DELIVERABLE D2.3:
TECHNICAL REPORT ON CHARACTERIZATION PROGRAM

ADVANCED TIDGEN® POWER SYSTEM
US DEPARTMENT OF ENERGY AWARD: DE-EE0007820

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1. Table of Contents

2. Purpose

To fulfill deliverable D2.*3 "Technical report on characterization program, including composite test data, design FMEA for composite structure, material selection, composite design, PFMEA for the composite production process, reliability models, production process control plan and development plan"* for the Advanced TidGen® Power System Project.

3. Introduction

Materials for Marine Hydrokinetic (MHK) devices need to be evaluated before being utilized on a device with a service life of 20 years. For this reason, and the fact that ORPCs turbines are a complex manufacturing challenge, a composite optimization program is conducted. This program looked at novel material sets, production processes and developed tools to evaluate manufacturing defects and characterize their effect on structural performance over an extended operating time. This report will cover the work done during Budget Period 1 for Task 2 of the Advanced TidGen® Power System Project.

4. Baseline foil evaluation

This characterization program commenced with the evaluation of the baseline TidGen® 1.0 turbine foils.

Visual Inspection

A visual inspection of two baseline foils, one deployed and one non-deployed, as seen in Figure 1, was conducted.

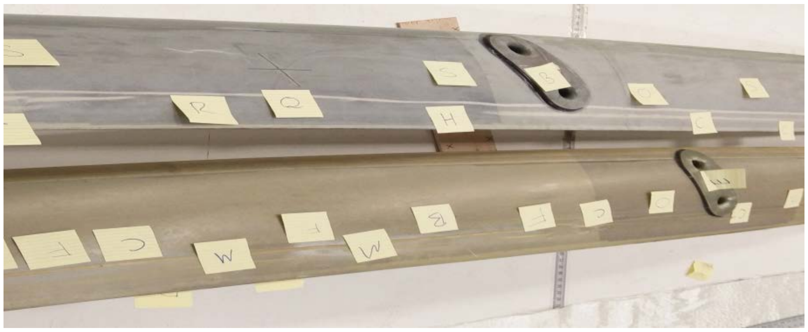


Figure 1: Visual inspection of baseline TidGen® 1.0 foils. Deployed (Top) Nondeployed (Bottom)

The results from this study showed that there were Out of Plane defects that were identified by either resin rich stripes that ran the length of the defect or post process filled patches. It was also observed on the deployed foils that one side of the foil showed resin starved exposed weave possibly due to environmental exposure.

Thermal imagining

After a visual inspection, thermal imagining was used to assess the internal laminate defects of the foil.

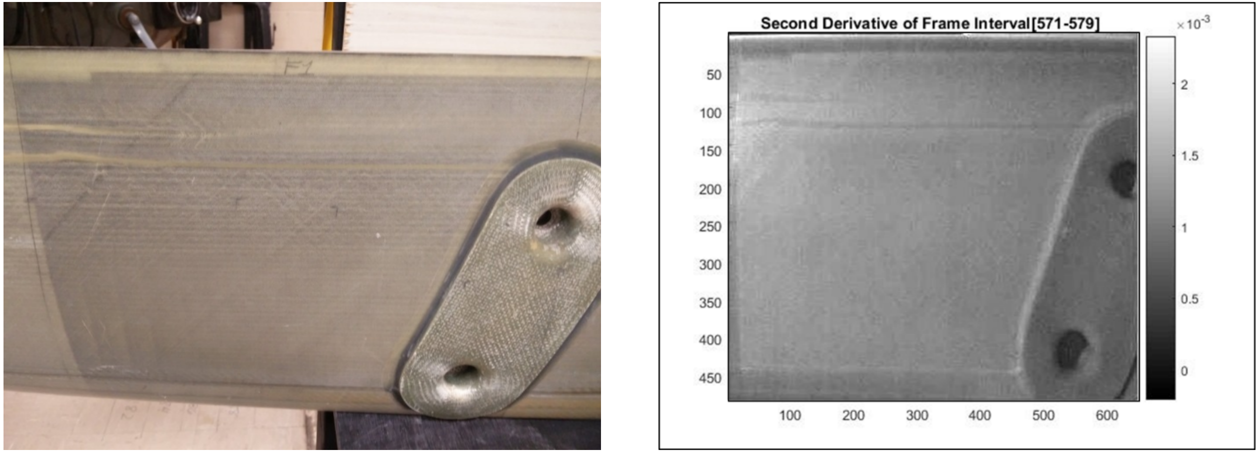


Figure 2: Image of foil to be thermal inspection (left) image of foil during thermal imaging (right)

The results from thermal imaging were inconclusive. For that reason, other NDI techniques were pursued.

Ultrasonic Inspection

To characterize the baseline foil laminate defects ultrasonic inspection techniques were developed. The curved foil profile lead to the need for a specialized rotary indexing inspection head for the ultrasonic test unit as seen in Figure 3.

Figure 3: Image of 3.5MHz RollerFORM probe by Olympus used to scan TidGen® foils.

This unit was setup specifically for use with the TidGen® foils to accommodate the foil camber. Typical ultrasonic heads with a flat rectangular scanning area were not able to confirm to the curved surface of the airfoil. Results are presented in Figure 4.

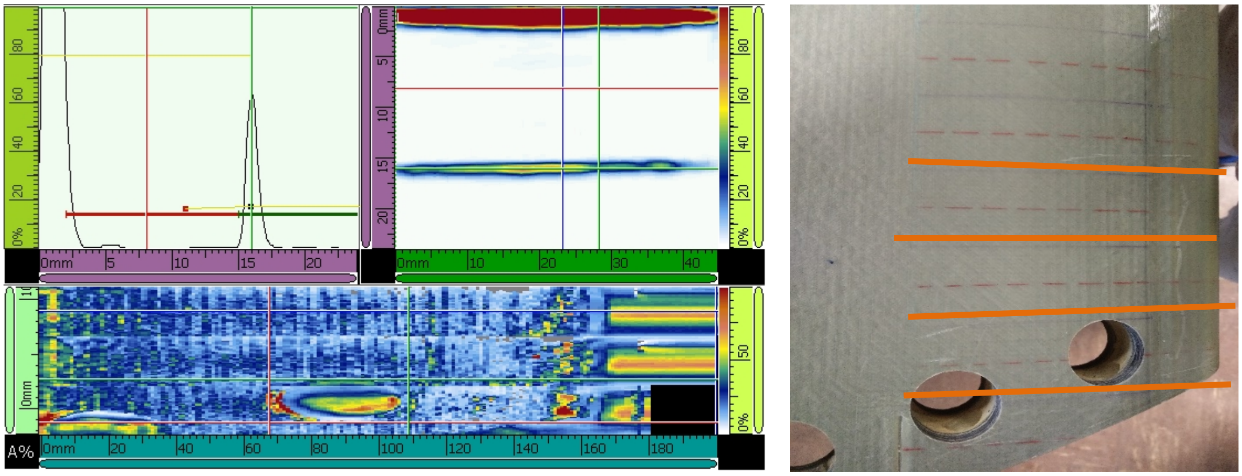


Figure 4: Ultrasonic test output of foil defects (left) foil marked for inspection (right)

The outcome of the ultrasonic testing was informative and promises to be a useful tool for evaluating foil manufacturing defects in future turbines. The Omniscan SX Raster Scan function gives the ability to scan large areas and maps the in a single view so large areas of the foil can be mapped for defects. This can be seen in the bottom left of Figure 4.

With a Rasterscan of a manufactured foil taken before deployment it will be possible to characterize any manufacturing defects and note areas of concern. These areas can then be monitored during routine maintenance using the same ultrasonic testing to determine if these defects have propagated or remained stable.

5. Composite Test Data

See D2.2 for a full test report outlining test results for ORPC's material sets.

Diffusion in Polymer Matrix Composites

An overview of the saturation rate of the coupons is given in Figure 5.

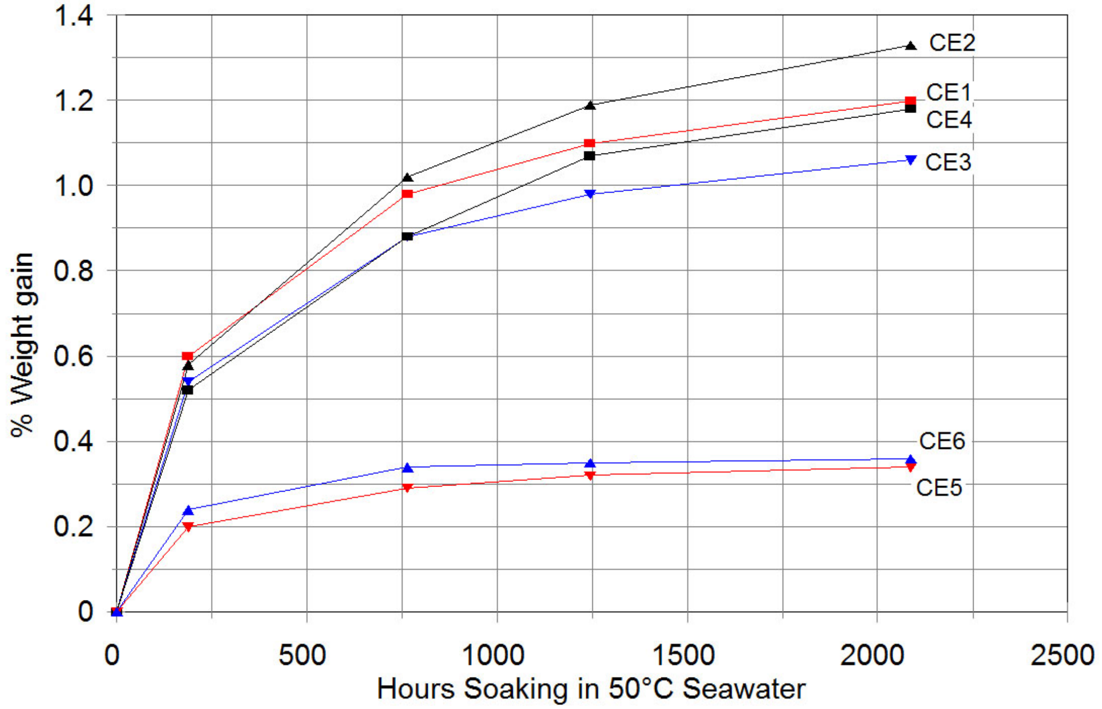


Figure 5: Weight gain versus hours soaking in 50 °C ASTM D1141 simulated seawater (without heavy metals)

As a rough conservative estimate of expected real life saturation rates MSU use this rule of thumb: For every 10°C reduction in temperature double the time to saturation. As an example, a saturation time of 2200 hour at 50°C would imply 35,200 hours at 10°C, or 4 years. To truly determine an accurate saturate rate for the real-world application, saturation rates at two temperatures is required. ORPC's coupons were all saturated at 50°C. Calculation of a more accurate diffusion rate will be addressed in future work with the final materials sets. The following section outlines the derivation to calculate the theoretical Fickian diffusion rate and determine estimated saturation rates at any temperature.

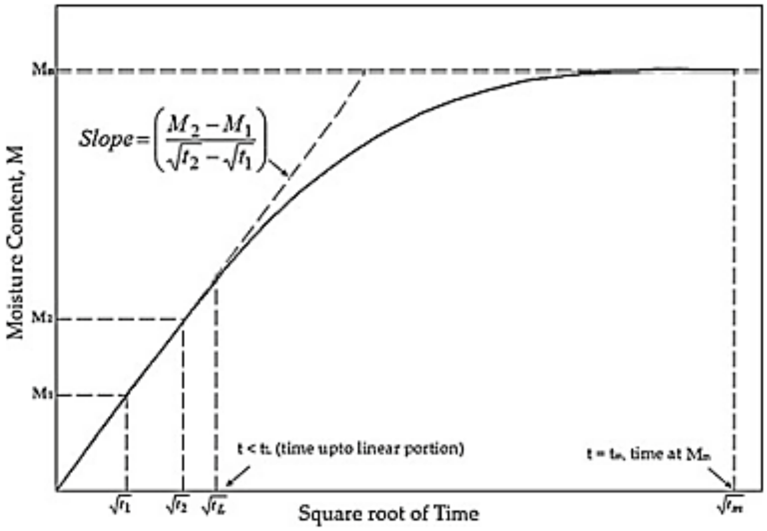


Figure 6: Theoretical Fickian Diffusion - Journal of Composite Materials, 1976. 10(Jan): p. 2-20

The linear portion of Fickian diffusion is given by Eqn. 1 where m_t is the bulk moisture content at time t, m_∞ is the maximum moisture content, h is laminate thickness, and D is the diffusivity coefficient for that temperature.

Linear Fickian Diffusion:

$$\frac{m_t}{m_\infty} = \frac{4}{h}\sqrt{\frac{Dt}{\pi}} \qquad (1)$$

The temperature-rate relationship is given by the Arrhenius rate relationship in Eqn. 2. D_T is the diffusivity at some arbitrary temperature T (kelvins), D_0 is the initial diffusivity coefficient, T is an arbitrary temperature, and C is a constant composted of an activation energy and Boltzmann's constant.

Arrhenius relation:

$$D_T = D_0 * \exp\left(\frac{-C}{T}\right) \qquad (2)$$

D_0 and C are needed, and can be derived from two empirical data points. Given two diffusion curves at different temperatures, T_1 and T_2, two diffusivity coefficients can be calculated from the slope of the linear portion by (from Eqn. 1):

Diffusion Coefficient:

$$D = \pi\left(\frac{h}{4m_\infty}\right)^2\left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2 \qquad (3)$$

Let D_1 be the diffusivity at T_1 and D_2 be the diffusivity at T_2. Eqn. 2 is applied for each case and combined so that C and D_0 can be determined.

Activation Energy:

$$C = \frac{\ln\left(\frac{D_1}{D_2}\right)}{\left(\frac{1}{T_2} - \frac{1}{T_1}\right)} \qquad (4)$$

Initial Diffusivity:

$$D_0 = \frac{D_1}{\exp\left(\frac{-C}{T_1}\right)} \tag{5}$$

Using D_0 and C in Eqn. 2, the diffusivity, D, can be determined for any arbitrary temperature T. Saturation times can be estimated using the relationship in Eqn. 1 but assuming $m_t = m_\infty$.

Linear Diffusion Time:

$$t = \frac{\pi\, h^2}{16\, D} \tag{6}$$

In Figure 1, this time will be the extrapolation of the linear region and will thus provide a conservative estimate of moisture content. As moisture content approaches m_∞, diffusion slows and will asymptotically approaching saturation. The analytical expression for this behavior could be used to determine a more accurate saturation time.

Theoretical Fickian behavior

$$\frac{m_t}{m_\infty} = 1 - \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left\{-\left[\frac{(2n-1)\pi}{h}\right]^2 Dt\right\} \tag{7}$$

Mechanical Results

These data are the result of the accelerated moisture testing performed as part of the Sandia / Montana State study related to composite mechanical properties measured after accelerated aging (50°C) in a simulated salt water environment. The data set include tensile behavior in longitudinal and transverse directions in static loading, and fatigue of the composite coupons in tensile longitudinal mode. Six laminates selected by ORPC were tested and results are provided in Table 1 and Table 2.

Table 1: Summary of static test data for control and simulated seawater conditioned coupons.

MSU Material	Layup	Average Volume Fraction (V_F) for static tests %	% moisture	Longitudinal Direction			Transverse Direction		
				E, GPa	UTS, MPa	% strain	E, GPa	UTS, MPa	% strain
CE1	[V/(+/-45)g/0c]$_S$	40.9	0	56.1	786	1.38	10.7	98.3	3.17
			1.2	58.3	787	1.33	8.54	68.3	1.84
CE2		35.8	0	54.8	773	1.40	9.02	83.3	3.26
			1.33	55.3	725	1.30	7.79	58.9	1.84
CE3		40.7	0	54.1	792	1.43	9.96	95.3	3.67
			1.1	52.1	691	1.31	8.62	68	1.92
CE4		36.1	0	53.7	774	1.36	8.91	83.9	3.69
			1.2	53.1	712	1.30	8.18	60.5	1.82
CE5		36.4	0	56.5	733	1.29	9.69	77.8	3.54
			0.34	57.9	695	1.15	8.05	63.6	2.05

CE6	[V/0/45/-45/0/V]	42.3	0	29.2	695	2.69	12.0	109	2.52
			0.36	28.7	590	2.36	16.6	126	2.36

Table 2: Carbon and glass fiber volume fractions in materials CE1 – CE6.

Material	Thickness Ave, mm	Fiber content (C = carbon, G = glass)			Fabrics	V_F, % glass	V_F, % carbon	V_F, % total
		% 0's	% 45's	% 90's				
CE1	2.78	57.6 C	42.2 G	0.4 G	E-BX-1700, Zoltek UD600	18.4	22.5	40.9
CE2	3.43	56.6 C	43.4 G	0	E-BX-1700, Vectorply CLA 1812	15.4	20.4	35.8
CE3	2.86	57.6 C	42.2 G	0.4 G	E-BX-1700, Zoltek UD600	17.6	23.0	40.7
CE4	3.35	56.6 C	43.4 G	0	E-BX-1700, Vectorply CLA 1812	15.3	20.7	36.1
CE5	3.18	56.6 C	43.4 G	0	E-BX-1700, Vectorply CLA 1812	16.8	19.5	36.4
CE6	2.56	69.2 G	22.5 G	8.3 G	Veil, E-BX 1700,Vectorply CLA 1812	42.3	0	42.3

Analysis of data

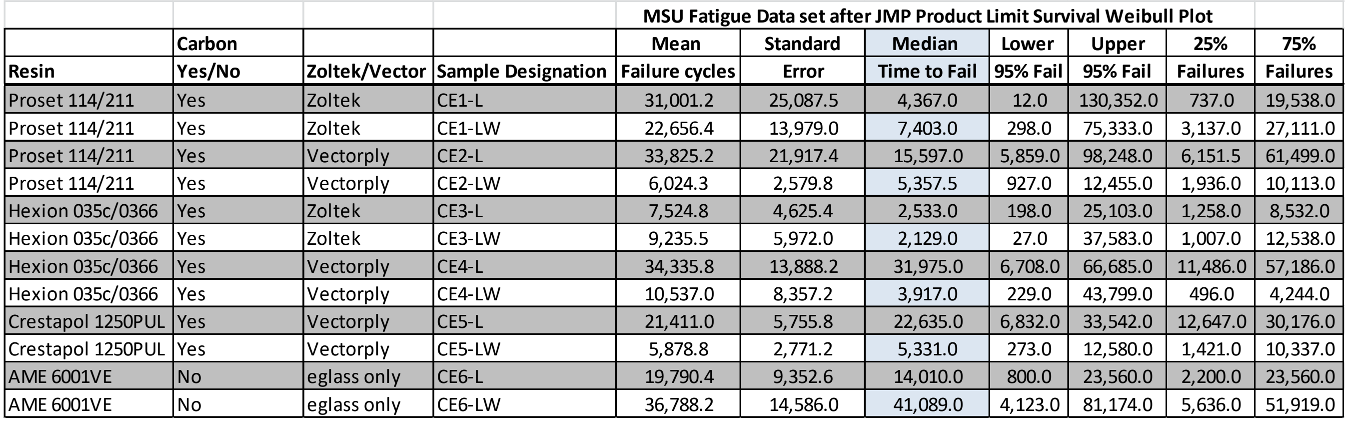
Observations made by Composites Engineering and Research Lab (CERL) on MSU test date are as follows.

To analyze the MSU test data CERL used SAS JMP (Statistical analysis program) to statistically characterize the raw data provided by MSU from this testing. One fundamental truth from this study is that the ingress of moisture had predominately a detrimental effect on performance of these composite laminates. This is clear when looking at Figure 8 showing that the Max % Strain decreases for all samples after saturation.

Fatigue Testing (Tensile, Longitudinal)

Longitudinal testing did not statistically separate out the performance of these laminate as seen in Figure 4, Figure 5 and Figure 6. This may be a directionality that indicates that the Vectorply Carbon Black had higher cycle time performance compared to the Zoltek.

Table 3: MSU fatigue data after JMP product limit survival Weibul plot



				MSU Fatigue Data set after JMP Product Limit Survival Weibull Plot						
Resin	Carbon Yes/No	Zoltek/Vector	Sample Designation	Mean Failure cycles	Standard Error	Median Time to Fail	Lower 95% Fail	Upper 95% Fail	25% Failures	75% Failures
Proset 114/211	Yes	Zoltek	CE1-L	31,001.2	25,087.5	4,367.0	12.0	130,352.0	737.0	19,538.0
Proset 114/211	Yes	Zoltek	CE1-LW	22,656.4	13,979.0	7,403.0	298.0	75,333.0	3,137.0	27,111.0
Proset 114/211	Yes	Vectorply	CE2-L	33,825.2	21,917.4	15,597.0	5,859.0	98,248.0	6,151.5	61,499.0
Proset 114/211	Yes	Vectorply	CE2-LW	6,024.3	2,579.8	5,357.5	927.0	12,455.0	1,936.0	10,113.0
Hexion 035c/0366	Yes	Zoltek	CE3-L	7,524.8	4,625.4	2,533.0	198.0	25,103.0	1,258.0	8,532.0
Hexion 035c/0366	Yes	Zoltek	CE3-LW	9,235.5	5,972.0	2,129.0	27.0	37,583.0	1,007.0	12,538.0
Hexion 035c/0366	Yes	Vectorply	CE4-L	34,335.8	13,888.2	31,975.0	6,708.0	66,685.0	11,486.0	57,186.0
Hexion 035c/0366	Yes	Vectorply	CE4-LW	10,537.0	8,357.2	3,917.0	229.0	43,799.0	496.0	4,244.0
Crestapol 1250PUL	Yes	Vectorply	CE5-L	21,411.0	5,755.8	22,635.0	6,832.0	33,542.0	12,647.0	30,176.0
Crestapol 1250PUL	Yes	Vectorply	CE5-LW	5,878.8	2,771.2	5,331.0	273.0	12,580.0	1,421.0	10,337.0
AME 6001VE	No	eglass only	CE6-L	19,790.4	9,352.6	14,010.0	800.0	23,560.0	2,200.0	23,560.0
AME 6001VE	No	eglass only	CE6-LW	36,788.2	14,586.0	41,089.0	4,123.0	81,174.0	5,636.0	51,919.0

Table 4: Statistical results from fatigue testing showing modulus (E). The red highlighted cells indicate p-values above 5% deemed statistically insignificant

Fatigue Modulus E						
Material Set's being compared		Difference	Str Err Dif	Lower CL	Upper CL	p-Value
CE1-LW	CE1-L	0.196	0.220837	-0.24852	0.640521	0.3794
CE2-LW	CE2-L	0.3275	0.246903	-0.16949	0.82449	0.1912
CE3-LW	CE3-L	0.484667	0.211435	0.05907	0.910263	0.0265
CE4-LW	CE4-L	0.5305	0.234233	0.05901	0.05901	0.0283
CE5-LW	CE5-L	0.2525	0.246903	-0.24449	0.74949	0.3118
CE6-LW	CE6-L	0.16	0.204455	-0.25155	0.571547	0.4379

Table 5: Statistical results from fatigue testing showing cycles to failure. The red highlighted cells indicate p-values above 5% deemed stasticially insignificant

Fatigue Cycles to Failure						
Material Set's being compared		Difference	Str Err Dif	Lower CL	Upper CL	p-Value
CE1-LW	CE1-L	8344.8	17685.17	-27253.6	43943.21	0.6393
CE2-LW	CE2-L	27801	19772.63	-11999.2	67601.23	0.1664
CE3-LW	CE3-L	1710.7	16932.26	-32372.2	35793.58	0.92
CE4-LW	CE4-L	23798.75	18757.96	-13959.1	61556.56	0.2109
CE5-LW	CE5-L	15532.25	19772.63	-24268	55332.48	0.4362
CE6-LW	CE6-L	16997.77	16373.29	-15960	49955.49	0.3046

Table 6: Statistical results from fatigue testing showing max % strain. The red highlighted cells indicate p-values above 5% deemed stasticially insignificant

Fatigue Max % Strain						
Material Set's being compared		Difference	Str Err Dif	Lower CL	Upper CL	p-Value
CE1-LW	CE1-L	0.046	0.076922	-0.10884	0.200836	0.5528
CE2-LW	CE2-L	0.01	0.086002	-0.16311	0.183112	0.9079
CE3-LW	CE3-L	0.024	0.073647	-0.12425	0.172245	0.746
CE4-LW	CE4-L	0.03	0.081588	-0.13423	0.194229	0.7148
CE5-LW	CE5-L	0.0325	0.086002	-0.14061	0.205612	0.7072
CE6-LW	CE6-L	0.008857	0.071216	-0.13449	0.152208	0.9016

Static Testing (Transverse)

The Transverse static test data yielded several valuable observations:

a. Static E (modulus) comparison wet to dry showed that in all but the CE6 laminate the modulus (E) decreased after moisture soak except for the CE6 laminate made with E-glass, which exhibited a significantly higher modulus than the other laminates due to significant 90° fiber compared to other laminate

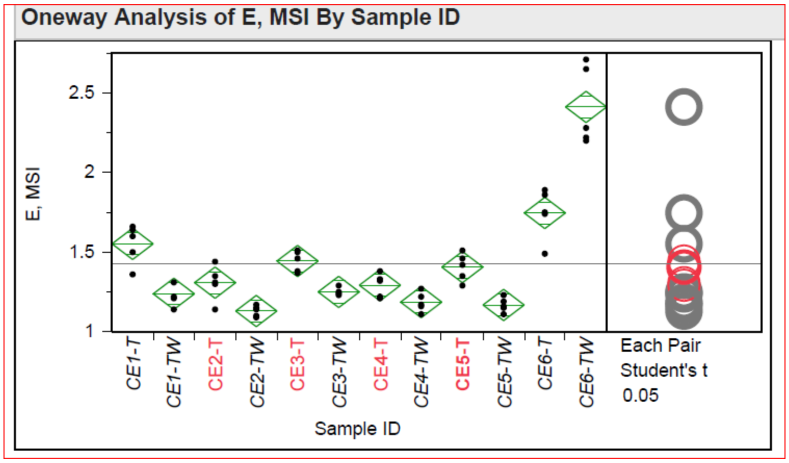


Figure 7: Plot showing Youngs Modulus E, for dry and saturated coupons for all material sets. (T – Transverse) (TW – Transverse Wet).

A comparison between the dry and saturated transverse static results showing the modulus (E) can be seen in Table 7. The transverse results are in general statistically significant. This is largely due to the uni-directional carbon having no tensile strength in the transverse direction.

Table 7: Statistical results of transverse static testing showing modulus (E). Green highlighted cells show a P-value less than 5% or statistically significant.

Transverse Static, Modulus E						
Material Set		Difference	Str Err Dif	Lower CL	Upper CL	p-Value
CE1-TW	CE1-T	0.314	0.069123	0.17502	0.452981	0.0001
CE2-TW	CE2-T	0.178	0.069123	0.03902	0.316981	0.0132
CE3-TW	CE3-T	0.194	0.069123	0.05502	0.332981	0.0072
CE4-TW	CE4-T	0.106	0.069123	-0.03298	0.244981	0.1317
CE5-TW	CE5-T	0.238	0.069123	0.09902	0.376981	0.0012
CE6-TW	CE6-T	0.666	0.069123	0.52702	0.804981	0.0001

b. The one way Max % Strain comparison also showed significant reduction in Max % Strain for the post moisture exposure samples compared to the dry, untested samples. The difference is statistically less for the CE6 laminate (VE with E-glass).

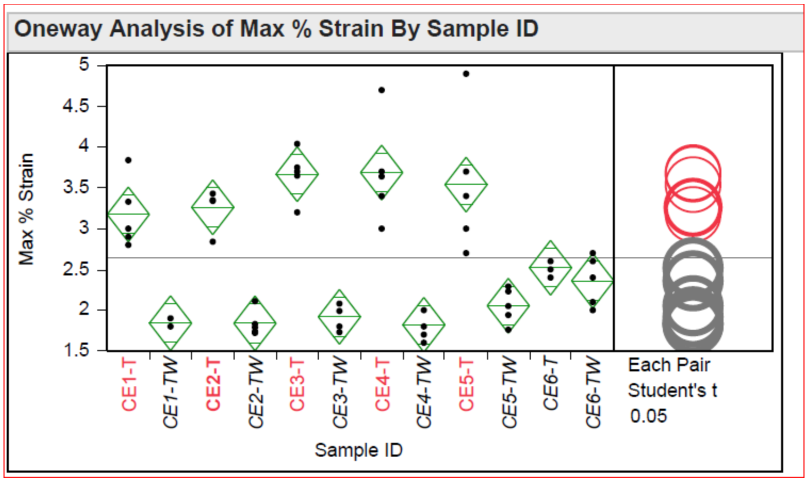


Figure 8: Oneway analysis of max % strain for dry and saturated coupons for all material sets. (T - Transverse) (TW - Transverse Wet)

A comparison between the dry and saturated transverse static results showing the max % strain can be seen in Table 8. The transverse results are in general statistically significant apart from CE6 whish has uni-directional E-glass with some tensile strength in the transverse direction compared to the uni-directional carbon that has no transverse tensile strength.

Table 8: Statistical results of transverse static testing showing max % strain. Green highlighted cells show a P-value less than 5% or statistically significant.

Transverse Static, Max % Strain						
Material Set		Difference	Str Err Dif	Lower CL	Upper CL	p-Value
CE1-TW	CE1-T	1.334	0.236172	0.85915	1.808855	0.0001
CE2-TW	CE2-T	1.424	0.236172	0.94915	1.898855	0.0001
CE3-TW	CE3-T	1.75	0.236172	1.27515	2.224855	0.0001
CE4-TW	CE4-T	1.868	0.236172	1.39315	2.342855	0.0001
CE5-TW	CE5-T	1.486	0.236172	1.01115	1.960855	0.0001
CE6-TW	CE6-T	0.16	0.236172	-0.31485	0.634855	0.5014

c. The one way fit for Comparison of % moisture absorption of the laminate samples after exposure, highlights the significant reduction in moisture of the CE-5 (Polyurethane acrylate) and the CE-6 (VE and E-glass) samples when compared to the carbon fiber containing laminate made with epoxy/hardener resin chemistries. It suggests that either the difference in moisture absorption is associated with the VE resin compared to the epoxy chemistries of CE1-CE4, or that there is a fundamental difference in the moisture absorption characteristics of E-Glass compared to Carbon Fiber.

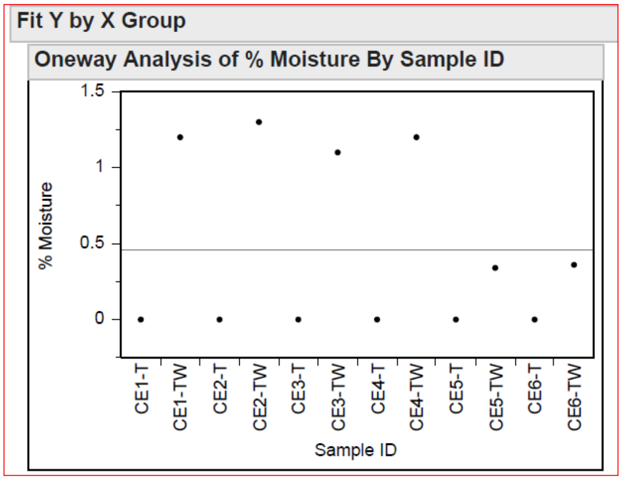


Figure 9: Oneway analysis of % moisture (% weight gain) for dry and saturated coupons for all material sets. (T - Transverse) (TW - Transverse Wet)

d. One way Analysis Max Stress PSI by sample ID – again there is a statistical difference between the performance of the laminate before and after moisture soak. With all but the CE-6 laminate exhibiting a significant reduction in Max Stress after Moisture soak. For the CE-6 laminate the Max Stress is much higher than that for the other laminate (this again relates to the 90° orientation of fiber tow compared to the carbon fiber-based laminate), however, again there is not the same trend of reduction in performance.

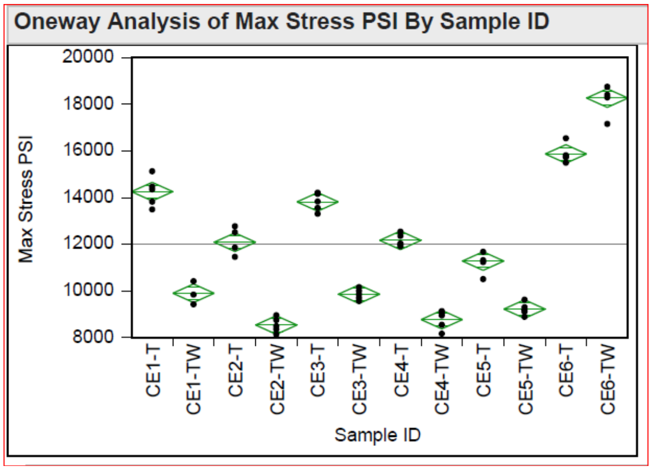


Figure 10: Oneway analysis of max stress (PSI) for dry and saturated coupons for all material sets. (T - Transverse) (TW - Transverse Wet)

Discussion

1. Fundamentally the moisture soak in this accelerated testing induced change to the mechanical behavior of the laminate.
2. The behavior of laminate CE6 made with all E-glass Vs. the laminate made with a combination of E-Glass and Carbon Fiber (dominate reinforcement of these laminate) which exhibited significantly greater loss of properties, may suggest that either the Carbon fiber and its associated coupling agents are more susceptible to moisture ingress and disbonding or that the

fiber itself absorbs moisture and therefore weakens the structural properties of the laminate in the salt water emersion environment.

3. The resin matrix utilized in this study specifically the Polyurethane acrylate laminate manufactured with the identical reinforcement schedule as CE-2 and CE-4 fundamentally reduced the overall moisture uptake of the laminate. The VE resin system laminate with reduced moisture absorption, may have been more influenced by the E-glass (which does not absorb moisture and has a robust coupling interface between the glass and resin) then by the VE resin chemistry.
4. If the stated belief that the diffusion rate of moisture is higher when the composite laminate is under stress, then these static emersion tests do not fully identify the detrimental effects of moisture absorption. It will be important to further explore and understand the influences of:
    a) Resin Chemistry
    b) Reinforcement behavior and absorption characteristics
    c) coupling agent robustness, stability, and compatibility
    d) Laminate Coating (in mold and secondary application) to control moisture ingress, biological growth and mechanical wear and degradation
    e) Mechanical stress induced degradation under sea water

6. Design FMEA

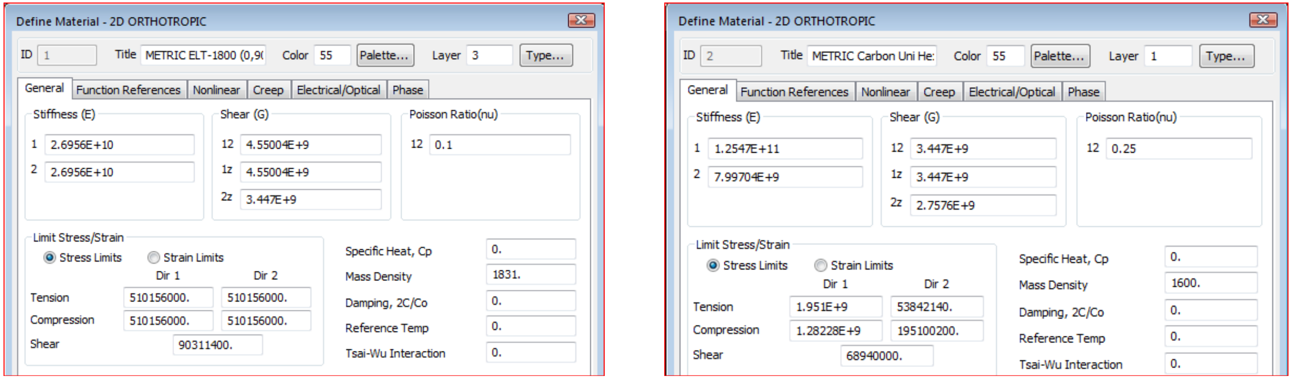
A Design Failure Model and Effects Analysis (FMEA) was created during the turbine design phase to highlight potential failure modes and determine their effect on the design. The turbine design FMEA is given in full in Appendix A.

Upon completion of the first round of coupon testing performed by MSU it was brought to light that fiber disbondment could be on concern. Fiber disbondment occurs when the resin system in a composite material becomes detached from the fibers causing the structure to become compromised. This failure mode would have consequences for the turbine structure. The failure mechanism for fiber disbondment is likely due to water uptake in the resin system causing the resin to swell and pull away form the fibers. This will be further evaluated in future test programs, but an immediate solution would be to use a hydrophobic resin system that resists water uptake.

7. Composite Design

The composite layup was designed by Blusource Energy Inc. and consists of +/- 45 E-Glass interlayered with two layers of unidirectional carbon fiber. The biaxial E-glass transmits shear loads on the foil while the unidirectional carbon adds stiffness to limit deflections and strains.

The material properties and laminate schedule for the FEA model are shown in Figure 5 and Figure 6.



METRIC ELT-1800 (0,90) Fiberglass/Epoxy

Define Material - 2D ORTHOTROPIC

ID 1
Title METRIC ELT-1800 (0,9
Color 55
Layer 3

Stiffness (E)
1 2.6956E+10
2 2.6956E+10

Shear (G)
12 4.55004E+9
1z 4.55004E+9
2z 3.447E+9

Poisson Ratio(nu)
12 0.1

Limit Stress/Strain
● Stress Limits ○ Strain Limits

	Dir 1	Dir 2
Tension	510156000.	510156000.
Compression	510156000.	510156000.
Shear	90311400.	

Specific Heat, Cp 0.
Mass Density 1831.
Damping, 2C/Co 0.
Reference Temp 0.
Tsai-Wu Interaction 0.

METRIC Unidirectional Carbon Uni Hexply 600 34%

Define Material - 2D ORTHOTROPIC

ID 2
Title METRIC Carbon Uni He:
Color 55
Layer 1

Stiffness (E)
1 1.2547E+11
2 7.99704E+9

Shear (G)
12 3.447E+9
1z 3.447E+9
2z 2.7576E+9

Poisson Ratio(nu)
12 0.25

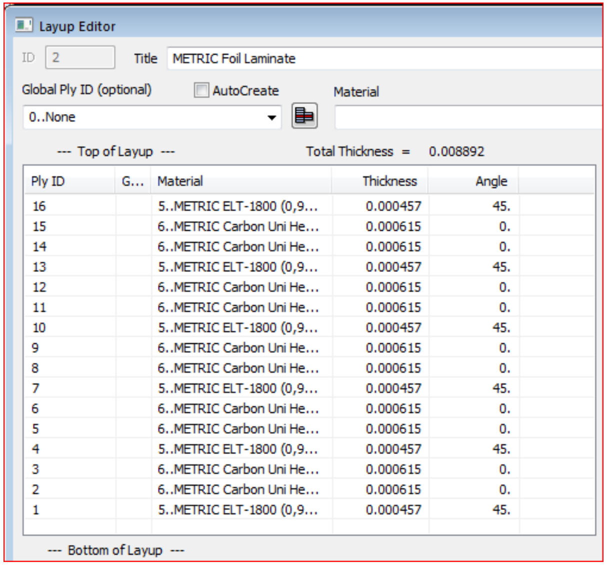
Limit Stress/Strain
● Stress Limits ○ Strain Limits

	Dir 1	Dir 2
Tension	1.951E+9	53842140.
Compression	1.28228E+9	195100200.
Shear	68940000.	

Specific Heat, Cp 0.
Mass Density 1600.
Damping, 2C/Co 0.
Reference Temp 0.
Tsai-Wu Interaction 0.

Figure 11: Composite Material properties for E-Glass and Carbon fiber

Foil Layup @ 8.89mm



ID 2 Title METRIC Foil Laminate
Global Ply ID (optional) 0..None ☐ AutoCreate Material

--- Top of Layup --- Total Thickness = 0.008892

Ply ID	G...	Material	Thickness	Angle
16		5..METRIC ELT-1800 (0,9...	0.000457	45.
15		6..METRIC Carbon Uni He...	0.000615	0.
14		6..METRIC Carbon Uni He...	0.000615	0.
13		5..METRIC ELT-1800 (0,9...	0.000457	45.
12		6..METRIC Carbon Uni He...	0.000615	0.
11		6..METRIC Carbon Uni He...	0.000615	0.
10		5..METRIC ELT-1800 (0,9...	0.000457	45.
9		6..METRIC Carbon Uni He...	0.000615	0.
8		6..METRIC Carbon Uni He...	0.000615	0.
7		5..METRIC ELT-1800 (0,9...	0.000457	45.
6		6..METRIC Carbon Uni He...	0.000615	0.
5		6..METRIC Carbon Uni He...	0.000615	0.
4		5..METRIC ELT-1800 (0,9...	0.000457	45.
3		6..METRIC Carbon Uni He...	0.000615	0.
2		6..METRIC Carbon Uni He...	0.000615	0.
1		5..METRIC ELT-1800 (0,9...	0.000457	45.

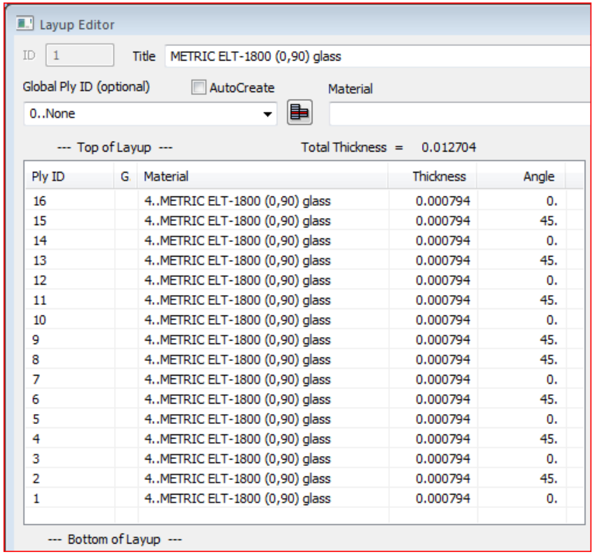
--- Bottom of Layup ---

Laminate Equivalent Properties

16 Plies - Total Thickness = 0.008892

In-Plane Properties
Ex = 9.1317E+10 Ey = 1.1347E+10 Gxy = 6.1624E+9
NUxy = 0.39771 NUyx = 0.0494182
Alphax = -1.3474E-7 Alphay = 7.25038E-6 Alphaxy = 0.
Bending/Flexural Properties
Exb = 8.23E+10 Eyb = 1.2174E+10 Gxyb = 6.87501E+9
NUxyb = 0.4226 NUyxb = 0.0625132
Alphaxb = -1.5425E-7 Alphayb = 5.94709E-6 Alphaxyb = 0.

TriSpoke Laminate @ 12 mm



ID 1 Title METRIC ELT-1800 (0,90) glass
Global Ply ID (optional) 0..None ☐ AutoCreate Material

--- Top of Layup --- Total Thickness = 0.012704

Ply ID	G	Material	Thickness	Angle
16		4..METRIC ELT-1800 (0,90) glass	0.000794	0.
15		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
14		4..METRIC ELT-1800 (0,90) glass	0.000794	0.
13		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
12		4..METRIC ELT-1800 (0,90) glass	0.000794	0.
11		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
10		4..METRIC ELT-1800 (0,90) glass	0.000794	0.
9		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
8		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
7		4..METRIC ELT-1800 (0,90) glass	0.000794	0.
6		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
5		4..METRIC ELT-1800 (0,90) glass	0.000794	0.
4		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
3		4..METRIC ELT-1800 (0,90) glass	0.000794	0.
2		4..METRIC ELT-1800 (0,90) glass	0.000794	45.
1		4..METRIC ELT-1800 (0,90) glass	0.000794	0.

--- Bottom of Layup ---

Laminate Equivalent Properties

16 Plies - Total Thickness = 0.012704

In-Plane Properties
Ex = 2.1528E+10 Ey = 2.1528E+10 Gxy = 8.40138E+9
NUxy = 0.281225 NUyx = 0.281225
Alphax = 0. Alphay = 0. Alphaxy = 0.
Bending/Flexural Properties
Exb = 2.2678E+10 Eyb = 2.2678E+10 Gxyb = 7.67926E+9
NUxyb = 0.242833 NUyxb = 0.242833
Alphaxb = 0. Alphayb = 0. Alphaxyb = 0.

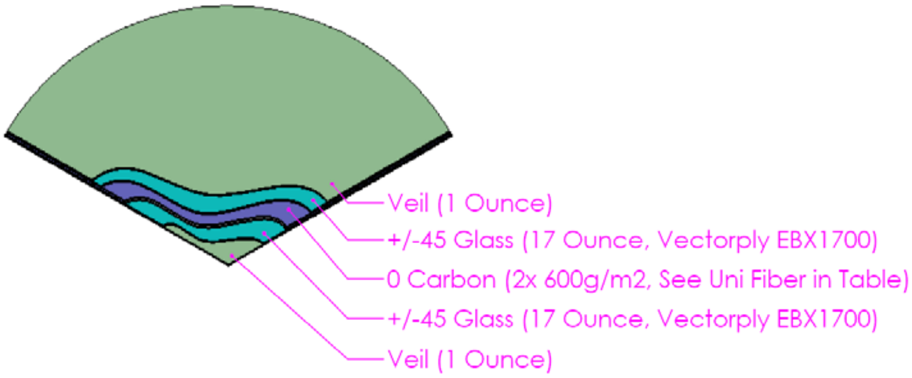


Figure 12: Foil laminate schedule

Dogbone coupons were produced by CERL for testing at MSU, and were thinner than the foil laminate, so they could be tested accurately but still had to be representative. Figure X shows the laminate schedule for the coupons.

8. Process FMEA

A turbine Process FMEA was produced assuming the vacuum infusion process will be used. This FMEA was used to identify areas of concern with the proposed production process and is provided in full in Appendix B. The final PFMEA will be developed in part by the manufacturer with details of their production process.

9. Reliability Models

The turbine reliability model is based on various analyses including, velocity profile distribution, cycle counting, coupon fatigue testing and cumulative fatigue damage model. DNV-GL-ST-0164 section 8.3.3 outlines the cumulative damage model to be used in the design of offshore structures.

ORPC use a program called UTide to calculate the expected current flows at a representative site over the life of a project. This is time consuming and computationally intense, so a generic tidal site was developed. The generic velocity profile's velocity distribution was compared to the velocity distribution of known sites, for both measured and UTide predicted velocity values (Figure 3). These comparisons show the generic tidal site is slightly above the highest measured or predicted site velocity (ie: ultimate limit state velocities) and is also conservative from a complete distribution standpoint, which will result in conservative fatigue load cases.

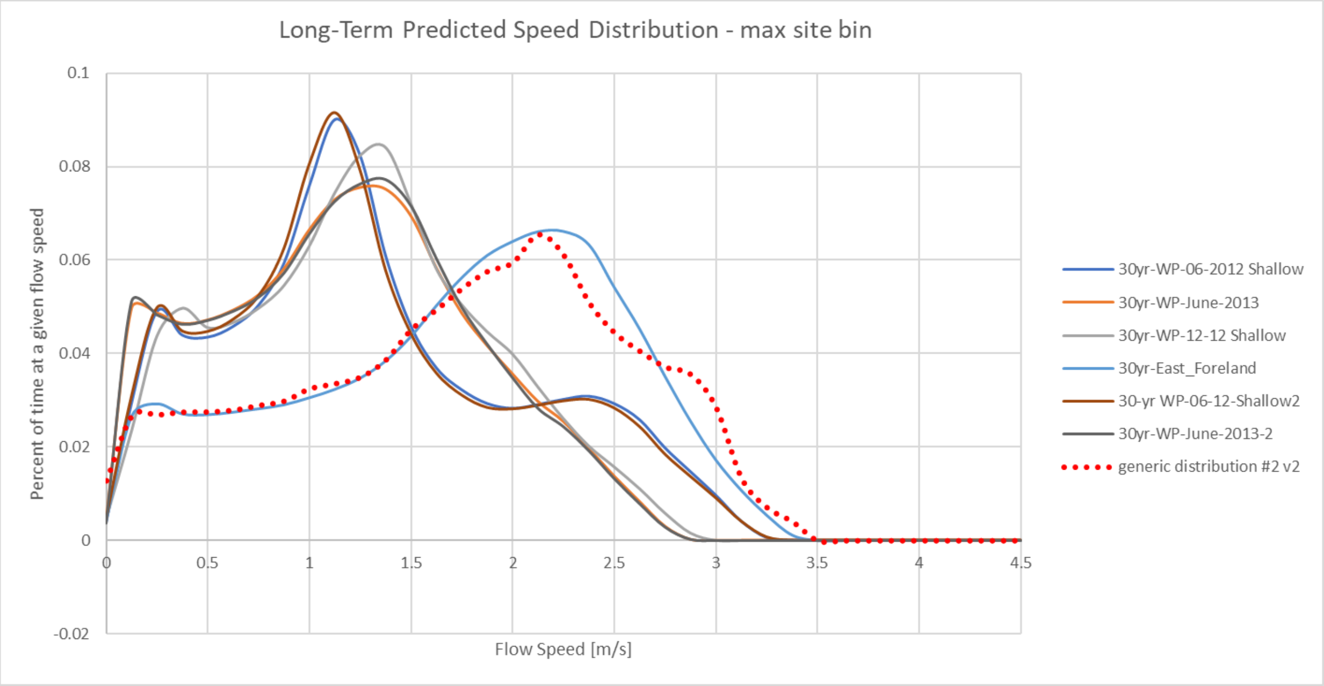


Figure 13: Example: Comparison between long-term UTide predicted site data velocity distribution and the generic profile site distribution (note: the above distribution does not include added turbulence)

Using the characteristic velocity profile along with torque-limited operational considerations and an assumption that 1 hour per day is spent in freewheel (TSR=4.0), the number of predicted rotations at a given TSR and flow speed is determined based on a 20 year life (Figure 19). Note, the freewheel assumption is considered conservative based on the TidGen® 2.0 ability to stall the turbines using both the generator and mechanical brake in the event that a fault leads to a freewheel condition.

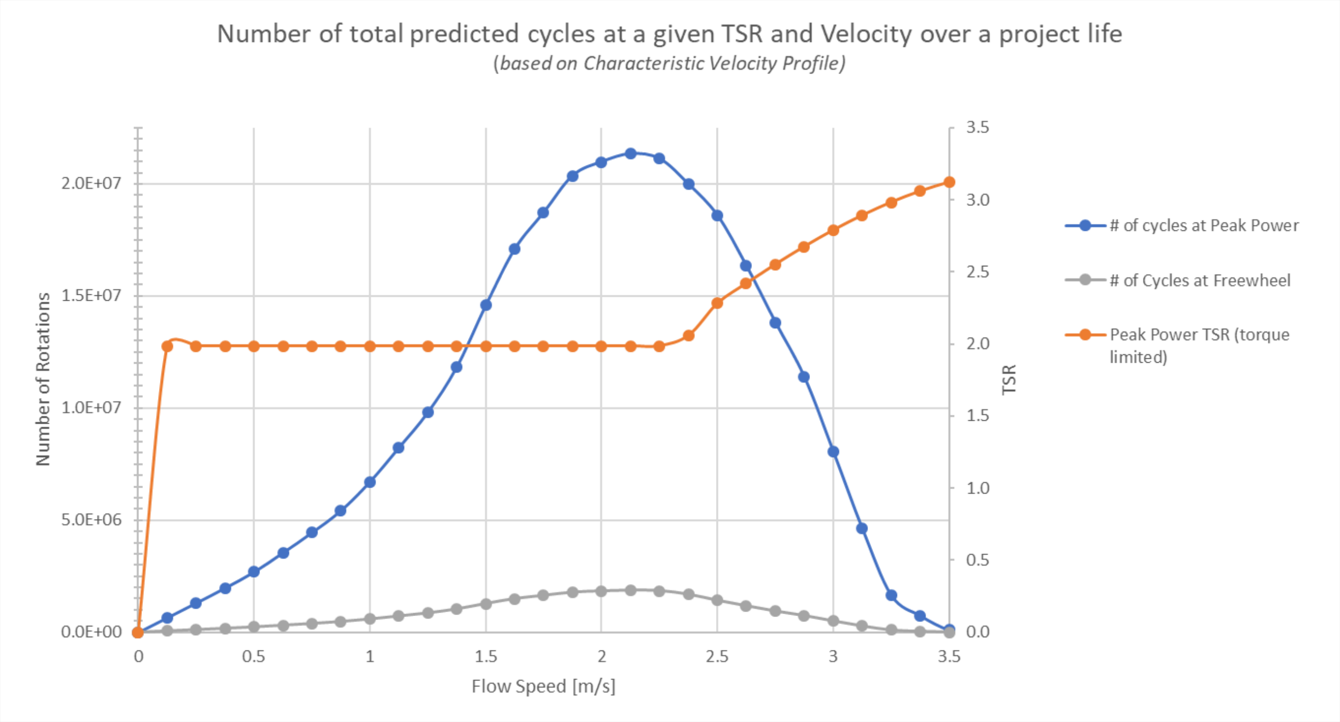
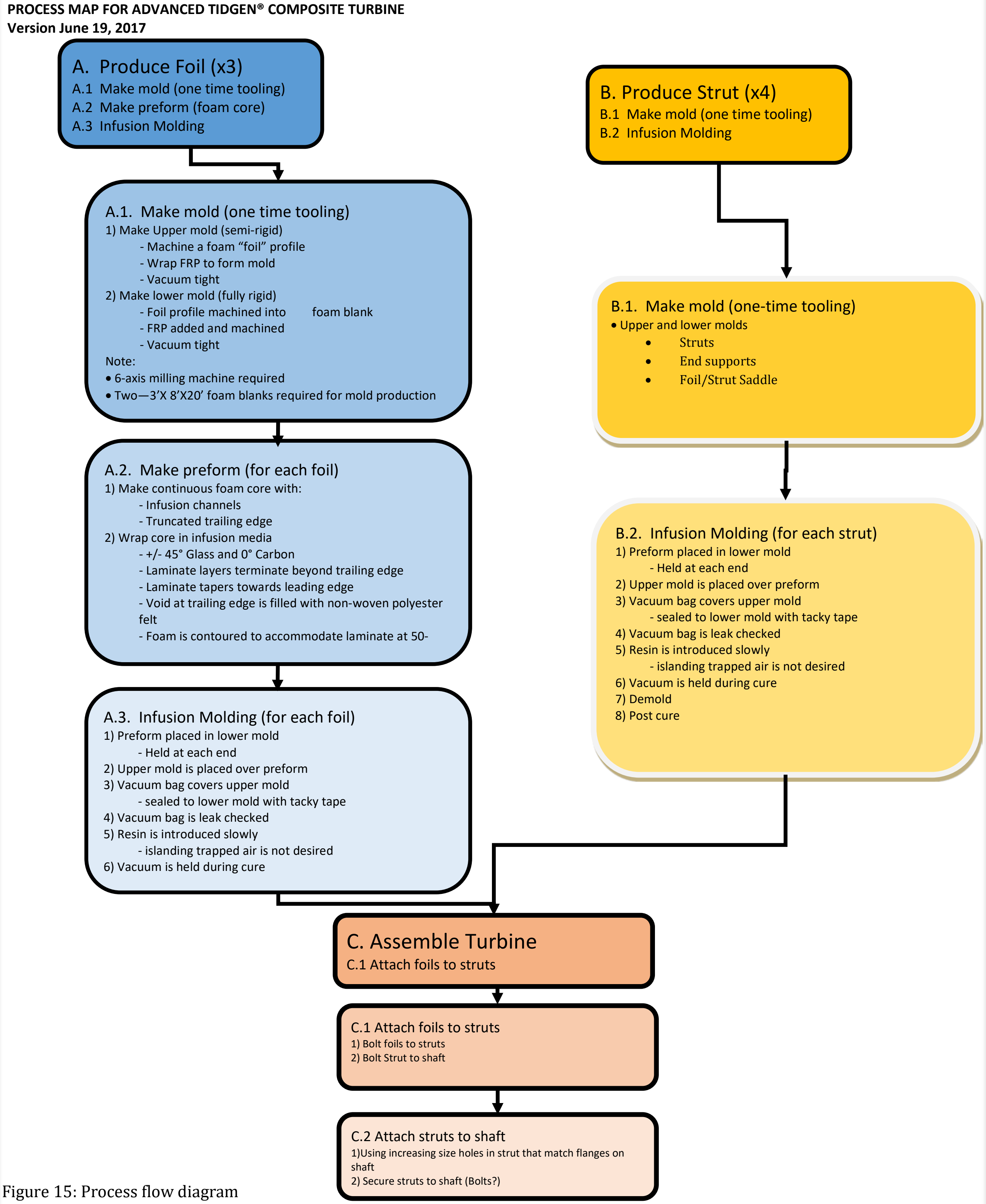


Figure 14: Predicted cycle count at a given TSR and flow speed

With the fatigue cycle count and max strain at multiple loading conditions it is possible to use an S-N curve to calculate cycles to failure and percent damage to estimate the total damage over the project life of 20 years. These models have been created and will continue to be refined but currently the composite coupon fatigue date on hand is not adequate to produce an S-N curve due to gaps in the data. As the characterization program continues these gaps will be closed and a high-quality S-N will be produced for the chosen material set.

10. Production Process Control Plan

To understand the turbine production process a flow diagram was created with input from Blusource Energy Inc. to visually see the required steps in the manufacturing process and pinpoint areas of concern. This diagram can be seen in Figure 5.



PROCESS MAP FOR ADVANCED TIDGEN® COMPOSITE TURBINE
Version June 19, 2017

A. Produce Foil (x3)
A.1 Make mold (one time tooling)
A.2 Make preform (foam core)
A.3 Infusion Molding

A.1. Make mold (one time tooling)
1) Make Upper mold (semi-rigid)
    - Machine a foam "foil" profile
    - Wrap FRP to form mold
    - Vacuum tight
2) Make lower mold (fully rigid)
    - Foil profile machined into foam blank
    - FRP added and machined
    - Vacuum tight
Note:
- 6-axis milling machine required
- Two—3'X 8'X20' foam blanks required for mold production

A.2. Make preform (for each foil)
1) Make continuous foam core with:
    - Infusion channels
    - Truncated trailing edge
2) Wrap core in infusion media
    - +/- 45° Glass and 0° Carbon
    - Laminate layers terminate beyond trailing edge
    - Laminate tapers towards leading edge
    - Void at trailing edge is filled with non-woven polyester felt
    - Foam is contoured to accommodate laminate at 50-

A.3. Infusion Molding (for each foil)
1) Preform placed in lower mold
    - Held at each end
2) Upper mold is placed over preform
3) Vacuum bag covers upper mold
    - sealed to lower mold with tacky tape
4) Vacuum bag is leak checked
5) Resin is introduced slowly
    - islanding trapped air is not desired
6) Vacuum is held during cure

B. Produce Strut (x4)
B.1 Make mold (one time tooling)
B.2 Infusion Molding

B.1. Make mold (one-time tooling)
- Upper and lower molds
    - Struts
    - End supports
    - Foil/Strut Saddle

B.2. Infusion Molding (for each strut)
1) Preform placed in lower mold
    - Held at each end
2) Upper mold is placed over preform
3) Vacuum bag covers upper mold
    - sealed to lower mold with tacky tape
4) Vacuum bag is leak checked
5) Resin is introduced slowly
    - islanding trapped air is not desired
6) Vacuum is held during cure
7) Demold
8) Post cure

C. Assemble Turbine
C.1 Attach foils to struts

C.1 Attach foils to struts
1) Bolt foils to struts
2) Bolt Strut to shaft

C.2 Attach struts to shaft
1)Using increasing size holes in strut that match flanges on shaft
2) Secure struts to shaft (Bolts?)

Figure 15: Process flow diagram

The process control plan will continue to be developed with aid from the chosen turbine manufacturer. The expertise and experience the manufacture can offer in relation to a process control plan will be valuable and will results in a plan that will be executed with excellence.

A detailed Process Control Plan produced in part by CERL can be seen in Appendix C.

As previously discusses, NDI will be utilized to inspect the turbine foils for manufacturing defects using the ultrasonic inspection techniques developed by CERL. The characterization of manufacturing defects will be invaluable when a second inspection using the same techniques is performed after a year of operation. ORPC will be able to see how the known defects propagate over time and help determine what an acceptable defect is. This will lead to cheaper more reliable turbines in the future.

11. Development Plan

The conclusion of Task2 of budget period 1resulted in preliminary composite characterization results. The testing that was carried out on the candidate material sets was information but not conclusive. The FMEAs for process and design are informative and based on assumed production process. Moving forward into Budget Period 2 the obtained information will be leveraged and expanded upon to fully characterize the composite material sets.

ORPC will partner with a composite manufacture and use their experience to refine the current turbine design, material set selection and production process including a process control plan and qualification plan. An area of interest to examine further is the use of adhesives to join components. Adhesives perform well in fatigue compared to bolts, so for a state-of-the-art turbine it is worth pursuing. These novel joints will be tested and compared to analytical models to ensure durability and longevity.

Along with design refinements, additional coupon testing will be required to fully characterize a material set. Tensile testing in longitudinal and transverse direction give insight into the fiber strength, but to understand the composite as a whole, compression, flexural or shear testing is required. This additional testing was outside of the scope of the test program for the MHK database at MSU.

The resin system in a composite is arguably the most crucial element in a composite material. For this reason, to further characterize the failure mechanism for subsea operation further investigation into the resin chemistry will be carried out. Characterization of diffusion rates, moisture absorption and coefficient of thermal and moisture expansion will be investigated.

Finally, a full turbine will be build and tested in a controlled environment off a barge type test platform. This testing will be performed for three main reasons.

1) Characterize the hydrodynamic performance.
2) Determine accurate load profiles from turbine
3) Evaluate turbines durability and ability to handle mechanical and biological environmental loadings.

12. REVISION HISTORY

Revision	Date	Description	Author	Reviewer
00	4/27/2018	Initial	MEB	C. Marnagh

Appendix A

REF #	PBS Component	Design requirement/ functionality impacted	+ -	TYP	SEV	FRQ	DET	RPN	Potential Failure Mode	Effect Description
1	2.1 - Turbine	Structural integrity of joint between blade and torsion web.	-		5	2	4	40	Shear, fatigue.	If one of the joints on the torsion web fails, the load from that blade must be redistributed to other blades through intermediate tie-ins.
2	2.1 - Turbine	Bolted connections between the foils and support rings	-		5	2	4	40	Fatigue failures and potential leak sites for moisture into internal cavities.	Rigidty of overall structure decreased, other blades and joints potentially overloaded.
3	2.1 - Turbine	Manufacturability	-		5	5	3	75	How the composite structure will be manufactured is the primary concern within the design process.	If the ultimate design for the hydrofoil does not consider manufacturability, then the cost, schedule, performance, and others, will suffer.
4	2.1 - Turbine	Structural failure modes- cyclic loading, impact, vibrational, steady operational, 20 yr max loads, or transportation loadings, etc.	-		5	4	4	80	The structure may experience loads that were not accounted for within the design envelope.	Catastrophic failure of structural elements most often occur from loadings outside the designed application. Engineers are very good at designing around standard/typical loads. However, good design principles also account for non-standard loading cases, or at minimum, administratively control the environment to suppress the occurance of non-typical loads.
5	2.1 - Turbine	Impact resistance of structure and coatings	-		4	2	4	32	Can the hydrofoil survive a direct point loading from an impact at any angle? This is both a local and global question.	An impact loading, either from transportation or during operation, both loads the hydrofoil in out-of-plane bending, and locally damages the coating and composite structure.
6	2.1 - Turbine	Designed lifetime	-		4	4	3	48	Premature failure of the system	Completely understanding and identifying the expected lifetime of the system will effect material selection (for moisture uptake calculations) and cycles to failure (for fatigue resistance)
7	2.1 - Turbine	Ply drop inside of airfoil.	-		4	3	2	24	Steep ply drops can create resin rich areas and severe internal stress concentrations leading to composite delaminations.	Delaminations and potential loss of spar cap stiffness/strength.
8	2.1 - Turbine	Hollow cross-section or back-filled	-		4	4	2	32	If joints and seals fail, the internal cavities may become filled with water.	Direct access of water to internal surfaces could significantly alter many things. Such as the mass balance of the rotating hydrofoil, and increased uptake to unprotected internal surfaces.

9	2.1 - Turbine	Structural health or load monitoring	-		4	3	2	24	Monitoring key performance items, or loadings on the structure may indicate when maintenance is required.	Real-time monitoring of the structural health of key components could reduce down-time of the structure without risking ultimate failure of the system
10	2.1 - Turbine	Coatings for biofoulings and moisture barrier	-		3	3	4	36	Buildup of biofouling on hydrofoil could reduce efficiency of the torque generation. The outer coating on the foil could be a diffusion barrier to reduce moisture uptake.	Biofouling -Decreased efficiency of power generation, increased loading on the hydrofoil. Moisture Barrier - Not employing a barrier would not take full advantage of all material systems.
11	2.1 - Turbine	Material selection of composite airfoil	-		3	4	1	12	Moisture absoprtion and resultant degredation.	Loss of strength in hydrofoil.
12	2.1 - Turbine	Stiffness design or strength design	-		3	4	1	12	Will the system be designed to minimize deflection or minimize material/weight?	If the structure is designed to minimize deflection, typically the stresses within the structure remain small and safety factors are large. This design process often has increased cost and weight implications. Strength design reduces the amount of material and thus increase the stresses in the structure. Strength design requires a good estimate of loads the structure must support.
13	2.1 - Turbine	Maintenance and Inspection	-		2	2	2	8	A maintenance and inspection protocol could overcome uncertainty within the design	Periodic maintenance and inspection could overcome some uncertainties within the design; however, this also effects the deployment cost. Poor designs could be overcome with periodic inspection.
14	2.1 - Turbine	Leading edge radius.	-		2	4	4	32	Manufacturing defects. Waves and resin rich areas.	Delaminations starting from the leading edge. Decreased stiffness and strength.
15	2.1 - Turbine	Galvanic corrosion if carbon fibers are utilized	-		2	2	4	16	Salt water, metal and conductive fibers connecting parts	Increased rate of corrosion of structural material and components.

Appendix B

Composites Engineering Research Laboratory

The Maine Composites Alliance

COMPOSITES ENGINEERING RESEARCH LABORATORY

Failure Modes Effects Analysis - Process (PFMEA)

System: ORPC TidGen Foil - Generic Vacuum Infusion Process
Date: 20-Aug-17
Tech: Drew T. Sfirri
Review: Andrew Schoenberg

PFMEA Generated using some assumptions:
1. Foils mfg using Vacuum Infusion Processing.
2. Foils will be made in 2 parts, then bonded together to make the final part.
3. Foils will be infused at or near ambient conditions (25°C - 30°C) using an epoxy resin system.

Process Step	Potential Modes of Failure How did the part fail?	Potential Effects of Failure	SEV	Potential Mechanisms of Failure What caused the part fail?	PROB	Current Design Controls	DET	Risk Priority Number	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	NEW SEV	NEW PROB	NEW DET	NEW RPN
Mold Preparation	Laminate Stuck to Mold	Dmg to part and/or tooling	9	Improper application of release chemisty	1		5	45	Follow vendor specs for release chemistry						
									establish methodology for tooling surface release check such as Tape test.						
			9	Use of imcompatible release chemistry for mold or resin system.	1		6	54	Ensure release chemistry is appropriate for the mold surface. Contact vendor if necessary.						
	Laminate has a porous surface or exposed glass fibers	Part requires repair. If too severe the foil could be rejected.	5	Improper application of tooling release chemistry	4		6	120	Follow vendor specs for release chemistry						
			5	Use of imcompatible release chemistry for mold or resin system.	2		8	80	Ensure release chemistry is appropriate for the mold surface. Contact vendor if necessary.						
			5	Material was laid up before release chemistry cured properly.	2		3	30	Follow vendor specs for release chemistry, allow proper time to cure.						
	Areas of non-wetted fibers	Part requires repairs out of the mold.	6	Mold not properly cleaned, residual contaminate affected infusion.	8		4	192	Develop a method for large surface area cleaning to ensure full coverage.						

									Ensure all mold prep is done with clean cotton rags to prevent contaminating the mold.						
Material Kitting	Areas of non-wetted fibers	Part requires repair out of the mold. If too severe the part could be rejected.	6	Contaminatetion transferred to materials during cutting, measuring, and handling.	8		6	288	Standardize use of PPE for all operators.						
									Ensure work and material storage areas are clean and free of potential contaminates.						
	Manufacture to Design Defect	Part not built to design spec results in a reject.	9	Reinforcement plies not cut to proper dimensions.	2		6	108	create pattern for material kitting.						
									Have material dimensions prominently displayed in work areas.						
									Quality check all cut materials						
			9	Cut reinforcement plies frayed during handling and storage, which can reduce mechanical properties at stress concentrating edges.	2		2	36	Implement a proper storage and handling plan. QC checks should happen before and after material cutting.						
Material Layup	Out of Plane Defect	OoP defects listed as catastrophic by Sandia Nat'l Labs. Severe OoP defects will results in a rejected part.	7	Reinforcement plies buckled during placement creating a ridge that propigated through the rest of the laminate stack during layup.	8		8	448	Add quality checkpoint after each ply is laid into the mold to prevent OoP defect propigation.						
			7	Reinforcement fiber weave does not easily conform to complex foil mold geometry.	2		8	112	Consider a different cloth weave that better conforms to contours.						
									Readdress the ply layup design to better for the mold and reduce potential buckling.						
	In Plane Defects	In Plane Defects listed as potentially catastrophic by Sandia Nat'l Labs. Severe in plane defects could result in a rejected part.	7	Reinforcement fiber linearity gets skewed during placement in the mold.	8		8	448	Add quality checkpoint after each ply is laid into the mold to prevent in plane defects from being built upon.						

Internal Voids	Voids larger than ~3mm in diameter are considered catastrophic.	9	Fiber placement on the leading edge of the mold leaves opportunity for voids, observed in non-deployed foils.	7		9	567	Add special consideration note in process documents, this area of the laminate has high potential for voids.						
								Add additional glass to the leading edge to ensure all gaps between plies get filled.						
Areas of non-wetted fibers	part would require repair out of the mold. If too severe, part could be rejected.	6	Any holes in the vac bag can cause areas of reduced vacuum leading to dry fibers.	1		6	36	Remove sharp objects from work area when vacuum bagging part so as not to accidently poke a hole.						
								Ensure materials are properly stored when not in use.						
								label inventory to avoid using old or sub-par materials.						
Porosity	Large areas of porosity will negatively affect the mechanical properties, result in repair or part rejection.	6	Using too much of an incompatible tack spray can inhibit fiber wet-out.	4		7	168	Use a tack spray that is compatible with the resin chemistry.						
								Consider an alternate means of securing fiber plies in place. Ie.e Tape.						
		6	Part stack not properly de-bulked before infusion.	6		7	252	Standardize a period for stack de-bulk to remove residual air and moisture prior to infusion.						
		6	Leaks in the bag cause air to be pulled in to the part during infusion.	2		5	60	Remove sharp objects from work area when vacuum bagging part so as not to accidently poke a hole.						
								Ensure materials are properly stored when not in use.						
								label inventory to avoid using old or sub-par materials.						

	Manufacture to Design Defect	Part not built to design spec results in a reject.	9	Alternating reinforcement ply schedule did not follow design.	6		6	324	Add quality check after each ply is laid into the mold.						
				Ply fiber orientation did not follow design.	1		2	0	Add quality check after each ply is laid into the mold.						
	Delamination	delamination defects are catastrophic defects that propigate and cause early failure.	8	non-compatible (peel ply or vac bag) material caught between reinforcement plies.	1		6	48	Add quality check after each ply is laid into the mold.						
Infusion	Incomplete Infusion	Results in a rejected part.	9	Improper infusion line placement does not adequately distribute resin to the entire part.	1		2	18	no more than 24" between feed or vacuum lines.						
			9	Resin gel time is too short for large batch mixtures.	1		3	27	Stage resin batch mixtures to accomidate chemistry gel time, allow time to de-gas resin before infusion.						
									Adjust Hardener chemistry if possible to achieve the desired gel time for infusion.						
			9	Loss of vacuum due to bag failure.	1		2	18	Establish a drop-test procedure to determine how well the bag is sealed.						
	Porosity	Part may reqire repair out of the mold. If too severe part could be rejected.	6	Resin was not properly de-gassed prior to infusion.	5		5	150	Establish a method for full resin de-gassing.						
									Use light to check for remaining trapped air within the resin mixture.						
									If gel time allows, slowly mix resin chemistry to avoid whipping air into the mixture.						

			6	Resin feed line pulled air during the infusion.	3		2	36	Clamp the hose to the infusion bucket so that it can't be lifted out of the resin and pull air.						
									Keep observation on the resin bucket so as not to allow the resin level to fall too low and pull air into the part.						
2 - Part Assembly	Delamination	delamination defects are catastrophic defects that propigate and cause early failure.	8	Contaminate present on either of the two bond halves can affect adhesion, resulting in a delamination type defect.	3		6	144	Clean the bond line areas with appropraite solvent in preparation for assembly bonding						
	Internal voids	Air voids reduce the mechanical strength of the bonded parts.	9	Air bubbles trapped between the two bonded halves.	2		8	144	Apply bond paste using an applicator gun (like a caulking gun) to ensure no air is trapped in the bond paste bead.						
			9	Inconsistent bond line thickness	6		6	324	Use a bond line thickness control. I.e glass beads.						
Post Processing	Delamination	delamination defects are catastrophic defects that propigate and cause early failure.	8	Holes drilled through the foil for mounting hardware left delaminations around the holes.	10		4	320	Diamond coated rasp bit and very high RPM are needed to drill holes without causing dmg.						

			8	Contamination present on the surface where mounting bracket is bonded.	2		6	96	Thouroughly clean the bond area with an appropriate solvent to remove contamination.						
	Resin starved surface	Lack of resin on the surface will reduce the protection the reinforcement has from the environment. Would require repair, or could be cause for a rejected foil.	5	Failure to properly post cure the chemistry to maximize cross-linking.	5		9	225	Follow Vendor specs for post curing resin chemistry.						
									Consider using a surface coating to increase environmental protection.						
			5	Material selection issue: Resin chemistry not suitable for sub-sea application.	7		9	315	Readdress the resin chemistry used for this product.						
	Manufacture to design defect	Part not built to design spec results in a reject.	9	Mid-foil mounting bracket incorrectly located	9	Molded "X" located on the spot where mounting bracket should go.	3	243	Use a two person accountability system for post processing steps.						
						Design drawing shows placement of mounting bracket.			Use a two person accountability system for post processing steps.						

Appendix C

Prototype Prelaunch Production Control Plan Number		Key Contact/Phone	Date(Orig)	Date (Rev.)
Part Number/Latest Change Level		Core Team	Customer Eng. Approval/Date	
Part Name/Description		Organization/Plant Approval/Date	Customer Quality Approval/Date (if Req'd)	
Organization/Plant	Organization Code	Other Approval/Date (If Req'd)	Other Approval/Date (If Req'd)	

			Characteristics				Methods						
Part/ Process Number	Process Name/ Operation Description	Machine, Device, Jig, Tools, for Mfg.	No.	Product	Process	CTQ-critical to Qual.	Product/Process Specification/ Tolerance	Evaluation/ Measurement Technique	Size	Freq.	Control Method	Reaction Plan - Out of Compliance Action Plan	OCAP Required? (To be written by mfg'er)
1	Mold Surface Cleaning	TidGen Foil Mold, 2 part; Appropriate Solvent		Mold	Wipe on/Wipe off of appropriate cleaning solvent such as acetone to remove contaminate	Y	No defined tolerance. Properly cleaned surfaces will bond well with standard masking tape.	Tape Test and Visual inspection for foreign debris on mold surface.	every 10 ft. of mold surface	At every cleaning	Standard Operating Procedure; 100% Operator monitored	Cleaning process repeated till mold is clean and passes Tape test	N
1A	Mold Surface Sealing	TidGen Foil Mold, 2 part; Mold Sealant Chemistry		Mold	Wipe on/Wipe off of appropriate sealant chemistry. Apply per vendor specifications to seal pores /cracks in mold surface	Y	No defined tolerance. Sealant should not be used on large damaged areas of the mold. Properly sealed surfaces will have reduced topography of surface scratches and pores.	Visual and physical inspection for mold imperfections.	Entire surface area	prior to mold release	Standard operating Procedure; Operator controlled	If imperfections found, apply second coat of sealant	N
1B	Mold Surface Release	TidGen Foil Mold, 2 part; Mold Release Chemistry		Mold	Wipe on/Wipe off of appropriate release chemistry. Apply per vendor specification to prevent part sticking to mold	Y	Process should be limited to $<9ft^2$ when applying release chemistry. Control of application is critical for infusion success.	Tape Test. A properly released surface will resist bonding with standard masking tape.	every 9 ft.^{2} of mold surface	prior to release of mold to production	Standard Operating Procedure; 100% Operator monitored	If mold does not pass tape test, release re-applied until mold passes tape inspection	N
2	Material Kitting	Reinforcement material, VIP consumable materials, Scissors, Tape Measurer.		Reinforcement schedule / Processing materials	Reinforcement and consumable materials cut to proper dimensions.	Y	Refer to design drawing for dimensional tolerances as well as ply schedule.	Operator monitered using tape measurer / templates.	Entire surface area	All plies cut	Standard Operating Procedure w/ material templates; 100% Operator monitored	STOP. Consult mfg supervisor or engineer for disposition of materials.	Y
3	Infusion Layup	Kitted Reinforcement Materials, TidGen Foil Mold.		VIP schedule in mold.	Hand placement of the reinforcement plies following the laminate schedule in the design drawings	Y	Refer to design drawing for placement tolerances.	Visual Inspection	Entire surface area	Every ply	Standard Operating Procedure w/ placement references; 100% Operator monitored	STOP. Consult mfg supervisor or engineer for disposition of materials.	Y
		Kitted Consumable materials, TidGen Foil Mold		Consumable schedule in mold	Hand placement of VIP consumables placed following SOP.	Y	Refer to Standard Operating Procedure for proper consumables placements.	Visual Inspection	entire surface area	Every ply/component	Standard Operating Procedure; 100% Operator Monitored	STOP. Consult mfg supervisor or engineer for disposition of materials.	Y
4	Vacuum Bagging	TidGen Foil Mold, 2 part; reinforcement and consumable materials laid up.		Foil part ready for infusion.	Apply vacuum bagging with appropriate pleating and accessories such that the bag conforms to the part without excessive bridging.	Y	Consult design drawings if pleat placement has been pre-determined. Fittings for hoses and lines are predetermined in SOP	Vacuum Gage Drop Test, no more than 5 inHg/10 minutes.	All	Every bag	Standard Operating Procedure; Drop Test	Carefully inspect each pleat and corner of the bag for leaks. If no leaks can be found/sealed and drop test still fails, STOP. Consult mfg suporvisor or engineer for disposition of materials.	Y

5	Resin Mixing	Scale; Mixing apparatus.		Initiated Resin Chemistry	Weigh and mix resin chemistry with appropriate additives at proper ratios. (inhibitor,promoter, initiator or hardener) for specified time and degassing	Y	Refer to resin vendor spec for proper mix ratios. Refer to SOP for mix time and degassing process	Scale weighing, verify calibration using known weights. Degassing for set time	All	Every mix	Standard Operating Procedure with formula template for proper ratio mix; Calibrated Weight measurements.	If resin mixed incorrectly, STOP do not infuse. Consult mfg suprvisor or engineer for disposition of materials.	Y
6	Resin Infusion	TidGen Foil Mold; Vacuum Pump; Initiated Resin; Thermocouple		Infused TidGen Foil part.	Saturate the reinforcement schedule with liquid resin to and predetermined Resin : Reinforcement ratio to create a hardened TidGen foil once cured.	Y	1 atm of pressure for VIP; consult resin vendor spec for expected infusion geltimes to ensure adequate wet-out time.	Exotherm Temp Measurement, Physical inspection for hardness of chemistry.	Random checks across entire part surface area	all parts	Calibrated Thermocouple Measurements	STOP. Consult mfg supervisor or engineer for disposition of materials.	Y
7	In Mold Cure	TidGen Foil Mold; Infusion part; Timing device; Thermocouples		Infused TidGen Foil part.	Monitor the ambient and part temperatures as well as elapsed time from mix to determine when part has undergone required cure.	Y	Refer to resin vendor spec for gelation times and temperature. This step can vary greatly between ambient and elevated cure system, and is important in understanding how cure is developed via temperature and time.	Time and temperature measurements using calibrated TC	Random checks across entire part surface area	all parts	Time device; Calibrated Thermocouple; Physical inspection	If part does not attain desired cure specified behavior -STOP -do NOT demold. Consult mfg suporvisor or engineer for disposition of materials	Y
8	Demolding	TidGen Foil Mold; Infused Part		TidGen Foil part in mold	Strip away VIP consumable materials from infused part.	Y	Refer to Standard Operating Procedure for consumables removal.	Visual inspection	entire surface area	all parts	Standard Operating Procedure; 100% Operator monitored	If unable to remove consumable materials from areas where secondary bonding is required, Consult the mfg supervisor or engineer for disposition of materials.	Y
		TidGen Foil Mold; Infused Part; Barcol Tester		TidGen Foil	Remove foil part from mold.	Y	Foil must pass ASTM D2583 spec for Barcol Hardness prior to removing part from mold. The dwell time of typically 24 hours is the in mold cure time	Barcol Hardness Test ASTM D2583	29 samples, random placement	Every foil part	Industry Std. Barcol Hardness ASTM D2583; Standard Operating Procedure	STOP. Do not attempt to remove mold until Barcol hardness passes specified level. Consult engineer for disposition	Y
9	2 Part Assembly	TidGen Foil parts; Assembly jig, UT		Assembled TidGen Foil	Bonding the two halves of the foil to combine the final part. Care needs to be taken to ensure the parts align correctly, and bond line consistent across part	Y	Refer to design drawing for bondline tolerances. Process would use an assembly jig or other method for alignment and bondline control measures.	Bondline thickness measurement, UT Bondline for gaps/voids.	entire bond line interface	All	Standard Operating Procedure; Calibrated Ultrasonic testing instrument.	STOP. Consult mfg suporvisor or engineer for disposition of materials.	Y
10	Finish Processing	Assembled TidGen foil part, UT, micrometer		Finished TidGen Foil	Drill hardware mounting holes, locate mid-foil mounting bracket for foil support structure.	Y	Refer to design drawing for hardware hole diameters and locations. Mid-Foil mounting bracket must be placed within carbon mount patch.	UT inspection of drilled holes to check for microcracking caused by drilling.	All holes drilled.	All parts	Standard Operating Procedure; Calibrated Ultrasonic testing instrument, micrometer measurements	STOP. Consult mfg suporvisor or engineer for disposition of materials.	Y