin flow passage of sufficient size to transport the resin quickly around the circumference of the CWP. This action is accomplished by means of two inflated tubes bonded to the soft tool, with a rigid set of bridges spanning in between the two air tubes. The resin enters this passage at only one circumferential location, namely at the resin inlet line (RIL). As infusion is completed, the air pressure is released and vacuum is pulled on the two air tubes, collapsing them and pushing the RURDL flat against the workpiece. Thereby, no objectionable cured resin protrusions are left on the workpiece.

Inflate RURDL tubes during infusion



Collapse RURDL tubes during cure



Design of RURDL creates large passage for circumferential resin flow when air tubes are inflated, but passage collapses completely when air tubes are deflated

US Patent Application Publication #13/070,618, March 24, 2011

Janicki Industries graphic

Figure 21. Re-usable Resin Distribution Line (RURDL) enables stepwise VARTM with minimal change-out of expendable processing materials.

4.3.1.2 Control system

The Molding Region has a number of subsystems activated by air pressure and/or vacuum. For each of these, the pressure or vacuum is turned on and off by electrically-operated solenoid valves (some of which are visible on Figure 22, left), with sensors installed at the subsystem itself for the most accurate readings. For this stand-alone validation of the Molding Region, a relatively simple control system was designed and implemented. Manually-operated switches controlling the solenoid valves were all mounted on a single control panel (Figure 22, right) alongside panel gages displaying the readings of the corresponding sensors. An Excel program was written to display, step-by-step, the proper settings of each switch as an aid to the operator. A 16-channel video display unit also visible on Figure 22, right shows the view from each of the cameras that monitored the resin height within the workpiece.

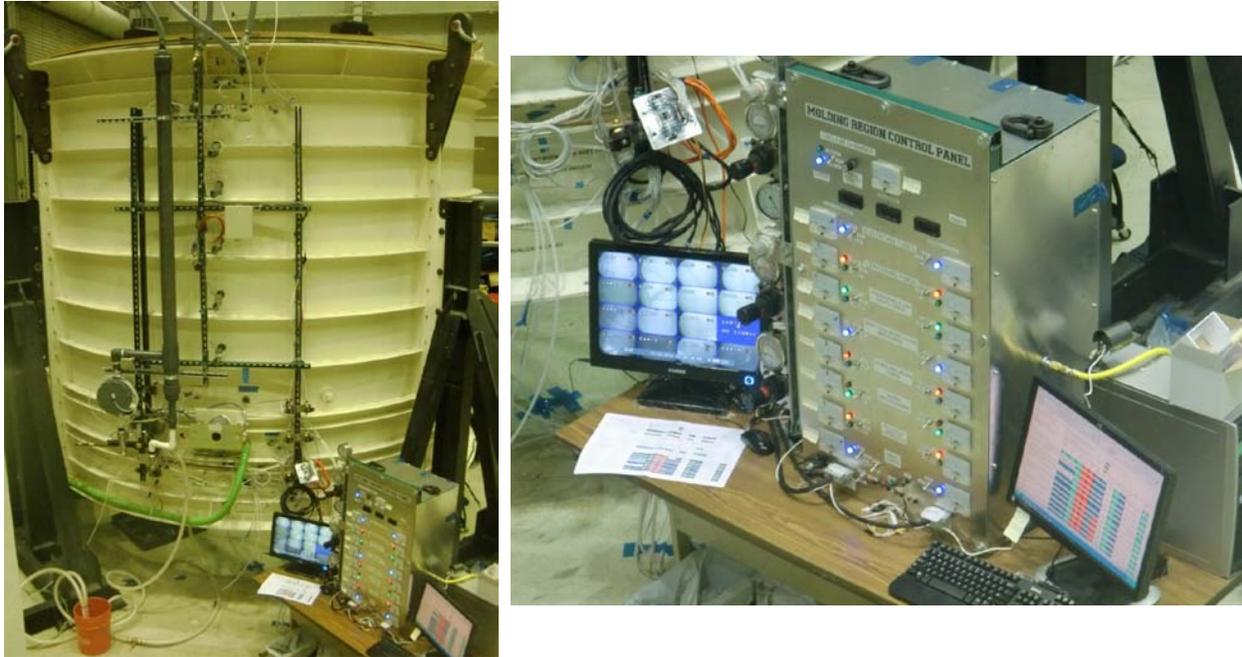


Figure 22. Molding region control system

4.3.2 Infusion of workpieces

Figure 23 shows the infusion plan for this initial validation workpiece. The inner face sheet was infused in two steps, in order to create and examine a representative “knitline” between steps. To do this without being able to move the workpiece vertically in our limited-height lab, additional Resin Distribution Medium (RDM) was added after the first step, to carry (during the second step) the resin from the RURDL up to the bottom of the material to be infused during the second step. The outer face sheet was infused in one shot.

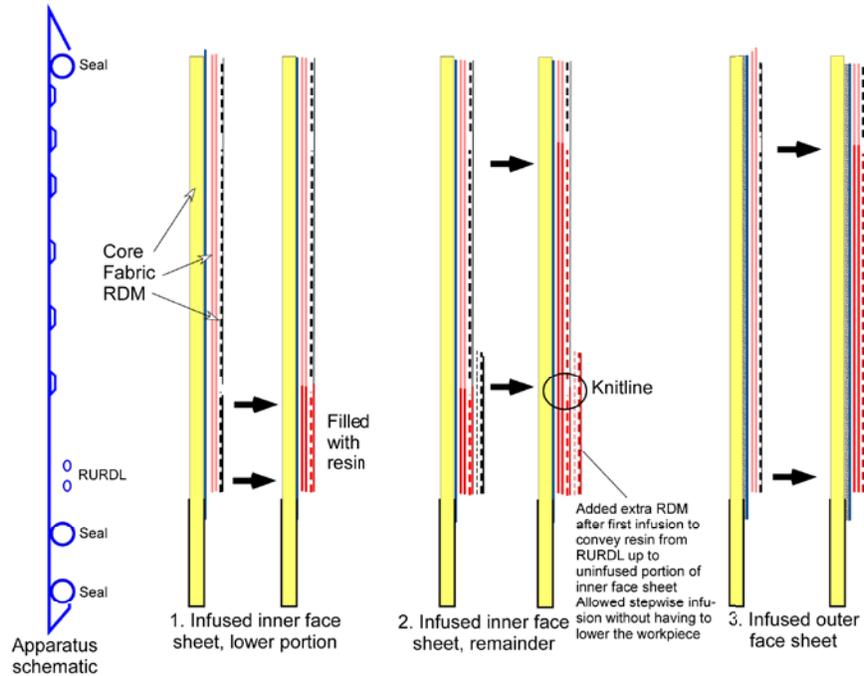


Figure 23. Configuration of the three infusions (only one side of the apparatus is shown)

4.3.2.1 Resin handling, labor requirements, accuracy of fill time prediction

Figure 24 shows the apparatus and crew during a typical infusion run, each of which involved several hundred pounds of resin. Use of a standard on-demand metering and mixing pump with a simple 5-gallon plastic pail as a catalyzed resin reservoir avoided creating any large bulk quantities of catalyzed resin, and consequently there were no problems with exotherm.

Figure 24 also notes that the actual fill time agreed to within 20% with predictions made using our specialized VARTM flow model, when correction was made for the quite low temperature of 18 °C (65 °F) in the lab at the time, compared to the 25 °C (77 °F) at which the viscosity of the resin is measured in standard tests.

As also noted on Figure 24, the specialized apparatus enables infusion to be done by a 2-person crew. This fact, combined with the totally machine-based fabric placement, is the key to the low recurring labor cost that is projected for manufacturing of Cold Water Pipes by this process.

Infusion of workpieces

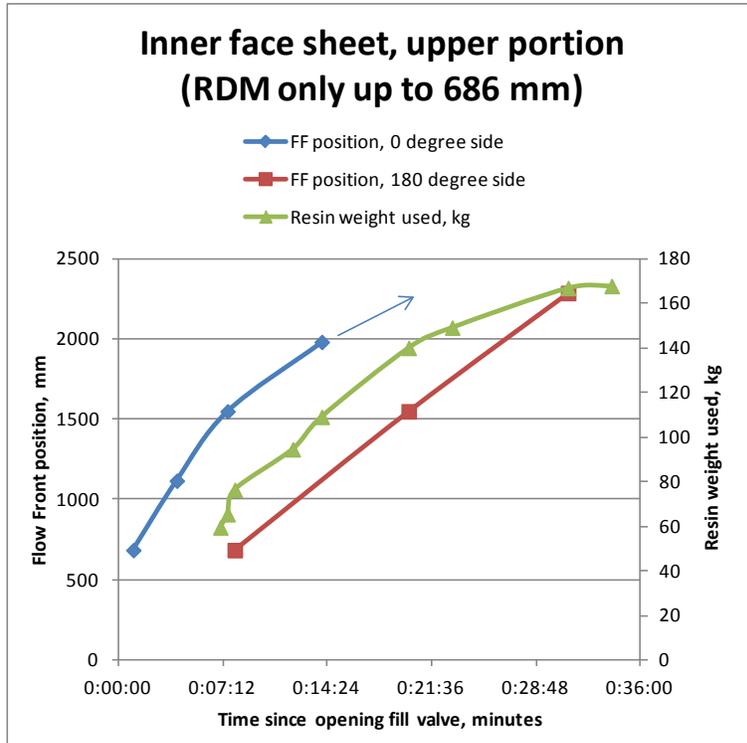
- About 455 kg (1000 lbs.) of resin was mixed and infused in 3 shots, including a stepwise infusion of the inner face sheet and a full-height infusion of the outer face sheet
- There were no problems with exotherm
- The fill time agreed with our specialized VARTM flow model to within 20%
- The specialized apparatus enables infusion to be done by a 2-person crew



Figure 24. Infusion of workpieces

4.3.2.2 Validation of RURDL functioning

Use of the video cameras allowed measurement of the flow front vs. time behavior at both the 0° (same side as the resin inlet line, RIL) and 180° locations. This data is plotted in Figure 25. The fill behavior at the 180° position is offset by about 10 minutes from that at the 0° position, which is a far shorter time than it would take resin to travel through the 6.2 m (245 in.) of RDM if the RURDL were not working properly. Hence, the data provides direct validation that the RURDL did, in fact, function properly.



- Actual resin consumed (167 kg/360 lb) agrees almost exactly with predicted (170 kg/373 lb)
- Rapid fill at 180 degrees (6.27 m/247 inches) away from RIL indicates that RURDL worked as planned

Figure 25. Fill pattern and resin consumption

4.3.3 Workpiece and laminate quality results

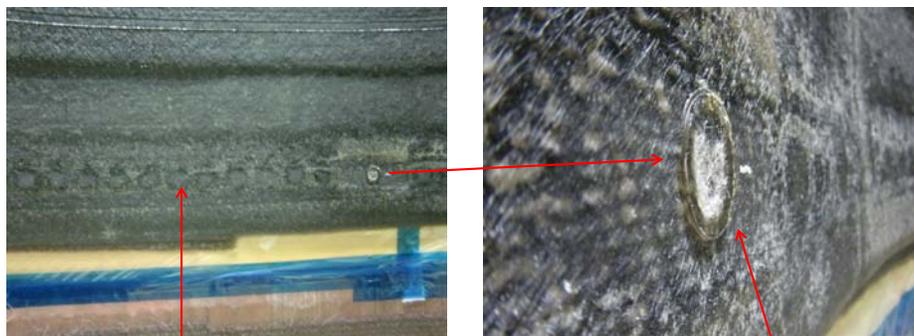
Following infusion and cure, the soft tools were easily pulled away from the workpiece by application of a very slight vacuum behind the soft tools. Removal of the workpiece from the Molding Region was also uneventful, albeit with only a small clearance to spare in our limited-height lab (see Figure 26).

In our process, the final position of the flow front can be controlled by cutting the active portion of the RDM. In fact, “castellations” were intentionally introduced into the outer face sheet RDM to test this behavior. One of these (a location where the RDM ends at a position about 305 mm (12 in.) lower than its neighboring material) is visible in Figure 26. The flow front stopped everywhere planned, including a very uniform flow front height on the inner face sheet, where there were no castellations.



Figure 26. Removing infused and cured workpiece from mold

Figure 27 shows photos of the inner face sheet at the location where it contacted the RURDL and was fed by the RIL. The photo on the left shows that only a barely discernable pattern is left on the cured workpiece at the RURDL. This validates the functioning of the RURDL with respect to its leaving the soft tool flat after it the RURDL tubes are collapsed. The photo on the right shows that only an insignificant resin stub is left on the cured workpiece at the RIL. This validates the RIL mechanism, which is designed to break the cured resin right at the workpiece as the RIL is replaced in between infusions.



- Barely discernable pattern left on cured workpiece at RURDL
- Insignificant resin stub left on cured workpiece at RIL

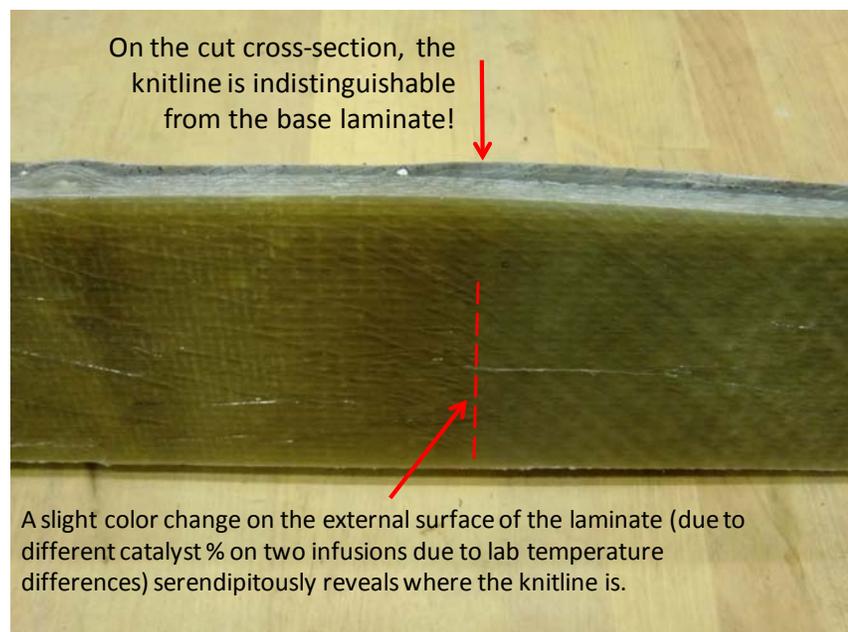
Behavior of the apparatus is validated for repeated stepwise infusions

Figure 27. Inner face sheet shows successful operation of RURDL and RIL mechanism

Small samples were cut out from various locations of the inner and outer face sheets, spanning the full range of positions within the infused workpiece. The inner and outer face sheet laminates are fully wet-out everywhere planned.

Finally, Figure 28 shows a sample of inner face sheet, cut out at the knitline. Much of the photo is of the inner surface, which serendipitously reveals the boundary between the two infusion steps because of a slight color change in the resin, introduced because of differing catalyst concentrations that were used on the two runs because of lab temperature differences. Examination of the cut cross-section at this same position reveals that the knitline is indistinguishable visually from the base laminate. This validates the concept of stepwise infusion molding that forms the foundation of our CWP fabrication method. Fatigue testing of knitline and baseline samples is being planned to validate the structural behavior at the knitline.

1. The inner and outer face sheet laminates are fully wet-out everywhere planned
2. On the outer face sheet, the flow front stopped where planned, everywhere
3. At the knitline, the results were extremely successful:



- The laminate is continuous at the knitline
- The stepwise infusion molding process is validated

Figure 28. Laminate quality results

5. SUMMARY AND FUTURE PLANS

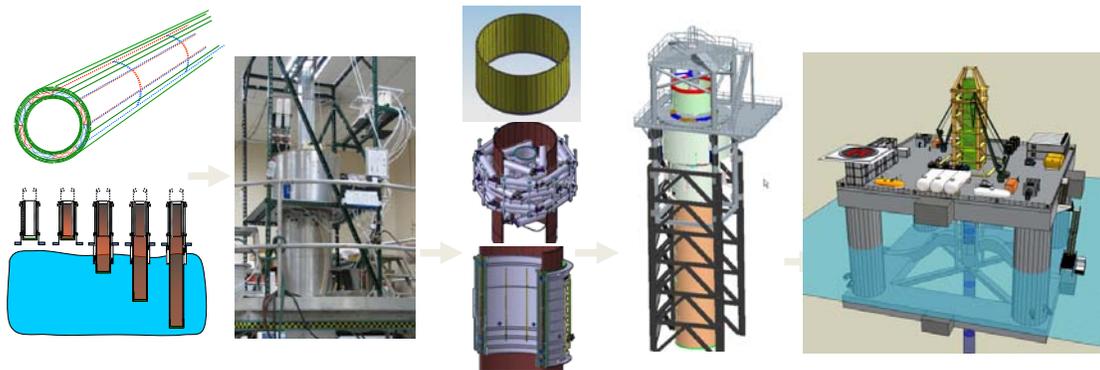
5.1 Summary

Critical elements of the LM OTEC CWP design and fabrication apparatus and process have been validated at a 4m diameter scale. These elements include:

- Core plank production and assembly into core rings
- Fabric architecture and dispensing
- Stepwise infusion molding

5.2 Future plans

The work described in this paper is an important, if partial, step within Lockheed Martin’s program developing OTEC as a viable, secure, and economically competitive source of energy, free from global warming emissions. Figure 29 shows the overall roadmap for Cold Water Pipe development and validation.



CWP Trade study Complete	Proof-of-Principle demo (PoP) Complete	4m Prototype Scale-up		Pilot Plant CWP	100 MW Plant
Jan-May 2008	June-Dec. 2008	Jan 2009 to Dec. 2010	TBD	TBD	TBD
Activity: Select •Material •Configuration •Fabrication process	•Small-scale (0.46m/18" ID) validation of fabrication process	•Large-scale (4m ID) validation of critical elements •Complete	•Large-scale validation of integrated process •Collect recurring labor cost data	•1000m CWP attached to TBD platform	•1000m CWP attached to 100 MW platform
Basis and size: 10m ID x 1000m long CWP for 100 MW	0.5m ID x 864 mm / 34" per step	4m ID x 2.28m / 7.5ft per step	4m ID x 6.3m / 19ft per step, 3 or more successive steps	4m ID x 6.3m /19ft or 11.8m /39ft. per step	10m ID x 6.3m /19ft or 11.8m /39ft. per step
Location: LMSSC-ATC and Sunnyvale	LMSSC-ATC and Sunnyvale	LMSSC Sunnyvale B/132	TBD	Hawaii	Hawaii
Funding: MS2 LTTI IRAD	MS2 LTTI IRAD	AWPP-DoE/MS2 CRADA	TBD	TBD	Commercial project

Figure 29. LM OTEC CWP development and implementation roadmap

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