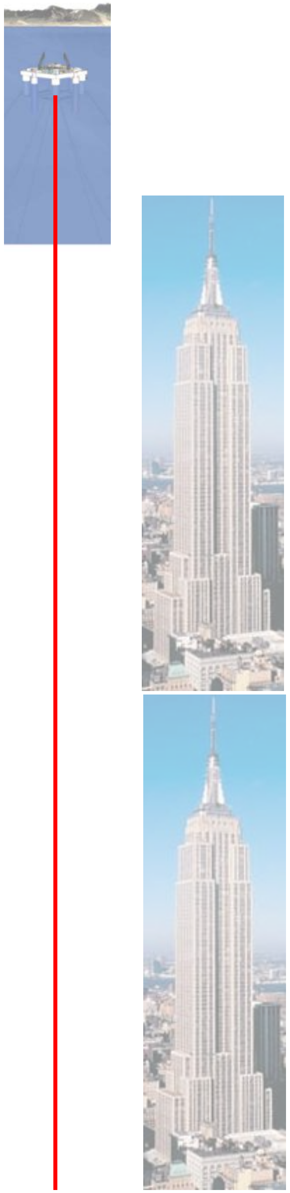
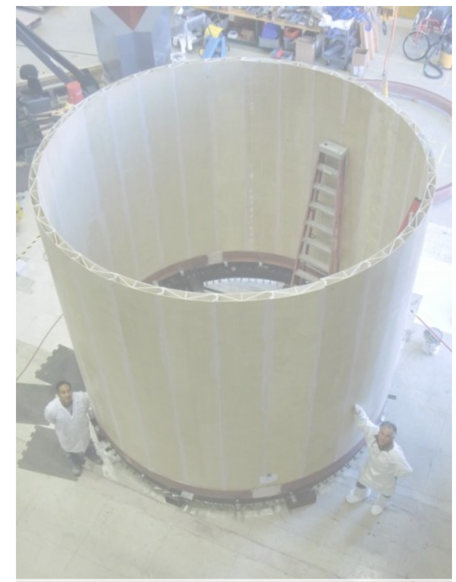
OTEC Advanced Composite Cold Water Pipe: Final Technical Report



Work sponsored by the US Department of Energy and performed by Lockheed Martin Corporation and its subcontractors under DoE / LM MS2 Cooperative Agreement # DE-FC36-08GO18172. Includes other related work for completeness.

Dr. Alan K. Miller
LMSSC-ATC
Principal Investigator and CWP sub-system lead
Mr. Matt Ascari
LM MS2
Program Manager



Rev. L, Sept. 4, 2011
Status: All slides released,
LM PIRA #MAN201104003

Abstract and 1-page Executive Summary

Ocean Thermal Energy Conversion can exploit natural temperature gradients in the oceans to generate usable forms of energy (for example, cost-competitive baseload electricity in tropical regions such as Hawaii) free from fossil fuel consumption and global warming emissions.

The #1 acknowledged challenge of constructing an OTEC plant is the Cold Water Pipe (CWP), which draws cold water from 1000m depths up to the surface, to serve as the coolant for the OTEC Rankine cycle. For a commercial-scale plant, the CWP is on the order of 10m in diameter. This report describes work done by LMSSC developing the CWP for LM MS2 New Ventures' emerging OTEC business. The work started in early 2008 deciding on the minimum-cost CWP architecture, materials, and fabrication process. In order to eliminate what in previous OTEC work had been a very large assembly/deployment risk, we took the innovative approach of building an integral CWP directly from the OTEC platform and down into the water. During the latter half of 2008, we proceeded to a successful small-scale Proof-of-Principles validation of the new fabrication process, at the Engineering Development Lab in Sunnyvale.

During 2009-10, under the Cooperative Agreement with the US Dept. of Energy, we have now successfully validated key elements of the process and apparatus at a 4m diameter scale suitable for a future OTEC Pilot Plant. The validations include:

•Assembly of sandwich core rings from pre-pultruded hollow "planks," holding final dimensions accurately
•Machine-based dispensing of overlapping strips of thick fiberglass fabric to form the lengthwise-continuous face sheets, holding accurate overlap dimensions
•Initial testing of the fabric architecture, showing that the overlap splices develop adequate mechanical strength (work done under a parallel US Naval Facilities Command program)
•Successful resin infusion/cure of 4m diameter workpieces, obtaining full wet-out and a non-discernable knitline between successive stepwise infusions.

After an introductory section describing the background and initial work, the major sections of this report describe (mostly by graphical means) the results of these validations at 4m scale. Within each section, the key results, evidence, and future improvements are summarized concisely in tables.

The last section of this report describes future plans to complete the CWP risk retirement and implementation.

An extended Executive Summary at the end provides the key results from this work at the level of one photo montage and one table per validation.

Contributors to this work

- CWP subsystem lead and Principal Investigator: Alan Miller
- LM MS2 CWP Program Manager: Matt Ascari
- LM SSC CWP Program Manager: Nat Shankar
- Design: Chad Nevills, Patrick Quigley, Bobby Lane
- Stress analysis: Matt Nahan, Doug Hillson, Matthew Nahan, Greg Cuzner
- Manufacturing engineering: Herman DeVliegher
- Engineering Development Lab: Ted Rosario (chief CWP technician), Mike Garcia, Jose Tellez, Frank Phillips, Gene Evans, Gill Hennessee, Manny Martinez (lead)
- Control system wiring: Loretta Robinette, Tina Retana
- Janicki Industries (Paul VanSant, project manager)
- Owens Corning Technical Fabrics
- Glasforms, Inc.
- West Virginia Univ. (Prof. Hota Gangarao; David Dittenber)
- Initial strategic approach: Steve Bailey

Table of Contents

I. OTEC and the Cold Water Pipe

- OTEC
- Major OTEC plant components
- The Cold Water Pipe is (literally) the single biggest challenge of OTEC
- The checquered past of Cold Water Pipes for OTEC projects
- Prior attempts at building OTEC plants have been bedeviled by disasters constructing and deploying the Cold Water Pipe

OTEC

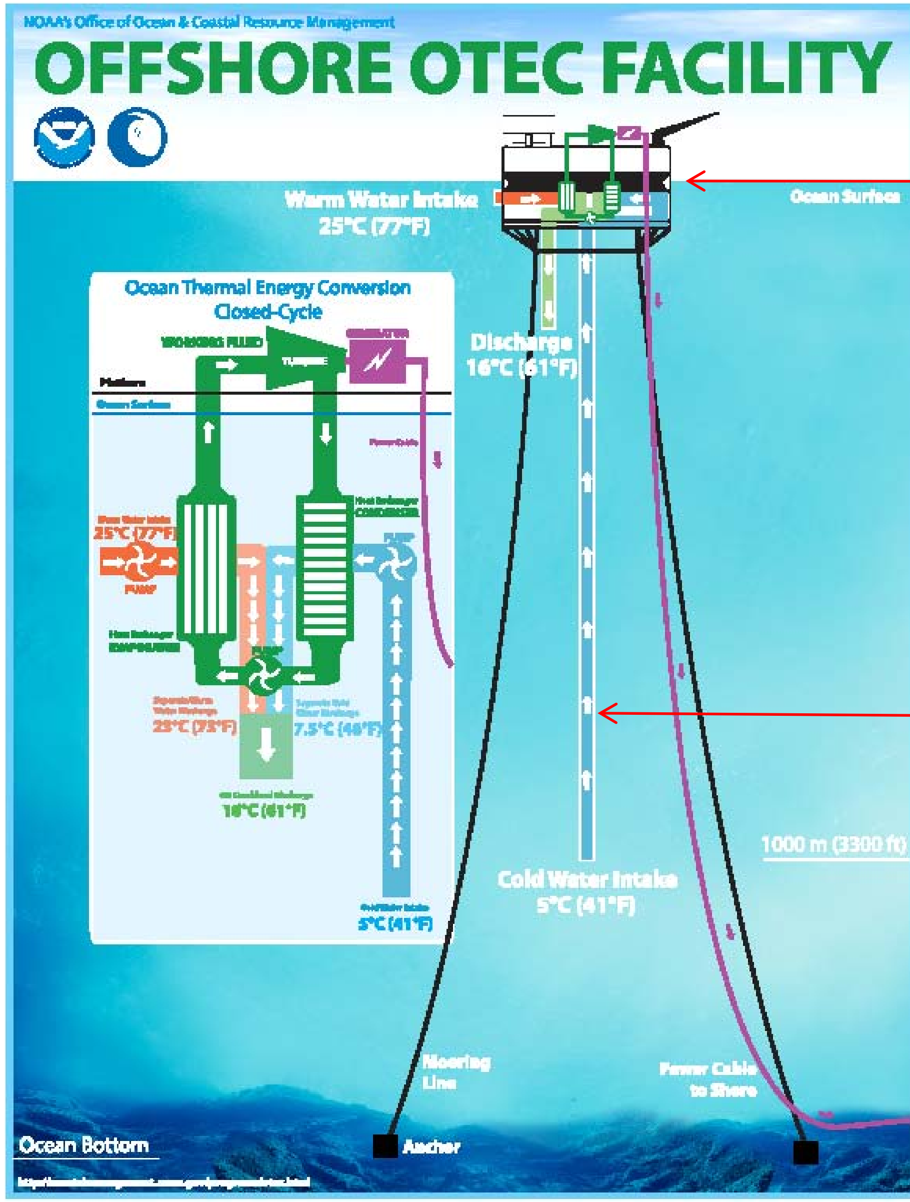
OTEC (Ocean Thermal Energy Conversion) is a renewable energy technology that can provide large quantities of baseload (24/7/365) electricity in tropical climates, for example in Hawaii and at overseas Navy bases. The key benefits are:

- *No fossil fuel is required*
- *No greenhouse gasses are emitted*

Major OTEC plant components

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

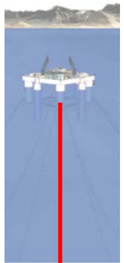


Heat exchangers, turbines, pumps, and generators are above and just under the surface

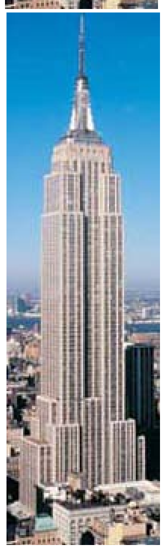
The **Cold Water Pipe** extends down to the cold water layer located at 1000m depth, and carries the cold water to the surface

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

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



The CWP for a full-scale plant is 1000m / 3300 ft long.....



That is 2+ Empire State Buildings....
.

........by 10m / 33 ft in diameter

...and about the width of a modest 2-story house

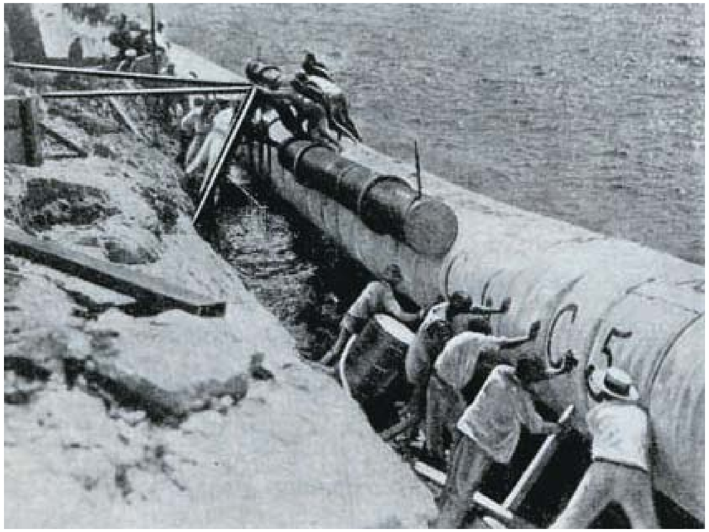
http://2.bp.blogspot.com/_7tB79IR_qrQ/SCVh6hwIVBI/AAAAAAAADn0/l5plCrhYsAk/s400/empireStateBuilding.jpg

http://www.trulia.com/property/1073310701-Single-Family-Home-Cedarhurst-NY-11516

The Checquered Past of Cold Water Pipes for OTEC projects

	Date	Diameter	CWP material	Results (CWP)
Claude – Cuba (on-shore plant)	1930	2m	Corrugated steel sections	1st 3 attempts to deploy CWP failed; 4th was successful
Claude – Brazil (plant ship)	1935	2.4m	Steel sections	CWP broke off in a storm during deployment; plant was abandoned
Mini-OTEC	1979	0.7m	HDPE (high density polyethylene)	Successful
DoE sub-scale CWP test (OTEC-1)	1983	2.4m x 122m long	Fiberglass face sheet / foam core sandwich sections	Successful
Japan (Nauru; shore-based demo)	1981	0.7m	HDPE	Built; operated; a hurricane wiped out the facility
India (Bay of Bengal)	2003	1m	HDPE	CWP dropped twice; project abandoned
Makai ONR study	2007	10m	Steel sections	Not built yet
Sea Solar Power studies			HDPE – multiple tubes	Not built yet

Prior attempts at building OTEC plants have been bedeviled by disasters **constructing and deploying** the Cold Water Pipe, starting with Georges Claude's OTEC plant in Cuba, 1930



"Deploying the 2,200-yard, cold water intake tube in Cuba, far left, proved the undoing of Claude, standing, left, inside the pipe. Storms, waves, and logistical problems encountered while laying the unwieldy and vulnerable pipe, above, sank Claude's dream to harvest energy from the ocean."

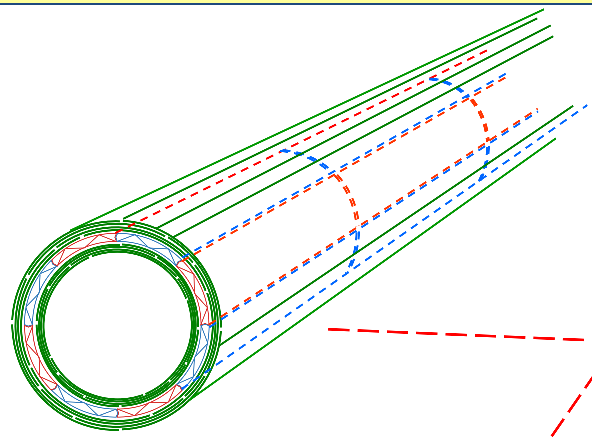
http://www.invitingdisaster.com/images/Ocean_Thermal_Energy_-_AHIT_Winter_09.pdf

II. The LM Advanced Composite Cold Water Pipe

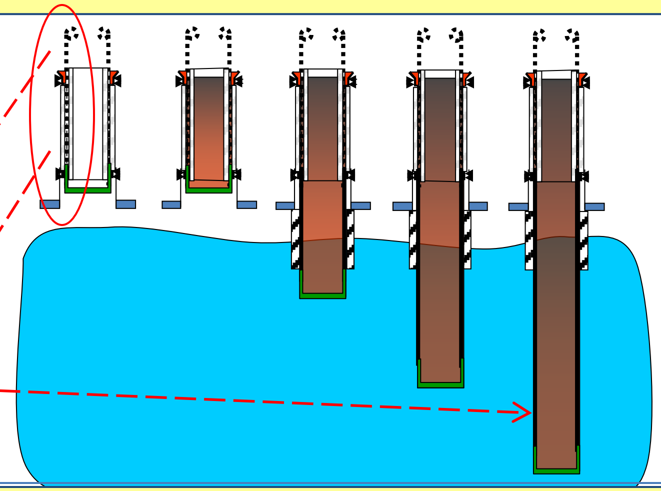
- Summary of LM Advanced Composite Cold Water Pipe Approach
- II.A - Selection of configuration, materials, and fabrication strategy
- II.B - Selection of fabrication method and major details

Pictorial summary of LM Advanced Composite Cold Water Pipe Approach

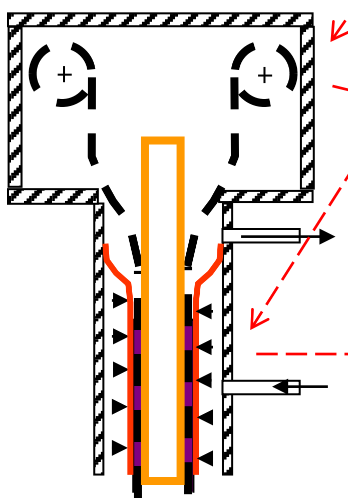
Integral one-piece sandwich-wall pipe with no joints in the main load-bearing face sheets maximizes durability and reliability



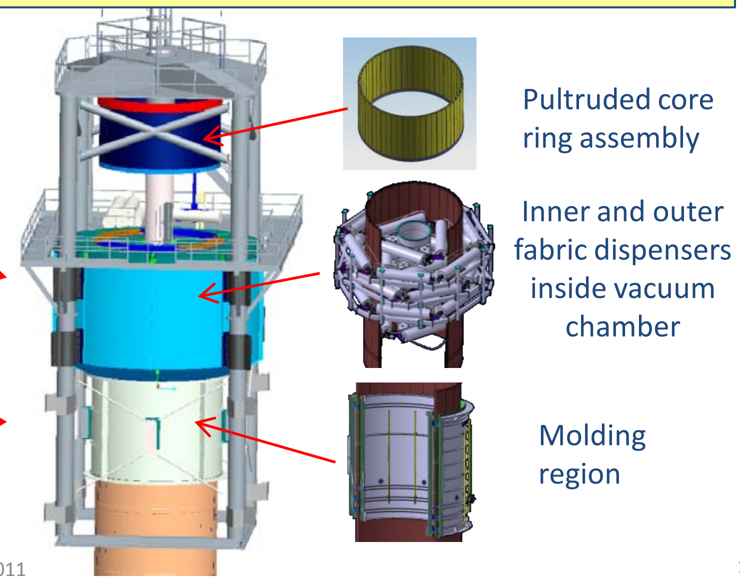
Fabrication off of the OTEC platform eliminates major deployment risks and enables affordable fabrication of huge integral pipe



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



Concept design of large-scale apparatus helped select critical elements for validation at 4m diameter scale



II. A - Selection of configuration, materials, and fabrication strategy

(Work done prior to the DoE program, under LM MS2 IRAD funding)

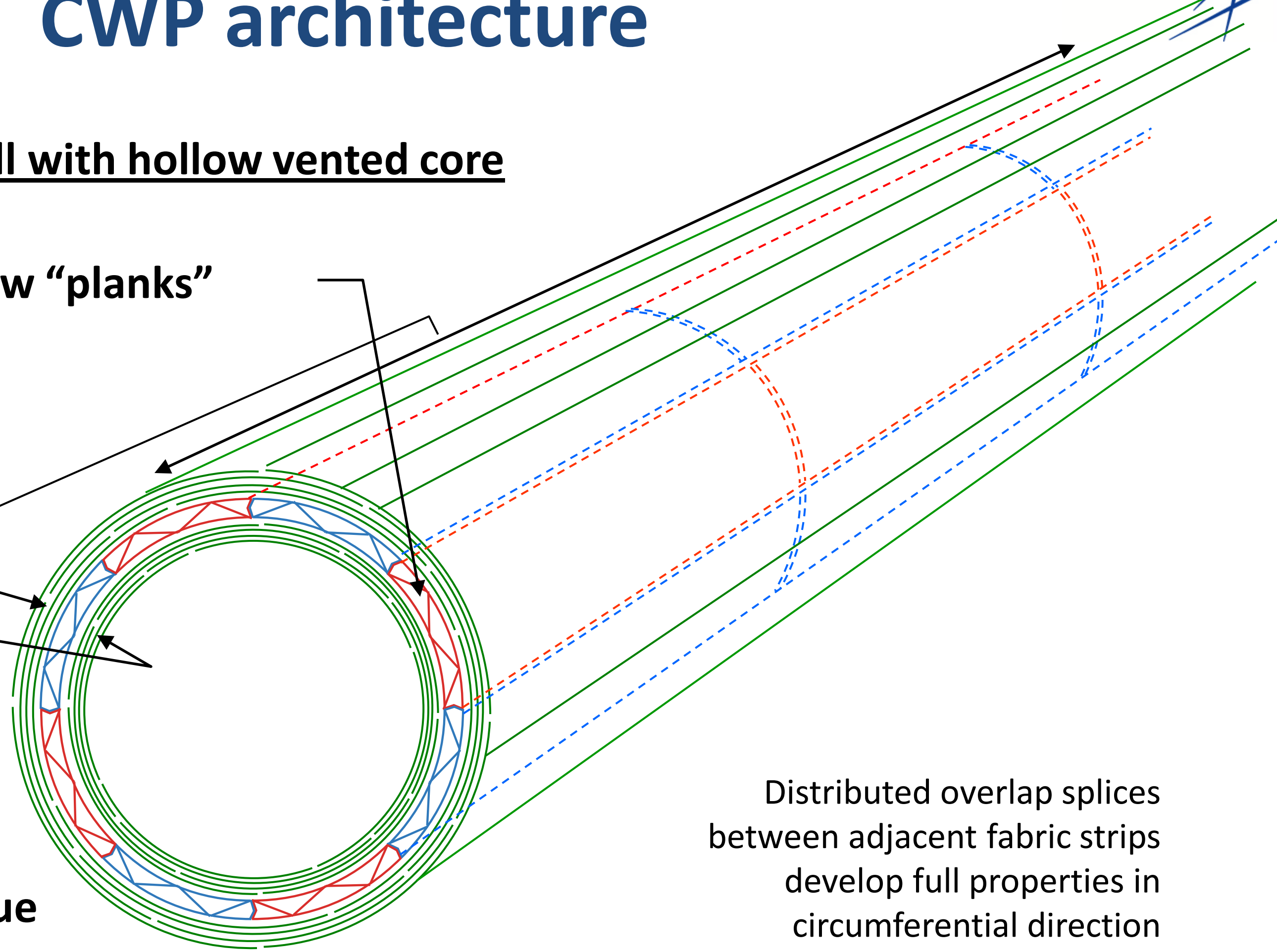
- Cold Water Pipe structural requirements
- CWP architecture
- A section of LM CWP at 4m diameter scale
- Fabrication strategy
- Primary basis for selecting the current CWP materials

Cold Water Pipe Structural Requirements:

Origins, loadings, resulting features, analysis status

Origin	Loading on CWP	Leads to feature (see next slide)	Analysis status
Wave-driven platform motions	Fatigue strains	Axial fibers; integral pipe without joints	OK
Internal suction	Net external global pressure	Hoop fibers; sandwich wall	OK
Grippers and bushings	Localized external pressure	Larger # of ribs in sandwich wall	OK
Clump weight, pipe wet weight	Axial strain	Axial fibers	OK
Water currents	Bending strain	Axial fibers	OK
1000m length	1500 psi water pressure at depth	Vented hollow core made of composite laminate	OK
Mildly negative wet weight			
30-year life, immersed	Seawater corrosion	Vinyl ester resin	OK by material heritage

CWP architecture



Construction: Sandwich wall with hollow vented core

- **Core: Pre-pultruded hollow "planks" assembled into core rings**
- **Face sheets: Longitudinally continuous fabric strips, applied over assembled core rings**

Distributed overlap splices between adjacent fabric strips develop full properties in circumferential direction

Materials

- **Low-cost X-Strand[1] glass fibers having superior fatigue resistance**
- **Derakane 8084[2] 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

A section of LM CWP at 4m diameter scale

Tongue-in-groove edges of pultrusions

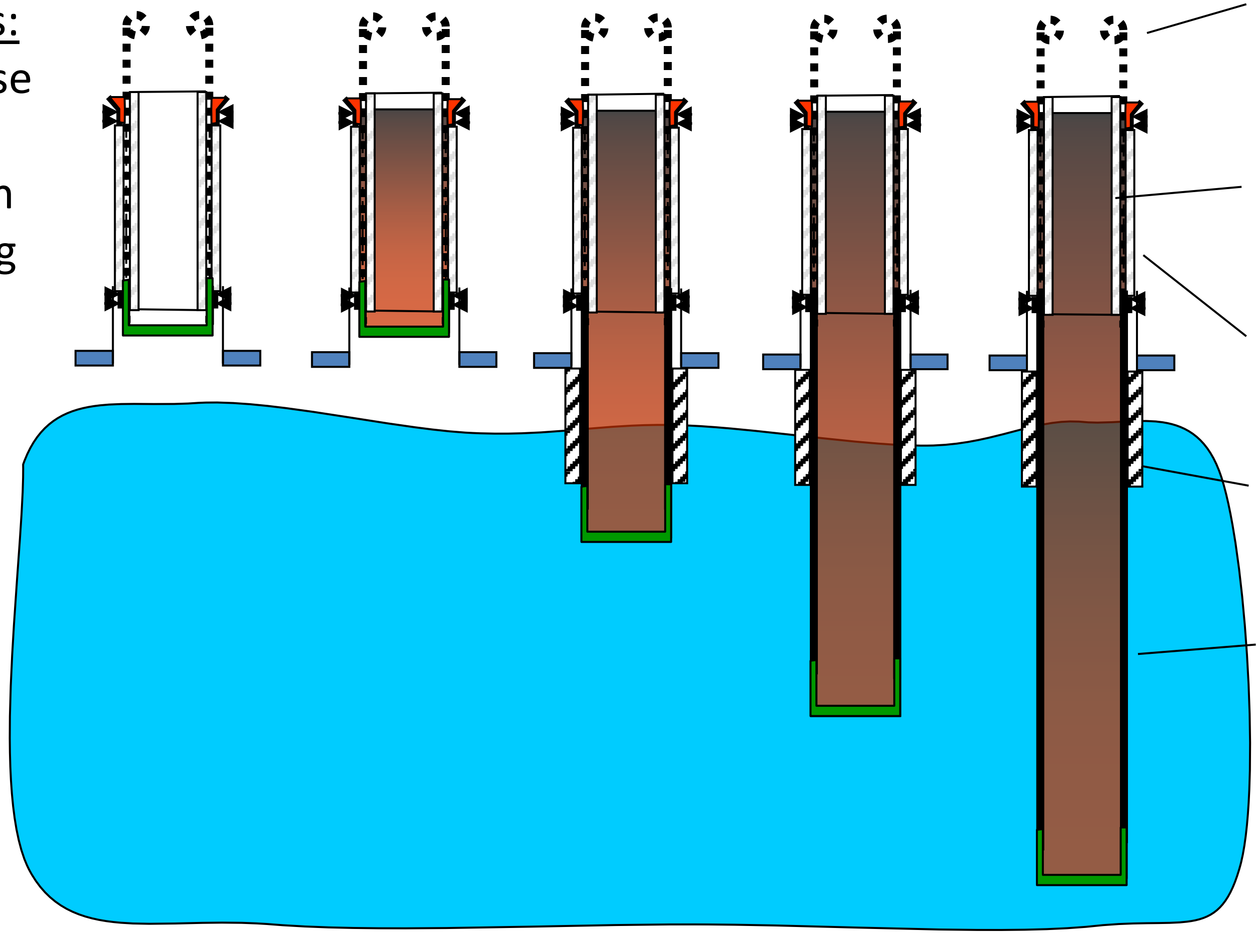
Resin distribution medium (RDM)

Fiberglass face sheet

Pultruded core

Fabrication strategy – Manufacture the CWP directly from the floating platform

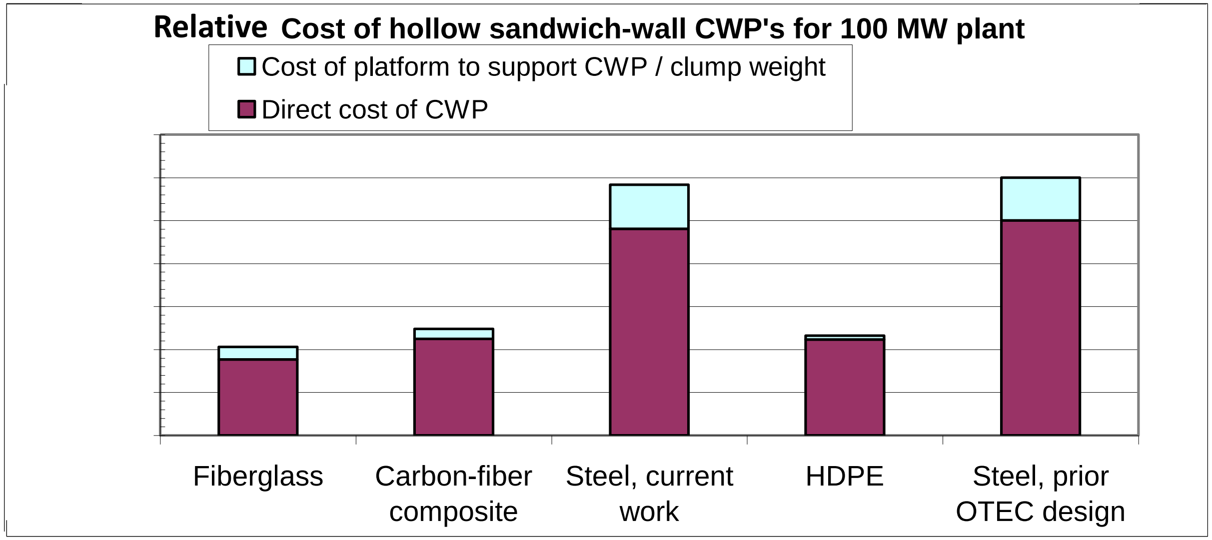
<u>Overall process:</u> Stepwise VARTM infusion molding



US Patent Application Publication # US2009/0309271A1, 2009; European Patent Office Application #PCT/US2009047388, 2009

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

Primary basis for selecting the current CWP materials: Recurring cost (materials and fabrication) of minimum-cost design of 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

- WIM = Wave-induced motions (from platform)
- VIV = Vortex-induced vibration

Fiberglass and carbon-fiber composite are the two candidates with no show-stoppers. 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 questions in the carbon fiber marketplace.

II.B - Selection of fabrication method and major details

(Work done prior to the DoE program, under LM MS2 IRAD funding)

- Can we use an off-the-shelf composite fabrication process?
- Various possible liquid resin infusion processes as applied to vertical stepwise molding of a CWP
- VARTM – A quick summary tutorial
- VARTM of a large wind turbine blade shell
- Recent applications of large-scale VARTM technology
- CWP processing steps using stepwise VARTM
- Tooling strategy
- Elements of VARTM that are "tweaked" for our application
- Holding, lowering, and supporting the CWP during on-the-water fabrication

Can we use an off-the-shelf composite fabrication process?

Process	*Comments relative to usage for OTEC CWP*
Spray-up (chopped fibers)	Insufficient properties, VOC's into environment
Wet layup (fabric)	Low fiber volume; VOC's into environment
Prepreg layup/ autoclave cure	Very expensive materials and labor; can only manufacture finite-length segments in autoclave
Automated tape laying	Very expensive equipment and materials
Filament winding	Very difficult to incorporate a sandwich core; finite-length manufacturable segments require joints
Pultrusion (of entire CWP)	Required CWP cross-section is way too large – Pulling force, fabric guidance machinery would be main issues
Matched die molding	CWP much too large – Mold rigidity and weight issues
Thermoplastic forming	Very expensive materials
Liquid resin infusion (RTM, VARTM)	*See next slide*

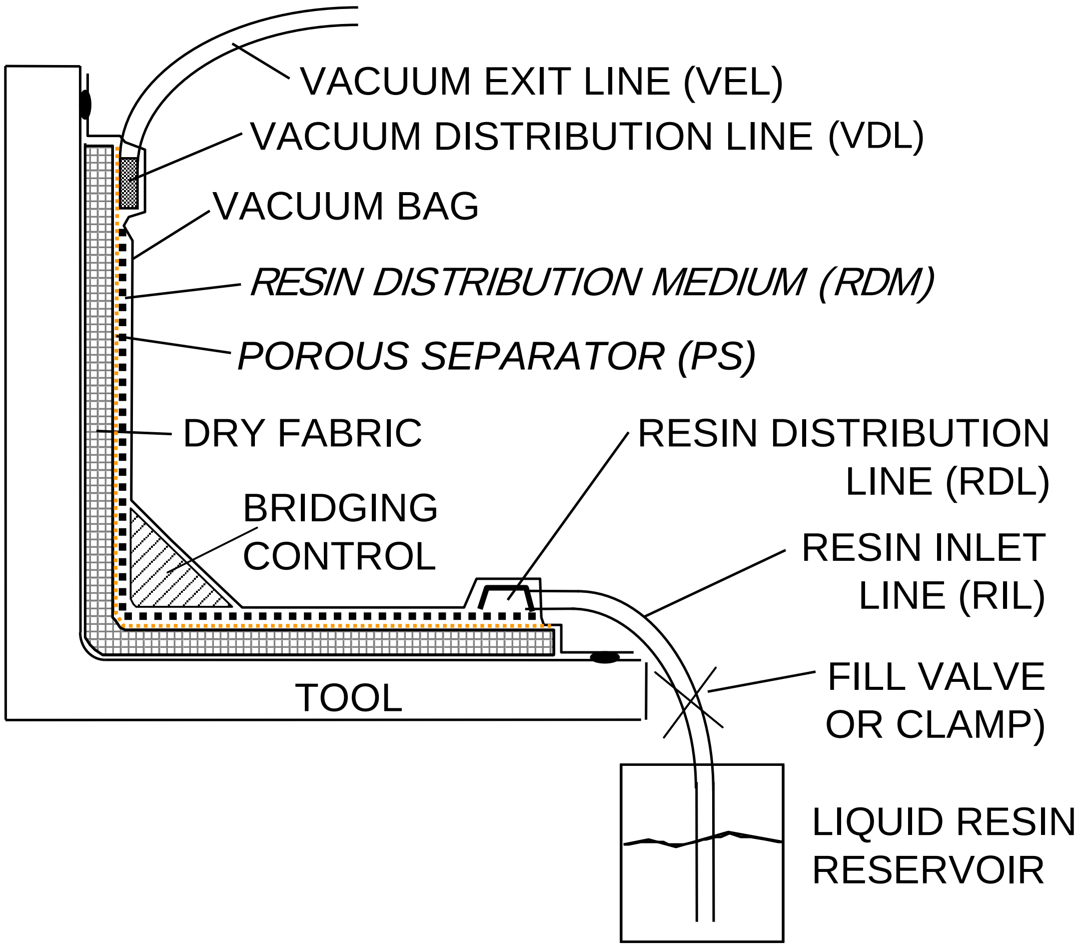
Various possible liquid resin infusion processes as applied to vertical stepwise molding of a CWP

Process	Mold	Mold fill process	Can voids be controlled?
1. Resin Transfer Molding ("ordinary RTM)"	Rigid fixed-cavity mold surrounds part.	Resin flows through the fabric itself. **Slow fill for large parts.**	**Yes. Apply high resin pressure during cure. But requires very rigid mold, prohibitive for large parts**
2. VARTM (Vacuum-Assisted Resin Transfer Molding)	One-sided tool with vacuum bag as the other side	Resin flows through high-permeability resin distribution medium. **Rapid fill for large parts.**	**Yes. Pull good vacuum on fabric before infusion, to evacuate the air.**

VARTM is the only composites fabrication process that meets the needs

VARTM* – A quick summary tutorial

Setup

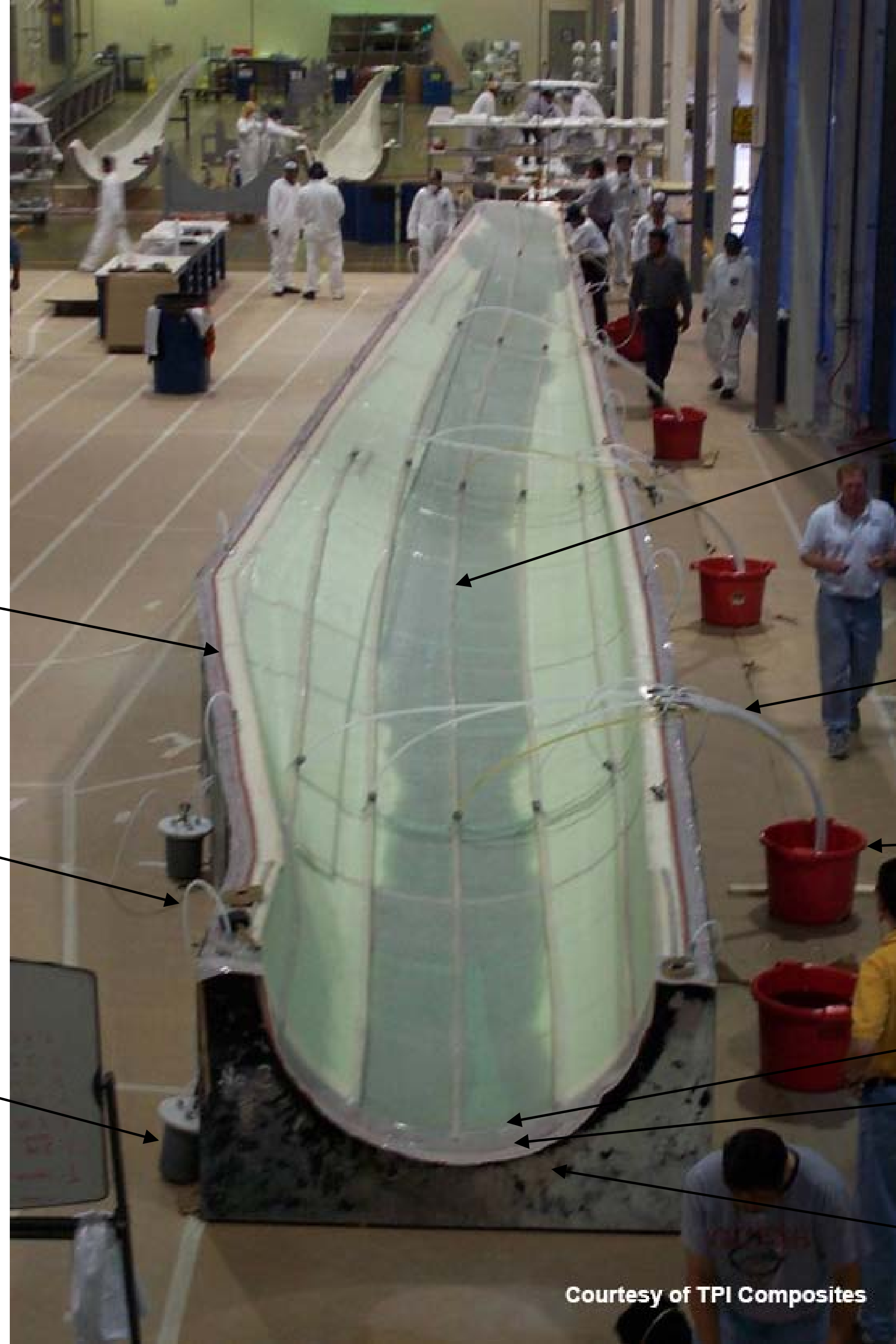


Process

- Lay up dry fabric on tool
- Apply PS, RDM, RDL, RIL, VDL, VEL, and vacuum bag
- Open fill valve
- Vacuum sucks liquid resin from a reservoir into the part
- Resin spreads quickly in the resin distribution medium (RDM, high permeability)
- Resin only has to travel through-thickness in the fabric (low permeability)
- Overall wetout time for large parts is short and within the pot life of many resins
- After cure, the porous separator (PS) allows the RDM to be peeled off of the part. Or the PS can be omitted and the RDM left on the part.

*Vacuum-Assisted Resin Transfer Molding

VARTM of a large wind turbine blade shell



Vacuum distribution line

Vacuum exit line

Vacuum trap

Resin distribution lines

Resin inlet lines

Resin reservoirs

Vacuum bag

Fabric

Mold

Recent applications of large-scale VARTM technology

Modern wind turbine rotor blades (fiberglass shells)

Size scale is similar to our CWP

http://www.compositesworld.com/articles/wind-blade-manufacturing-part-i-m-and-p-innovations-optimize-production.aspx

•VARTM is currently being used on some very large components

•There is a large business base of VARTM-experienced personnel, material suppliers, and equipment fabricators

Fiber composite highway bridge segments (integral deck & beams)

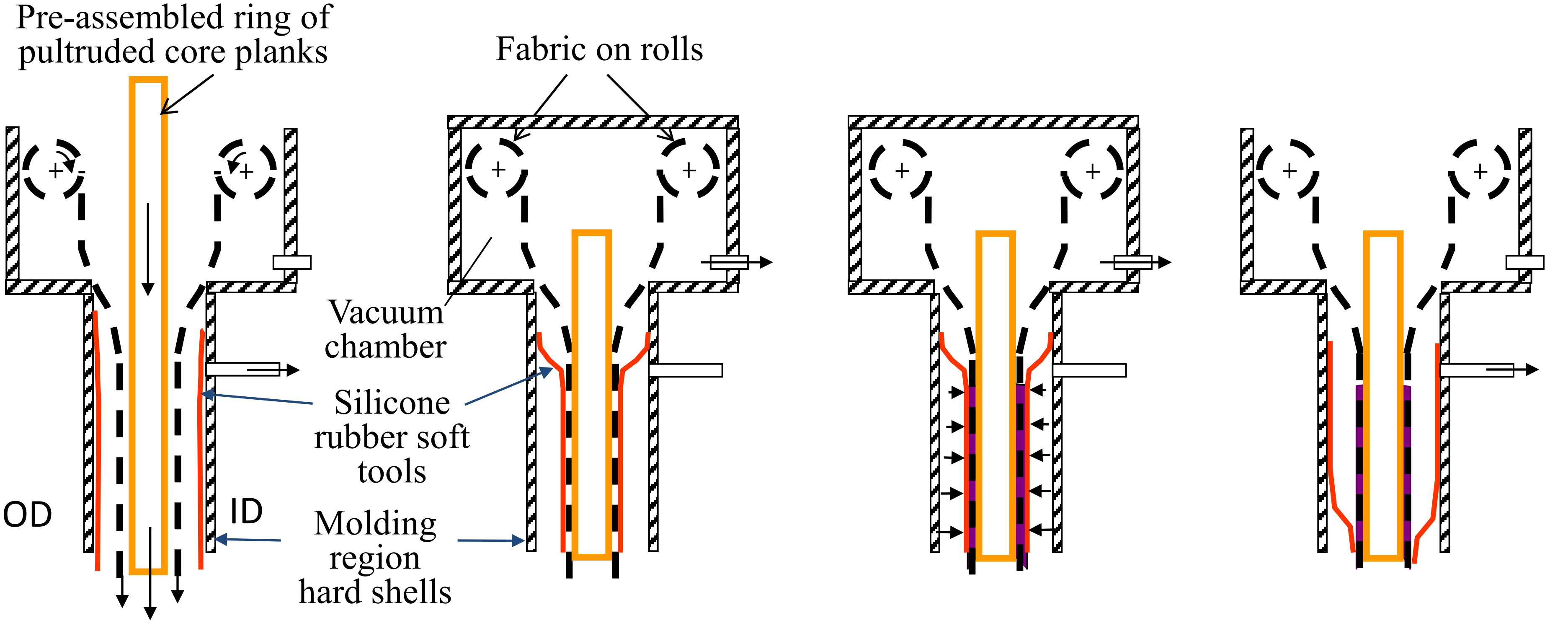
www.compositeadvantage.com

3m (10 ft.) demonstration Deep Space reflector antenna infused in one shot

LMSSC, Sunnyvale, CA

CWP processing sub-steps (a-f) using stepwise VARTM

(Cross-section through left side of apparatus)



(a) Load materials: Maintain vacuum behind soft tools. Move cured CWP down, which pulls new fabric, RDM, and core segments into molding region

(b) Evacuate air from fabric and compact it, by pulling vacuum on workpiece and fabric rolls

(c) Infuse resin from bottom: Use liquid behind soft tools to counteract hydrostatic pressure gradient in liquid resin column

(d) Initial cure: Ambient temperature

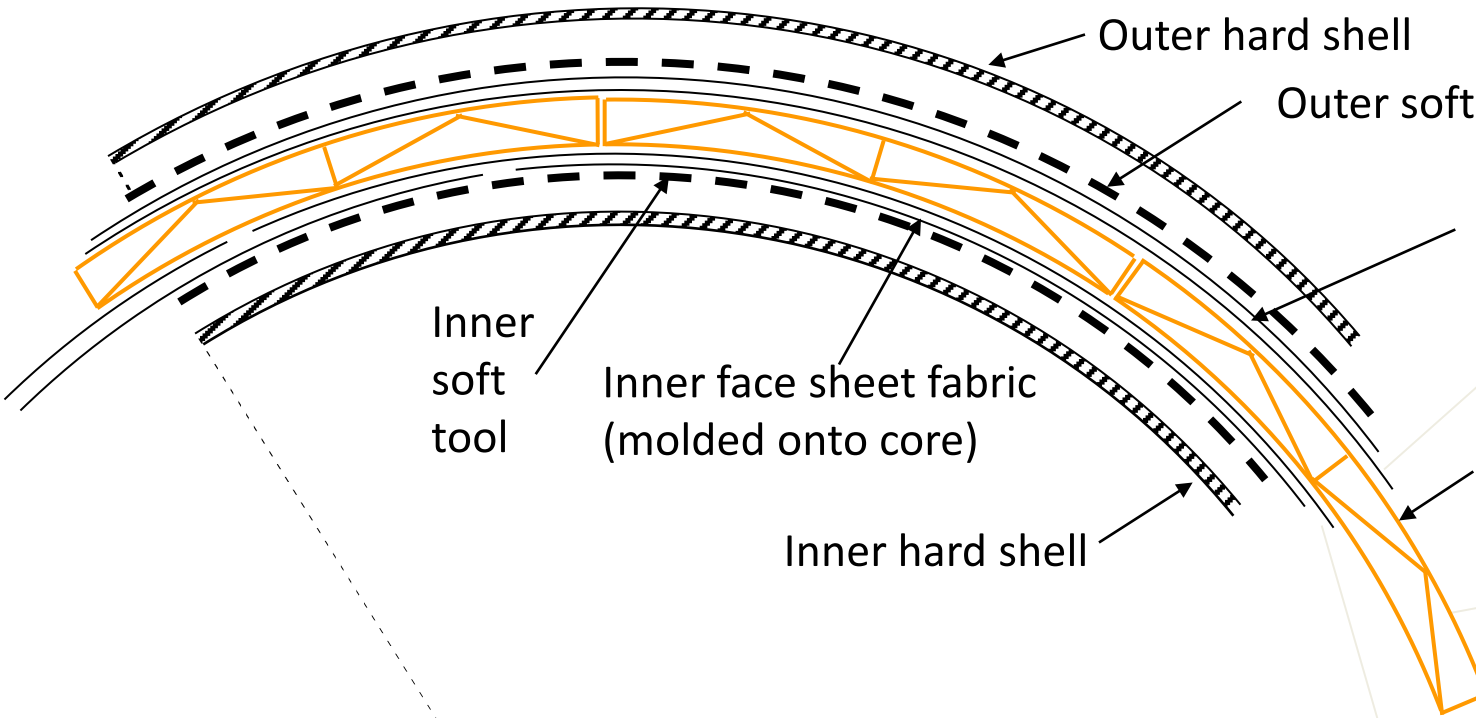
(e) Release: Apply vacuum behind soft tools

(f) Post-cure: Circulate hot air or hot water next to workpiece

Repeat

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

Tooling strategy: Use the pultruded core as a "flyaway tool" that defines the shape of the workpiece and becomes part of it. Silicone rubber "soft tools" (re-usable vacuum bags) compact the face sheet fabric against the outside and inside of the core to mold the CWP.



- 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*.

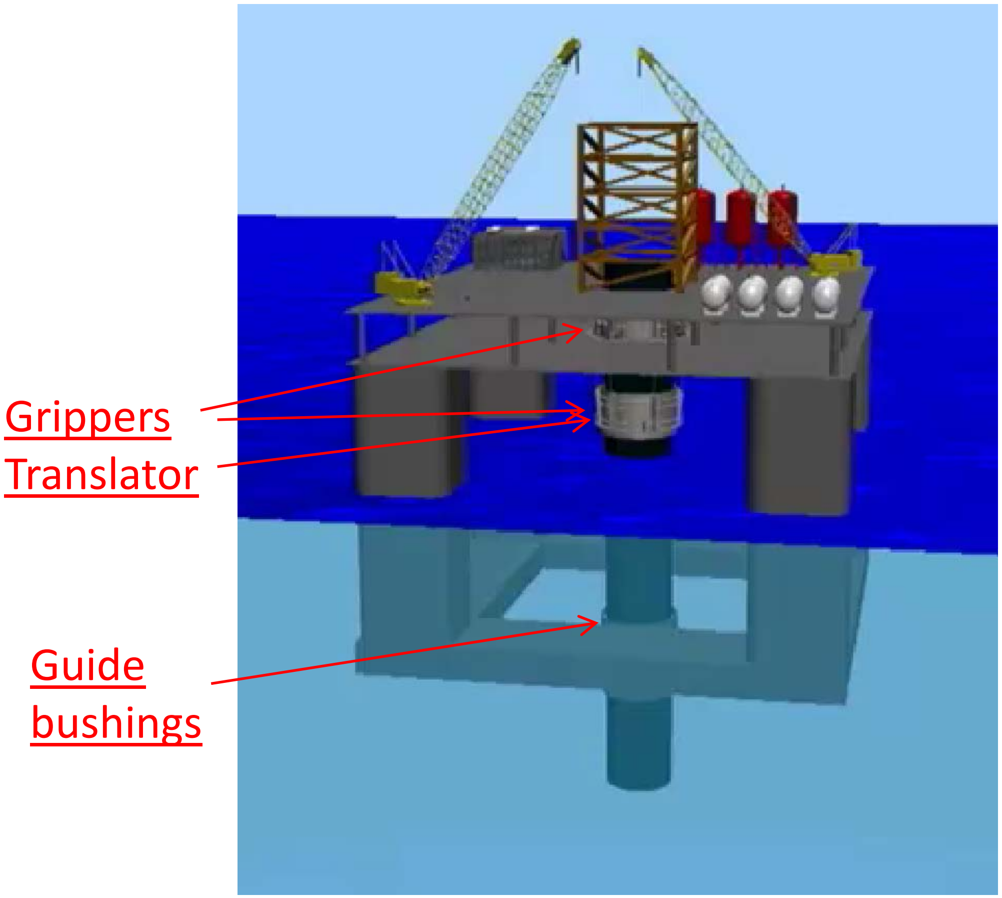
*US Patent Application Publication #12/951,239, Nov. 22, 2010

Elements of VARTM that are “tweaked” for our application

- The process is applied multiple times in a stepwise manner to a single workpiece
- The shape-defining element (assembled pultruded core) becomes part of the product
- The vacuum bag (soft tools) can be pulled away from the workpiece over the entire inner and outer surfaces
- The resin distribution lines are re-usable
- The resin distribution medium is left on the product and doubles as a “gel-coat”

Holding, lowering, and supporting the CWP during on-the-water fabrication

Work done by Makai Ocean Engg. under LM program N62583-09-C-0083 sponsored by the US Navy Facilities Command



A 21” scale model was tested successfully on a scale-model sandwich CWP.

Gripper and bushings have been designed by Makai Ocean Engineering to manipulate and support the CWP during fabrication and subsequent service.

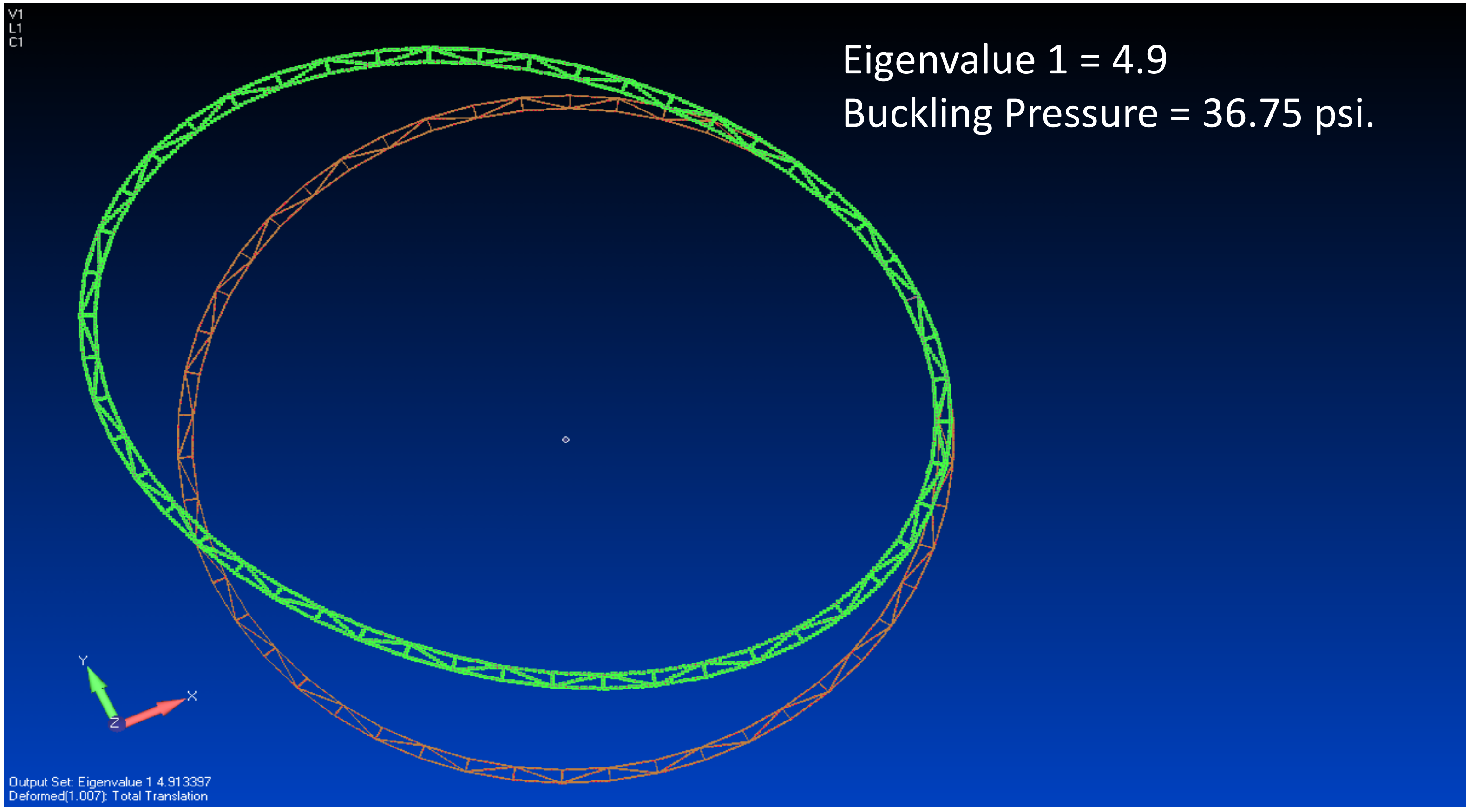
Makai Ocean Engineering

III. Analyses to date of CWP structural behavior

(Work done outside of the DoE program, under LM MS2 IRAD or US Navy funding)

- External pressure buckling
- Localized buckling from gripper and guide bushing pressures
- Fatigue resistance after seawater conditioning to saturation
- Coupled hydrodynamic analysis of fatigue from platform motions

External pressure buckling

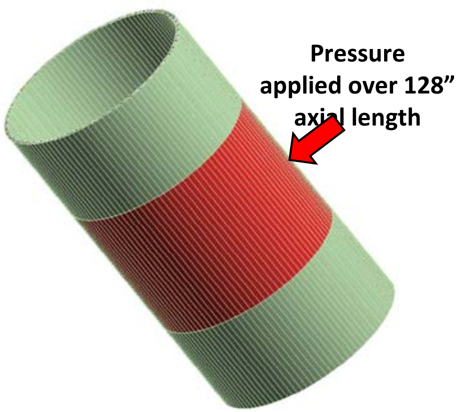


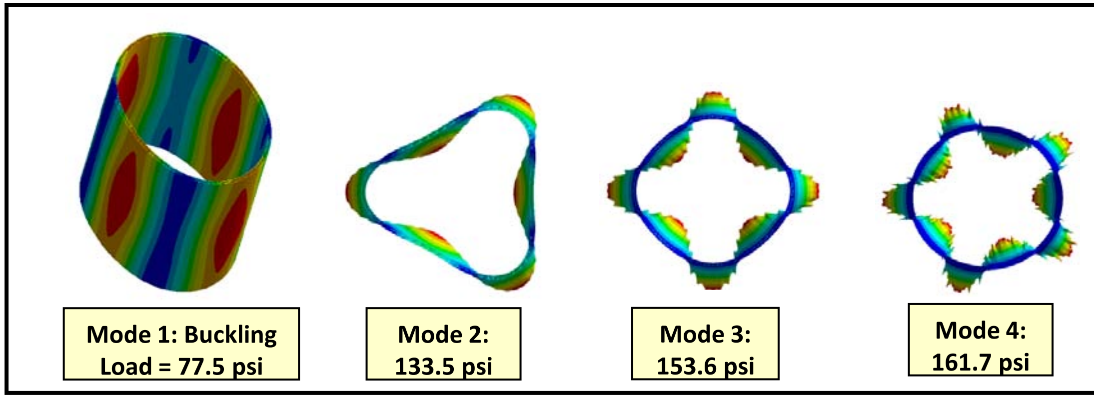
- **Triangular core cell design works well for external pressure loadings**
- **FEA predicted buckling pressure of 36.75 psi exceeds operating pressure of 7.5 psi by a large Margin-of-Safety**

Doug Hillson

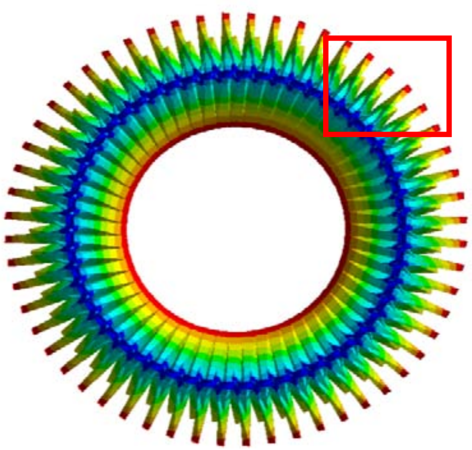
Localized buckling from gripper and guide bushing pressures

Work done at LM MS2 under LM program N62583-09-C-0083 sponsored by the US Navy Facilities Command

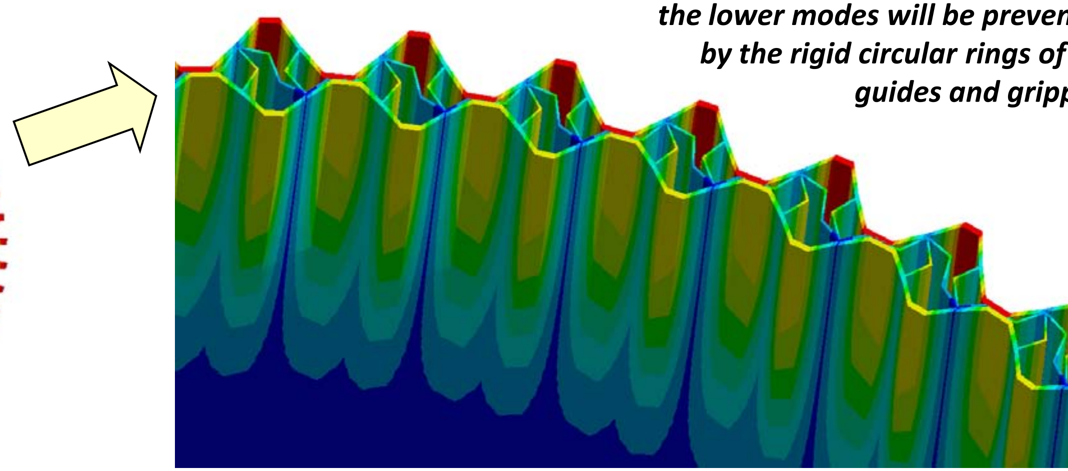




In the bushing and gripper regions, the lower modes will be prevented by the rigid circular rings of the guides and grippers



Mode 5: 163.8 psi



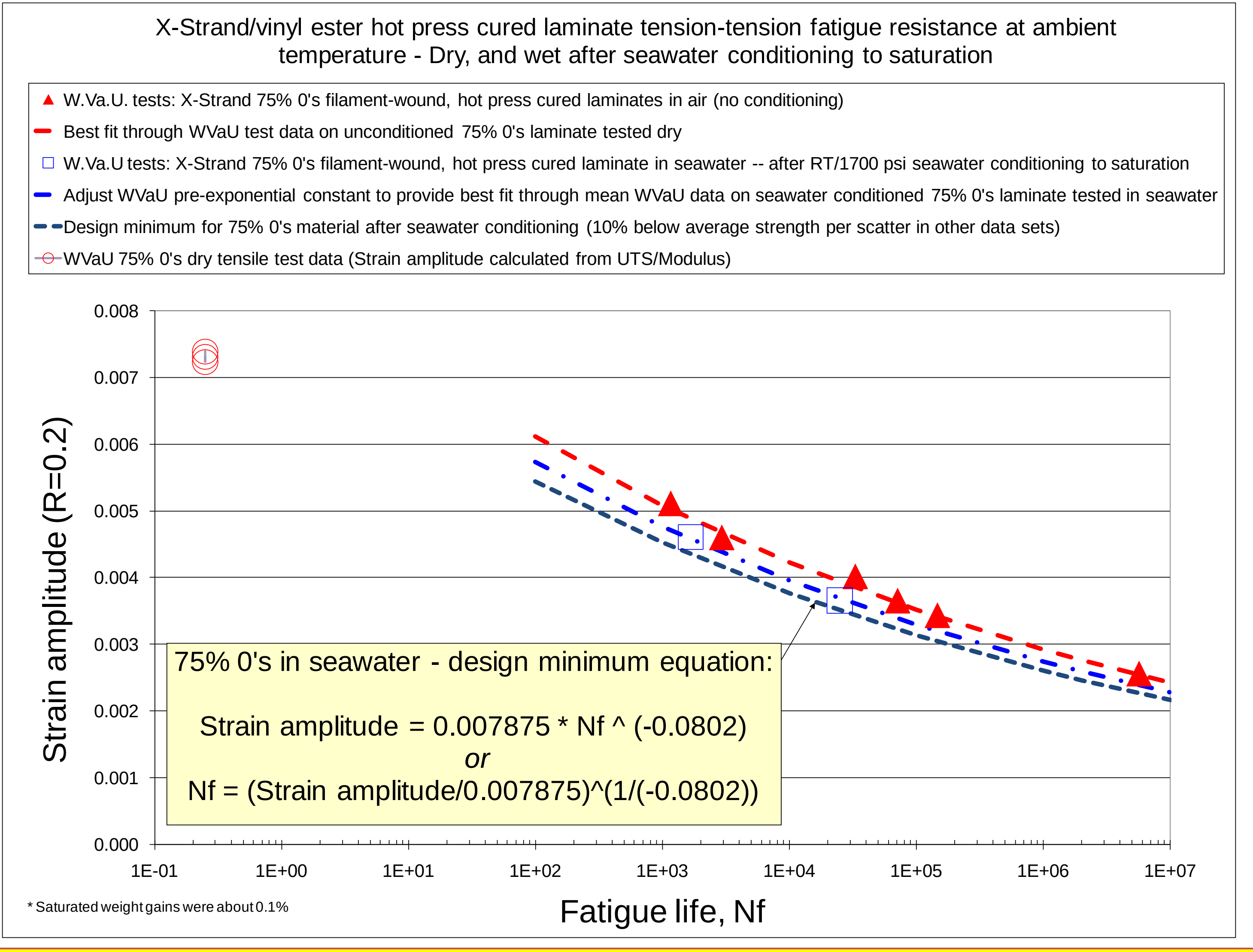
Detail View

Deflections magnified by 2X

4m CWP has local buckling pressure of 164 psi, adequate for the localized forces imposed by bushings operating at 50 to 75 psi local pressure.

Tony Paulic

Fatigue resistance after seawater conditioning to saturation: Selected CWP material shows only 6% knockdown relative to dry material



West Virginia Univ.

Seawater fatigue testing provides known material behavior for current work.

Coupled hydrodynamic analysis of fatigue from platform motions

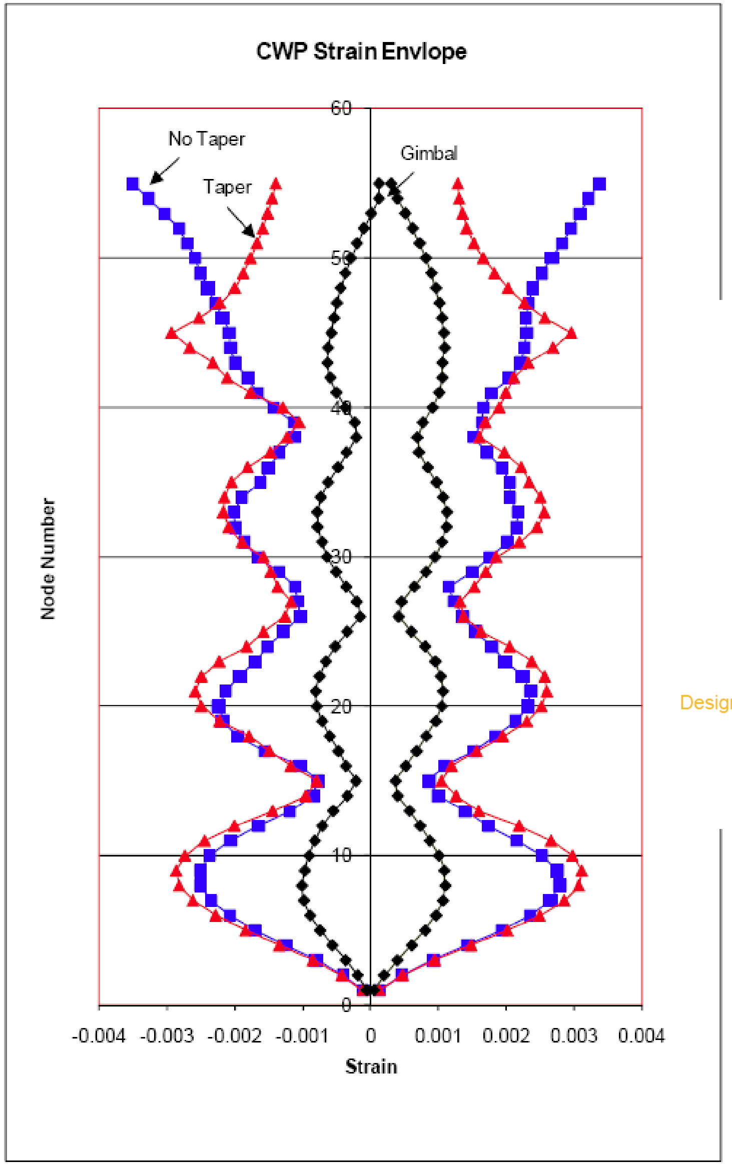
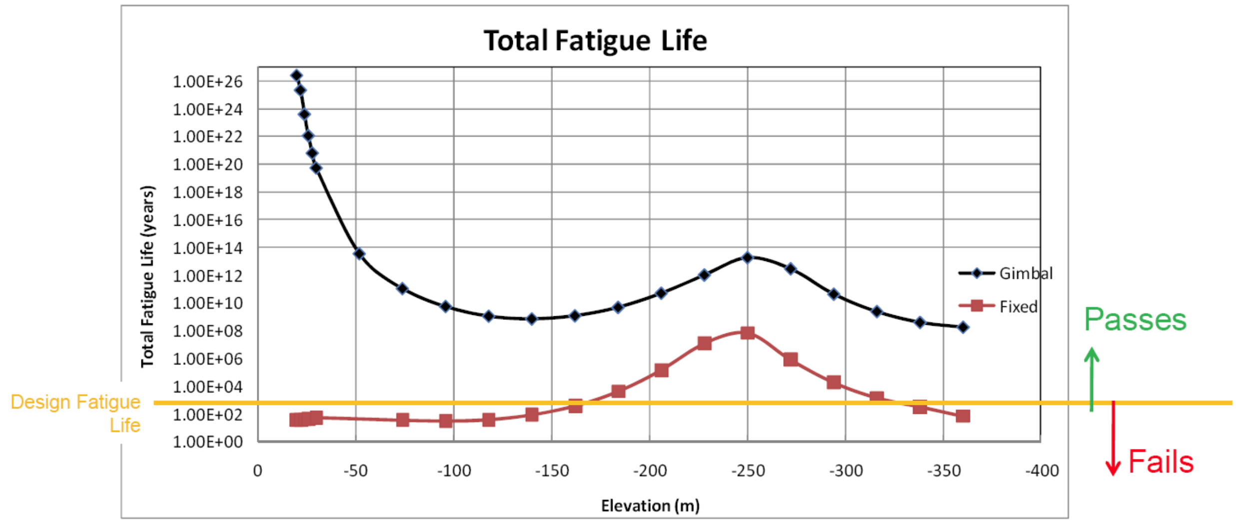


Figure 57. Strain Envelope for 10 m Tapered Pipe

Work done by John Halkyard and Associates and Houston Offshore Engineering under LM program N62583-09-C-0083 sponsored by the US Navy Facilities Command. Work utilized design minimum curve from the previous figure.



- **Without a gimbal, the current 10m CWP design has a slightly negative Margin-of-Safety**
- **Tapering does not help much**
- **A gimbal brings the MOS to a strongly positive level**

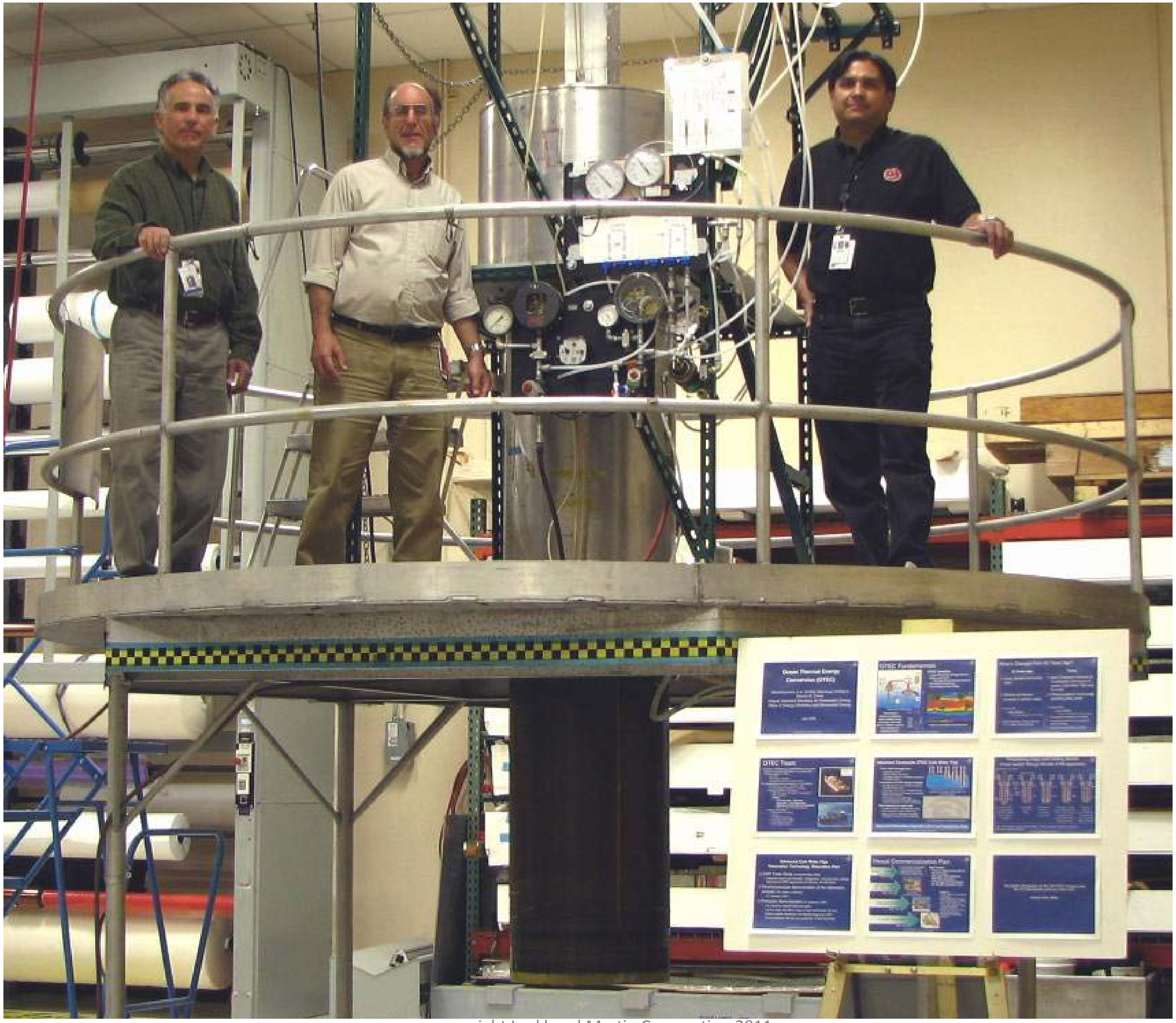
Shan Shi, John Halkyard

IV. Proof-of-Principles Validation of the CWP fabrication process

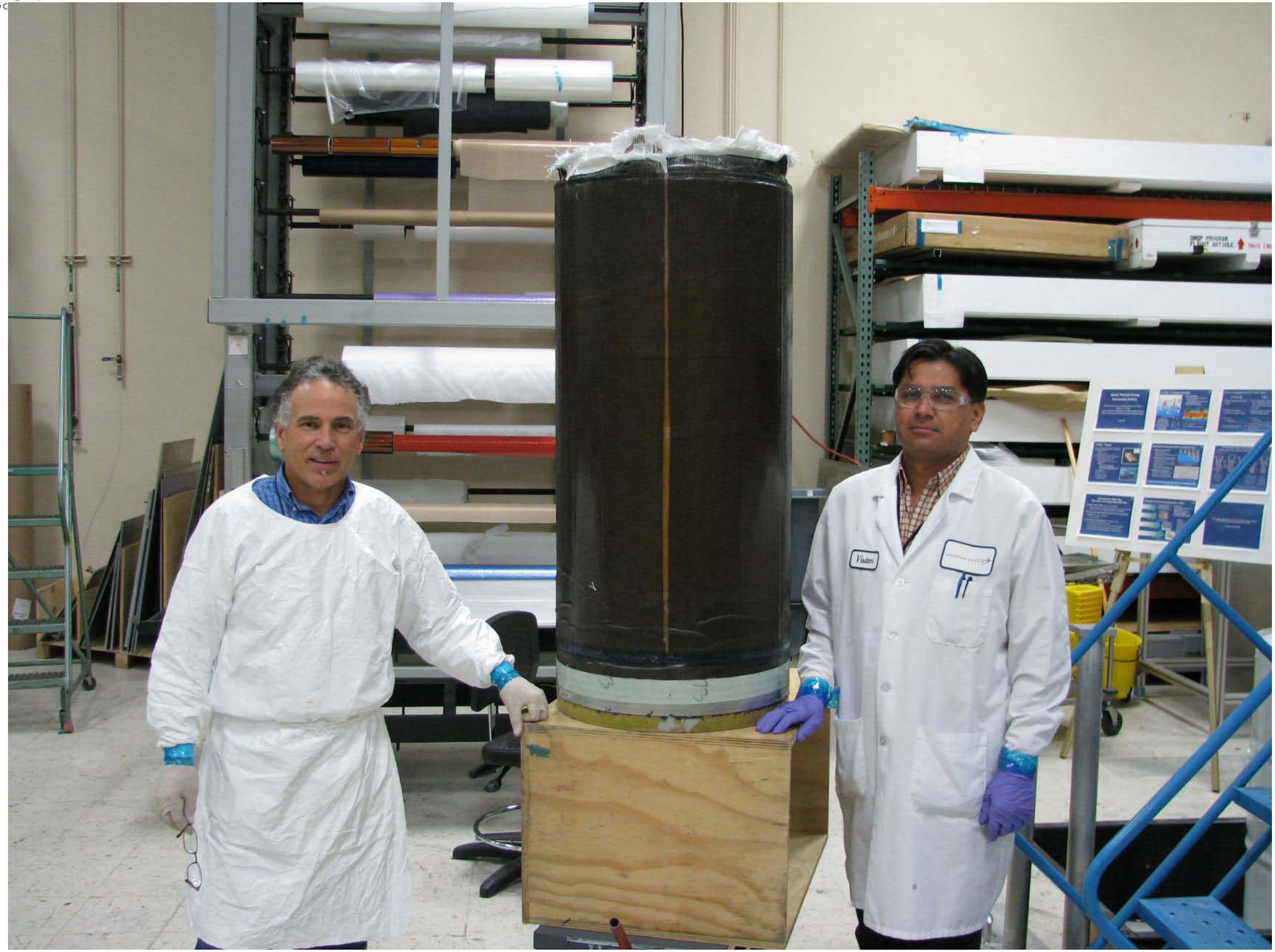
(Work done prior to the DoE program, under LM MS2 IRAD funding)

- Proof-of-Principles apparatus
- First Proof-of-Principles workpiece
- CWP fabrication process elements validated by the Proof-of-Principles work at 19” scale

The CWP fabrication process was first validated at laboratory scale (19” dia.) with a Proof-of-Principles apparatus



First Proof-of-Principles workpiece infused by VARTM



The PoP work validated behavior of the CWP fabrication process in the following areas, and provided the confidence to continue with the same approaches into the subsequent DoE-sponsored work

- **Mold action**
- **Fabric behavior**
- **Sealing ends of current workpiece / pulling vacuum**
- **Infusion behavior**
- **Resin behavior**
- **Co-bonding behavior**

Proof-of-Principles work validated the key elements at 19” scale (p. 1 of 2)

Element	Tested?	Works as expected?	Use same approach in Prototype and beyond?
Mold action			
Expanding/contracting soft tools	Yes	Yes	Yes
Good compaction of FS	Yes	Yes	Yes
Good release of soft tools from part	Yes	Yes	Yes
Fabric behavior			
Accurate mechanized dry fabric placement	Yes	Yes	Yes
No unacceptable wrinkling in outer FS	Yes	Yes	Yes – with pre-stitched unit fabric
Sealing / pulling vacuum			
Lower inflatable seals	Yes	Yes	Yes
Upper vacuum chamber over fabric rolls	Yes	Yes	Yes
Infusion behavior			
Good resin spreading (using VARTM)	Yes	Yes*	Yes
Full wetout through-thickness	Yes	Yes	Yes
Good wet-out at knit-line between steps	Yes	Yes	Yes

*After changing to a 2nd generation resin spreading method (VARTM) based on results with the 1st generation method

Proof-of-Principles work validated the key elements at 19" scale (p. 2 of 2)

Element	Tested?	Works as expected?	Use same approach in Prototype and beyond?
Resin behavior			
Resin mixing and handling without exotherm	Yes	Yes	Yes – Using metering/ mixing machine
Rapid ambient temperature cure	Yes	Yes	Yes
Good final properties			
Low void content	Yes	Yes	Yes
Uniform fiber volume	In progress		
Accurate fiber volume control	In progress		
Co-bonding behavior			
Good bond between infused face sheets and prefabricated core	Yes	Yes	Yes
Good dimensional control of part			
Circularity when using core "planks"	In progress		Yes
Uniformity of outer diameter	In progress		Yes
Shear key works OK	Yes	Did not engage fully	Yes, or use staggered planks instead

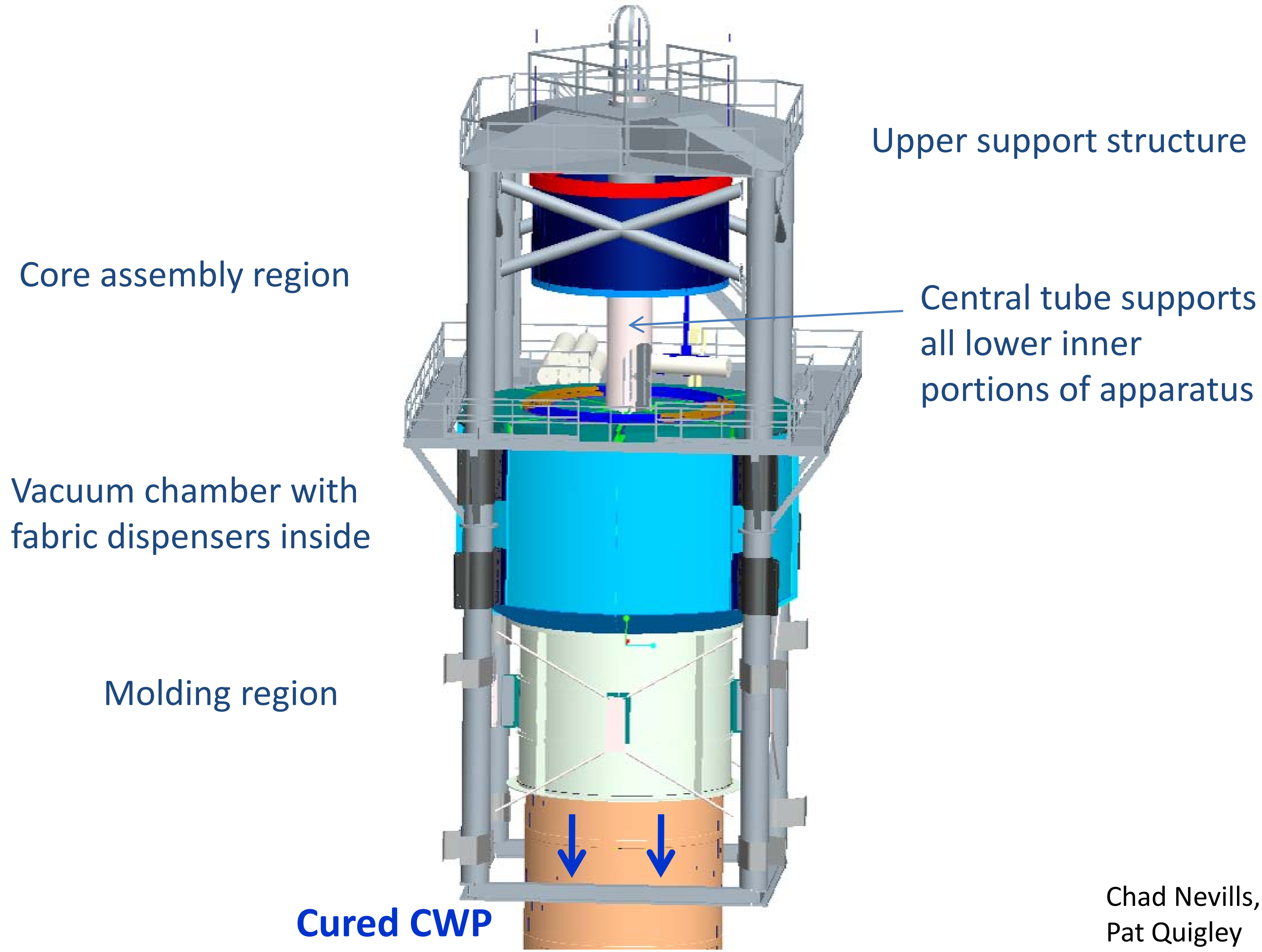
The PoP work identified the major improvements to be made in the scaled-up apparatus

Element	Inadequacy with PoP	Improvement in Prototype
Soft tools	Suspected pinhole may have led to water leakage onto part and incomplete cure of resin in run 3B	Use double layer of silicone rubber with monitoring between them for any water leakage
Shear key	Suspected lack of full engagement of shear key on Run 3B	More precise tolerancing and in-process checking to assure full engagement
Coverage with RDM	Excessive gaps between RDM strips caused incomplete wet-out	Use overlap splices between RDM strips
Monitoring resin height during infusion	External sight tube did not work reliably due to air bubbles getting into it from resin inlet, and shooting to top	Use pre-calculated resin quantity for fill; possibly also use embedded fiber optic as cross-check
Resin distribution line units	Non-reusable design requires excessive fabrication labor	Develop solvent-flushable unit that can be left in place
Fabric configuration	Some circumferential wrinkling observed; one cause may be double layer of fabric wound on supply rolls	Have fabric supplier pre-stitch fabrics together into a single unit (standard industry technique). Track down any other causes.
Lower vacuum seal	Using Tygon tubing limited radial travel	Use purchased SealMaster seals designed with ample radial travel
Access to inner resin distribution line unit	Lack of center access hole in cylindrical vacuum chamber makes access to inner RDL awkward	Incorporate large center access hole by changing to toroidal vacuum chamber
Vacuum leaks	Many joints between components were sealed with sealant tape	Incorporate standard vacuum sealing methods such as O-rings between components

V. Design configuration of the full CWP fabrication apparatus

- Design configuration of the full CWP fabrication apparatus
- The apparatus will go inside a weather enclosure on the floating OTEC platform

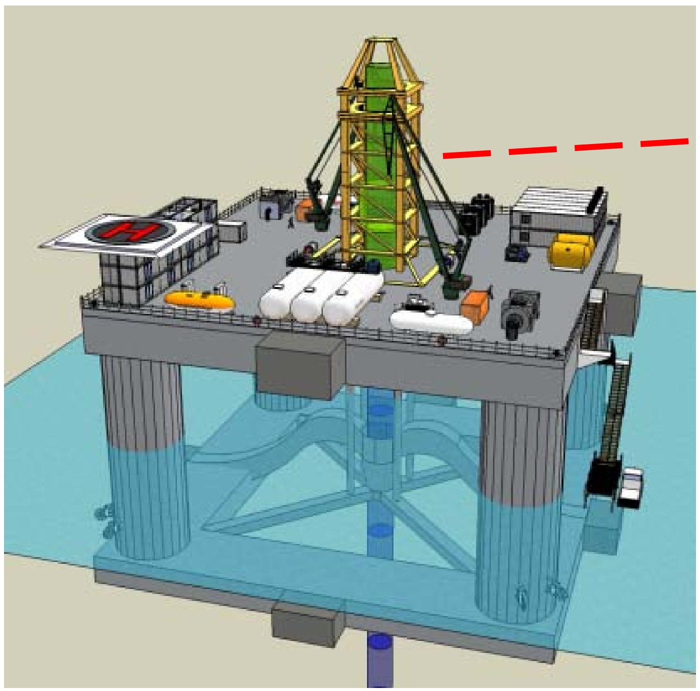
Design configuration of the full CWP fabrication apparatus implements the process at large scale

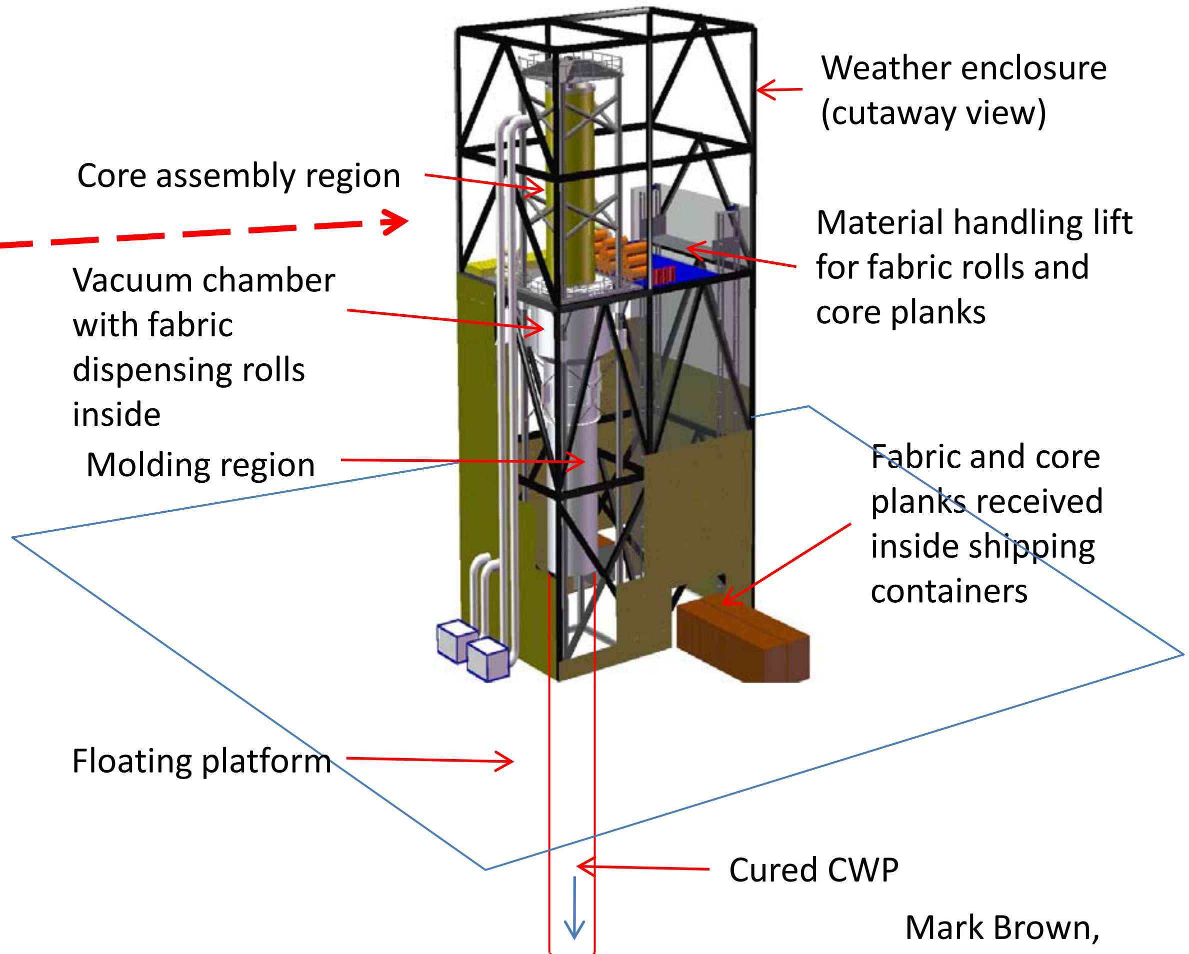


Chad Nevills, Pat Quigley

To fabricate the CWP for the Pilot Plant and commercial plants, the apparatus will go inside a weather enclosure on the floating OTEC platform

Work done by Sound and Sea Technologies under an LM program sponsored by the US Navy Facilities Command





Mark Brown, Sound and Sea

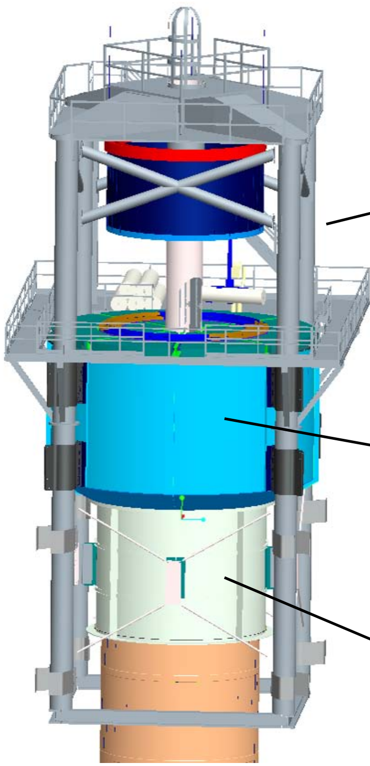
VI. Validation of the CWP fabrication process at 4m diameter scale

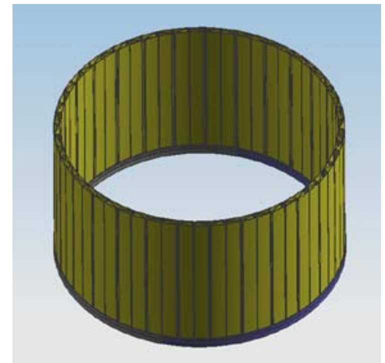
Work sponsored by the US Department of Energy and performed under DoE / LM MS2 Cooperative Agreement # DE-FC36-08GO18172

Validation of the CWP fabrication process at 4m diameter scale

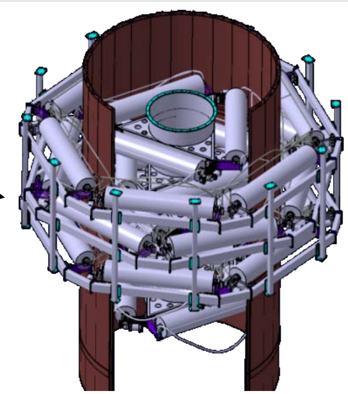
- Major apparatus and process elements selected for validation at 4m CWP scale under the DoE AWPP
- VI.A - Validation 1 – Core plank production and assembly into core rings
- VI.B - Validation 2 – Fabric architecture, production, overlap splice performance, and fabric dispensing process
- VI.C - Validation 3 – Stepwise infusion molding process

Major apparatus and process elements selected for validation at 4m CWP scale under the DoE AWPP

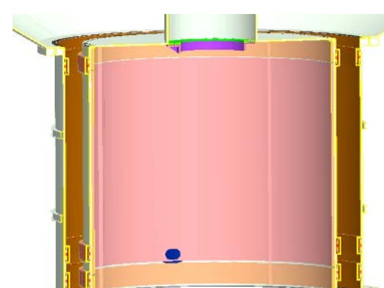




1. Core plank production and assembly into core rings



2. Fabric architecture, fabric production, and fabric dispensing mechanisms

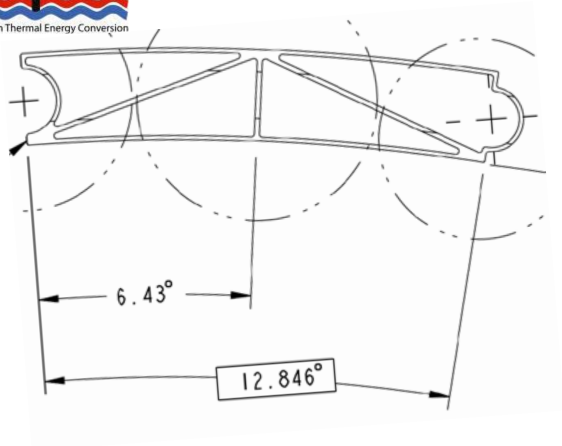


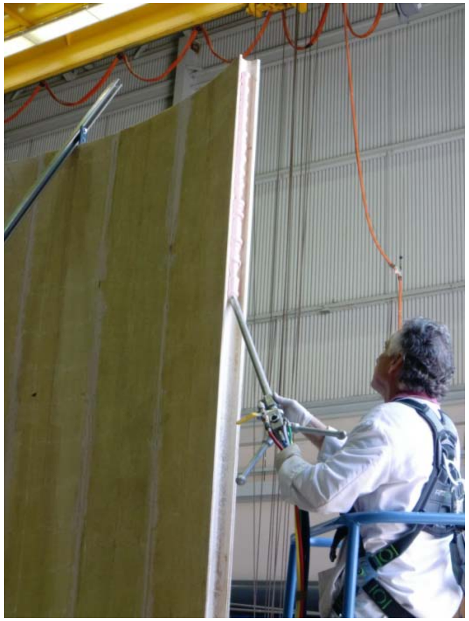
3. Molding region and stepwise infusion validation

VI.A - Validation 1 – Core plank production and assembly into core rings

- Pictorial summary of core assembly validation
- Pultruded Core Planks
- Shear keys
- Shear key tooling
- Shear key infusion
- Core assembly adhesive and application equipment
- Representative core ring assembly operations
- Assembling core ring
- First assembled core ring (still showing internal cross-section)
- Staggered planks method of joining adjacent core rings
- Tabular summary of core production and assembly validation results at 4m scale

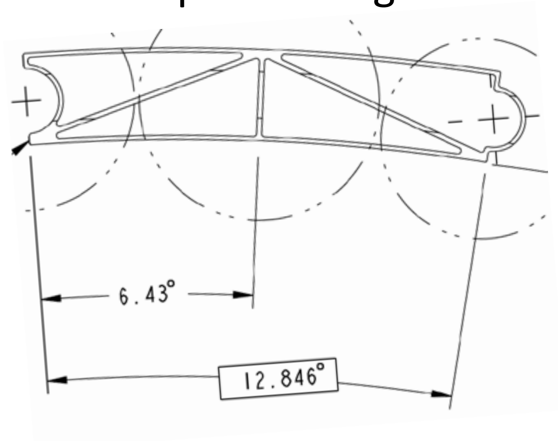
Pictorial summary of core assembly validation



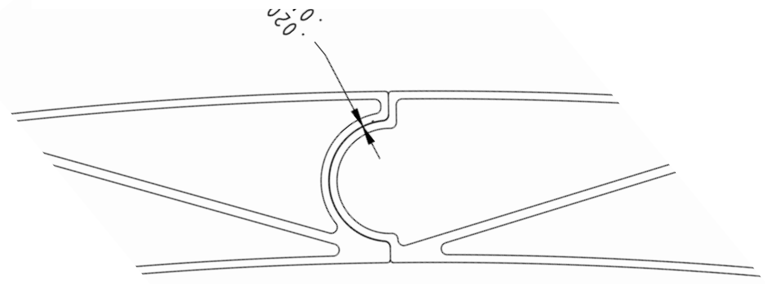


Pultruded Core Planks

Core plank design

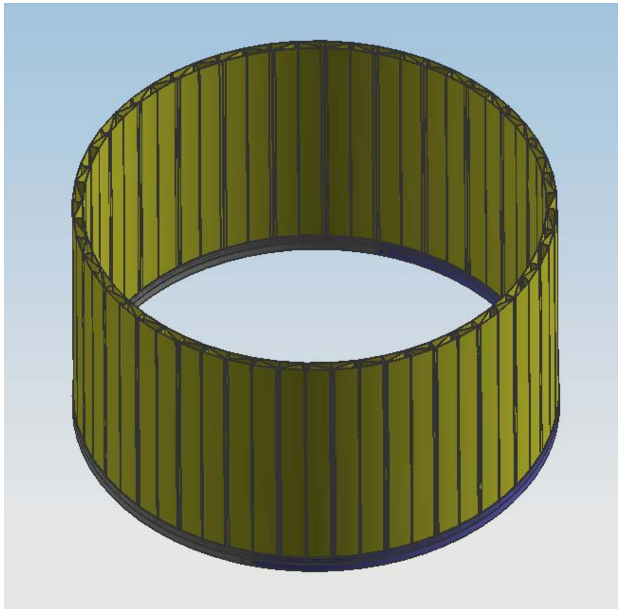


Tongue and groove edges lock adjacent core planks together radially



Core planks are made using the same fiberglass material, resin type, and fiber orientation distribution as face sheets
•Avoids any stresses due to mismatching elastic constants

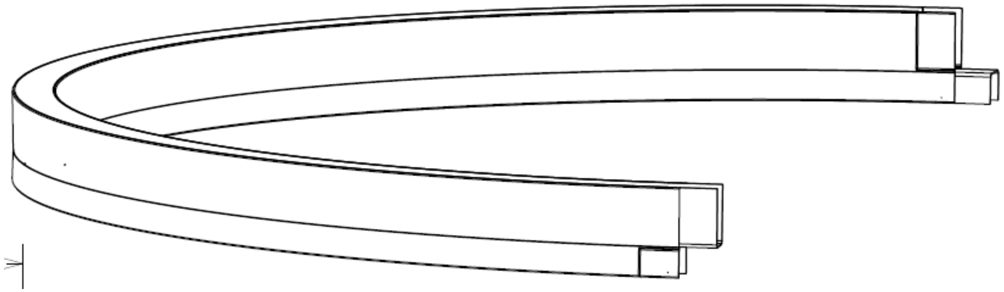
Assembled core ring (28 planks) with shear key at bottom



Pultruded core plank

Planks manufactured by Glasforms, Inc, Birmingham, AL

Shear keys



Shear keys manufactured by Janicki Industries, Sedro-Woolley, WA

Shear key tooling

(Putty over foam over wood base on steel frame)

Shear key tooling designed and manufactured by Janicki Industries, Sedro-Woolley, WA

Shear key infusion

Work done at Janicki Industries, Sedro-Woolley, WA

Core assembly adhesive and application equipment

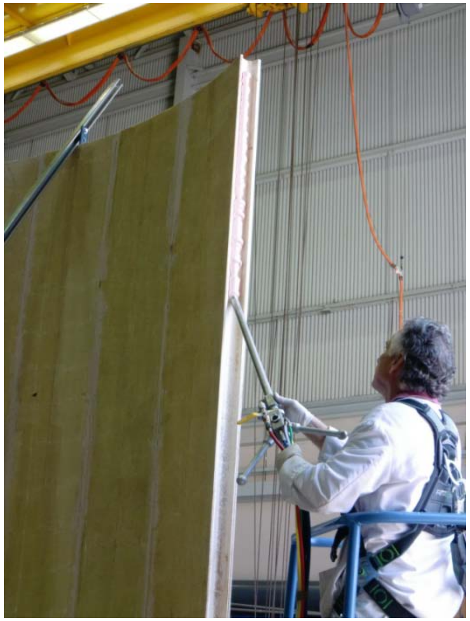
A COTS thick putty adhesive was selected based on the following behavior *:

- Even a ½" bead stays in place vertically
- Squeezes out well to fill the bondlines between planks

A COTS mixing and dispensing pump designed for thick adhesives was used

*Major requirement was fabricability of large assembly, not strength, because in the final CWP the face sheets hold the planks together.

Representative core ring assembly operations

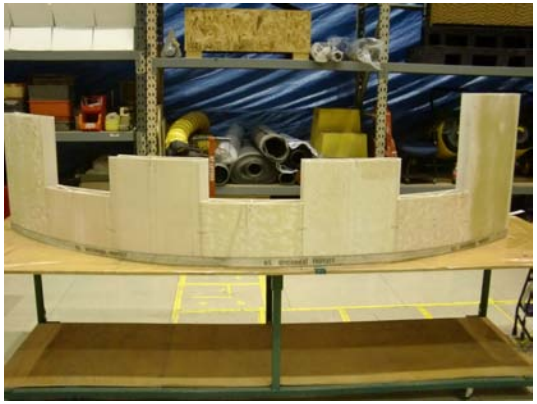


Assembling core ring

First assembled core ring
(still showing internal cross-section)

October 27, 2010

Staggered planks method of joining adjacent core rings (instead of shear keys) – p. 1 of 2



Advantages

•Direct transfer of core axial loads through plank edges instead of through face sheets (zero stress concentration in face sheets)
•No protruding elements on inside or outside of core
•Eliminates need to seal core planks to shear keys

Initial test: Forming leak-tight longitudinal plank-to-plank joints [(1)]

Results

•Plank-to-plank joints did not leak
•Air leakage through pultrusion wall prevented demonstration of a leak-tight assembly
•Some lessons were learned on details of assembly and methods of applying adhesive

Notes

[(1)] During face sheet infusion, interior of core will be vented to atmosphere. Any air leaks through joints or planks introduces air into fabric being infused with resin, with risk of voids.

Second test: Demonstrate a leak-tight staggered-planks assembly

Procedures:

•Choose a plank with relatively high surface porosity (as a severe test)
•Apply inexpensive COTS liquid sealant ("slosh compound") to the inside of the plank
•Cut plank into 4 portions
•Assemble two portions of the plank end-to-end, using same thick core assembly adhesive as earlier, incorporating configurational improvements based on lessons learned from 1st test
•Add two continuous planks along edges, to form the staggered joint configuration
•Vacuum bag over inner and outer assembled plank surfaces, and vacuum drop test

Results:

1. Adhesive application and assembly operations worked well and required minimal labor
2. Initial test after single application of slosh compound: High leak rate
3. Apply slosh compound to cut ends of planks, and re-test: Lower leak rate
4. Apply second coat of slosh compound to insides of all plank portions:
   - Still lower leak rate, about 6" Hg in 5 minutes (Close to an acceptable level for a VARTM tool)
   - No air leaks were audible at the end-to-end plank joints

Conclusions:

•A configuration has been developed which enables straightforward adhesive-joining assembly of longitudinally adjacent core planks into a staggered-plank joint, eliminating the shear keys
•The joints between planks are leak-free
•Attention should be given to production of leak-tight pultruded planks for future work. If necessary as a re-work measure at the pultrusion vendor in order to pass acceptance tests, low-cost liquid sealant slosh compound can be used to seal up any porosity in the planks.

Summary of validation results at 4m scale – Core production and assembly

Component and operations	Results and key challenges met	Evidence	Future Needs
Produce custom pultrusions designed to meet all initially known loads, and meeting requirements of stepwise infusion fabrication process (at Glasforms)	**Successful** – **Achieved proper fabric guidance, resin wet-out, and straightness in complex multi-cell hollow pultruded shape made from all-fabric with some sparse fiber directions**	Pultruded planks; good fit-up and dimensional control in assembled core ring	For fabrication of long CWP on-the-water, need to add more ribs to increase local buckling strength under pressure of gripper and bushings
Bond pultruded planks into core ring	**Successful** – **Achieved proper spacing to fit shear keys. Achieved good circularity and diameter control**	Results at multiple locations: +/- 1/8" variability in diameter over the 158" diameter	
Test vacuum tightness of as-received pultruded planks	**Not successful – A random sample core plank was vacuum bagged on its outside. Drop testing showed a 6" Hg drop in 5 minutes.**	This was despite the plank manufacturer's water-tank testing of best and worst planks, with application of resin on the outside of all to seal them.	Need to improve the leak-tightness of the core planks as-pultruded, or if necessary with subsequent sealing
Test vacuum tightness of plank-to-plank joints (staggered planks approach)	**Successful** – **The assembly leak tightness is as good as the planks themselves**	Same vacuum drop as the planks themselves. No audible evidence of air leakage at longitudinal joints	
Produce leak-tight core assembly by pre-applying a commercial "slosh sealing compound" inside each cell of each plank, then assemble into staggered-planks configuration, and vacuum test	**Successful** – Overall drop-test leak rate of staggered-joint assembly is close to acceptable level for VARTM tools.	6" Hg vacuum drop in 5 minutes	Improve the leak-tightness of the core planks as-pultruded, and use slosh compound as a re-work measure if necessary to ensure leak-free pultrusions.

VI.B - Validation 2 – Fabric architecture, production, overlap splice performance, and fabric dispensing process

- Pictorial summary of fabric dispensing validation
- VI.B.1 – Fabric architecture
- VI.B.2 - Validation of overlap splice strength
- VI.B.3– Fabric dispensing validation
- Tabular summary of fabric architecture and dispensing validation results at 4m scale –

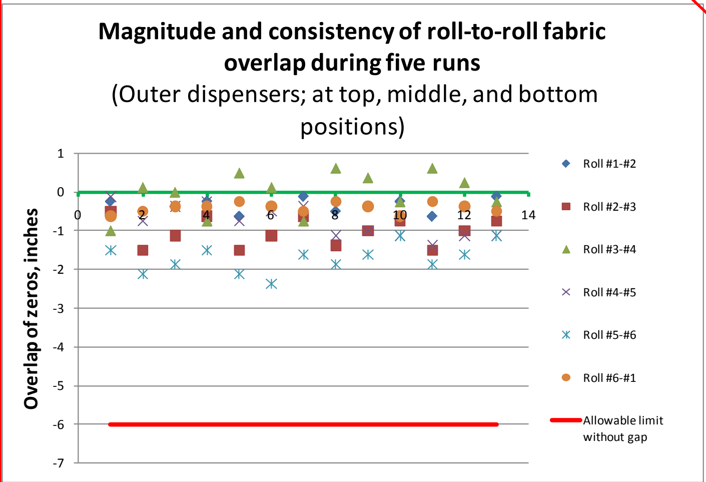
Pictorial summary of Fabric Dispensing validation

<u>Function</u>: Fabric is dispensed by machine under constant tension maintained by servomotor-driven rollers, and is guided by special "bibs" into its curved configuration.

Machine-based fabric placement eliminates hand layup labor and is the key to low recurring costs.

<u>Status</u>: Validation proved that the apparatus forms consistent overlap splices, well within required tolerances.

Note worker for scale



Outer face sheets

Inner face sheets

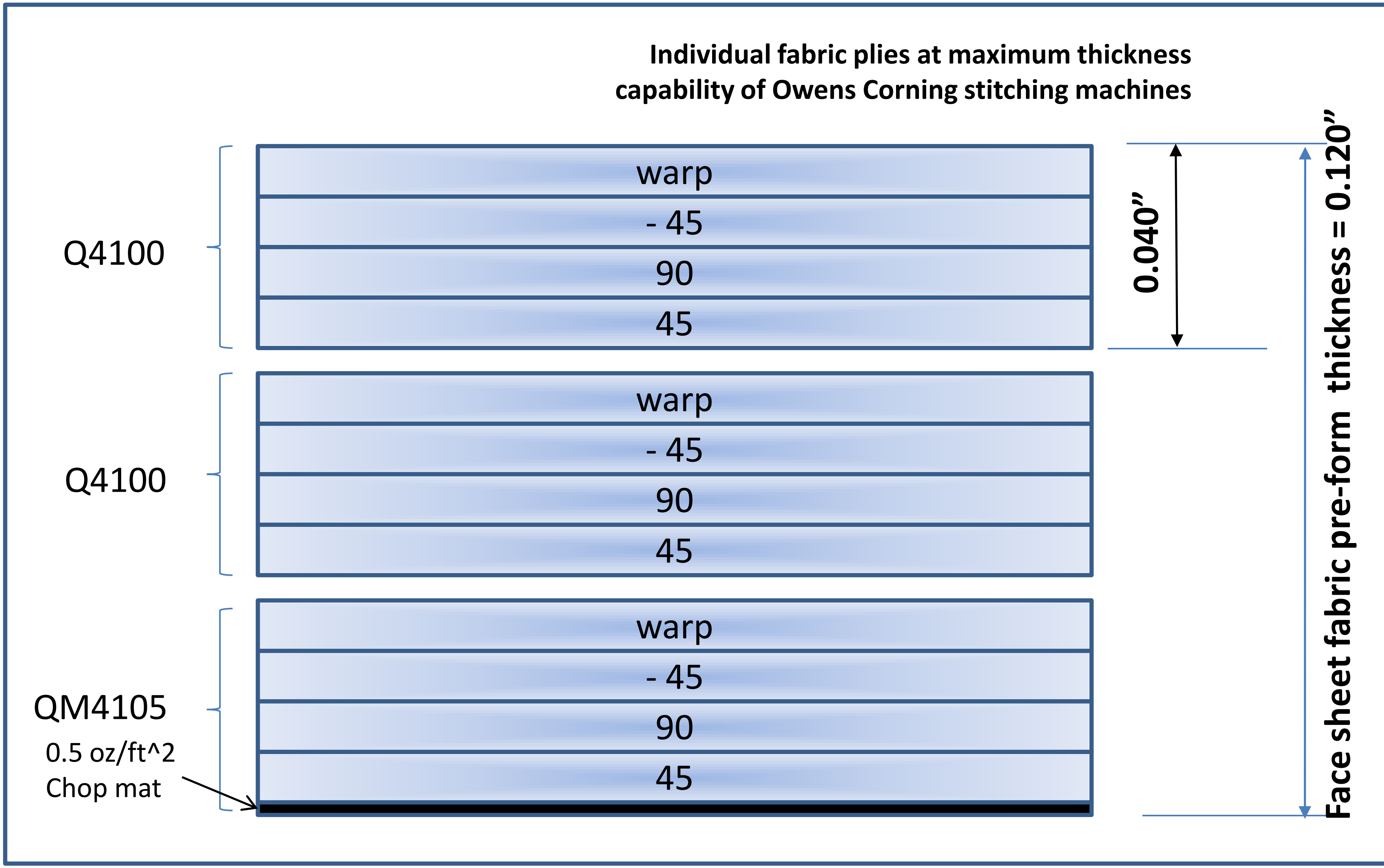
Work done at Janicki Industries (Paul VanSant, Project Manager) under subcontract from LM-MS2 with technical direction by LM-SSC.

August-Sept., 2010

VI.B.1 – Fabric architecture

- Custom pre-assembled 3-ply face sheet stitched preform
- Face sheet fabric architecture
- Photo of CWP segment including one fabric splice in each face sheet

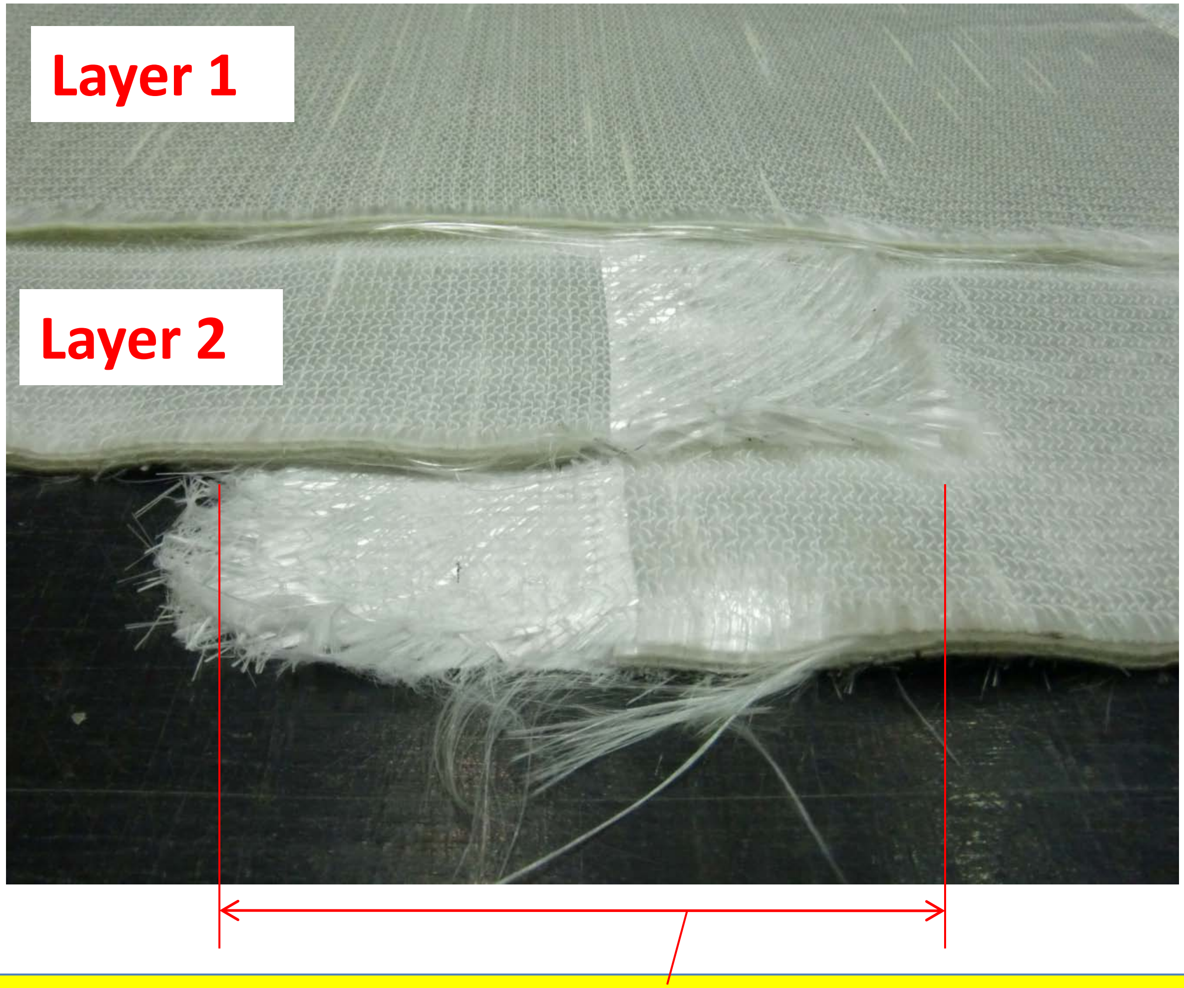
Custom pre-assembled 3-ply face sheet stitched preform



Pre-assembling the fabric into two thick preforms simplifies the fabric dispensing apparatus

Face sheet fabric architecture

Each face sheet is divided into two major layers (preforms) of stitch-assembled face sheet fabric

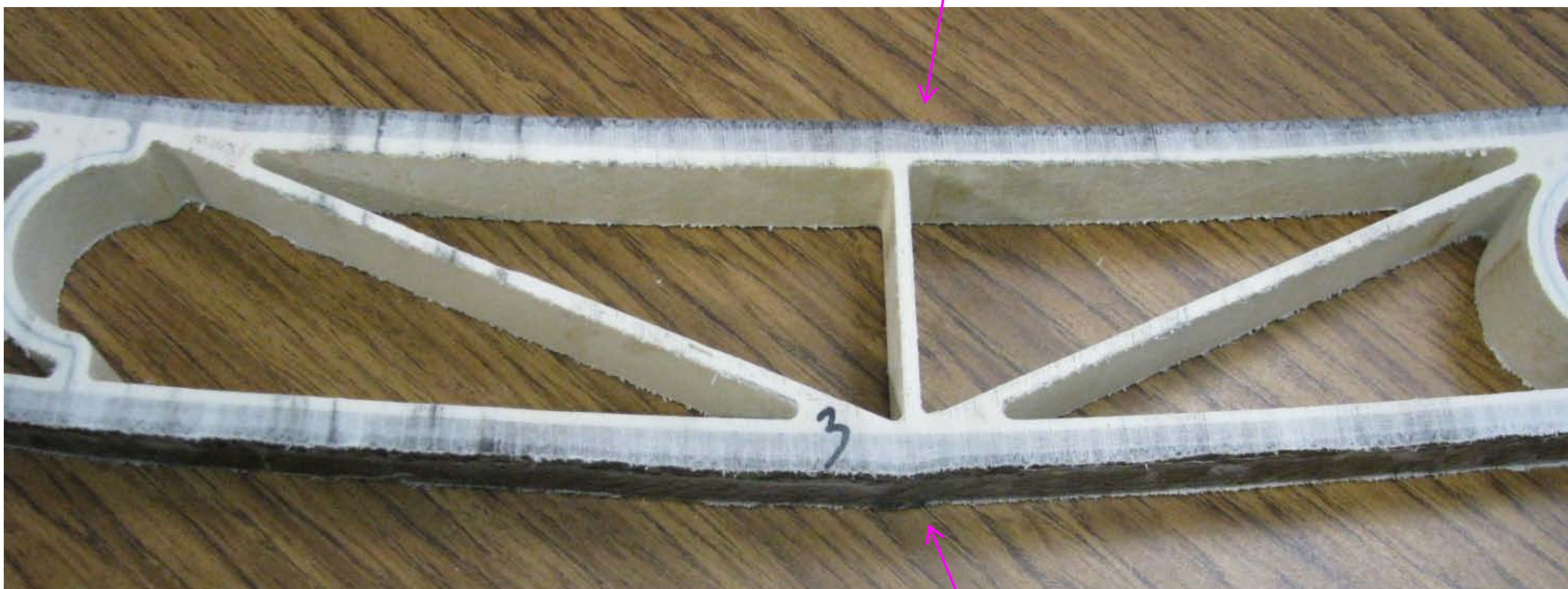


Fabric for 4m CWP

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

- Architecture creates generous 6" wide overlap splices for 90's and 45's carrying circumferential loads
- Splices in each major layer are reinforced by continuous fabric in other major layer
- By leaving out the 75% zeros in the overlap splices, the thickness increase at the splices is minimized

Photo of CWP segment including one fabric splice in each face sheet



Thickness increase at face sheet fabric splices is barely detectable, and presents no problem going through apparatus, gripper, and bushings

VI.B.2 - Validation of overlap splice strength

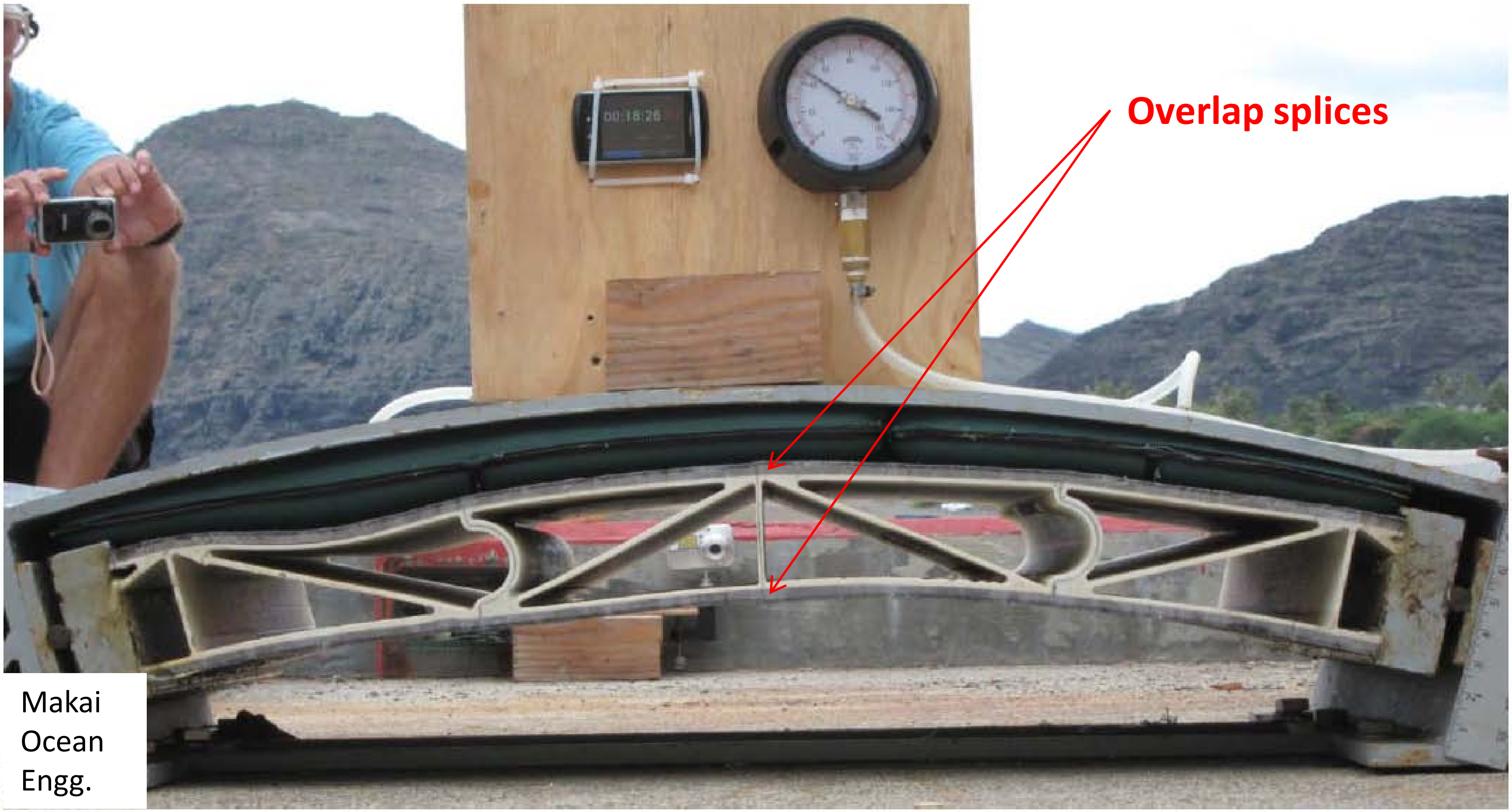
Under a parallel LM OTEC program sponsored by the US Naval Facilities Command, sections of our CWP design were fabricated and tested under local external pressure, to validate the predictions of its local buckling resistance. The validation was successful, and is described fully in the Technical Development Report of that program.

For one of the three fabricated specimens, we included overlap splices per our fabric architecture. As shown in the next figure, that specimen failed at a location away from the splice (and at about the predicted failure load) . This indicates that the splice regions held the required in-plane compressive load successfully, and provides initial validation of our fabric architecture.

Validation of fabric overlap splice strength

Local pressure buckling test on section of 4m CWP

Testing done by Makai Ocean Engg. under LM program N62583-09-C-0083 sponsored by the US Navy Facilities Command

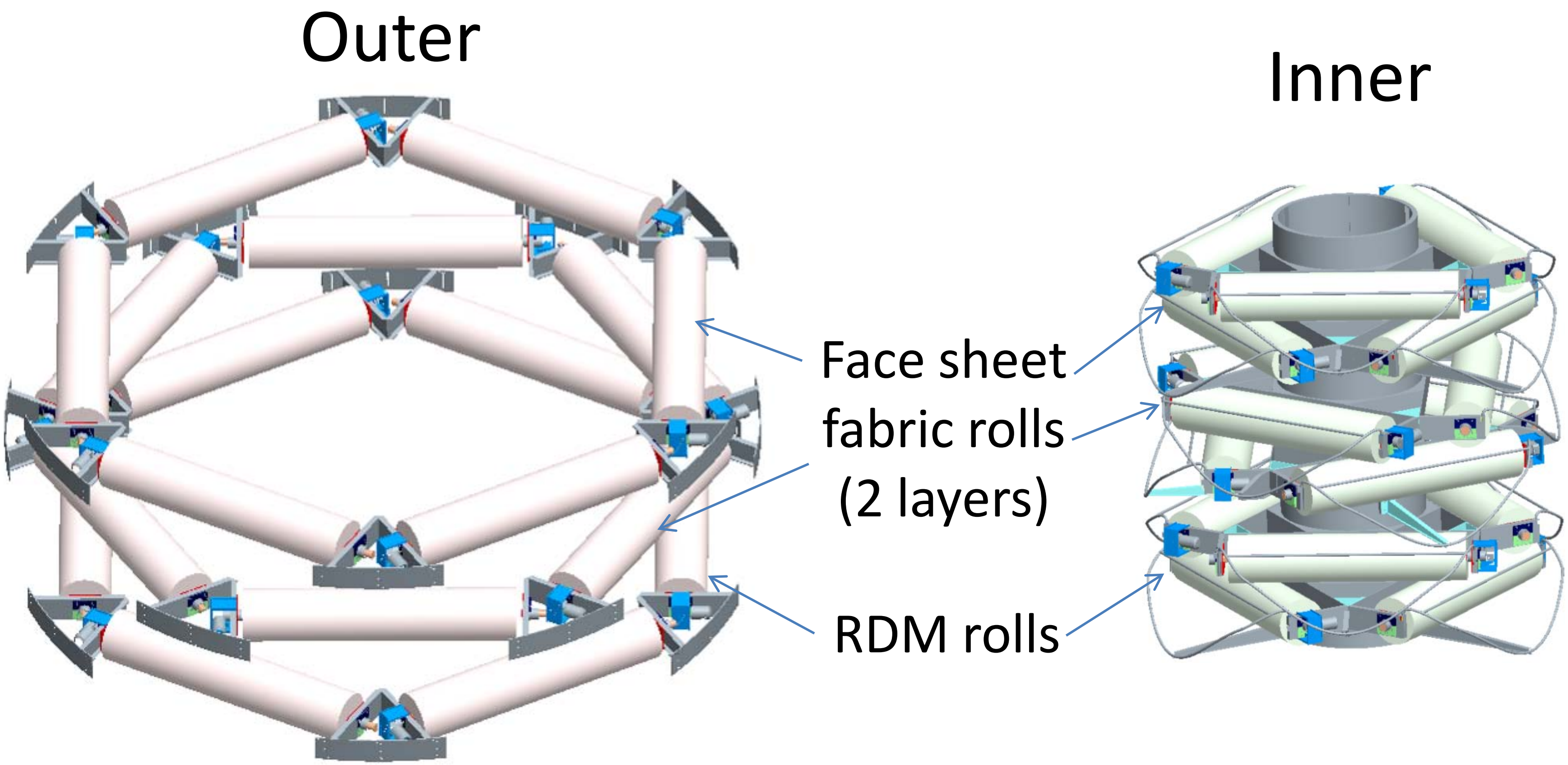


The specimen failed away from the splices, at about the expected pressure.
The fabric splices held the required in-plane compressive load. The concept is validated

VI.B.3– Fabric dispensing validation

- Configuration of fabric and RDM rolls
- Apparatus during assembly
- Assembled apparatus
- Fabric dispensers computer control system
- Testing constant-payout-tension behavior
- Outer fabric dispensers (typical)
- Outer fabric dispensing, with formation of typical overlap splice
- Inner fabric dispensers (typical)
- Inner fabric dispensing, with formation of typical overlap splice
- Validation of fabric dispensing accuracy
- Tabular summary of fabric architecture and dispensing validation results at 4m scale

Configuration of fabric and RDM rolls



Can put all rolls for any one layer at the same level

Need to put all rolls for any one layer on two adjacent levels

Apparatus during assembly

Inner dispensers support frame

Outer dispensers support frame

Janicki Industries photos

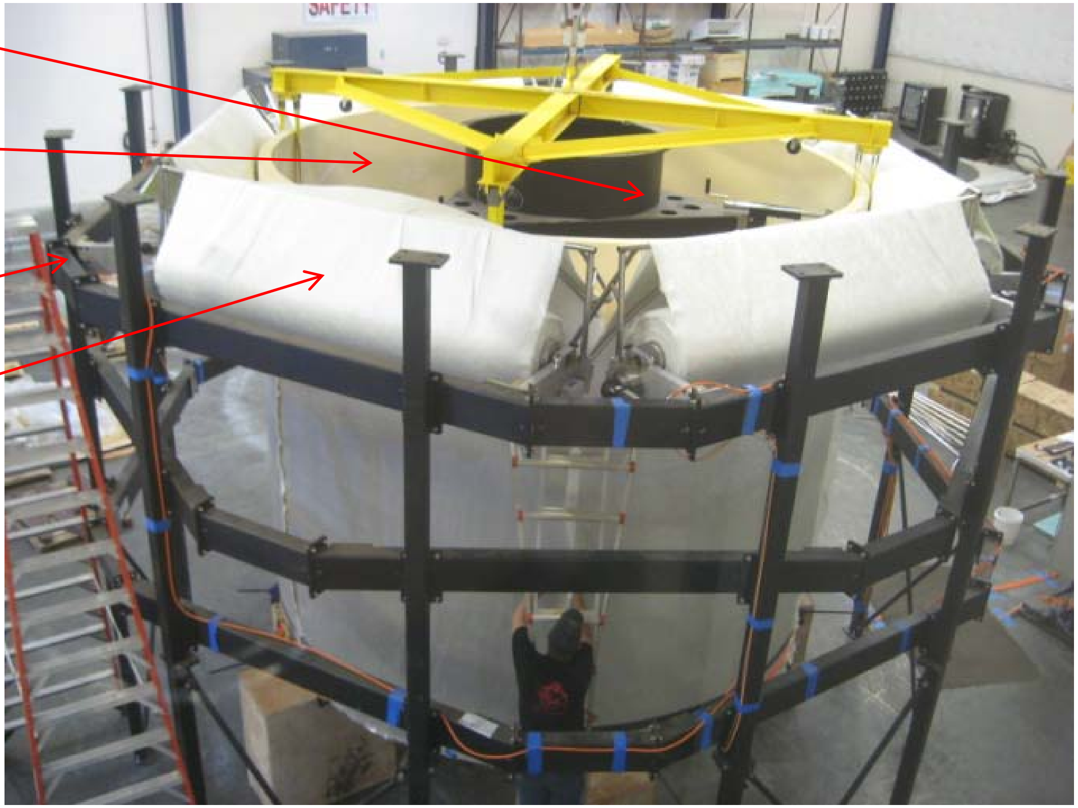
Assembled apparatus
(during validation of outer face sheet dispensing)

Inner dispensers frame

Inner face sheet fabric rolls go here

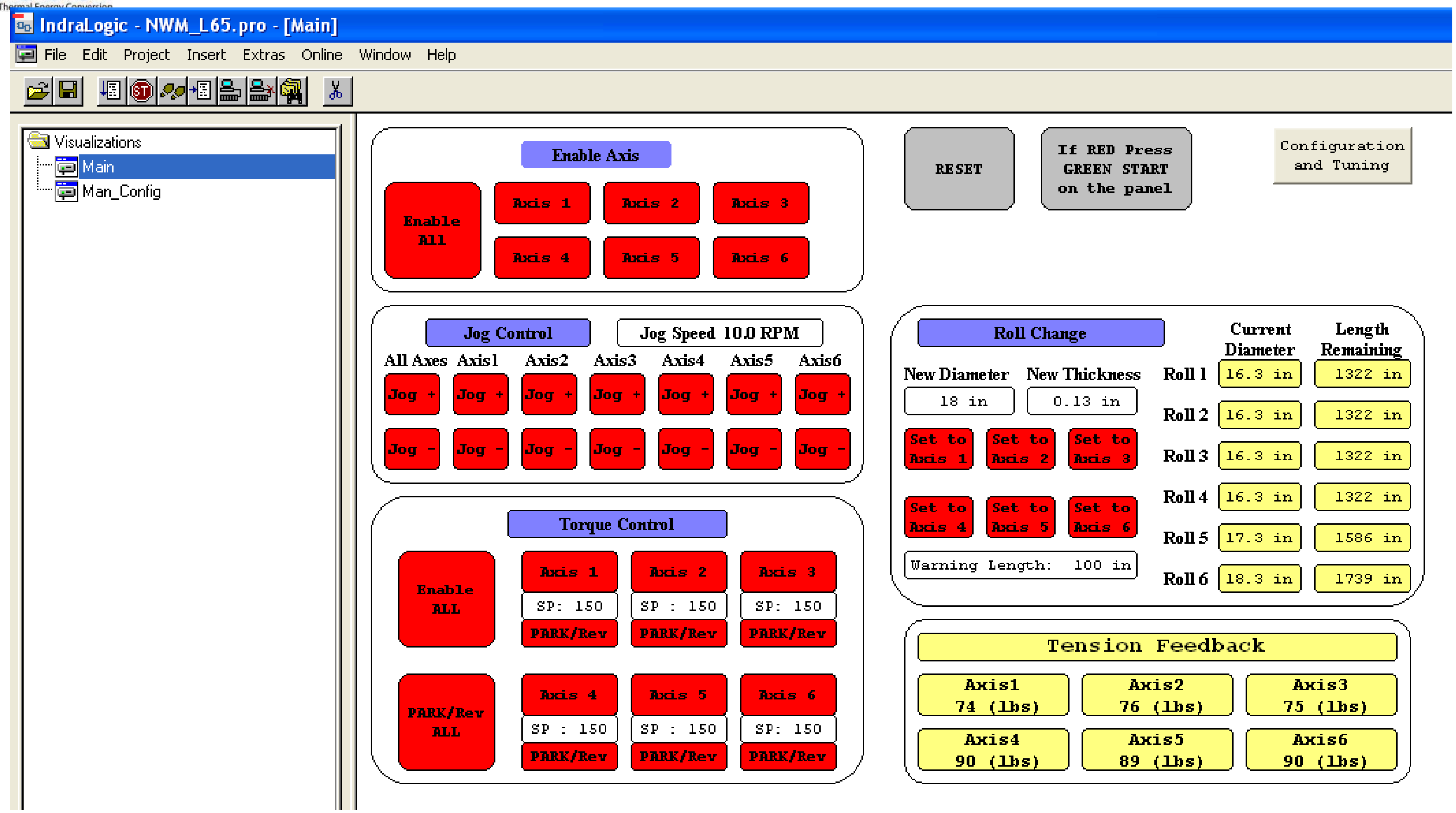
Outer dispensers frame

Outer face sheet fabric rolls



Janicki Industries photo

Fabric dispensers computer control system



Janicki Industries graphic

Unified control system allows operation of all rolls together or any rolls separately:

- Constant tension during payout (or backing up) with velocity controlled by gripper motions
- Controlled rotational speed if desired
- Zero motion (braking) at all other times, including loss of power

All specified behaviors have been validated during acceptance testing

Testing constant-payout-tension behavior

Outer fabric dispensers (typical)

Janicki Industries photo

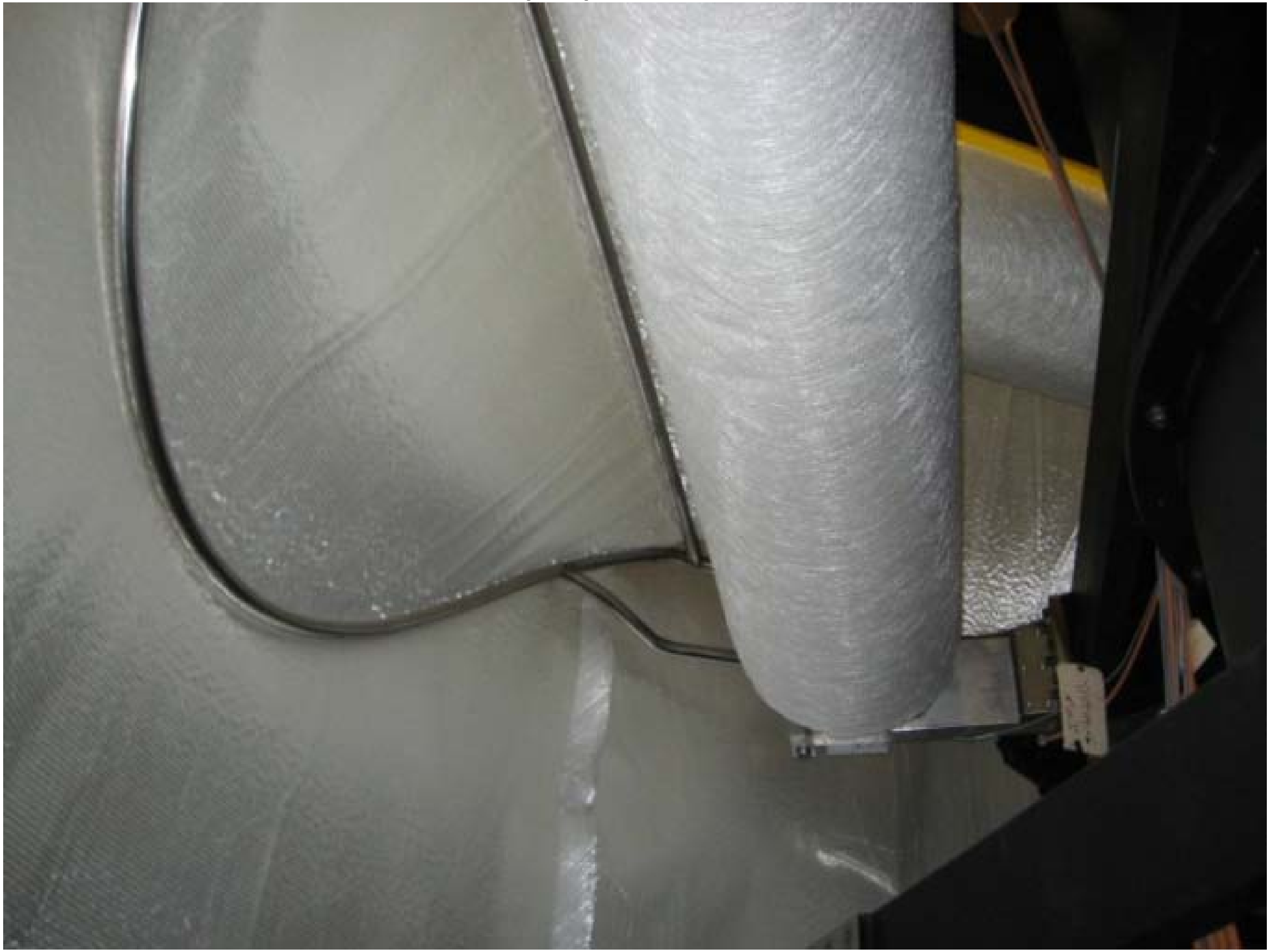
Outer fabric dispensing, with formation of typical overlap splice

Janicki Industries photo

Inner fabric dispensers (typical)

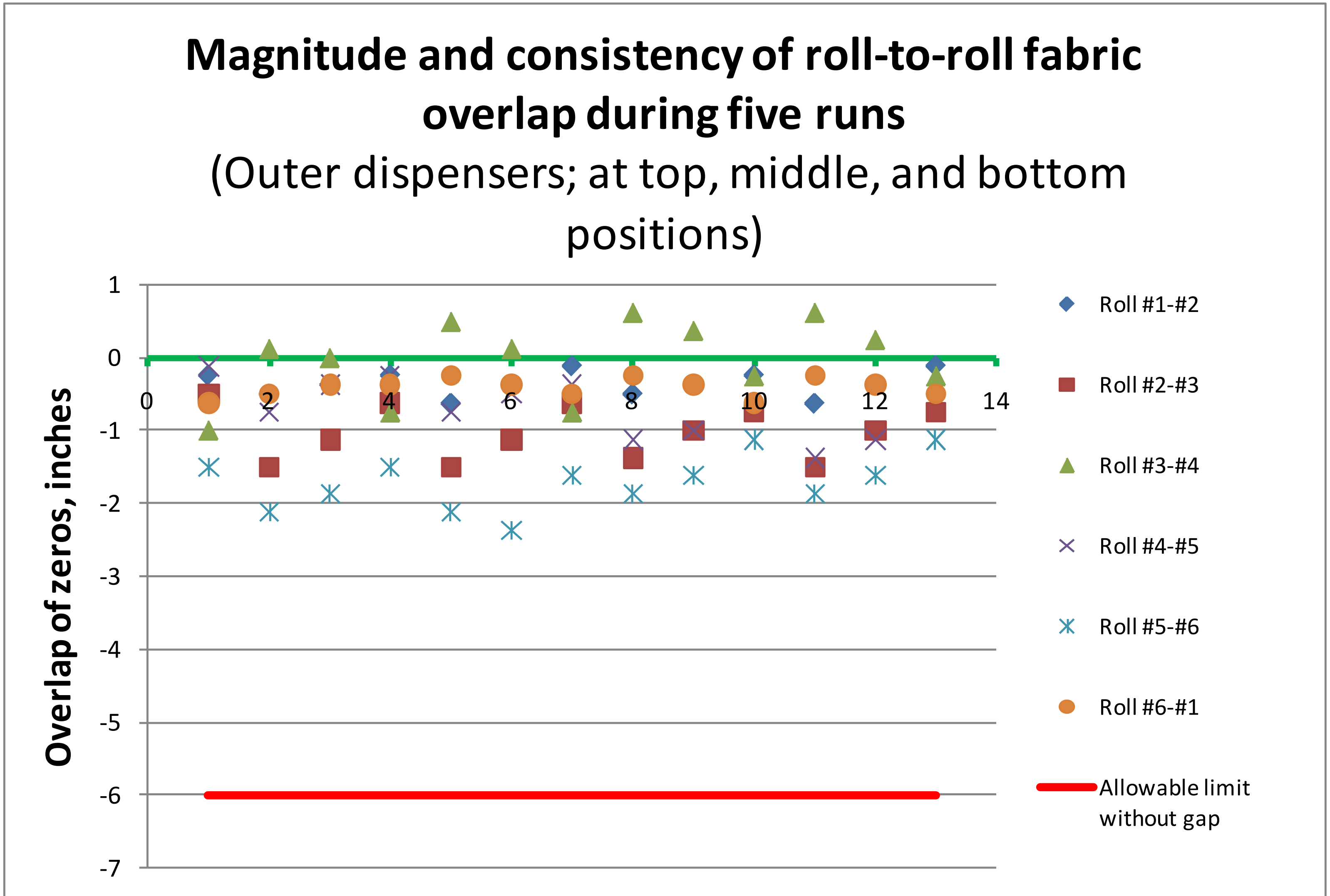
Janicki Industries photo

Inner fabric dispensing, with formation of typical overlap splice



Janicki Industries photo

Validation of fabric dispensing accuracy



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

Summary of validation results at 4m scale – Fabric architecture and dispensing

Component and operations	Results and key challenges met	Evidence	Future Needs
Overlap splices in face sheets	**Successful – Splice regions are as strong as the base laminate**	Local buckling specimen failed away from the splices	
Design and construct complex apparatus (w. Janicki)	**Successful**	Apparatus	Core chucks which do not require periodic re-charging with air pressure
Acceptance testing of apparatus (at Janicki)	**Successful** - **Maintained constant payout tension despite variations in "demand" payout velocity imposed at free end of fabric**	Acceptance testing COC, photos, videos	
Validate fabric dispensing operations (at Janicki)	**Successful** - **Variations in width of fabric overlap are well below allowable**	Validation testing report, photos, videos	

VI.C - Validation 3 – Stepwise infusion molding process

- Pictorial summary of stepwise infusion molding validation
- VI.C.1 – Apparatus
- VI.C.2 - Initial validation workpiece
- Tabular summary of stepwise infusion molding validation results at 4m scale
- Sidebar: Effects of axial forces on large seals

Pictorial summary of stepwise infusion molding validation

Workpiece (fabric not shown)

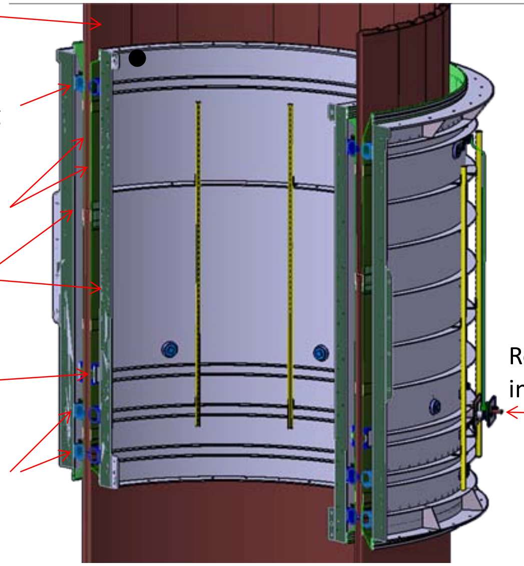
Upper inflatable centering ring and vacuum seal

Outer and inner soft tools

Outer and inner hard shells

Re-Usable Resin Distribution Line (RURDL)

Bottom inflatable vacuum seals



Resin inlet

Inner and outer hard shells, soft tools, and upper seals

Hanging outer face sheet fabric on test core

Removing infused and cured workpiece from mold

Infusion of workpiece

- About 1000 lbs. of resin was mixed and infused in 3 shots
- The fill time was within about 20% of predicted (after correcting the resin viscosity to the low temperatures in the unheated High-Bay)
- The specialized apparatus enables infusion to be done by a 2-person crew

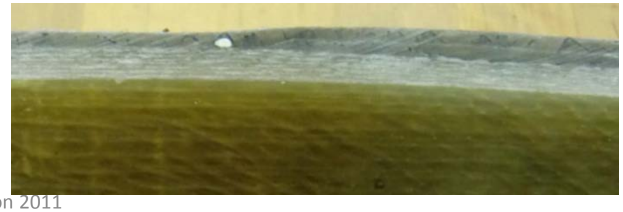
On-line resin metering and mixing pump with auto-level control allows use of a small mixed resin reservoir, avoiding exotherm concerns.

Molding Region showing outer resin inlet line (RIL) and solenoids controlling various subsystems

16-channel video display tracks resin flow fronts inside the mold

Manual control panel with computer display of step-by-step instructions and place to record all data and observations

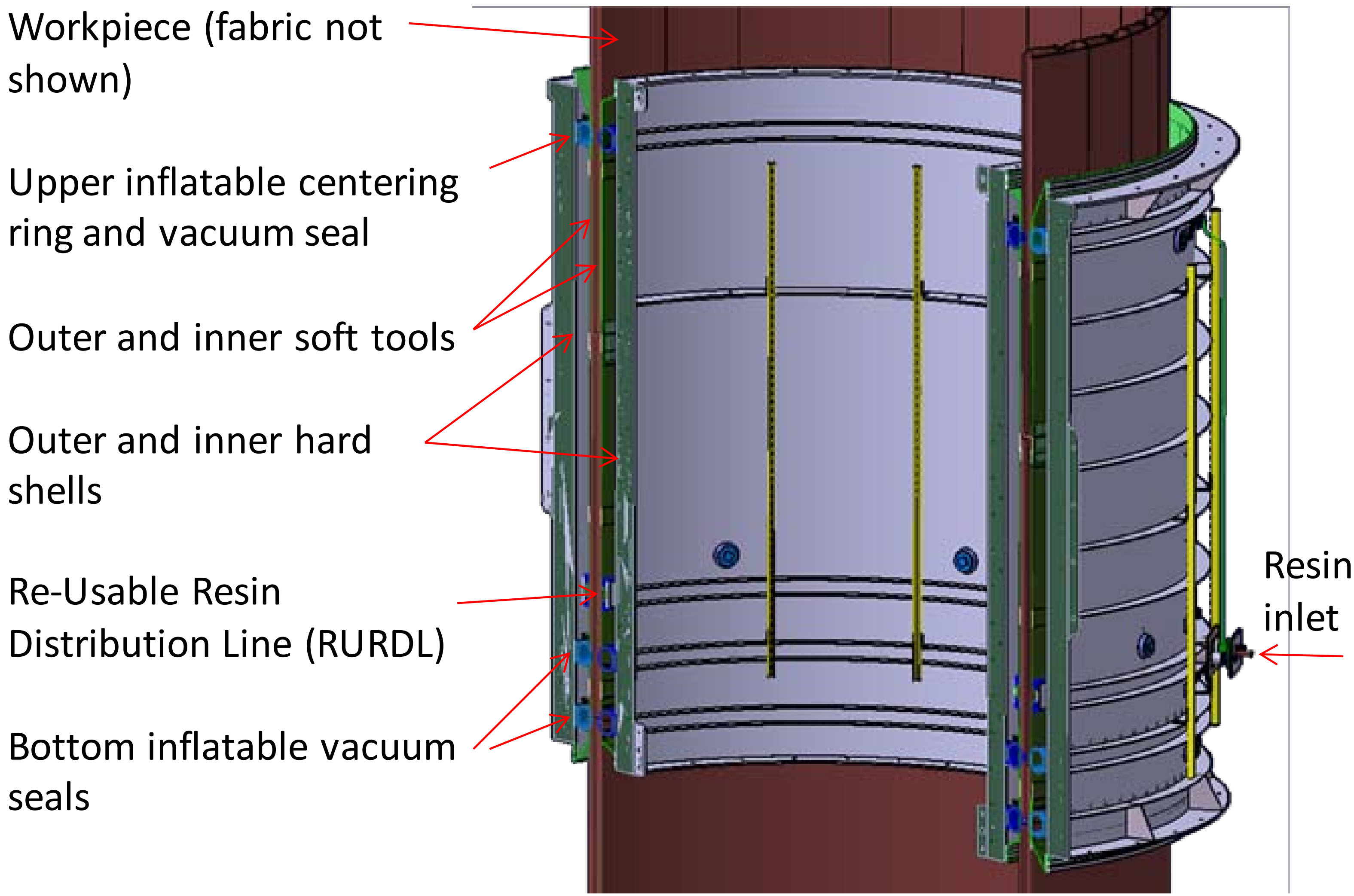
Key result: The knit-line between infusion steps is indistinguishable from the base laminate. The stepwise infusion process is validated!



VI.C.1 – Apparatus

- Molding Region apparatus elements and subsystems
- VI.C.1.a -- Hard shells (outer and inner)
- VI.C.1.b - Soft tools including Re-Usable Resin Distribution Line (RURDL)
- VI.C.1.c - Resin and resin handling elements
- VI.C.1.d - Acceptance testing at Janicki, transport to Sunnyvale, and installation in B/132 High Bay
- VI.C.1.e - Molding region control system

Molding Region apparatus elements and subsystems



Janicki Industries graphic

VI.C.1.a - Hard shells (outer and inner)

Janicki Industries photo

VI.C.1.b - Soft tools including Re-Usable Resin Distribution Line (RURDL)

- Achieving good sealing at the bottom of the apparatus
- Non-linear FEA was used to design key elements of the soft tools
- Re-usable Resin Distribution Line (RURDL)
- RURDL action
- Installing inner soft tool and RURDL around inner hard shell
- Photos of other elements of the Molding Region
- Durability of soft tool material

Achieving good sealing at the bottom of the apparatus

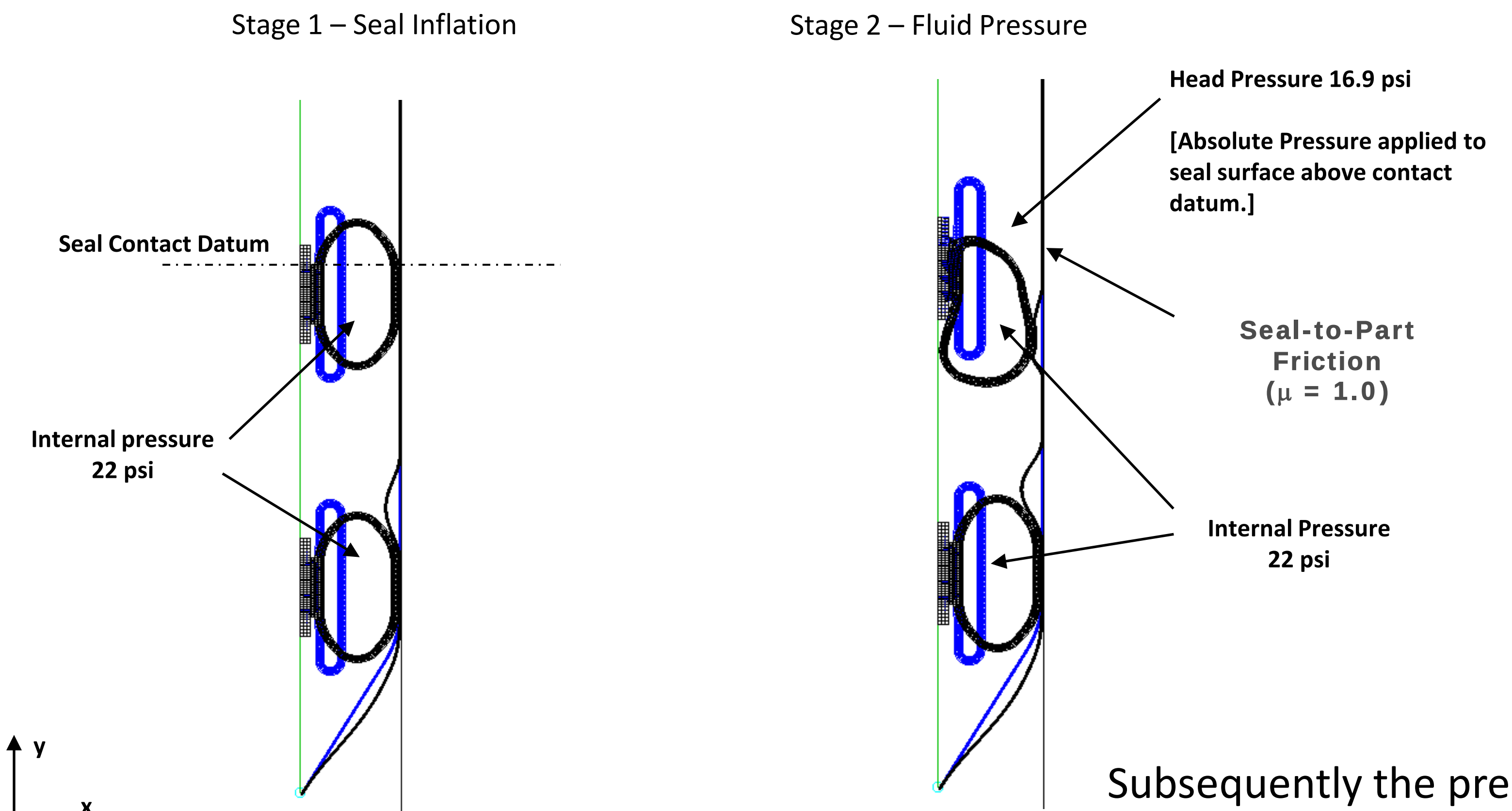
Approach:
Mechanical ingredients that seat the soft tool firmly against the protruding cured end of the workpiece

Results:
- Robust sealing from the start
- Apparatus vacuum level rises to source vacuum level (to within gauge accuracy) without any corrective actions
    - Excellent vacuum is the key to achieving a non-discernable knitline* during stepwise infusion
- No resin leakage whatsoever

*The knitline is the boundary between the resin cured in successive steps

Non-linear FEA was used to design key elements of the soft tools

Main bottom seals analysis is shown here

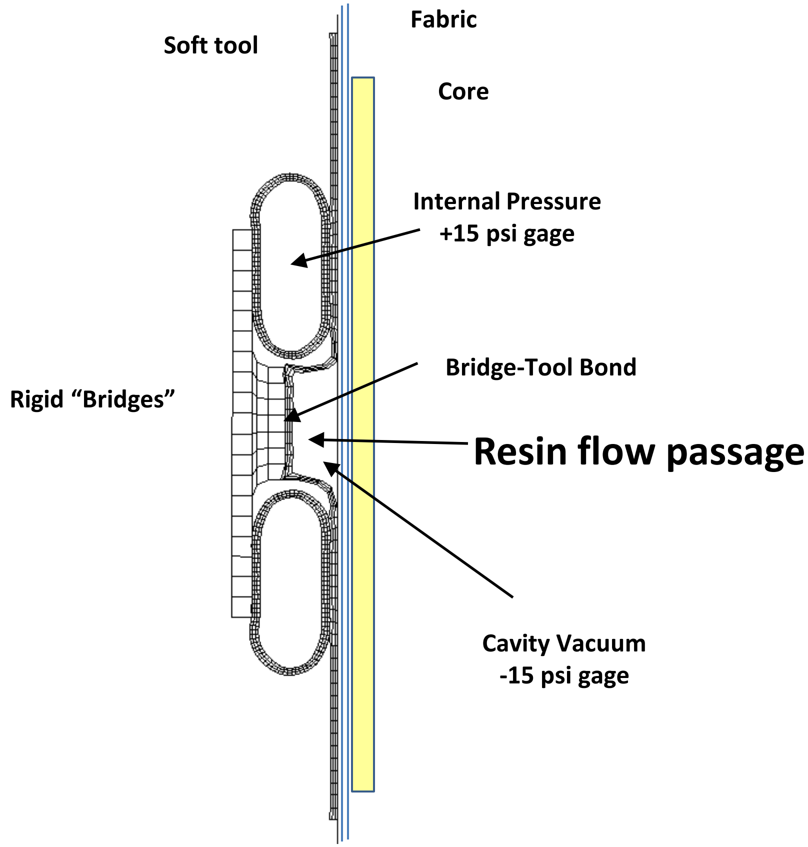


Subsequently the pressure was raised to 32 psi

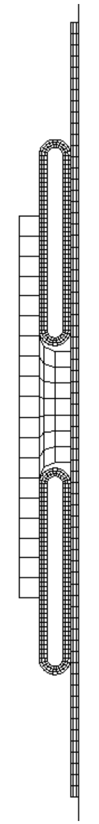
Janicki Industries subcontractor analysis

Re-usable Resin Distribution Line (RURDL)

Inflate tubes during infusion



Collapse tubes during cure



Excess resin is squeezed out of flow passage

Design of RURDL creates large passage for 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

RURDL action

Tubes not inflated

Tubes inflated to 15 psi; RURDL passage (on other side of black "bridges") opens up as planned

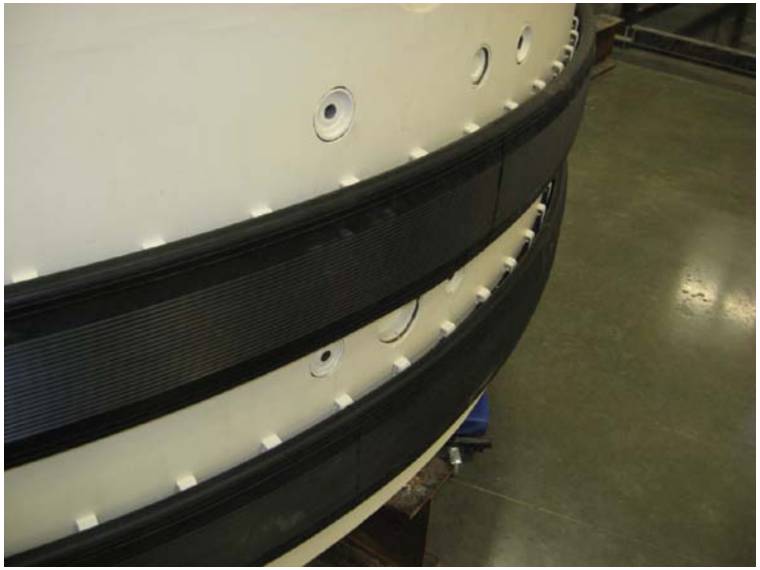
Janicki Industries photo

Installing inner soft tool and RURDL around inner hard shell

Janicki Industries photos

Photos of other elements of the Molding Region

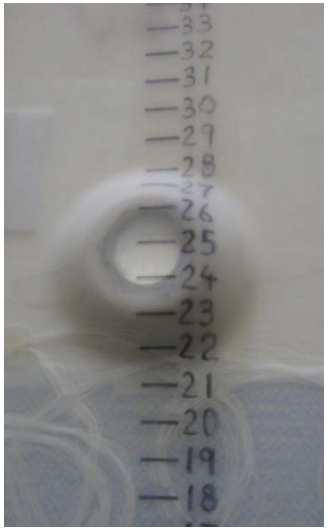
Inflatable seals



Flow front monitoring system

LED lighting

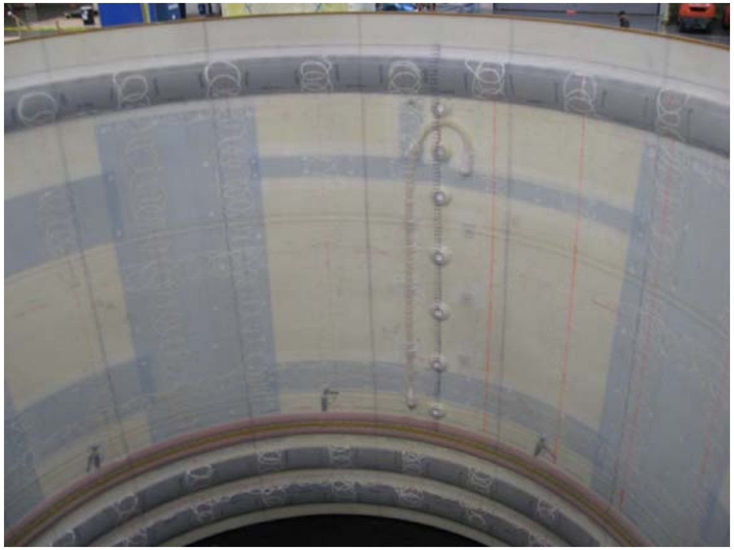
video camera port



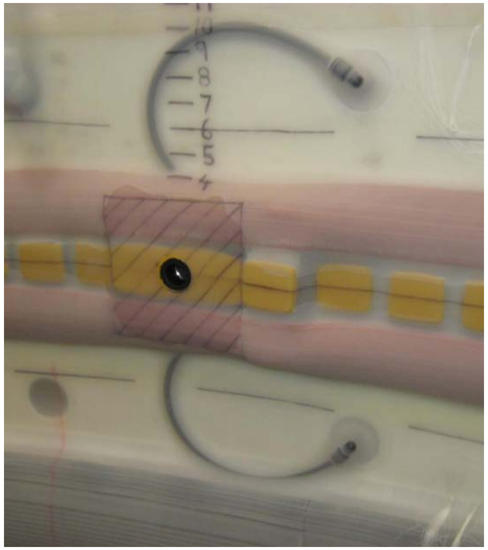
Inner

Soft tools

Outer



RURDL



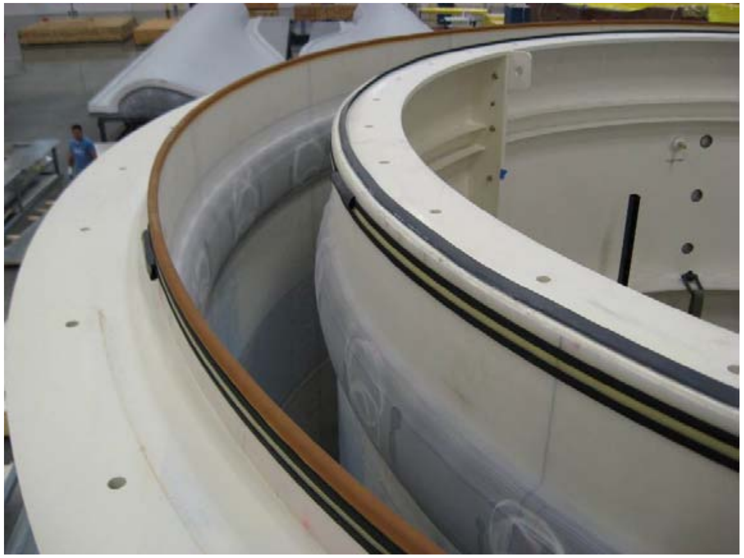
Janicki Industries photos

OTEC
Ocean Thermal Energy Conversion

"Flying" the soft tools prove-out test core (foam rings held together with fiberglass shear keys) into the Molding Region

Janicki Industries photos

Soft tools drawn back by vacuum



Top seals
Pressurized
lightly

Top seals engaged with test core

Janicki Industries photos

Tests to evaluate durability of soft tool material

Purpose

- The soft tools are re-usable vacuum bags against which the resin cures during each step of the fabrication process
- If the length per fabrication step is 39 ft. (current baseline), one Cold Water Pipe requires 80 steps
- Replacement of the soft tools during CWP fabrication is difficult
- Therefore tests were run in which samples of the soft tool material (silicone rubber) were repeatedly cured against laminates made with the Derakane 8084 vinyl ester resin of the CWP
- After each cure, the silicone rubber was peeled away from the cured laminate while the release force was measured.
- The purpose is to ascertain whether or not one set of soft tools is likely to survive for one CWP fabrication.

Various possible cure cycles were investigated

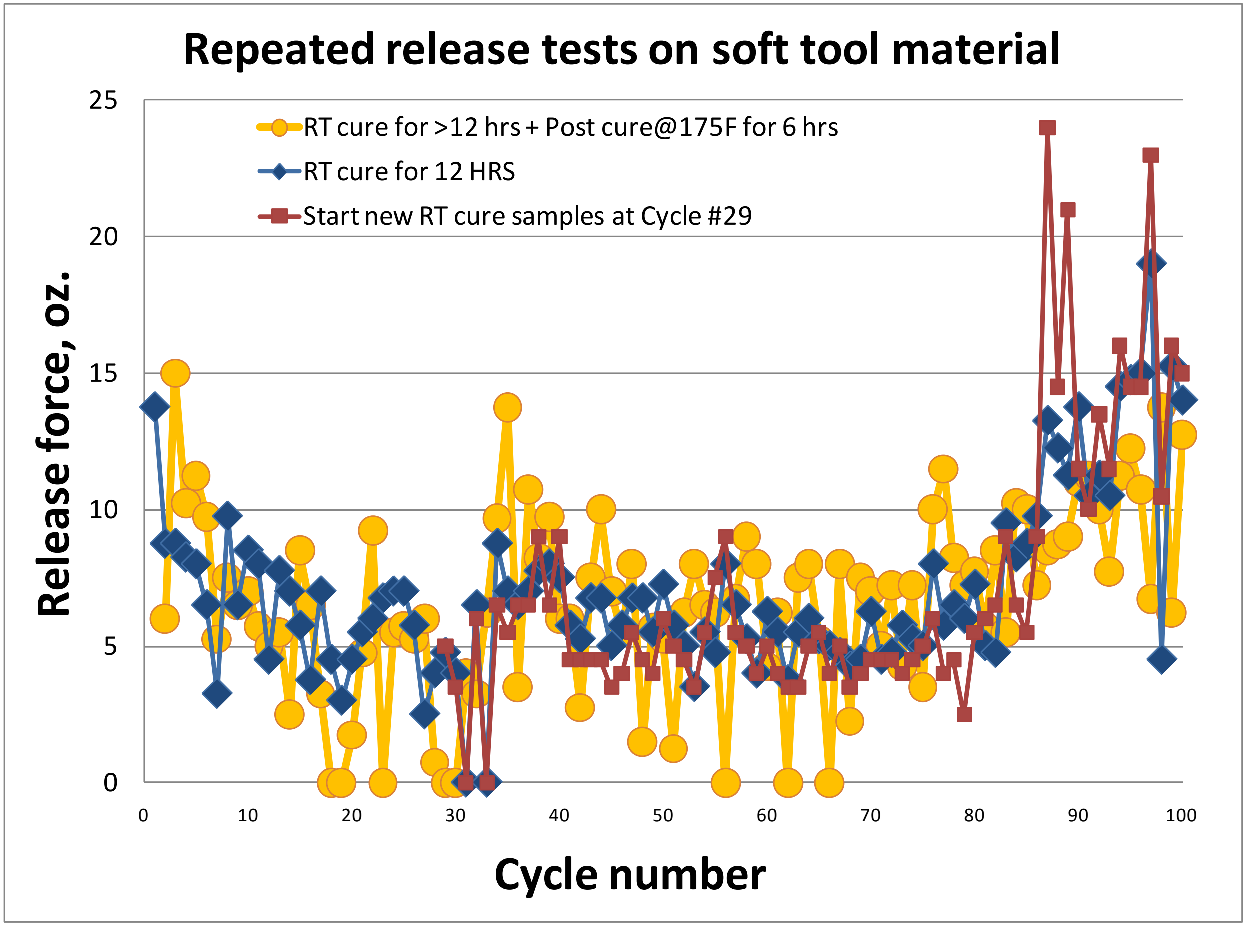
- Until seawater fatigue testing for various cure cycles is completed, it is not definite which of the following cure cycles typical for 8084 will be adequate:
    1. Ambient-temperature cure only
    2. Ambient-temperature cure + elevated-temperature (175F) post-cure (most likely cycle)
    3. Elevated-temperature only (220F)
- Accordingly, the repeated release behavior was evaluated for these three cure cycles.
- The 220F cure produced release forces much higher than the others, and was discontinued.
- Behavior for the other cure cycles is shown in the following two slides

Durability of soft tool material

- **Perform repeated layup/cure/release on samples of soft tool material**

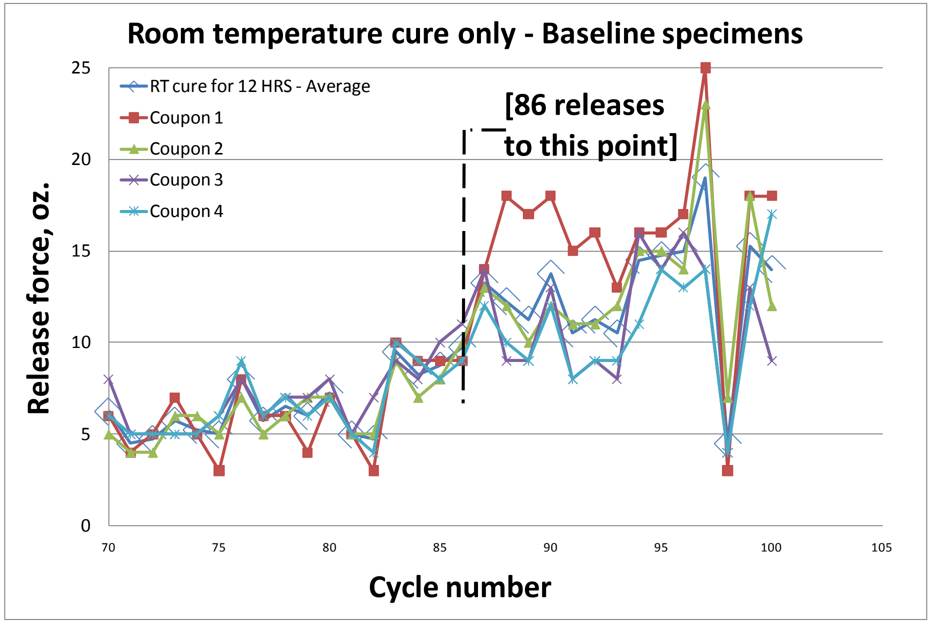
- **Compare:**
  - o **Room temperature (RT) cure + 175F post-cure**

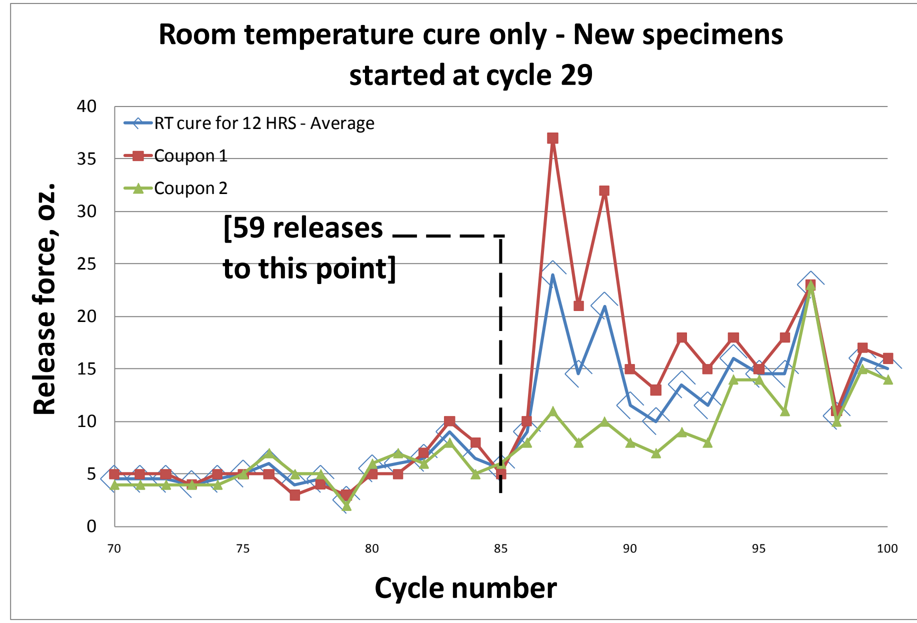
    vs.
  - o **RT cure only**

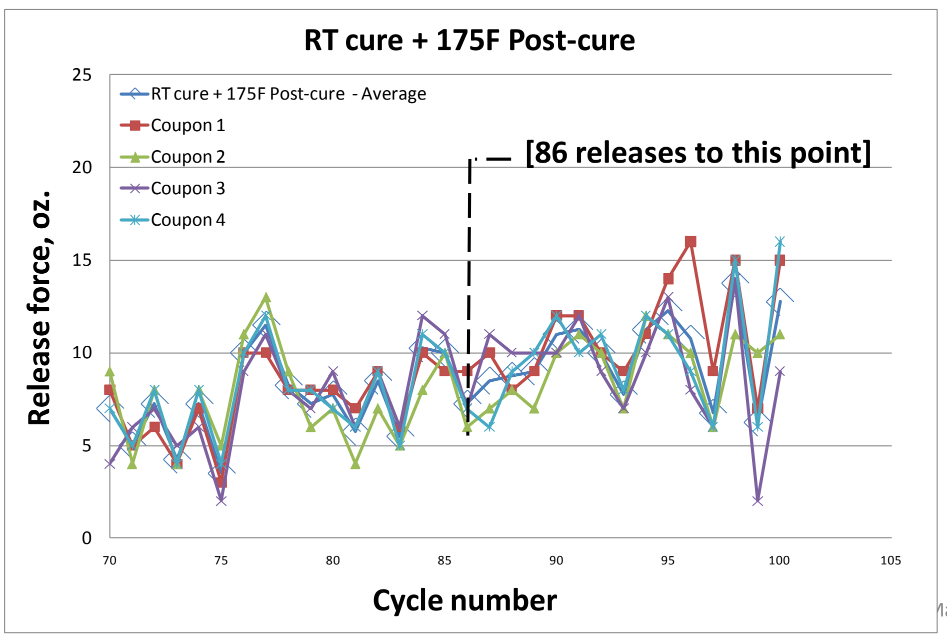


- After 100 cycles, release forces in baseline samples are no higher than at the start
- See next slide for interpretation of anomalous upswing in release forces over last 15 cycles
- Maximum release force with RT cure+175F post-cure is very similar to RT cure only
- **Conclusion: We can use RT cure + 175F post cure for on-the-water CWP fabrication with no detrimental effect on soft tool life compared to RT cure only**

Anomalous behavior seen during last 15 cycles







- The upswing in release force starts at cycle 87 of the overall test program
  - Same point for specimens that have seen 59 releases or 86 releases
  - Same point for RT only as for RT+post cure
- **These results suggest that the upswing was an artifact of some uncontrolled test variable, and is not an inherent property of the soft tool material /cure cycle**

VI.C.1.c - Resin and resin handling elements

- Resin system
- Resin Inlet Line (RIL) and actuators
- Resin mixing system
- Catalyzed resin supply system
- Catalyzed resin reservoir

Resin system

DERAKANE 8084 Epoxy Vinyl Ester Resin

January, 2006

High Elongation Tough Epoxy Vinyl Ester Resin

DERAKANE 8084 epoxy vinyl ester resin is an elastomer modified resin designed to offer increased adhesive strength, superior resistance to abrasion and severe mechanical stress, while giving greater toughness and elongation. DERAKANE 8084 and DERAKANE 8090 resins are the only vinyl esters available that offer this exceptional combination of properties.

Typical Liquid Resin Properties

Property[1]	Value
Density, 25°C/77°F	1.02 g/mL
Dynamic Viscosity, 25°C/77°F	360 mPa·s
Kinematic Viscosity	350 cSt
Styrene Content	40%
Shelf Life[2], Dark, 25°C/77°F	6 months

http://www.derakane.com/downloadServlet?docPath=DPAPP1.asco.ashland.com%5CData%5Cascc%5Cecomdocsasc.nsf%5C518971E5A3AD564485256FCE004AA0B6%5C%24FILE%5C8084.pdf

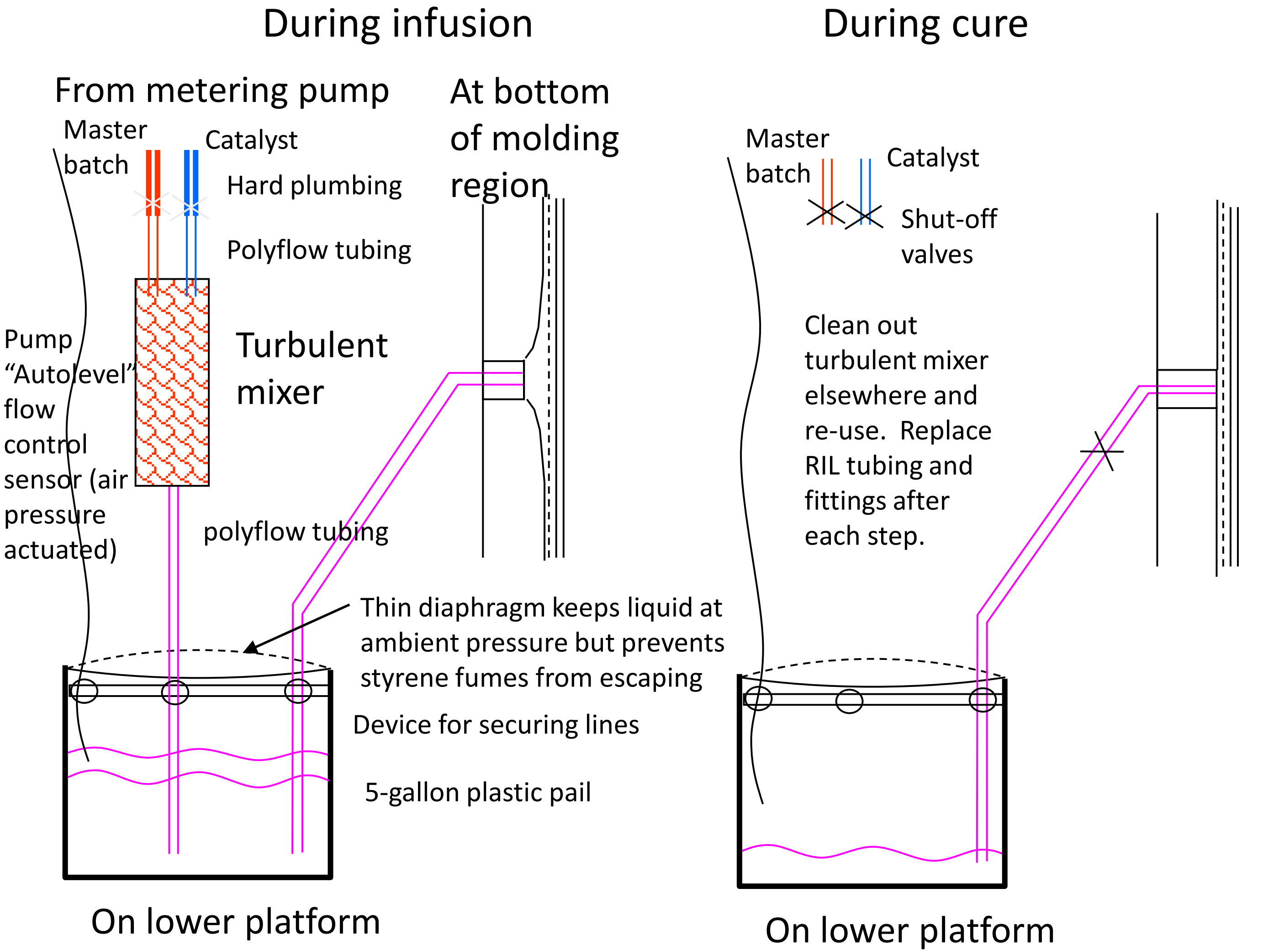
Resin Inlet Line (RIL) and actuators

- The only non-reusable element is the RIL itself
- Inexpensive leak-tight fittings and mechanical valves are used
- Shape of the fitting at the end of the RIL causes it to break off at the workpiece.
- Air cylinders press end of RIL against workpiece during cure, to ensure no stub is left.

Resin mixing system

http://www.mvpind.com/products/specialty-systems/infusion-system.html

Catalyzed resin supply system



Design of resin supply system allows huge workpiece to be filled quickly without requiring large batches of catalyzed resin that might be prone to exotherm. About 1000 lbs. of resin was mixed and infused in 3 shots, with no problems.

Catalyzed resin reservoir

Mixing gun

Swirl tube

Air line for autolevel control

At the end of the run, we bring the liquid level down to minimize the leftover catalyzed resin

VI.C.1.d - Acceptance testing at Janicki, transport to Sunnyvale, and installation in B/132 High Bay

- Molding Region during acceptance test at Janicki Industries
- Molding region arrives in Sunnyvale for installation in B/132
- Getting a 16’5” wide part through a 16’ wide rollup door
- “Lab supports” for inner and outer molding regions
- Installing outer lab supports
- Lifting inner mold back into outer mold
- Installing inner lab supports

Molding Region during acceptance test at Janicki Industries
(8-11-2010)

Final half of test was conducted outside to avoid possible damage to other work in Janicki's Hamilton facility just in case any water leaked out. It didn't.

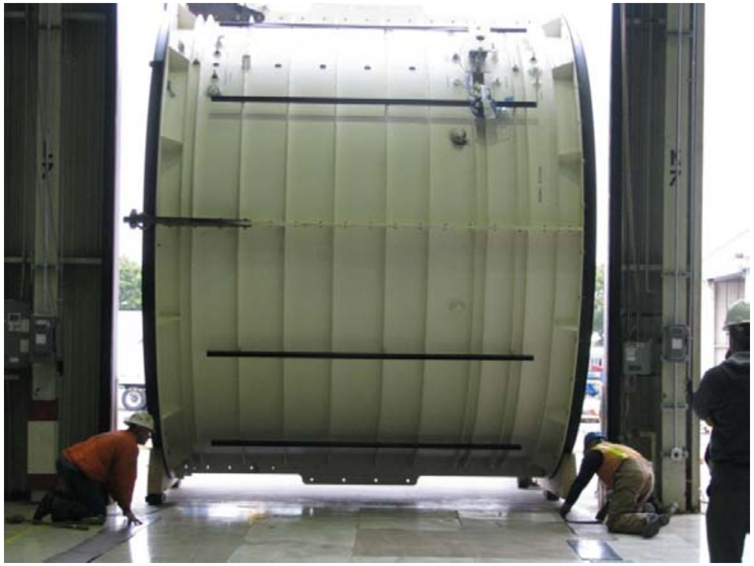
OMR lab supports were used to help stabilize the molding region on the bed of the low boy truck.

Janicki Industries photo

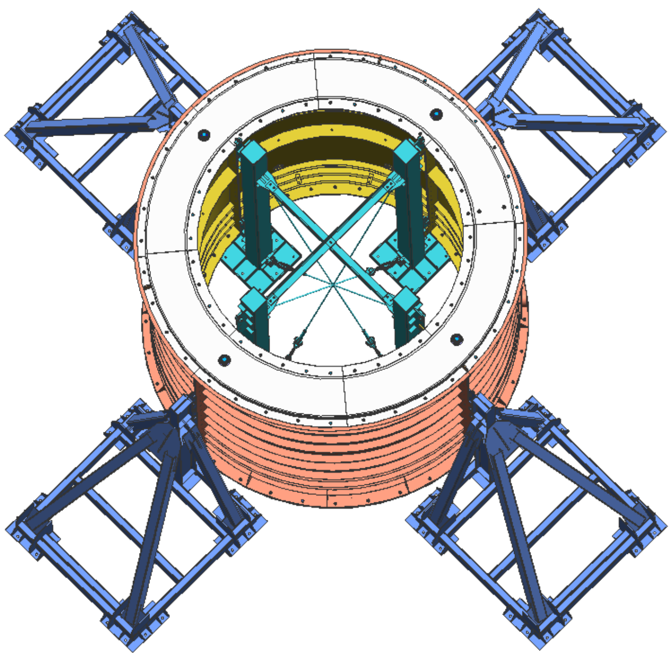
Molding region arrives in Sunnyvale for installation in B/132

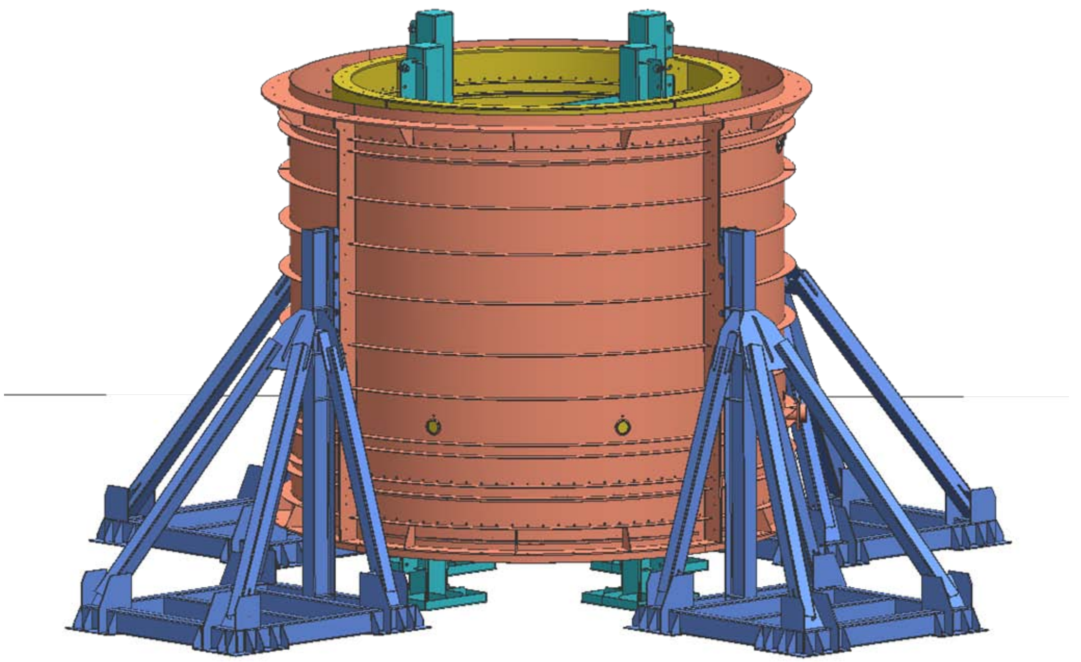
Getting a 16'5" wide part through a 16' wide rollup door





"Lab supports" for inner and outer molding regions

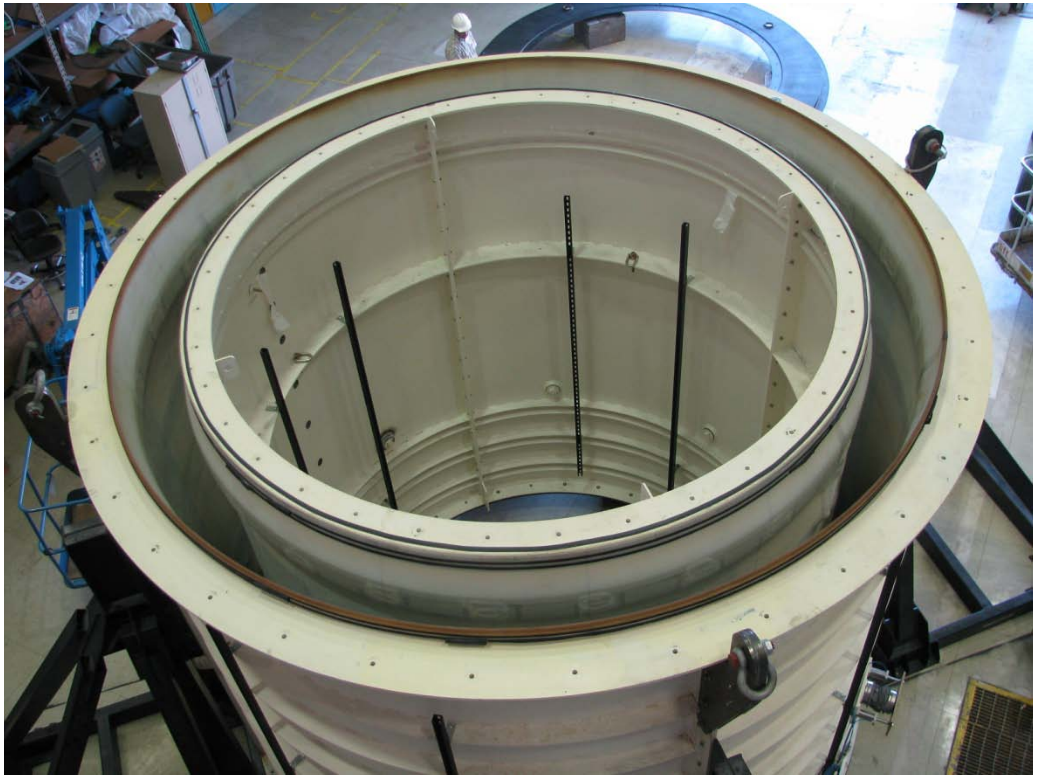




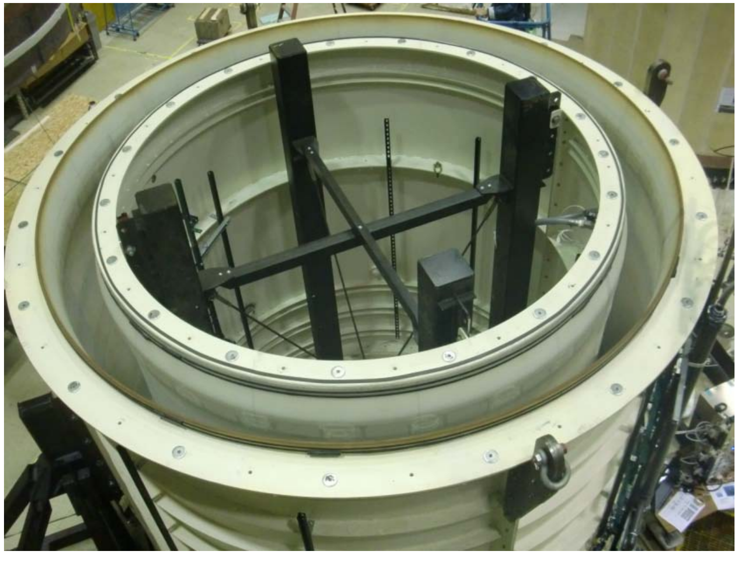
Janicki Industries graphic

Installing outer lab supports

Lifting inner mold back into outer mold



Installing inner lab supports



VI.C.1.e - Molding region control system

- Control system approach for current program
- Control system components
- Resin flow-front height visual sensing system
- Installation of control system elements
- Control system - Installed

Control system approach for current program

- Control all principal subsystems from a centralized location using clear, easy-to-follow step-by-step settings
- Install and use actuators and sensors that will become part of the full integrated CWP fabrication apparatus in the future
- Control these actuators manually by simple and inexpensive toggle switches mounted in a panel. Read out the sensors by simple and inexpensive analog voltmeters.
- Provide step-by-step instructions for operation of the control system by a computer next to the control panel
  - The graphical and macro-based features of this Excel program were written by Matt Ascari
- Use the same computer for logging in of data, results, and comments during the runs

The alternative would have been a full computer control system for the Molding Region, and this was judged to be out-of-scope and not needed for the current program, in which flexibility was preferred over automation.

When the Molding Region is combined with the Fabric Dispensing System, we may expand the latter's computer control system to also cover the molding operations

Control system components

Solenoid valves

Pressure or vacuum sensors

Vacuum regulators

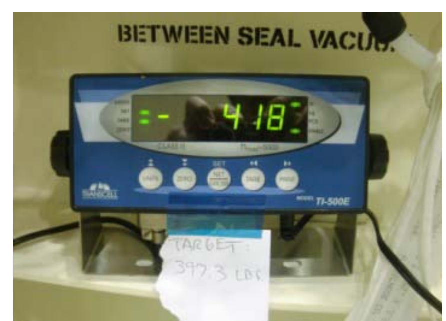
1/2” NPT

Air pressure regulators

2” NPT

Panel meters

Toggle switches



Platform scale

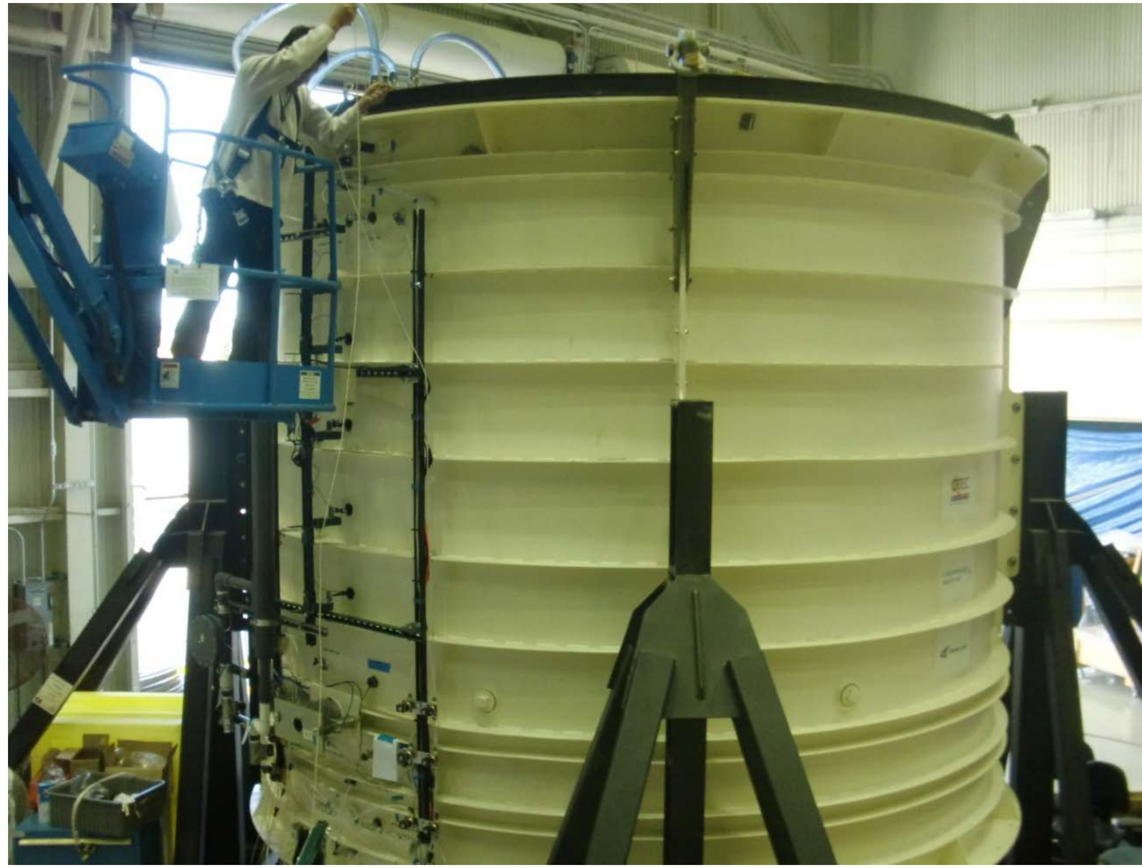
Resin flow-front height visual sensing system

Sight glasses built into hard shells of molding region

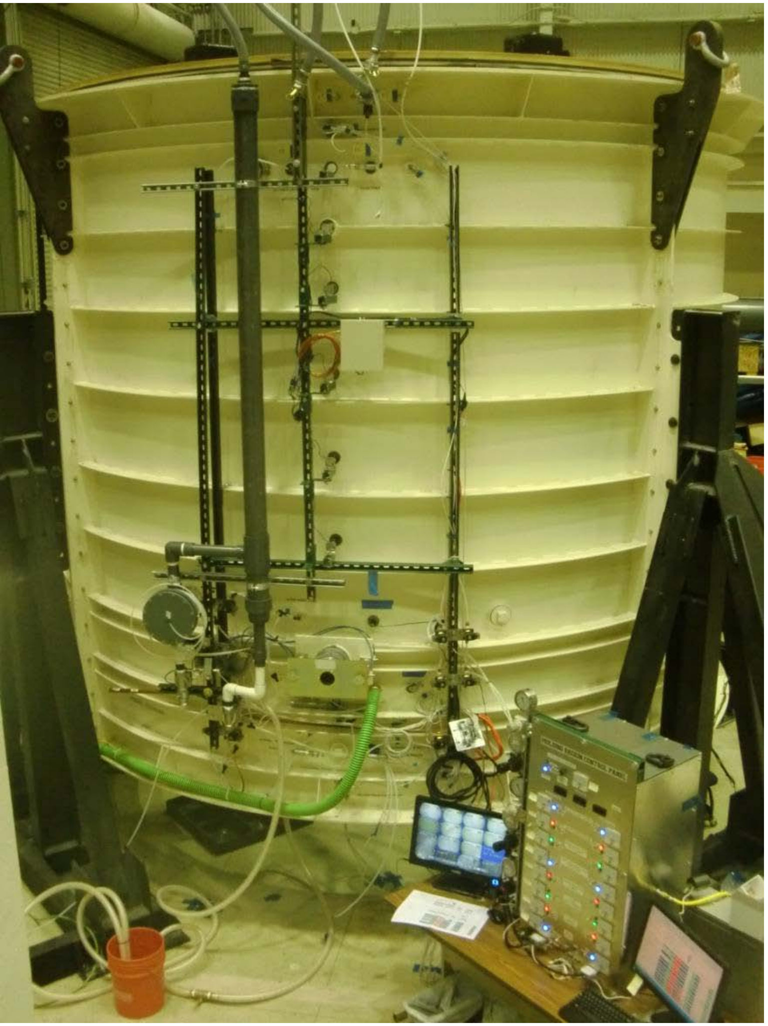
16 Sony HD230 “bullet” cameras with wide-angle f2.1 lens

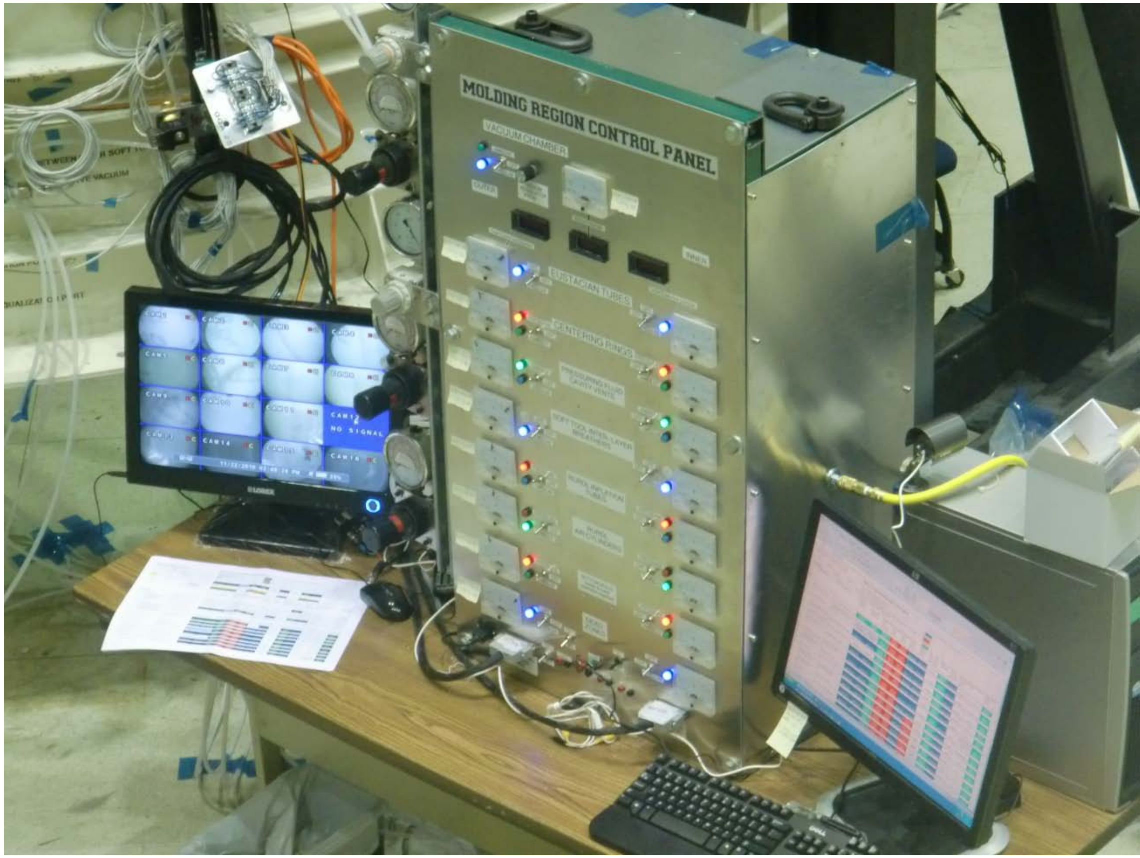
16-channel video display and recorder

Installation of control system elements



Control system - Installed





VI.C.2 - Initial validation workpiece

- VI.C.2.a - Layup and insertion into Molding Region
- VI.C.2.b - Infusion of workpiece
- VI.C.2.c - Results on infused workpiece
- VI.C.2.d - Validation of analytical tools for predicting infusion behavior

VI.C.2.a - Layup and insertion into Molding Region

- Manual fabric layup on foam core
- Inner fabric layup
- Resin distribution medium
- Adding Resin Distribution Medium (RDM)
- Lift workpiece into mold
- Installing core stoppers and temporary upper seal-flip-prevention devices
- Install lid

Initial validation workpiece -- Manual fabric layup on foam core*

Hang fabric plies (over nylon release film - allows re-use of foam core just in case)

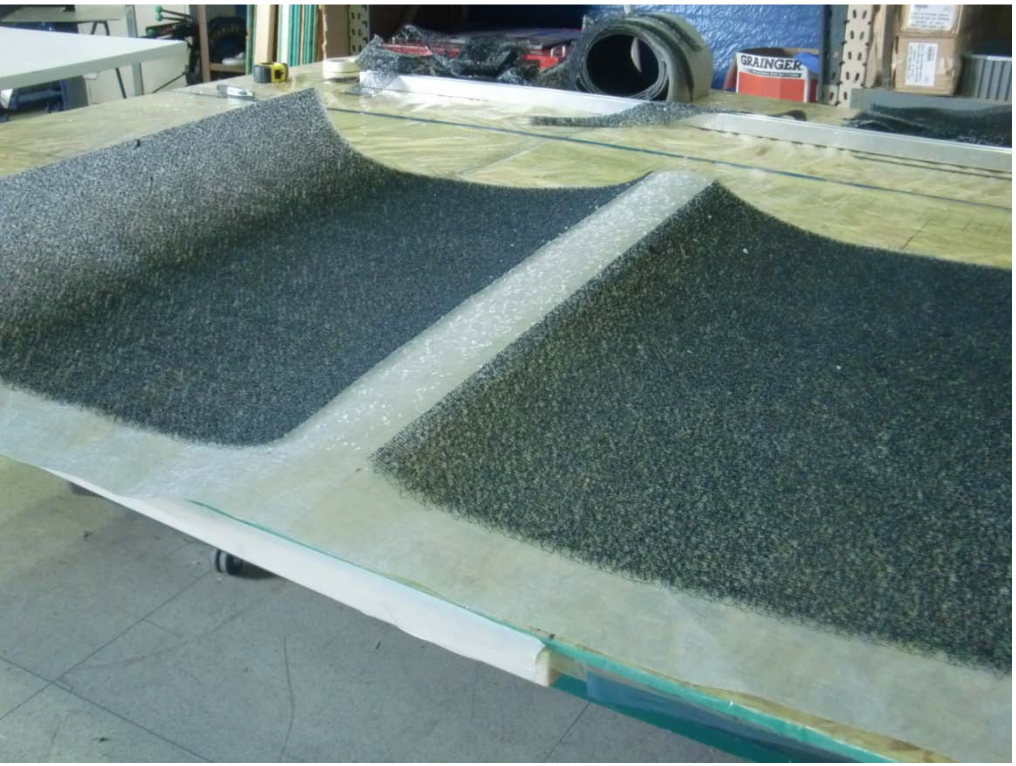
Outer fabric layup

*Because of delays receiving acceptable pultruded planks, the foam core that had been used in Molding Region acceptance testing was used for the first Molding Region infusion trials instead of the pultruded plank core ring

Inner fabric layup

OTEC Ocean Thermal Energy Conversion

Resin distribution medium – Colbond EnkaRain Drain 9714

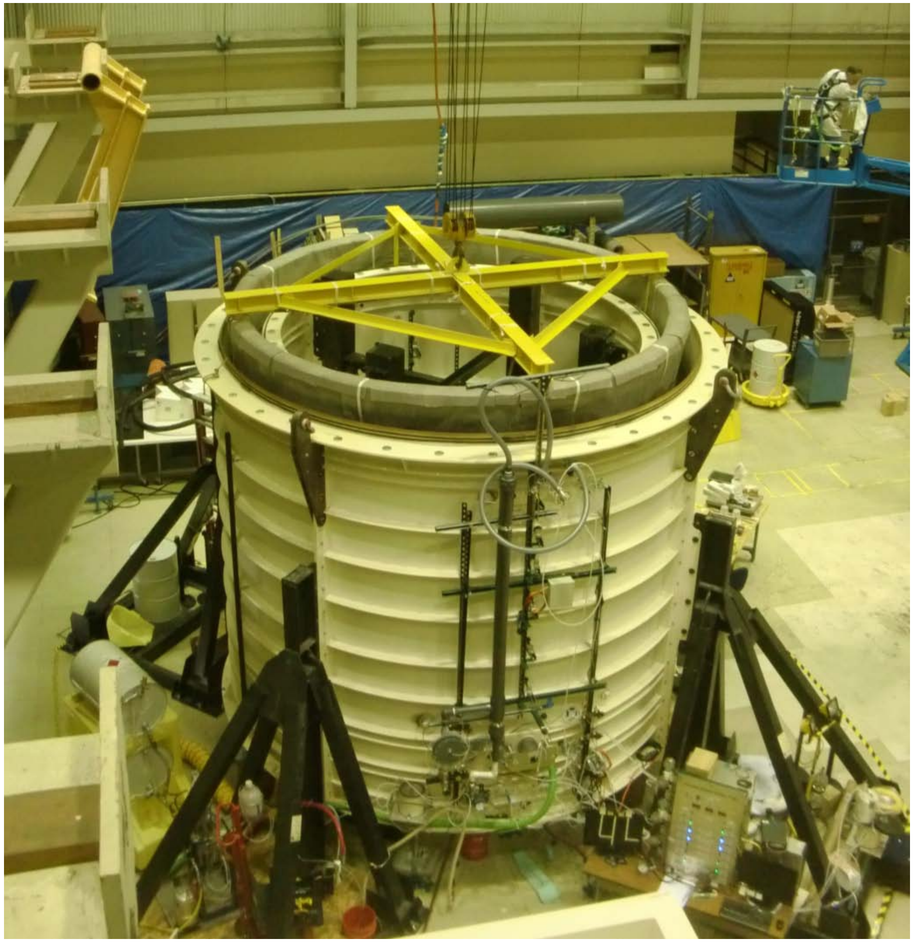


Active portion of RDM is removed wherever we want the resin to stop

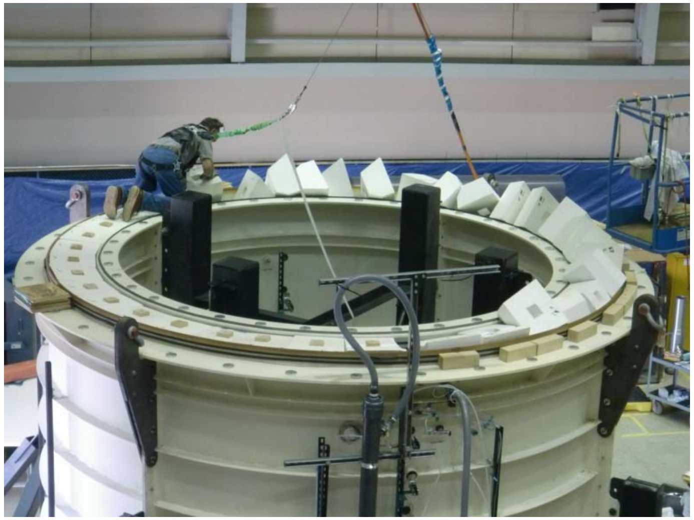
Add Resin Distribution Medium (RDM)

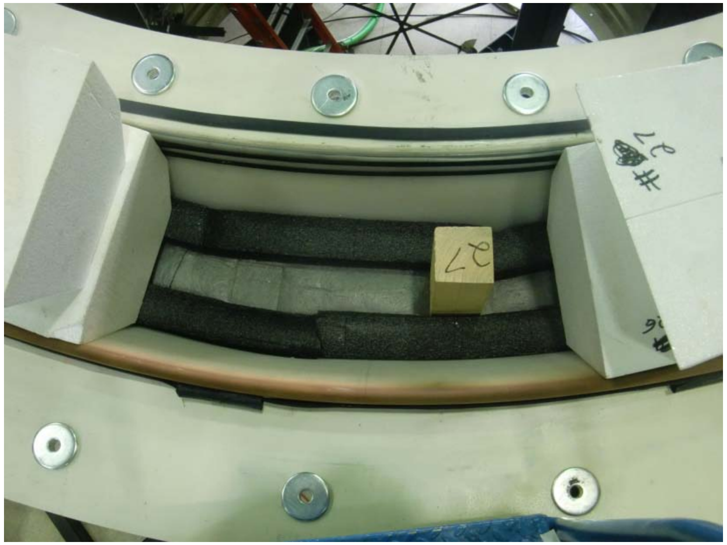
Top of active outer RDM was intentionally "castellated" to check that resin stops controllably

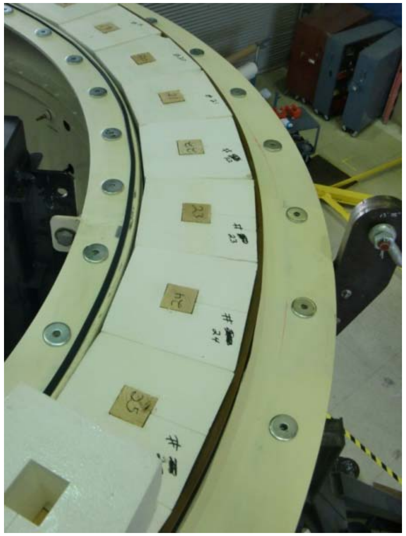
Lift workpiece into mold



Installing 4x4 core stoppers and temporary upper seal-flip-prevention devices (foam blocks and foam strips) on top of workpiece







Install lid

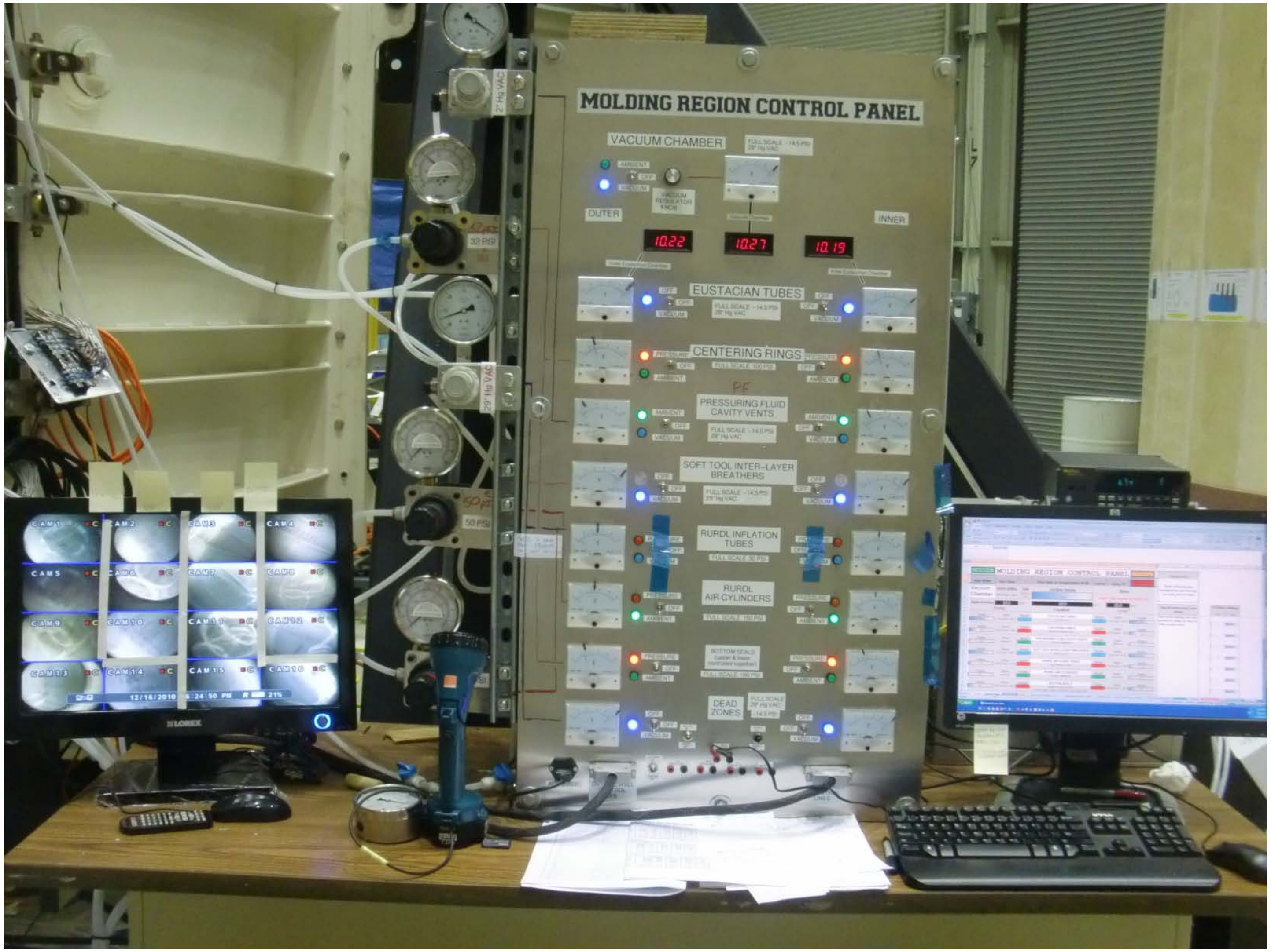
VI.C.2.b - Infusion of workpiece

- Labor requirements for infusion of workpieces
- Video monitor, regulators and gages, control panel, and computer that provides step-by-step running procedures and data note-taking
- Vacuum levels achieved
- Configuration of the three infusions
- Photos concerning the infusion process
  - Infusion #1: Inner facesheet – Cured lower portion
  - Infusion #2: Inner facesheet - Preparation to infuse remainder
  - Infusion #3: Outer facesheet, full height - Monitoring flow front position

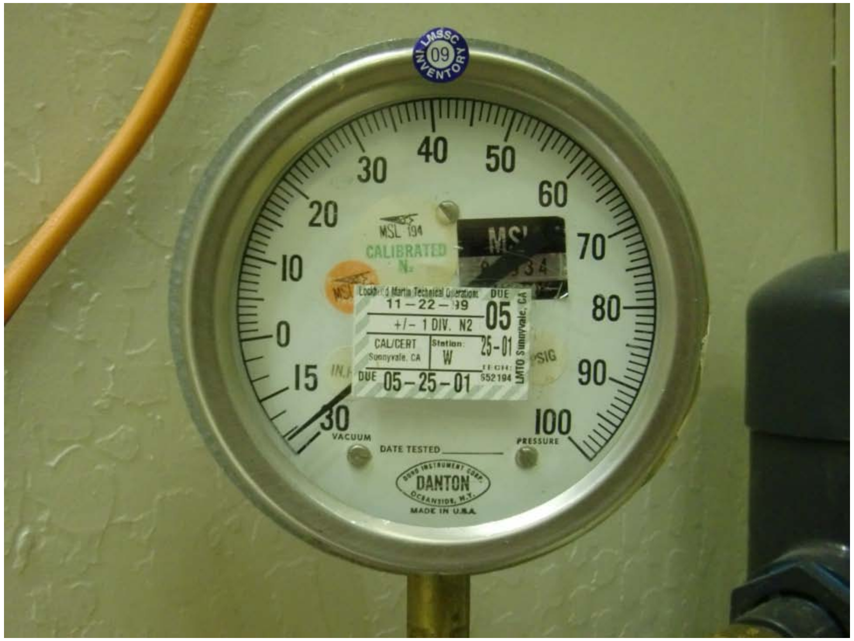
Labor requirements for infusion of workpieces

- The specialized apparatus enables infusion to be done by a 2-person crew
- About 1000 lbs. of resin was mixed and infused in 3 shots

Video monitor, regulators and gages, control panel, and computer that provides step-by-step running procedures and data note-taking



Vacuum levels achieved

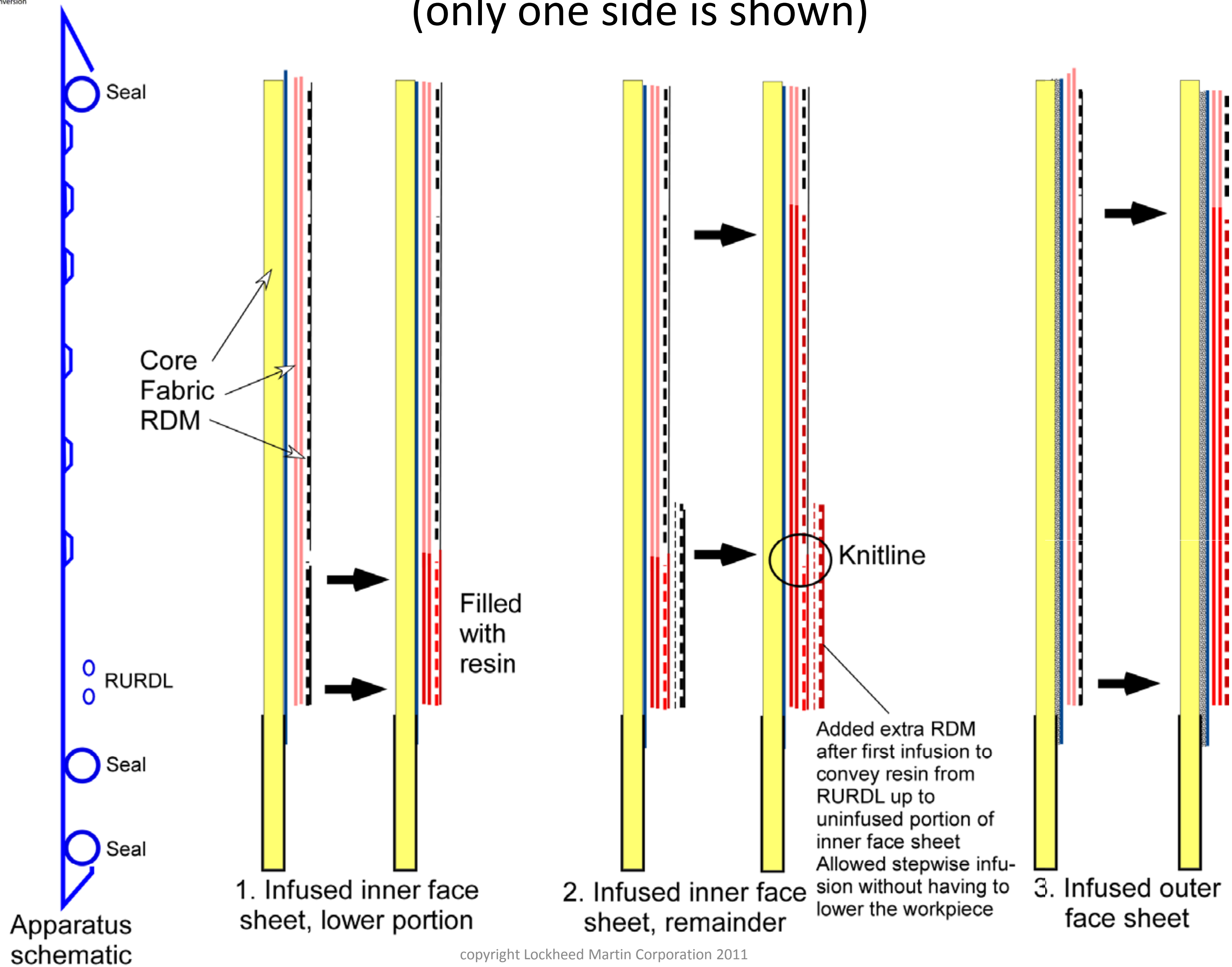


Source vacuum gage reads 26” Hg

Vacuum chamber gage reads 27.5” Hg

Excellent vacuum achieved is the key to high-quality VARTM with no visible knitline

Configuration of the three infusions
(only one side is shown)



Photos concerning the infusion process

Infusion #1: Inner facesheet – Cured lower portion

- This edge becomes the "knitline" after the rest of the inner facesheet is infused

- Face sheet filled to a uniform height all around

Infusion #2: Inner facesheet - Preparation to infuse remainder

Insertion of extra RDM to carry resin from the RURDL up to the not-yet infused region

Infusion #3: Outer facesheet, full height - Monitoring flow front position

Before infusion

0 deg completing fill at top

180 deg completing fill at top

VI.C.2.c - Results on infused workpiece

- Removing infused and cured workpiece from mold
- Inner face sheet showing uniform wet-out height
- Control of wet-out height
- Observations concerning longitudinal wrinkling in outer face sheet (only) of 4m validation workpiece fabricated on foam core
- Understanding wrinkling observed in outer face sheet of 4m workpiece, and path forward that should eliminate it
- Inner face sheet shows successful operation of RURDL and RIL mechanism
- Samples cut from finished 4m diameter validation workpiece
- Results at knitline

Removing infused and cured workpiece from mold

Inner face sheet showing uniform wet-out height

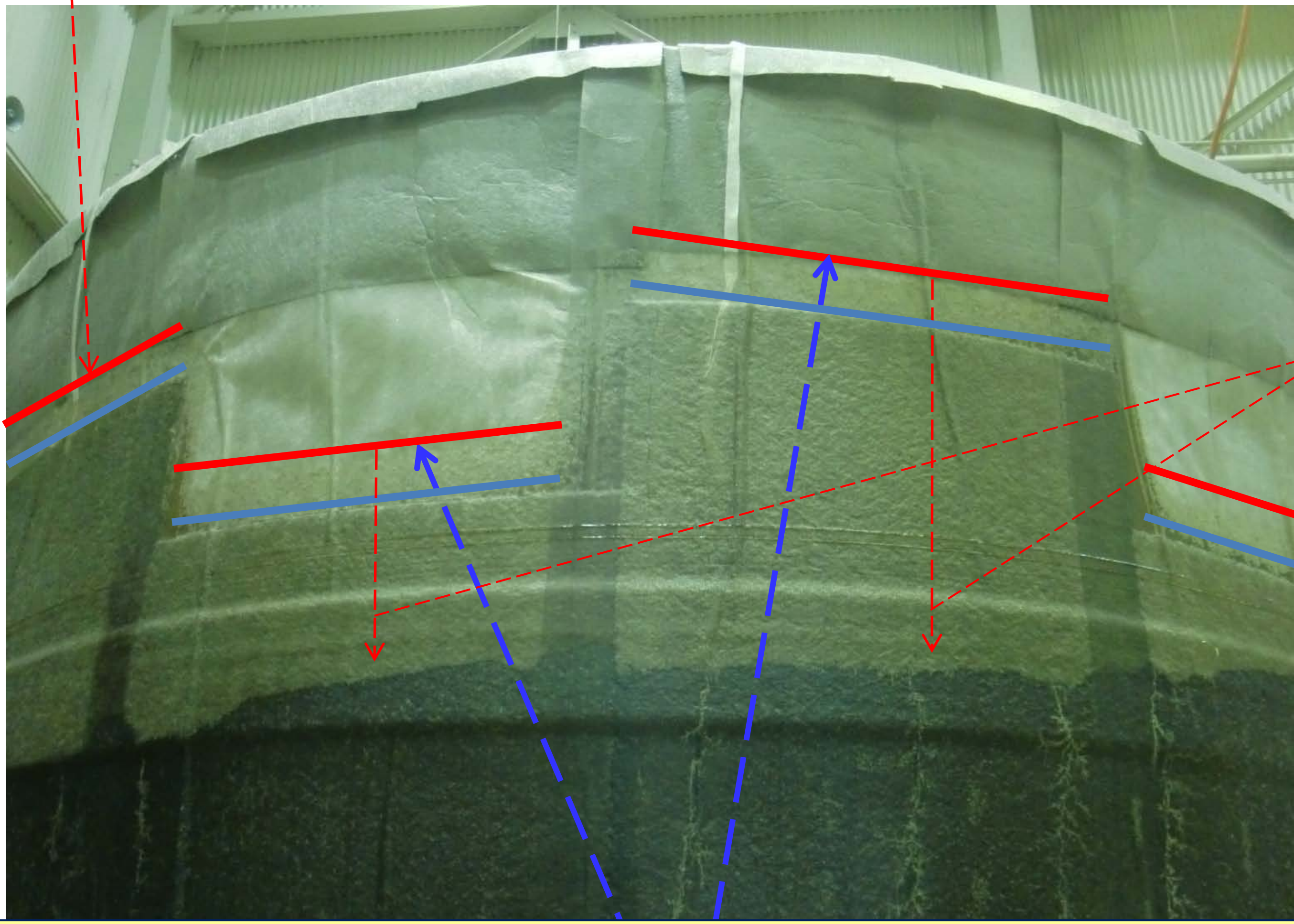
•As individual fabric tows continue to soak up resin after fill valve is closed, the resin **in the RDM** drops to a common liquid level, but the structural fabric stays filled at the maximum resin height. The RDM appearance can probably be improved by keeping the fill valve open longer than we did on this run.

•Ring patterns are from shear keys holding the foam core rings together, and overlaps of the double RDM. These are not part of the CWP design

•The flow front stops at a uniform height all around the circumference
•This validates our method of controlling the flow front height for stepwise infusion

Control of wet-out height

Boundary of wet-out in the fabric



As individual fabric tows continue to soak up resin after fill valve is closed, the resin **in the RDM** drops to a common liquid level, but the structural fabric stays filled (see next slide). The appearance can probably be improved by keeping the fill valve open longer than we did on this run.

The outer fabric wet out to a uniform margin of about 4 inches above the intentionally placed "castellations" at the top of the active RDM, again indicating good uniformity and control of wet-out height within the apparatus

Observations concerning longitudinal wrinkling in outer face sheet (only) of 4m validation workpiece fabricated on foam core

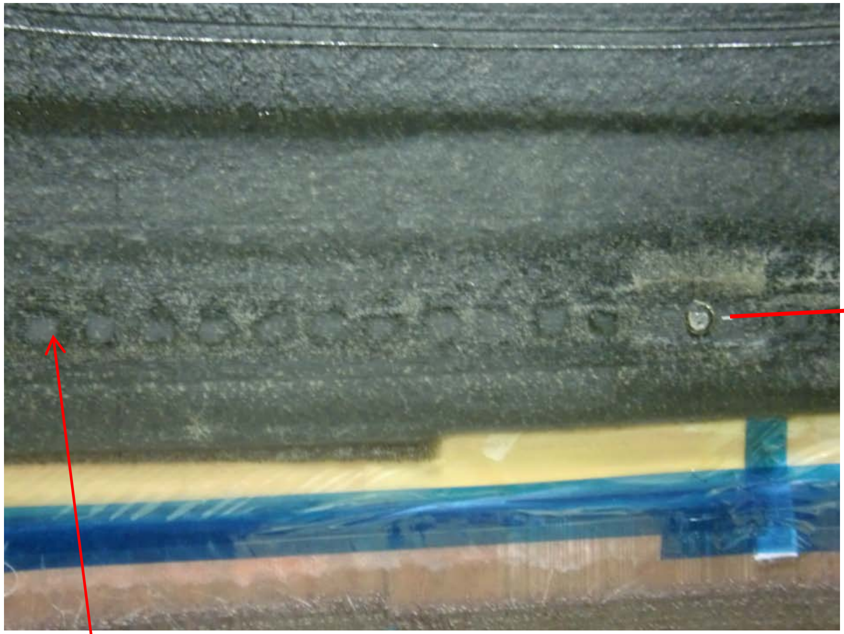
Proof-of-principles workpiece:
No longitudinal wrinkling

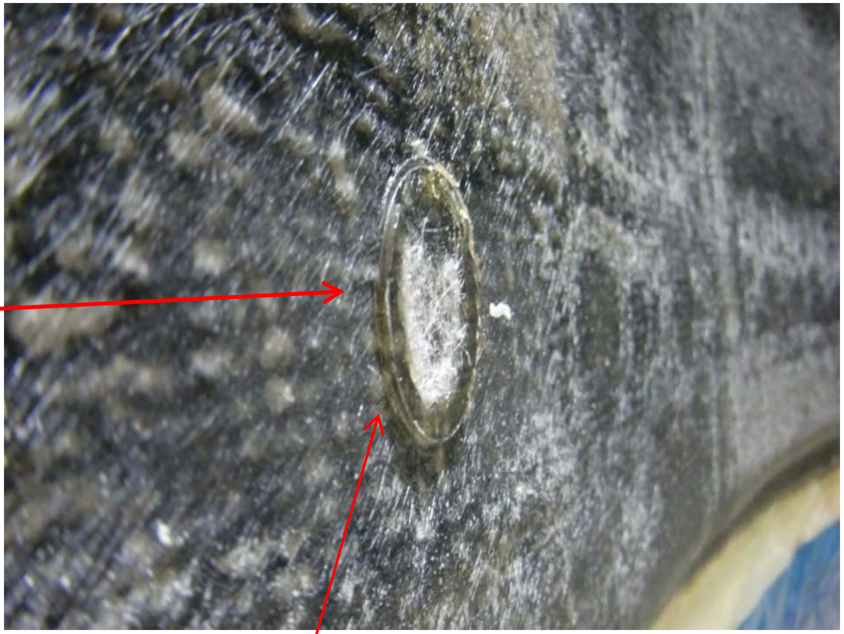
4m validation workpiece:
Got longitudinal wrinkling

Understanding wrinkling observed in outer face sheet of 4m workpiece, and path forward that should eliminate it

Component and operations	Prior and current results	Details of prior or current operations	Interpretation	Path forward
Outer fabric dispensing and molding	19" Proof-of-Principles apparatus: No longitudinal wrinkles	1. Bottom edges of all fabric rolls were attached to a "pull ring" and were pulled into the molding region axially from fabric rolls and directly in contact with the core. No tackifier was needed or used.	1. Individual fabric strips started out very close to their final diameter, and were free to slide over each other circumferentially as they debulked onto the core when vacuum was pulled.	
Outer fabric support materials and layup	4m Molding Region tested by itself: Got longitudinal wrinkles in outer face sheet	1. We used an available foam core because the pultrusions were late. 2. To be sure we didn't crush the weak foam core by possible resin shrinkage effects, we put breather cloth under the outer face sheet. This inadvertently created excess circumference in the fabric and RDM. 3. Because this was a standalone workpiece, individual fabric strips were draped over the top of the foam core. They billowed out, creating additional excess circumference. 4. Fabric also hung away from workpiece in between the intermediate shear keys, creating additional excess circumference 5. Some sprayable tackifier was used to help hold the fabric strips in place.	1. The breather debulks substantially when vacuum bag pressure is applied, forming wrinkles in the overlaid fabric and RDM. 2. The billowing from draping probably also contributed to wrinkling 3. Circumference changes at shear keys may have contributed to wrinkling 4. The tackifier may have prevented the fabric strips from sliding over each other at their edges, contributing to wrinkling.	1. There will not be any breather fabric with regular pultruded core. 2. Fabric dispensing bibs should keep fabric against core as it is dispensed vertically, and tension in dispensing mechanisms should tend to keep it from wrinkling. 3. We plan to get rid of shear keys by going to staggered core planks. This will get rid of excess circumference there. 4. No tackifier will be used

Inner face sheet shows successful operation of RURDL and RIL mechanism



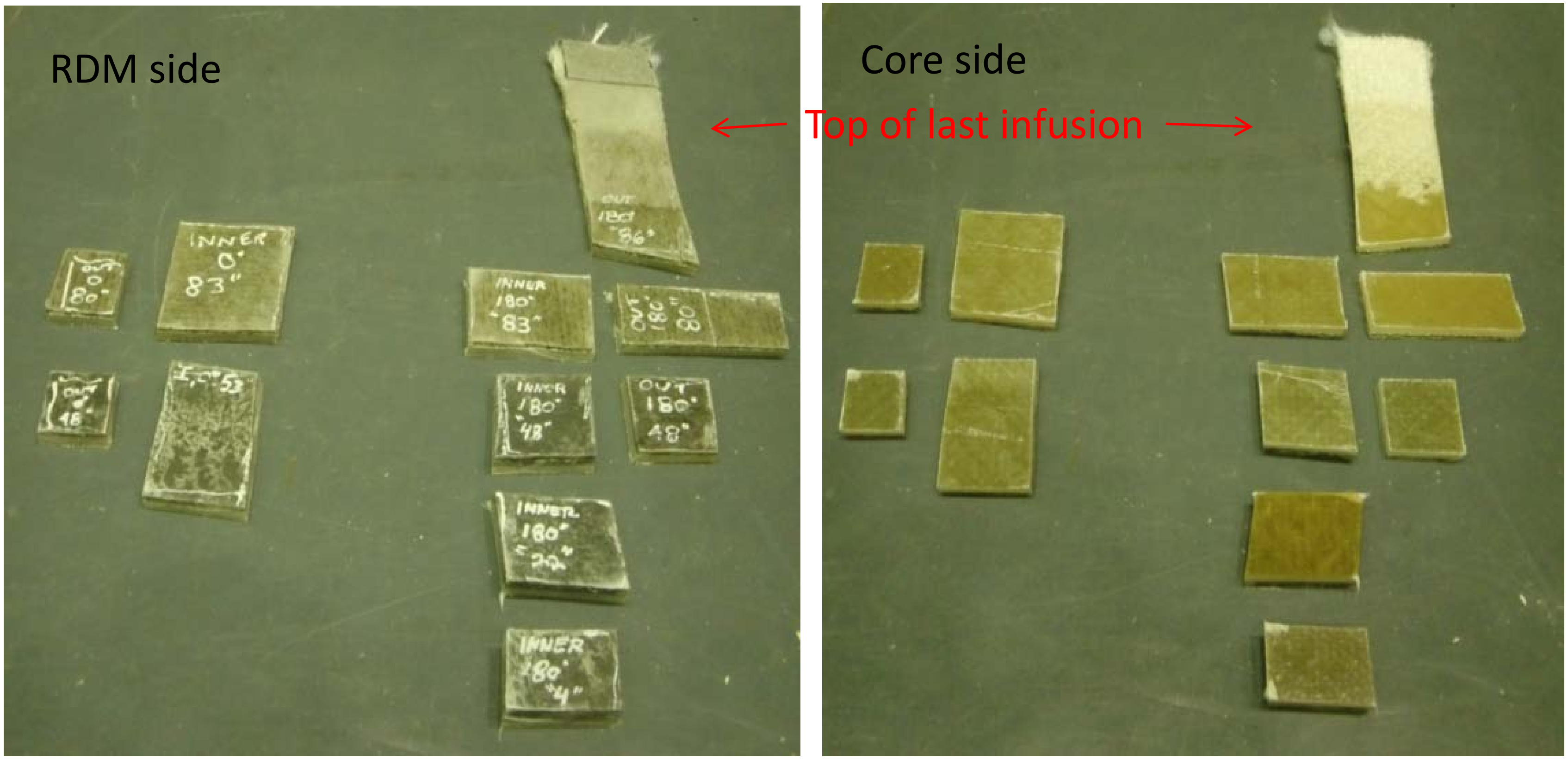


Key results:

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

Behavior of the apparatus is validated for repeated infusions with minimal expendable material replacement (only the RIL itself) between infusions

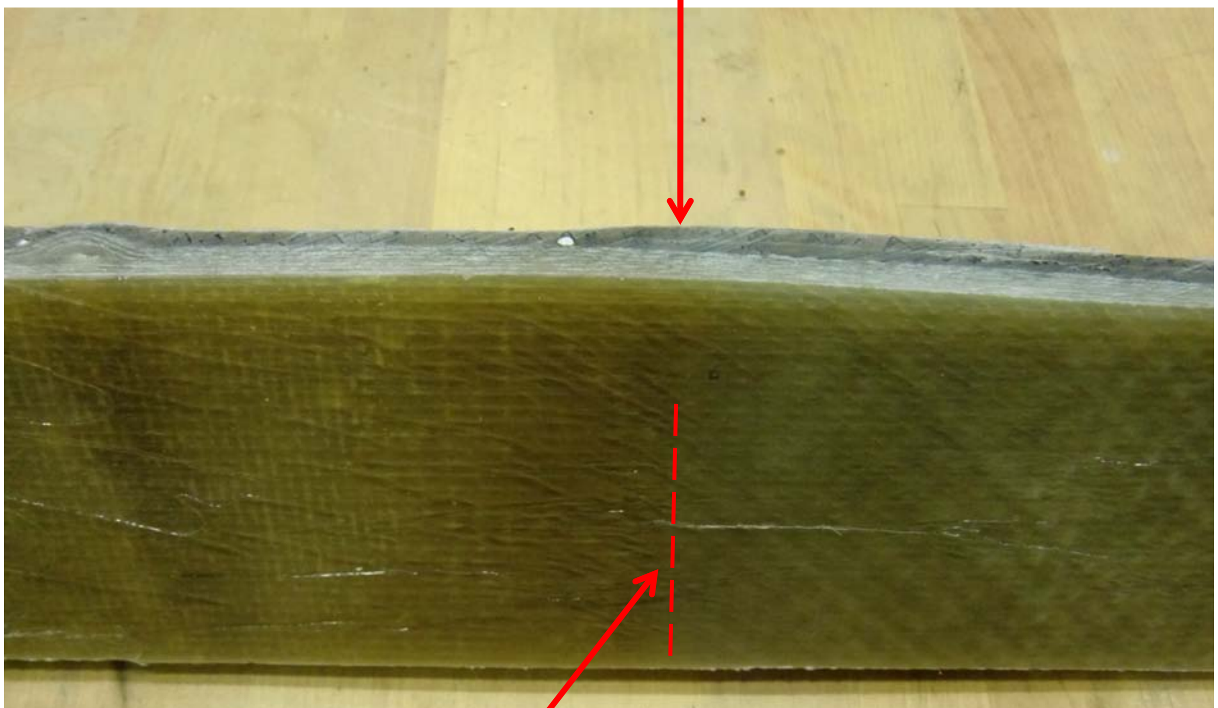
Samples cut from finished 4m diameter validation workpiece



Laminate is fully wet-out everywhere, including regions where resin level dropped in the RDM during cure

Results at knitline

Key result: The knit-line between infusion steps is indistinguishable from the base laminate.



A slight color change on the external surface of the laminate (due to different catalyst % on two infusions due to lab temperature differences) serendipitously reveals where the knitline is.

The stepwise infusion molding process is validated

VI.C.2.d - Validation of analytical tools for predicting infusion behavior (fill time and resin consumption)

- Predicting resin quantity and fill time including lines and valves
- Fill pattern and resin consumption
- Fill time corrected for viscosity vs. temperature, compared to prediction

Predicting resin quantity and fill time including lines and valves

Input from LMSSC flat panel VARTM model

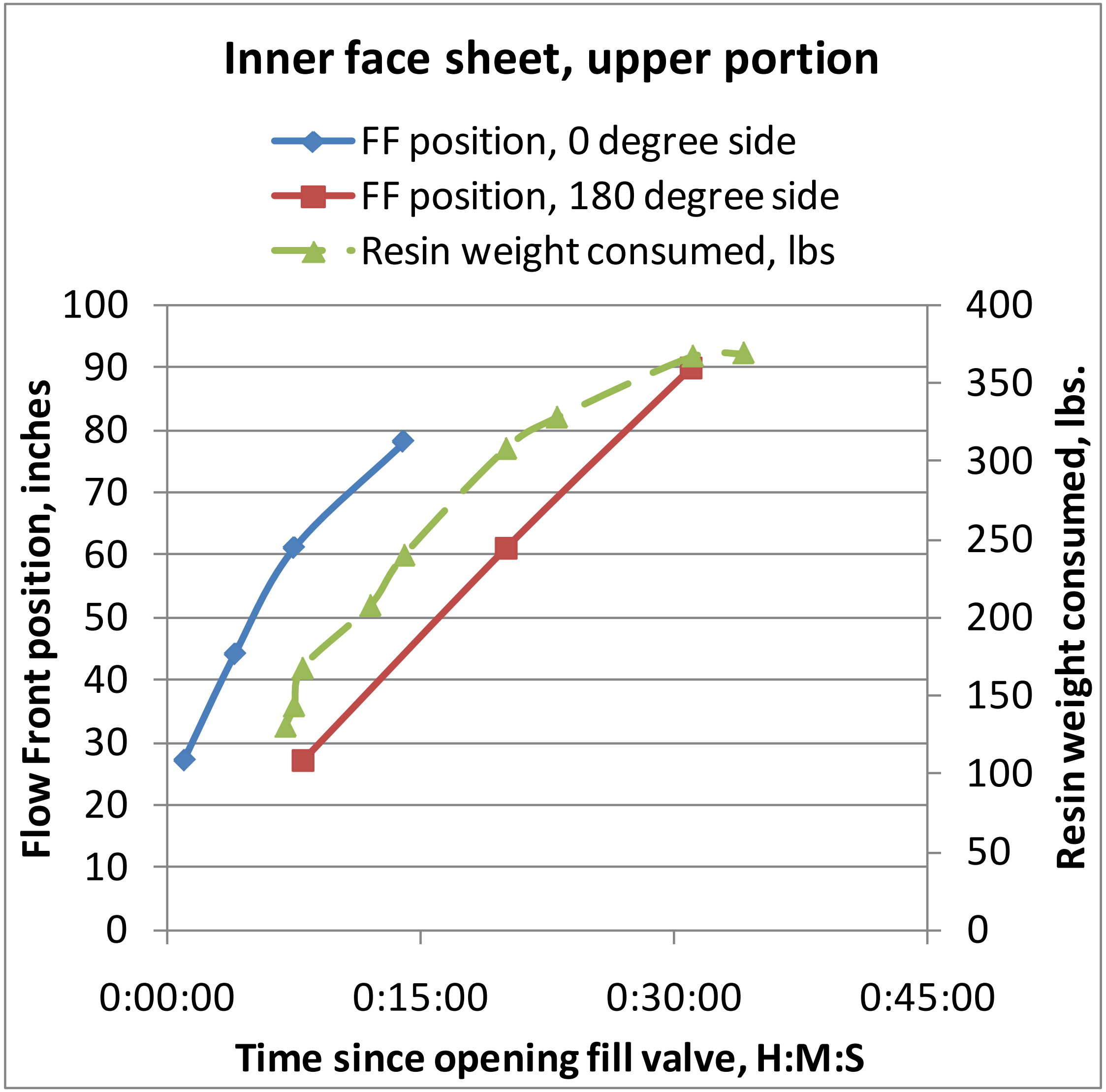
Number of panels	1	Mixture, in^	Mixture, cc	
Panel length, in	82.00			64" of fabric + RDM, + anot
Panel width, in	501.39936			
Fabric thickness, in	0.237			
Margin in bottom of reservoir: 1/2" depth x 2" diameter: in^3		0.0	0	
RIL inside diam., in.	1.000			
RIL inside area, in^2	0.785			
RIL length, in.	184			
RIL volume, in^3, cc		144.4	2366.9	
RDL length, ID, in.	501.40			
RDL ID, in	1.316			
RDL area (in^2)	1.360			
RDL vol in^3 , cc		681.9	11174.3	
Active RDM thickness, in	0.12			
Active RDM porosity	0.88			
Active RDM mixture quantity, in^3		4347.3	71239.0	
Outer RDM thickness, in	0.02			
Outer RDM porosity	0.67			
Outer RDM mixture quantity, in^3		550.9	9028.2	
VDM mixture quantity, in^3		0.0	0	
Fabric mixture content	0.49328			Measure laminate fiber v/o
Fabric mixture volume, in^3, cc		4806.6	78766.19093	
Resin in gaps between planks, in^3		0.0		
VDL length, in., vol in^3	0	0.0	0	
VEL's: How many?	*0*			
VEL inside diam, in.	0.170			
Total VEL length, volume	48	0.0	0	
Fill time, Upper reservoir volume, fabric fraction u	0	0.0	0%	
Total calculated mixture: in^3, cc		10531.2	172575	
Flushing margin and mixture required:	**0%**	0.0	0	
Contingency and mixture required:	**0%**	0.0	0	
Total mixture to be mixed, lb, in^3, cc	380.1	10531.2	172575	
Catalyst PHMB by wgt; Catalyst PHMB by vol	*1.986097319*		*1.899705173*	
Density(g/cc)-Master batch, avg, hardener	*1.01305008*	*1.020*	*1.039*	
Master batch (g)	*169214*	*Catalyst (g)*	*3361*	
Master batch (lb)	*373*	*Catalyst (lb)*	*7.403*	
Master batch (cc)	*167034*	*Catalyst (cc*	*3235*	
Master batch (gallons)	*44.1*	*Catalyst (ga*	*0.9*	

<u>Calculate acceptable size of resin inlet line, subfeeds, and fill valve</u>

Total resin	Total resin	Expected fill time without lines and valves		Avg flow rate	
cc.	g	min.	sec.	g/sec.	
172575	176053	9.1667	550.002	320.0959675	Fill time without feed, subfeeds, or valve (VAR

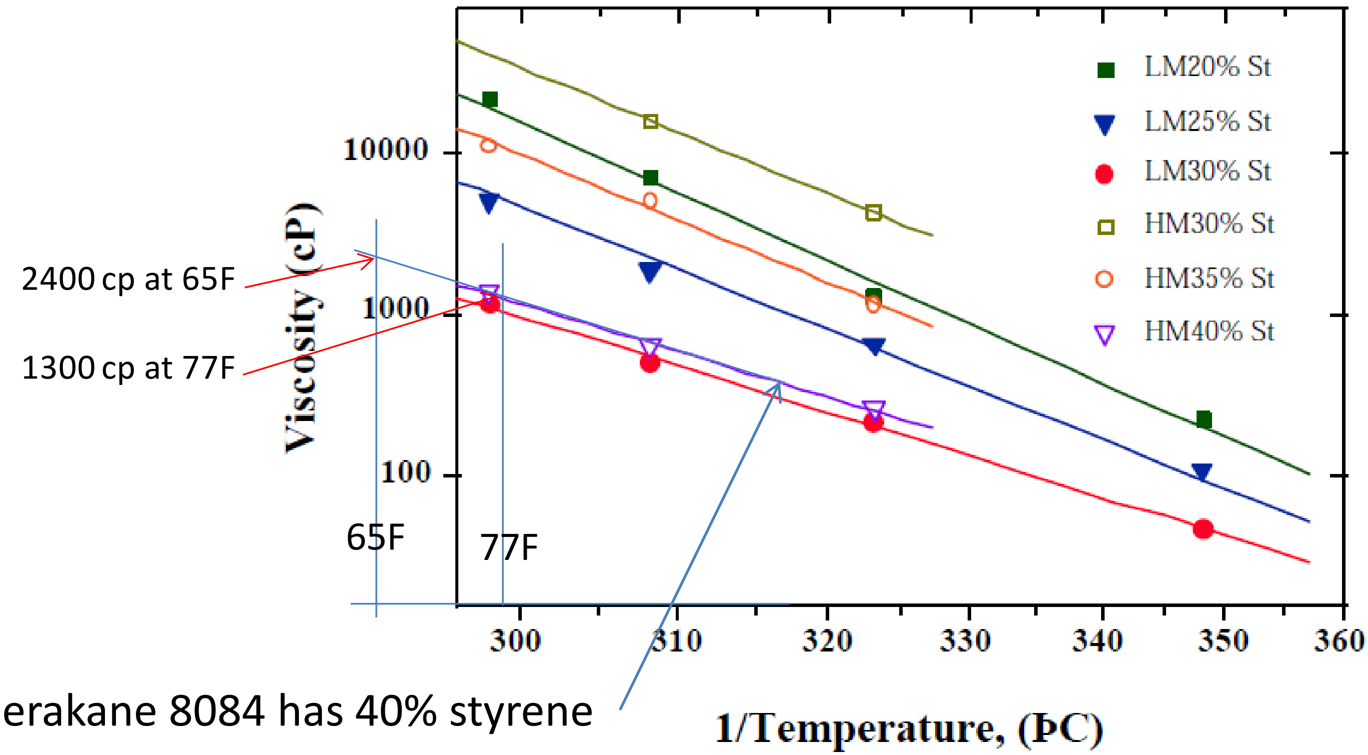
Fluid density			1.020E+06	g/m^3	8084		
gravitational constant			1.00E+02	g/(Pa-sec^2-m)			
<u>Pressure drop through main feed tube a</u>		inches	meters				
Tube length		184	4.67360				
wall thickness, outer diar	0.0675						
Inside diameter, inches	"=D9-2*C9"	1	0.02540				
Flow area		0.7850	5.06E-04				
Fluid viscosity			0.37	Pa-sec	8084	at 77F	
Average mass flow rate	320.0959675	g/sec	Fluid velocity	0.48634606	m/sec		
Reynolds number	340.6000932	Per Shepard					
Friction factor f	0.187903648	Per Marks p.	Friction factor prime (=f/4)		0.046976	Per Marks p. 4-66	
Estimated pressure drop for feed tube			**4.17E+04**	Pa			
Feed tube mass (g), flow	301.57	767.36	0.39				
<u>Pressure drop through fill valve</u>							
Length of flow passage inside valve body		1	0.02540	was =2*0.75*D20/0.375			
Tube nominal size, OD, inches							
Flow passage inside diameter, inches		0.75	0.01905				
Flow area		0.4416	2.85E-04				
Fluid viscosity			0.37	Pa-sec	8084	at 77F	
Average mass flow rate	320.0959675	g/sec	Fluid velocity	8.646E-01	m/sec		
Reynolds number	4.54E+02	Per Shepard					
Friction factor f	0.140927736	Per Marks p.	Friction factor prime (=f/4)		0.035232	Per Marks p. 4-66	
Estimated pressure drop for valve			7.17E+02	Pa			
<u>Pressure drop through RDL</u>		inches	meters				
<u>Number of sub-feed tubes</u>	2						
Tube length		250.69968	6.36777				
wall thickness, outer diar	0	1.31590339					
Inside diameter, inches	"=D31-2*C31"	1.316	0.03342				
Flow area		1.360	8.77E-04				
Fluid viscosity			0.37	Pa-sec	8084	at 77F	
Average mass flow rate	160.0479838	g/sec	Fluid velocity	1.404E-01	m/sec		
Reynolds number	1.29E+02	Per Shepard					
Friction factor f	0.494526095	Per Marks p.	Friction factor prime (=f/4)		0.123632	Per Marks p. 4-66	
Estimated pressure drop for subfeed			9.48E+03	Pa			
subfeed tube mass (g), fl	1992	625.29	3.19				
Total pressure drop for valve, feed, subfeeds			**5.19E+04**	Pa			
Atmospheric pressure			1.00E+05	Pa			
Total Pressure to fill part in same time			1.52E+05	Pa			
Corrected fill time for 1 atm avail pressur			13.92	min.	835	sec.	
Estimated pot life of resin			114	min.			

Fill pattern and resin consumption



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

Fill time corrected for viscosity vs. temperature, compared to prediction



Used generic data on viscosity of vinyl ester resins vs. temperature. Derakane 8084 is a 40% styrene resin

http://scholar.lib.vt.edu/theses/available/etd-42198-113329/unrestricted/ch3-3.pdf

- Predicted fill time at 77F = 14 minutes (LMSSC VARTM model; panel data)
- Fill time increase due to viscosity increase at 65F temperature = 2400/1300 = 1.85
- Predicted fill time corrected to 65F = 1.85 x 14 = 25.9 minutes
- Actual fill time = 31 minutes

Predicted fill time (corrected to actual temperature) is within 20% of measured fill time

Tabular summary of validation results at 4m scale - Stepwise infusion molding

Component and operations	Results and key challenges met	Evidence
Vacuum testing of hard shells (at Janicki)	**Successful** - Achieved good vacuum in assembly after welding quadrants together	Acceptance testing COC
Acceptance testing of basic apparatus (at Janicki)	**Successful** - Achieved good vacuum; operated RURDL's; filled fully with pressurizing fluid (water)	Acceptance testing COC, photos, videos
Resin height monitoring system (at LMSSC)	**Successful** – Can see resin through soft tools	Photos and clips from 16-channel video recorder
Control system (at LMSSC)	**Successful** – Operates all sub-systems from a central control panel	Notes within control system software records
Resin supply, on-line mixing, and resin feed system (at LMSSC)	**Successful** – **Mixes and feeds large quantities without exotherm**	Complete fill and cure of workpiece as planned, negligible temperature rise in curing workpiece
Functional test of RURDL and RIL (at LMSSC)	**Successful** - **RURDL spreads resin circumferentially, then collapses. RIL breaks off as planned.**	2-step infusion filled as planned, leaving negligible trace of excess cured resin on workpiece
Pull good vacuum on workpiece (at LMSSC)	**Successful** – Double lower seals arrangement was extremely effective in avoiding any air leakage past "cured CWP"	Vacuum gage readings at apparatus are very close to supply vacuum
Infuse large workpiece (at LMSSC)	**Successful** – Infused about 1000 lbs. of resin in 3 "shots". **Got full wetout of fabric everywhere planned, in about the planned time (correcting for temperature). Flow front stopped at expected locations**	Overall visual inspection of workpiece. Data on flow front position vs. time.
Cure shrinkage behavior of large workpiece	**Successful** – **Inner face sheet stays in close contact with core and does not pull away**	Small cut-out samples
Stepwise infusion molding (at LMSSC)	**Successful** – **"Knit-line" between infusion steps is not discernable visually.**	Knit-line cut-out sample

Sidebar: Effects of axial forces on large seals

Component and operations	Results	Evidence and diagnosis	Future Needs
<u>3. Infusion molding</u>			
Large inflatable seals under axial forces from water column and vacuum (at LMSSC)	•**Outer bottom seal leaked** while filling with water to the top (before second step of inner stepwise infusion). It had held just fine during first step, which was to a lower water elevation. It had held just fine during Janicki acceptance testing. •**Outer RURDL disbonded from outer soft tool.**	**Outer seals flipped out of position axially**, causing major water leakage. Both outer bottom seals were "flipped" over about 90 degrees of arc. Outer RURDL disbonded from outer soft tool. **LMSSC preliminary diagnosis** (concurred with by Janicki) is that outer soft tool slipped downward on the RDM of the workpiece under the large axial forces induced by the water column, in a way that did not happen during acceptance testing at Janicki because during that test, the soft tools were pressing directly on the foam test core, not the more slippery RDM. Downward slippage of the outer soft tool tore it from the outer RURDL, which was supported by straps from the outer hard shell. Upper "centering ring" seals, also under axial forces because of 1 atm vacuum pressure differential across them, did not flip out because of foam blocks inserted above them to protect against such an event. (Note: One upper seal had flipped out at Janicki before foam blocks were inserted.)	Janicki and LMSCC convened a telecon including all individuals familiar with the work. All agreed that the root cause was the instability in the large inflatable seals under strong axial forces, and that an improvement was needed to stabilize them. Two possibilities were identified, both designed to prevent axial movement of their non-anchored sides: a. Add diagonal straps over seals, connected to hard shells b. Mold 2nd-generation axial seals to a triangular shape

Despite this fairly major failure of one mechanical element of the apparatus, we were able to recover and complete the molding region validation. The inner soft tool and inner RURDL were undamaged, and we validated the RURDL behavior and stepwise infusion process on the inner face sheet. To complete the outer face sheet molding validation, we installed an ad-hoc disposable RDL consisting of several turns of standard "spiral-wrap" RDL, with some extra spiral wrap at the RIL to form a large open interface. Infusion of the outer face sheet was then successful.

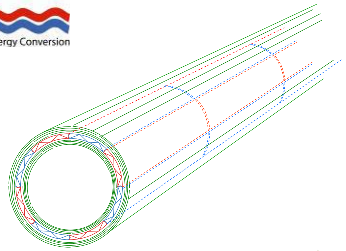
It's time to declare victory for this phase of the CWP development

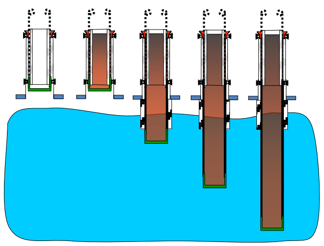
Nat Shankar, Matt Ascari, Alan Miller, Ted Rosario

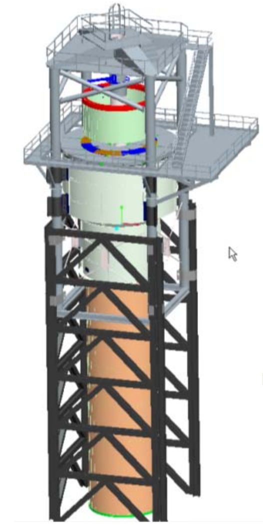
VII. Path forward

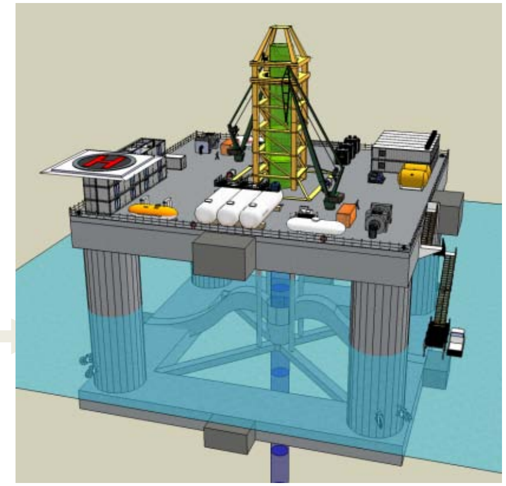
The next figure summarizes the overall CWP roadmap in terms of past and recently completed steps, and future planned steps.

LM OTEC CWP development and implementation roadmap









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 (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 34" per step	4m ID x 7.5 ft per step	4m ID x 19 ft per step, 3 or more successive steps	4m ID x 19 or 39 ft. per step	10m ID x 19 or 39 ft. 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

VIII. Executive Summary

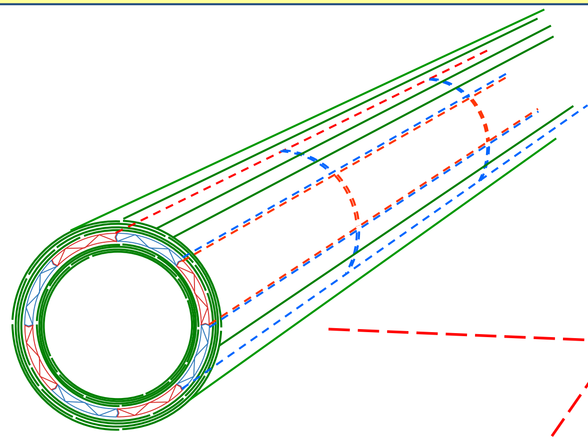
Critical elements of the LM OTEC CWP design and fabrication apparatus and process have been validated at a 4m diameter scale. These elements include:

- Core plank production and assembly into core rings
- Fabric architecture, fabric dispensing, and overlap splice performance
- Stepwise infusion molding

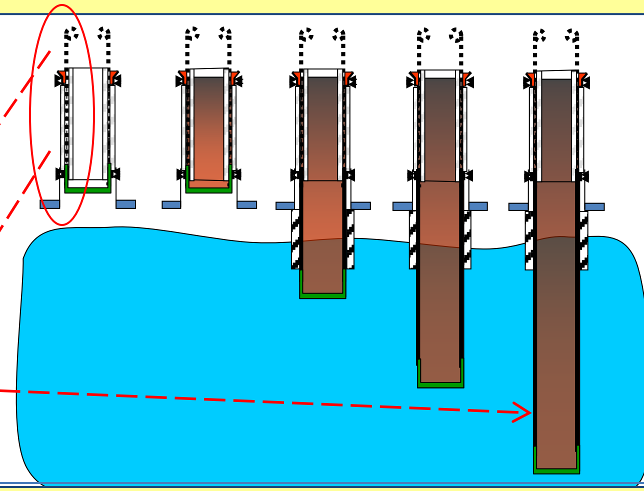
The following slides summarize the major results and conclusions, at the level of one photo montage and one table per validation element.

Pictorial summary of LM Advanced Composite Cold Water Pipe Approach

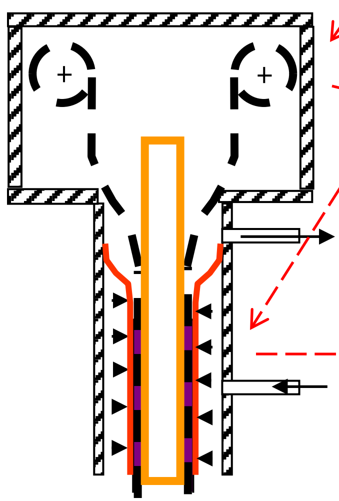
Integral one-piece sandwich-wall pipe with no joints in the main load-bearing face sheets maximizes durability and reliability



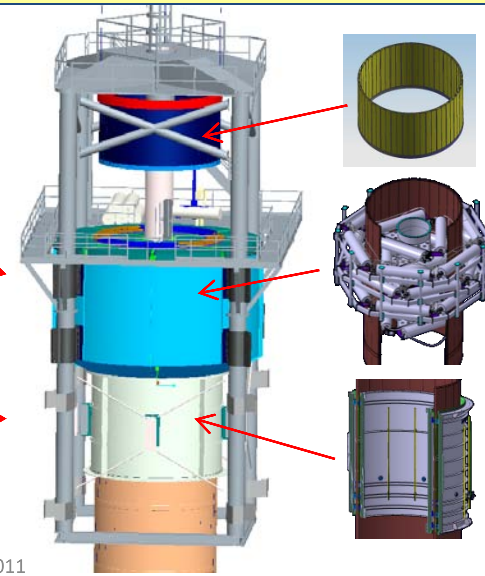
Fabrication off of the OTEC platform eliminates major deployment risks and enables affordable fabrication of huge integral pipe



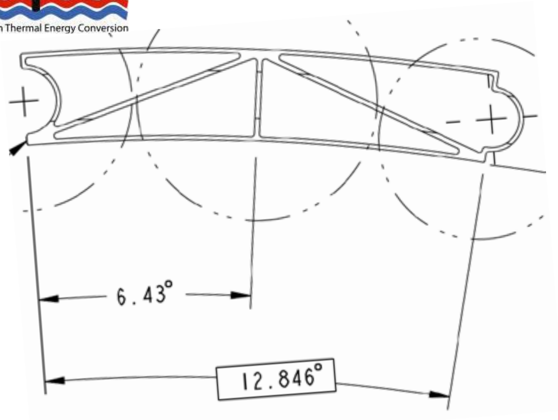
Stepwise VARTM process enables fabrication of a 1000-m long one-piece CWP

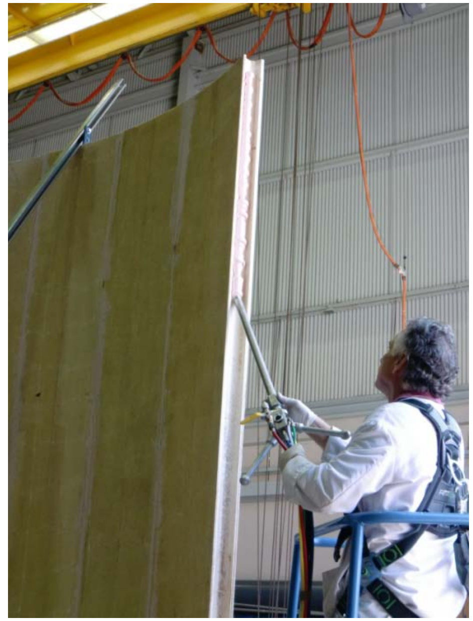


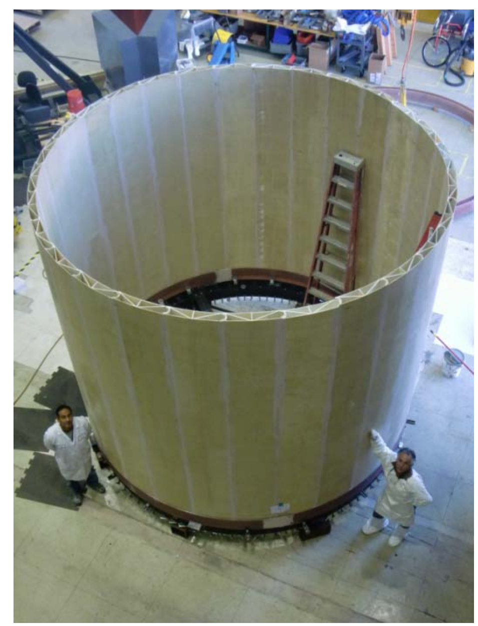
Concept design of large-scale apparatus helped select critical elements for validation at 4m diameter scale



Pictorial summary of core assembly validation







Tabular summary of validation results at 4m scale – Core production and assembly

Component and operations	Results and key challenges met	Evidence	Future Needs
Produce custom pultrusions designed to meet all initially known loads, and meeting requirements of stepwise infusion fabrication process (at Glasforms)	**Successful** – **Achieved proper fabric guidance, resin wet-out, and straightness in complex multi-cell hollow pultruded shape made from all-fabric with some sparse fiber directions**	Pultruded planks; good fit-up and dimensional control in assembled core ring	For fabrication of long CWP on-the-water, need to add more ribs to increase local buckling strength under pressure of gripper and bushings
Bond pultruded planks into core ring	**Successful** – **Achieved proper spacing to fit shear keys. Achieved good circularity and diameter control**	Results at multiple locations: +/- 1/8" variability in diameter over the 158" diameter	
Test vacuum tightness of as-received pultruded planks	**Not successful – A random sample core plank was vacuum bagged on its outside. Drop testing showed a 6" Hg drop in 5 minutes.**	This was despite the plank manufacturer's water-tank testing of best and worst planks, with application of resin on the outside of all to seal them.	Need to improve the leak-tightness of the core planks as-pultruded, or if necessary with subsequent sealing
Test vacuum tightness of plank-to-plank joints (staggered planks approach)	**Successful** – **The assembly leak tightness is as good as the planks themselves**	Same vacuum drop as the planks themselves. No audible evidence of air leakage at longitudinal joints	
Produce leak-tight core assembly by pre-applying a commercial "slosh sealing compound" inside each cell of each plank, then assemble into staggered-planks configuration, and vacuum test	**Successful** – Overall drop-test leak rate of staggered-joint assembly is close to acceptable level for VARTM tools.	6" Hg vacuum drop in 5 minutes	Improve the leak-tightness of the core planks as-pultruded, and use slosh compound as a re-work measure if necessary to ensure leak-free pultrusions.

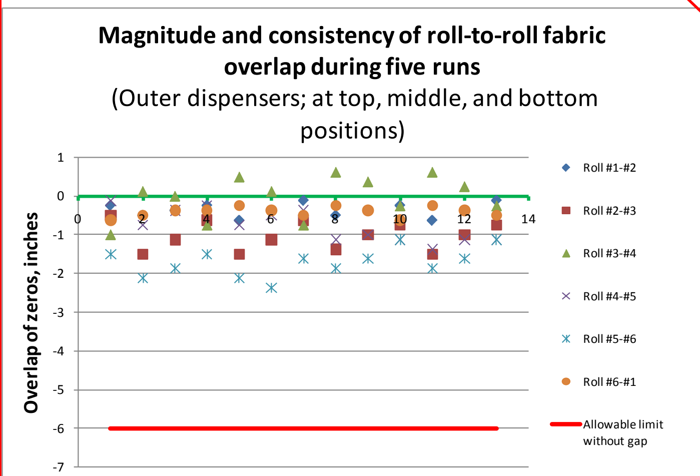
Pictorial summary of Fabric Dispensing validation

Function: Fabric is dispensed by machine under constant tension maintained by servomotor-driven rollers, and is guided by special “bibs” into its curved configuration.

Machine-based fabric placement eliminates hand layup labor and is the key to low recurring costs.

Status: Validation proved that the apparatus forms consistent overlap splices, well within required tolerances.

Note worker for scale



Outer face sheets

Inner face sheets

Work done at Janicki Industries (Paul VanSant, Project Manager) under subcontract from LM-MS2 with technical direction by LM-SSC.

August-Sept., 2010

Tabular summary of validation results at 4m scale – Fabric architecture and dispensing

Component and operations	Results and key challenges met	Evidence	Future Needs
Overlap splices in face sheets	**Successful – Splice regions are as strong as the base laminate**	Local buckling specimen failed away from the splices	
Design and construct complex apparatus (w. Janicki)	**Successful**	Apparatus	Core chucks which do not require periodic re-charging with air pressure
Acceptance testing of apparatus (at Janicki)	**Successful** - **Maintained constant payout tension despite variations in "demand" payout velocity imposed at free end of fabric**	Acceptance testing COC, photos, videos	
Validate fabric dispensing operations (at Janicki)	**Successful** - **Variations in width of fabric overlap are well below allowable**	Validation testing report, photos, videos	

Pictorial summary of stepwise infusion molding validation

Workpiece (fabric not shown)

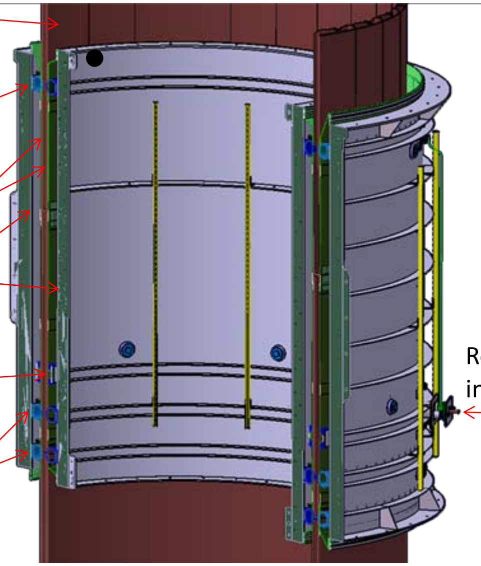
Upper inflatable centering ring and vacuum seal

Outer and inner soft tools

Outer and inner hard shells

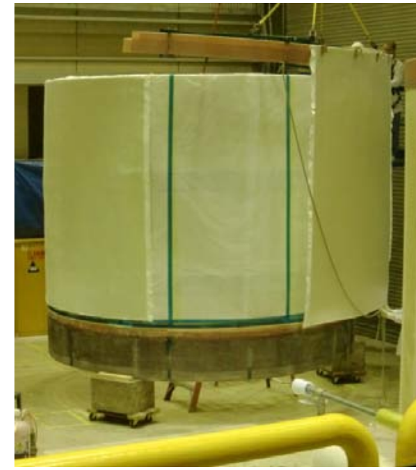
Re-Usable Resin Distribution Line (RURDL)

Bottom inflatable vacuum seals



Inner and outer soft tools and upper seals

Hanging outer face sheet fabric on test core



Removing infused and cured workpiece from mold

Infusion of workpiece

•About 1000 lbs. of resin was mixed and infused in 3 shots

•The fill time was within about 20% of predicted (after correcting the resin viscosity to the low temperatures in the unheated High-Bay)

•The specialized apparatus enables infusion to be done by a 2-person crew

On-line resin metering and mixing pump with auto-level control allows use of a small mixed resin reservoir, avoiding exotherm concerns.

Molding Region showing outer resin inlet line (RIL) and solenoids controlling various subsystems

Manual control panel with computer display of step-by-step instructions and place to record all data and observations

Key result: The knit-line between infusion steps is indistinguishable from the base laminate. The stepwise infusion process is validated!

Tabular summary of validation results at 4m scale - Stepwise infusion molding

Component and operations	Results and key challenges met	Evidence
Vacuum testing of hard shells (at Janicki)	**Successful** - Achieved good vacuum in assembly after welding quadrants together	Acceptance testing COC
Acceptance testing of basic apparatus (at Janicki)	**Successful** - Achieved good vacuum; operated RURDL's; filled fully with pressurizing fluid (water)	Acceptance testing COC, photos, videos
Resin height monitoring system (at LMSSC)	**Successful** – Can see resin through soft tools	Photos and clips from 16-channel video recorder
Control system (at LMSSC)	**Successful** – Operates all sub-systems from a central control panel	Notes within control system software records
Resin supply, on-line mixing, and resin feed system (at LMSSC)	**Successful** – **Mixes and feeds large quantities without exotherm**	Complete fill and cure of workpiece as planned, negligible temperature rise in curing workpiece
Functional test of RURDL and RIL (at LMSSC)	**Successful** - **RURDL spreads resin circumferentially, then collapses. RIL breaks off as planned.**	2-step infusion filled as planned, leaving negligible trace of excess cured resin on workpiece
Pull good vacuum on workpiece (at LMSSC)	**Successful** – Double lower seals arrangement was extremely effective in avoiding any air leakage past "cured CWP"	Vacuum gage readings at apparatus are very close to supply vacuum
Infuse large workpiece (at LMSSC)	**Successful** – Infused about 1000 lbs. of resin in 3 "shots". **Got full wetout of fabric everywhere planned, in about the planned time (correcting for temperature). Flow front stopped at expected locations**	Overall visual inspection of workpiece. Data on flow front position vs. time.
Cure shrinkage behavior of large workpiece	**Successful** – **Inner face sheet stays in close contact with core and does not pull away**	Small cut-out samples
Stepwise infusion molding (at LMSSC)	**Successful** – **"Knit-line" between infusion steps is not discernable visually.**	Knit-line cut-out sample