Final Report to

Qualification of FFRP for 10000 ft WD
Project 10121-4402-02.FINAL

April 05, 2016

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ACKNOWLEDGEMENTS

The authors wish to thank the following for their support and contributions to the Project. This project and the progress made to date could not have been possible without them.

- DEEPFLEX
  - Board of Directors and Investors
  - Houston Management Team, Engineering Team and Support Staff
  - Manitowoc Manufacturing Team
  - Amir Salimi – Phase 1 Lead Project Engineer, Phase 2A Principal Investigator
  - Bill Berry – Project Administrator

- RPSEA
  - James Pappas – President
  - Bill Head – Project Manager
  - Program Advisory Committee
  - Technical Advisory Committee
  - RPSEA Staff

- DOE/NETL
  - Richard Baker – Project Manager

- TOTAL USA – Project Champion
  - Khalid Mateen – VP Engineering and Technology – TOTAL USA
  - Herve DeNaurois – Deep Offshore Technology Manager – TOTAL USA
  - Mayela Rivero – Deep Offshore Technology Manager – TOTAL USA
  - Jean-Philippe Roques – Risers, Flexibles and Umbilicals Specialist

- SHELL – Cost share participant for Phase 1
  - Nicole Liu – Riser Specialist

- BG GROUP – Cost share participant for Phase 1

- STATOIL – Cost share participant for Phase 1

- ETA – DeepFlex Subcontractor

- WOODGROUPKENNY – DeepFlex Subcontractor

- DNV – DeepFlex Subcontractor

- SOUTHWEST RESEARCH INSTITUTE – DeepFlex Subcontractor

ABSTRACT

Research Objectives

The objective of this program is to develop a novel hybrid (composite/metal) unbonded flexible ultradeepwater riser which meets the following oil & gas industry requirements:

- 10,000 foot (3048m) water depth
- 10,000 psi (690 barg) design pressure
- 7 inch internal diameter
- 120 °C design temperature
- 25 year field life
- Sour gas capability

The top tension reduction offered by flexible fiber-reinforced pipe (FFRP®) enables light weight and small footprint installation vessels and production platforms. FFRP enables installation vessels and floating production systems which previously had water depth limits of 3300 - 6600 ft to be used in ultra-deepwater of up to 10,000 ft. This greatly expands the number of existing installation vessels and FPSO's that can be used in ultra-deepwater, substantially reducing overall project cost and risk.

Approach

This project is to develop, and qualify, FFRP for ultra-deepwater applications in the Gulf of Mexico. FFRP is unbonded flexible pipe with composite reinforcement layers which have the advantages of light weight, high flexibility and corrosion resistance. Due to these advantages, a simple, low top tension riser configuration is enabled. The initial design basis, is a 7-inch ID, 10,000 psi design pressure, 120°C design temperature, 3,048 meter design water depth production riser application. The Phase 1 Engineering Study confirmed the FFRP riser and riser system design to be employed in the subsequent phases. In Phase 2A, key aspects of the new technology being introduced in the product were tested. In Phase 2B, a prototype pipe was to be manufactured and qualification testing conducted in accordance with API RP 17B.

Accomplishments

Phase 1, the Engineering Study was completed with the following reports documenting the work submitted to RPSEA: Design Premise, Design Report, Failure Mode Effects and Criticality Analysis (FMECA), Manufacturing, Qualification, and Field Development Plans. Phase 2A, including material and layer qualification tests, and the manufacture and test of a pre-prototype was also successfully completed. Unfortunately, the project was halted after Phase 2B started, due to lack of capital investment needed to complete the manufacturing facility.

Significant Findings

In Phase 1, a feasible FFRP design which meets the project design premise requirements was developed. A comprehensive FMECA and qualification plan was completed to define a clear qualification path which addresses all known potential failure modes and mechanisms. The governing standards API 17J, API 17B, DNV OS-C501 were applied in the design phase, and DNV RP-A203 and API 17B qualification testing guidelines were utilized to develop the qualification plan.

In Phase 2A, the successful material and layer qualification tests and full scale burst and failure tension tests on the pre-prototype pipe proved out key aspects of the design.

The API 17N Technology Readiness Level of FFRP was increased from 1 to 3 over the course of the project.

1.0 EXECUTIVE SUMMARY

This project is to develop, qualify, and field deploy flexible fiber reinforced pipe (FFRP) for ultra-deep water applications in the Gulf of Mexico. FFRP is unbonded flexible pipe with composite reinforcement layers which have the advantages of light weight, high flexibility and corrosion resistance. Due to these advantages, a simple, low top tension riser configuration is enabled. The approximately 50% top tension reduction offered by FFRP enables installation vessels and floating production systems which previously had water depth limits of 3,000 to 5,000 ft to be used in ultra-deep water of up to 10,000 ft. This greatly expands the number of existing installation vessels and FPSO's that can be used in ultradeepwater, substantially reducing overall project cost and risk. The design basis is a 7-inch ID, 10,000 psi design pressure, 120°C design temperature, 10,000 foot design water depth production riser application.

The Project was scoped to be performed in three phases [1-3]:

- Phase 1 – Engineering Study
- Phase 2 – Prototype Manufacturing and Qualification Testing
- Phase 3 – Field Deployment Supply

The Phase 1 Engineering Study confirms the product and system design to be employed in the subsequent phases. Subject to approval via a Phase 1 decision stage gate, in Phase 2, a prototype pipe was to be manufactured and qualification testing conducted in accordance with API 17B recommendations. With successful testing, and subject to approval via a Phase 2 decision stage gate, Phase 3 was to be an actual field deployment of the riser system with 6 months of performance monitoring.

The project went as planned in the initial proposal through completion of Phase 1. Table 1-1 provides the project history and deviations from the proposed scope agreed with DOE/NETL/RPSEA, the RPSEA Technical Advisory Committee (TAC), and the Working Project Group (WPG) over the course of the project.

Table 1-1 Project 10121-4402-02 Key Milestones

Date	Project Activities
April 2011	RPSEA request for proposal issued [1]
June 2011	DeepFlex proposal submitted to RPSEA [2]
Oct 2012	Project awarded to DeepFlex. Subcontract issued [3]. Phase 1 kick-off
Sept – Nov 2013	Phase 1 completed. As DeepFlex did not yet have the manufacturing capability to build the Phase 2 prototype, Phase 2 was split into Phase 2A to qualify the new technology, and Phase 2B to build the full scale prototype and qualify the FFRP design and construction with API 17B tests. The split of Phase 2 into Phase 2A and 2B was agreed by RPSEA and the WPG, but was not a formal subcontract modification.
Nov 2013	Phase 2A started
Dec 2014 – Feb 2015	Phase 2A completed and Phase 2B started. WPG advised that a field trial was potentially not going to be feasible prior to the Sept. 30, 2016 RPSEA sunset date.
Mar 2015	Due to market conditions, capital investment in completing facilities necessary to build the Phase 2B prototype were put on hold.
May 2015	DeepFlex suspended all operations
June 2015	DeepFlex recommenced operations. Based on the proposal presented by DeepFlex at the June 9, 2015 RPSEA UDW TAC meeting, DOE/NETL/RPSEA agreed for DeepFlex to prepare a recovery plan in the form of a modification to the project scope of work. Work on Phase 2B engineering activities re-started. The Phase 3 scope was removed from the project.
July – Aug 2015	DeepFlex modification to the project scope of work, including the detailed narrative schedule and budget completed and submitted to DOE/NETL/RPSEA.
Oct 2015	DOE/NETL provided DeepFlex with a draft Modification 03 (never executed) to the Subcontract [4]. DeepFlex unable to secure capital investment necessary to proceed with Phase 2B pipe sample manufacture. Project closed and this final report prepared.

Thus, this report presents a summary of the work conducted in Phase 1 and Phase 2A and the work completed on Phase 2B through October 2015. Although DeepFlex was unable to produce and test the Phase 2B full scale prototype, the extensive work conducted proved out key aspects of the FFRP pipe and riser system, and in cooperation with our WPG and Subcontractors made a substantial contribution towards accelerating the commercial application of composite armor in unbonded flexible pipe with composite armor layers. The API 17N Technology Readiness Level of FFRP was increased from 1 to 3.

Table 1-2 presents the project tasks by phase, as presented in the latest RPSEA approved Project Management Plan [5].

Table 1-2 Project 10121-4402-02 Tasks by Phase

Task No.	Description	Phase 1	Phase 2A	Phase 2B
1	Project Management Plan	X	X	X
2	Technology Status Assessment	X		
3	Technology Transfer	X	X	X
4	Other Reports and Special Items	X	X	X
5	Design Premise	X		
6	Design, Engineering & Analysis of the FFRP Structure	X		
7	Failure Mode, Effects and Criticality Analysis (FMECA)	X		
8	Manufacturing Documentation for Phase 2 Prototype	X		
9	Phase 2 Qualification Test Plan	X		
10	Field Development Cost Estimates	X		
11	Proposal for Phase 2	X		
12	Composite Material Qualification Extension	X	X	X
13	Gap Spanning Test		X	
14	Wear Test		X	
15	Permeation Test		X	X
16	Phase 2A Prototype Manufacture and Tests		X	
17	Carcass and Liner Test		X	
18	Pipe Sample Manufacture			X
19	Phase 2B Full Scale Prototype Testing (Static)			X
20	Prototype Testing – Dynamic Fatigue Test			X
21	Prototype Testing – Thermal Cycling			X
22	Prototype Testing – Bending with External Pressure/Curved Collapse			X
23	Phase 3 Proposal			X

2.0 PHASE 1 – Engineering Study

The purpose of Phase 1 is to complete the Engineering activities to develop and verify the FFRP riser structure and riser system, and prepare the documentation for manufacture and deployment of the riser in a field application. A description of the work to be conducted and summary of results for each task follows.

Tasks 1 through 4 are common to all RPSEA projects, therefore in what follows, only the scope of work and summary of work completed for technical Tasks 5 through 11 are presented. Final reports presenting the work conducted under Tasks 1-3 and 5-10 are completed and have been submitted to RPSEA [5-13]. Task reports were submitted to the RPSEA WPG as drafts for review. Comments that were received from the WPG and were incorporated into the final reports.

2.1 Task 3.0 - Technology Transfer

References [14-16] are the technical papers that were published and presented at Conferences under the Technology Transfer Task. In addition, DeepFlex made presentations at each RPSEA UDW Conference and UDW TAC meeting. These presentations are available at www.rpsea.org.

2.2 Task 5.0 – Design Premise

Scope of work:

The Subcontractor shall prepare a design premise, presenting functional and design requirements that the FFRP must satisfy for the project. The design premise confirms a common understanding and agreement between the purchaser and manufacturer of the functional requirements in accordance with Section 5 and Annex A of API 17J. The data and load cases defined in the design premise shall form the basis for the work to be conducted in Task 6.0. The RPSEA working committee will agree upon and provide the parameters for a typical ultra-deep water project, including Gulf of Mexico lease location, host FPSO, installation vessel and scenario assuming Phase 3 field deployment. The Subcontractor shall prepare the Design Premise document and submit it to the RPSEA working committee for review and approval.

Summary of work completed:

The design premise document [8] contains the target design parameters for the engineering study as summarized in Table 2-1. The design premise confirms a common understanding and agreement between the purchaser (represented by the RPSEA WPG) and manufacturer (DeepFlex, Inc.) of the functional requirements in accordance with Section 5 and Annex A of Reference [17]. Any change in the design premise requires verification of functional and design requirements of particular field and installation against the current riser system capabilities. The document also presents a summary of the design methodology, design data and design criteria that are used to design the pipe and end fittings. Metocean and vessel data included in this document are used during the design phase to determine the system configuration, the need for auxiliary equipment, and perform dynamic analysis to confirm the suitability of the configuration.

Table 2-1 Project Design Parameters

Parameter	Value
Internal Diameter	7-inch
Design Pressure	690 barg
Design Temperature	120 °C
Maximum Operating Temperature	110 °C
Design Water Depth	10000 ft (3048 m)
Internal Fluid	Sour Multiphase Production Materials which are suitable for sour service applications will be specified.
Location	Gulf of Mexico
Vessel	Disconnectable turret moored FPSO
Service Life	25 years

Some of the other important information collected in the design premise document includes project requirements such as internal fluid and external environment parameters, system requirements such as vessel data and mooring layout, design and analysis requirements such as allowable utilization factors, load cases and end fitting design requirements.

2.3 Task 6.0 – Design Engineering & Analysis of the FFRP Structure

Scope of Work:

The Subcontractor shall conduct the analyses to confirm the design of the FFRP pipe structure and riser configuration. The work shall be conducted in accordance with API 17B [17], Section 5.3.2 and Figure 11. This task is divided into six subtasks as described in the following subsections, which also present a summary of the work completed for each subtask. The design report [2] includes all FFRP design work conducted under this task.

2.3.1 SubTask 6.1 – Materials Selection and Cross Section Design

The Subcontractor shall prepare an initial layer by layer material selection and structure design. The layer stress analysis shall be conducted based on load cases identified in the design premise to verify that allowable utilization values are not exceeded based on design requirements per the governing standards API 17J [17], API 17B [18] and DNV OS-C501 [19].
The pipe structure was designed using DeepFlex software PipeDesigner. The cross section of the pipe is shown in Figure 2-1 and the description of layers along with the utilized materials is summarized in Table 2-2. Figure 2-2 is the pipe datasheet generated by PipeDesigner.

The FFRP pipe structure has some unique and innovative attributes for optimizing weight, performance and cost:

- The pipe is a hybrid structure, with metallic and composite reinforcement layers, using appropriate materials and design based on the layer functions.
- To minimize the weight of the metallic layers, the design employs an anti-collapse sheath (E1 Membrane), which enables the combined ring strength and stiffness of both the Carcass (R0) and Hoop Layer 1 (R1) to resist hydrostatic pressure.
- The pressure armor is a patent pending hybrid design, with the composite hoop layer (R2) providing external support to the metallic hoop layer (R1).
- As shown in Figure 2-1, the pipe wall has both an inner and outer annulus. Permeated gases from the bore are vented to the topside end fitting via the inner annulus helical flow path. This design attribute allows the R1 layer to provide both internal and external pressure structural capacity.
- The outer annulus is designed to be flooded with seawater. This design attribute allows design based on differential rather than absolute pressure across the E1 membrane layer. Furthermore, as permeated gases are vented from the inner annulus, the composite armor will be in a seawater environment, rather than in contact with condensed permeated gases.

The design report [9] includes the detailed description of each layer materials, function and design.

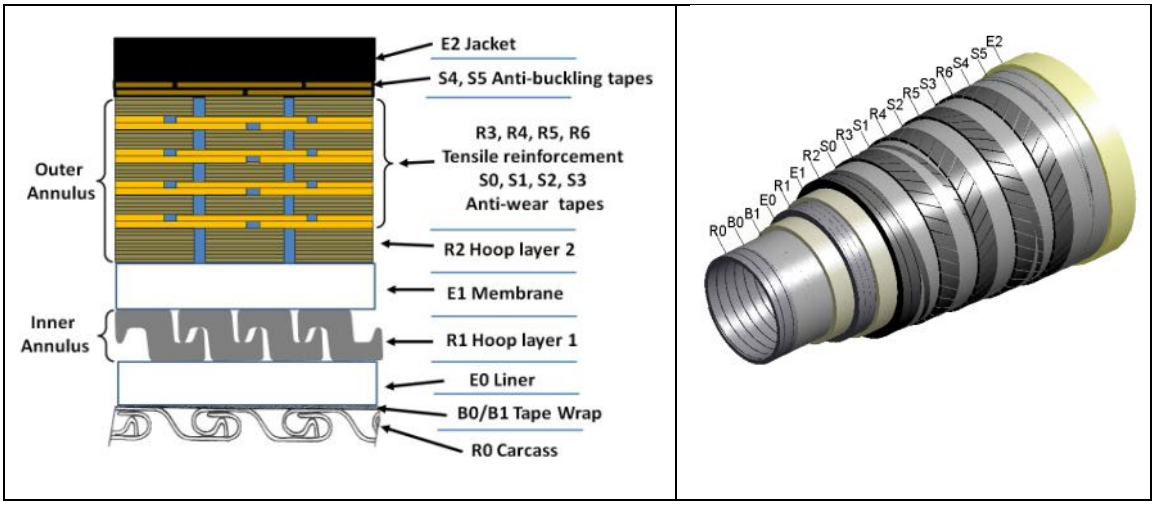


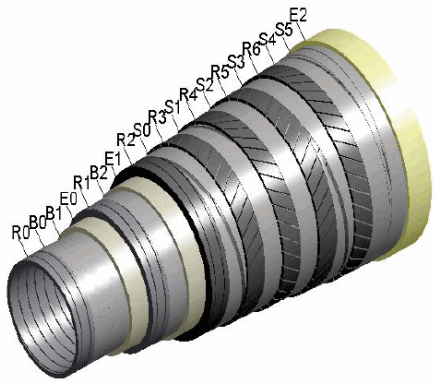
Figure 2-1 Pipe Cross section design

PIPE DATA SHEET

Design Status: Pre-production Release (Draft)

Customer	RPSEA		DeepFlex Project No.	A0015	
Inner Diameter	177.8 mm	7.00 in	Pipe Design No.	7.0-25K0-7D6-03057-D	
Design Pressure	68.9 MPa	10000 psi	Design Water Depth	3048 m	10000 ft
Design Temperature	0 - 120 °C	32 - 248 °F	System Description	Riser	
Operational Pressure	68.9 MPa	10000 psi	Application Definition	Dynamic	
Operational Temperature	0 - 110 °C	32 - 230 °F	Conveyed Fluid	Production fluid, Sour	

Layer		Layer Material
R0	Carcass Reinforcement	Duplex 2205
E0	PVDF	PVDF Solef 60512/0000
R1	Pressure Armor	Carbon Steel, Sour Service,110ksi
E1	Membrane	PVDF Solef 60512/0000
R2	Burst Reinforcement	Type 2B Reinforcement Material
S0	Anti-Wear	PVDF Solef 60512/0550 (AW)
R3	Tensile Reinforcement	Type 2A Reinforcement Material/Type 2AD Reinforcement Material
S1	Anti-Wear	PVDF Solef 60512/0550 (AW)
R4	Tensile Reinforcement	Type 2A Reinforcement Material/Type 2AD Reinforcement Material
S2	Anti-Wear	PVDF Solef 60512/0550 (AW)
R5	Tensile Reinforcement	Type 2A Reinforcement Material/Type 2AD Reinforcement Material
S3	Anti-Wear	PVDF Solef 60512/0550 (AW)
R6	Tensile Reinforcement	Type 2A Reinforcement Material/Type 2AD Reinforcement Material
S4	Anti-birdcaging Reinforcement	Type 1 Anti-Buckling Tape
S5	Anti-birdcaging Reinforcement	Type 1 Anti-Buckling Tape
E2	PA11 Jacket	PA-11 Rilsan Besno P40TLX yellow



Property	Metric	Imperial	Property	Metric	Imperial
Outer Diameter	361.1 mm	14.22 in.	Internal Volume (@ID)	26.60 l/m	0.29 ft³/ft
Weight in air empty	173.15 kg/m	116.35 lb/ft	External Volume (@OD)	102.40 l/m	1.10 ft³/ft
Weight in seawater empty	68.14 kg/m	45.79 lb/ft	S.G. in seawater empty	1.65	
Weight in air full of seawater	200.43 kg/m	134.69 lb/ft	S.G. in seawater full of seawater	1.91	
Weight in seawater full of seawater	95.42 kg/m	64.12 lb/ft	Minimum Storage bend radius	2460 mm	97 in.
Factory Acceptance Test pressure	103.42 MPa	15000 psi	Minimum Operating bend radius	3691 mm	145 in.
Burst pressure	129.32 MPa	18756 psi	Burst / Design Ratio	1.9	
Collapse Pressure	65.52 MPa	9503 psi	Collapse Depth	6518.2 m	21384.8 ft
Bending stiffness	172.2 kN m²	417 kips ft²	Collapse / Design Ratio	2.1	
Axial Failure tension	12865.3 kN	2892.2 kips	Axial Failure compression	2323.6 kN	522.4 kips
Axial tension stiffness	967.3 MN	217447.8 kips	Axial compression stiffness	299.3 MN	67293.5 kips
Torsional stiffness (stiff direction)	14591.6 kNm²/deg	35309.0 kip.ft²/deg	Torsional stiffness (limp direction)	11739.8 kNm²/deg	28408.1 kip.ft²/deg
Overall heat transfer coefficient @ ID	7.02 W/m²K	1.24 Btu/hrft²°F	Thermal Exchange Coefficient	3.92 W/mK	2.26 Btu/hrft°F

Data is for information only, all properties are given at 23 °C in air. Refer to the Project Design Report for properties required per API 17J Section 8.4.

Note:

Pipe Designed By: Jing Liu Approved By: Date: 4/2/2015

Design Software: DeepFlex Pipe Designer Production 2014 v1. Database : DeepFlexSQLNew

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Figure 2-2 Pipe Datasheet

Table 2-2 FFRP Layer Description with Industry Equivalent and Material

FFRP Layer	Structure & Function	Material
R0 Carcass Reinforcement	Interlocked metallic layer that prevents collapse of the liner or pipe due to pipe decompression, external pressure, tensile armour pressure, and mechanical crushing loads	Duplex 2205
B0, B1	Prevent the formation of crack initiation sites in liner at carcass gaps	Polyester film, glass fiber reinforced tape (subject to change based on trials and tests)
E0 Liner	Extruded polymer layer that ensures internal fluid integrity.	Solef PVDF 60512/0000
R1 Hoop Layer 1	Interlocked metallic layer that provides the primary hoop strength of the pipe to resist internal pressure as well as the external hydrostatic collapse and crushing loads.	Carbon Steel, Sour Service
E1 Membrane	Extruded polymer layer that prevents seawater intrusion to underlying layers, thereby allowing the pressure armour layer to withstand the external hydrostatic collapse load	Solef PVDF 60512/0000
R2 Hoop Layer 2	Helical reinforcement stacks that provide additional internal pressure hoop resistance and crush load resistance.	DeepFlex Type 2B Composite reinforcement
R3,R4,R5,R6 Tensile Reinforcement Layers	Counterwound pairs of helical reinforcement layers that provide tensile strength	DeepFlex Type 2A Composite reinforcement.
S0, S1, S2, S3 Anti-Wear Tape	Tape wrapping applied between structural layers to minimize wear	Solef PVDF 60512 with PTFE additive to improve wear resistance
S4, S5 Anti-Buckling Tapes	Fiber reinforced polymeric helical tape layers wound around the tensile reinforcement layers, to resist radial buckling of the reinforcement stack	Anti-birdcaging (ABC) tape
E2 Jacket	Extruded polymer layer that protects the FFRP structure against abrasion and mechanical damage.	PA-11 Arkema Rilsan Besno P40TLX yellow

Pipe Cross Section Analysis - Pipe layers are designed to the criteria given in Table 2-3, which provides allowable strain for the polymer layers and allowable utilization for the structural layers. The design criteria for the metallic and polymer layers are in accordance with API 17J [17] requirements. The allowable utilization factors for composite reinforcement layers per Annex H of API 17B [18] are determined from the Load and Resistance Factor Design (LRFD) method, and the partial load and resistance safety factors selected based on the methodology presented in DNV OS-C501 [19]. The partial load factors are selected based on the load category and limit state, while the partial resistance

factors are selected according to uncertainty in material properties. The allowable utilization factors are then calculated as one over the product of partial load factor and partial resistance factor.

Table 2-3 Allowable Utilization Factors (K_a)

Layer	Failure Mode	Design Criteria	Operating Conditions			Non-operating Conditions			Survival
			Permanent			Temporary			
			Normal	Extreme	Abnormal	Normal		Extreme	
						Installation	Test		
Internal Carcass	Collapse	Load	0.85						
Internal Pressure sheath	Rupture	Thinning	The maximum allowable reduction in wall thickness over the service life below the minimum design value, due to deformation into gaps in the supporting structural layer, shall be 30 % under all load combinations.						
		Strain	The maximum allowable bending strain at nominal dimensions shall be 7,7 % for PE and PA, 7,0 % for PVDF in static applications and for storage in dynamic applications, and 3,5 % for PVDF for operation in dynamic applications [5].						
Metallic Pressure armour	Loss of interlock breakage	Stress	0.67	0.85	0.85	0.67	0.91	0.85	0.97
	Collapse	Load	0.85						
Anti-collapse Sheath	Rupture	Strain	The requirements for the internal pressure sheath will apply.						
Non-metallic Pressure reinforcement	Ovalization	Crushing Load	–			K3	–		-
	Burst	Stress	K1	K2	K2	K3	K3	K2	K4
Non-metallic Tensile armour	Tension rupture	Stress	K1	K2	K2	K3	K3	K2	K4
	Buckling	Load	–			K3	–	K2	K4
Anti-buckling tape	Bird-caging	Strain capacity	0.67	0.67	0.85	0.85	0.85	0.85	0.91
Outer Sheath	Rupture	Strain	The maximum allowable bending strain shall be 7,7 % for PE and PA						

Local stress analysis was conducted for the load cases in Table 2-4, which verified that the utilization was within allowable limits.

Table 2-4 Local Stress Analysis Load Cases

Category		Load case*		Critical location**		Internal fluid	P_{int} (barg)	P_{ext} (barg)	T_{int} (°C)	T_{ext} (°C)	Effective Tension (kN)	MBR (m)
Operation	Permanent	Normal (100 year winter storm)	HO	Max. Teff (NS 84)		Produced Oil	689.5	0	100	30	3874.5	26.3
				Max. C (NS 24)		Produced Oil	689.5	0	100	30	2394.9	8.84
			TDP	Max. Teff (NS 84)		Produced Oil	928.7	306.5	110	4	343.7	142.12
				Max. C (NS 15)		Produced Oil	928.7	306.5	110	4	434.88	12.04
		Extreme (100 year hurricane)	HO	Max. Teff (NS 83)		Produced Oil	689.5	0	110	30	3867.8	18.2
				Max. C (NS 87)		Produced Oil	689.5	0	110	30	2367.3	9.17
			TDP	Max. Teff (NS 83)		Produced Oil	928.7	306.5	110	4	325.5	142.85
				Max. C (NS 16)		Produced Oil	928.7	306.5	110	4	107.3	6.17
	Abnormal (100 year hurricane)		The abnormal case is assumed to not drive the pipe or riser system design. It is assumed that the FPSO would disconnect from the turret and sail off for these cases.									
Non-operation	Normal	Installation***	HO	Max. Teff (INS 5)		Seawater	0	0	30	30	2964.27	110.02
				Max. C (INS 7)		Seawater	0	0	30	30	2511.73	75.25
				Static x1.3		Seawater	0	0	30	30	3521.7	3333.3
			TDP	Max. Teff (INS 5)		Seawater	306.5	306.5	4	4	276.56	765.66
				Max. C (INS 9)		Seawater	306.5	306.5	4	4	123.58	54.58
		FAT	All			water	1075.6	0	23	23	0	2.87
		OLT*****	HO	Max. Teff (SIT 3)		Produced Oil	759	0	30	30	2803	111.67
				Max. C (SIT 4)		Produced Oil	759	0	30	30	2760	75.57
		SIT*****	HO	Max. Teff (SIT 3)		Produced Oil	862.5	0	30	30	2803	111.67
				Max. C (SIT 4)		Produced Oil	862.5	0	30	30	2760	75.57
	Extreme		TDP	Max. Teff (EMP 4)		Empty	0	306.5	Associated	4	320	230.38
				Max. C (EMP 4)		Empty	0	306.5	Associated	4	106.89	45.49
				Static		Empty	0	306.5	Associated	4	319.2	242.7
Survival			The survival case is assumed to not drive the pipe or riser system design. It is assumed that the FPSO would disconnect from the turret and sail off for this cases.									

Additional work conducted to verify the pipe structure design included:

- Finite element modeling and analysis to evaluate local stresses in the metallic pressure armor to verify they were allowable
- Finite element modeling and analysis of the liner and membrane to confirm the liner wall thickness reduction stays below 30% under the combination of worst design conditions of maximum gap in interlocked pressure armor, maximum operation pressure and maximum operation temperature
- Crush analysis to verify maximum allowable tensioner loads with 3 and 4 track tensioners
- Axial compression capacity analysis to verify the resistance of the tensile reinforcement layers to radial and lateral buckling and axial compression failure.
- Permeation, annulus water condensation and gas venting system analysis to verify that the inner annulus flowpath was sufficient to prevent overpressure of the inner annulus to above the collapse pressure of the internal carcass.
- Service life analysis, including fatigue analysis of the pressure and tensile armor layers and thermal analysis of the outer sheath to verify the 25 year service life.
- Learnings from the results of the Phase 2A tests presented in Section 3.0 were incorporated into the design

2.3.2 SubTask 6.2 – System Configuration Selection

The Subcontractor shall select the riser configuration from available options. Free hanging catenary will be considered as the base case and lightweight catenary configurations shall be evaluated as necessary.

One of the major activities in this task was to conduct the global dynamic analysis to develop the riser system configuration and to determine the maximum system dynamic responses based on the environment and vessel specified in the Design Premise. While primarily, the focus was to deploy the pipe with the free hanging catenary configuration, due to the limitation in the top end effective tension and touchdown point curvature, the second less complicated arrangement which is the low lazy wave configuration was selected for the riser system.

2.3.3 SubTask 6.3 – Dynamic Analysis

The Subcontractor shall conduct the dynamic analysis using the software OrcaFlex, an industry recognized tool used for dynamic analysis of offshore marine systems. The guidelines in API 17B were followed in conducting this activity. The riser configuration is subject to the global analysis load cases which are defined in the design premise. If allowable loads are exceeded, or unacceptable interference or clashing is experienced with neighboring risers, mooring or the vessel, then the riser configuration shall be modified as necessary. Installation dynamic analysis shall also be conducted in this SubTask. SubTasks 6.1, 6.2 and 6.3 are iterative and progress until a suitable pipe structure and riser configuration that meets all design requirements is confirmed.

Figure 2-3 shows the model developed in OrcaFlex to study the response of the system with the low lazy wave configuration. Section 5 of the Design Report [9] provides further details of the system configuration.

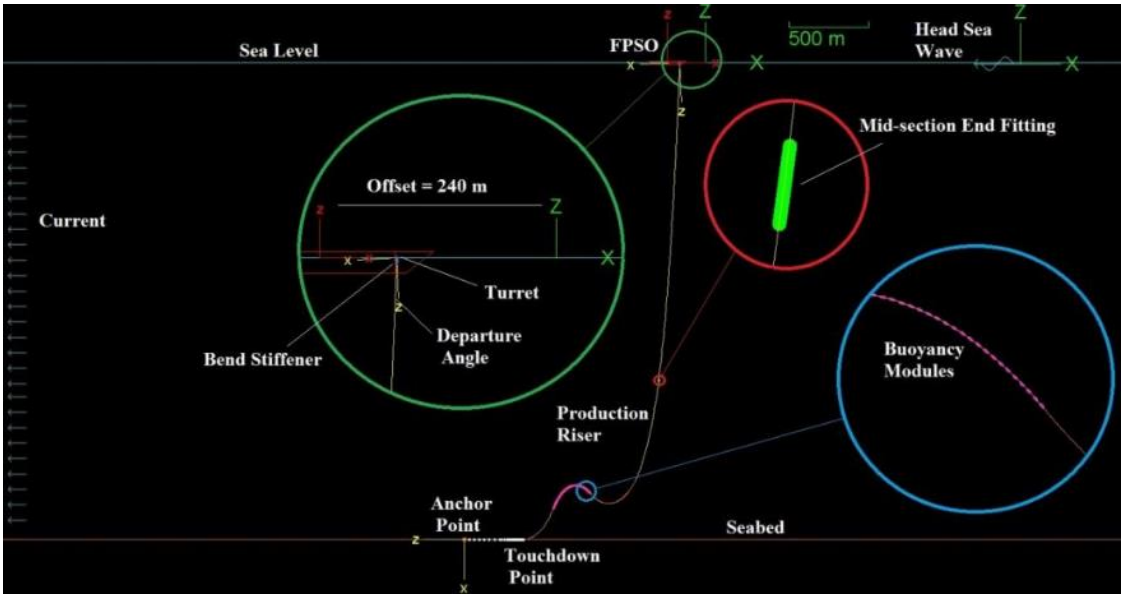

Figure 2-3 OrcaFlex model of the low lazy wave configuration for near case

The load cases for global analysis are developed based on possible design load combinations. These combinations include wave condition, current condition, pipe service, installation condition and accidental scenario. Loads for normal and extreme permanent operational cases corresponding to the 100 year winter storm environmental condition were evaluated. 10 year hurricane and 10 year winter storm environmental loads were also investigated but were found to be less critical compared to the 100 year winter storm case. Various combinations of 3 wave and current directions, 7 wave periods for each direction, 5 different vessel positions and 2 maximum offsets resulted in 210 load cases that were analyzed. Table 2-5 summarizes the most significant analysis results by providing the riser's maximum dynamic responses in normal and extreme permanent operational conditions.

Table 2-5 Result summary

Load Conditions	Parameter	Maximum Top Effective Tension (kN)	Maximum Top Curvature (rad/m)	Maximum Touchdown Point Compression (kN)	Maximum Touchdown point Curvature (rad/m)
Permanent Operational	Maximum	3874.5	0.113	49.8	0.083
	Load Case	NS 84	NS 24	NS 17	NS 15,NS 85
Extreme Operational	Maximum	3867.8	0.1065	51	0.162
	Load Case	NS 83	NS 87	NS 82	NS 16, NS 86

As a complimentary activity, the harshest environment in which the free hanging catenary configuration is feasible was also investigated.

2.3.4 SubTask 6.4 – Detail and Service Life Design

The Subcontractor shall perform an end fitting design and analysis for the pipe structure. The end fitting structural analysis and polymer layer seal design methodology shall be in accordance with API 17J. The tensile reinforcement anchoring takes into consideration the guidelines in DNV Standard OS-C501 Section 7, Joints and Interfaces. This activity shall be conducted using SolidWorks and, ABAQUS for special finite element analysis and internal calculation methodologies. End fitting assembly dimensions and weights shall also be determined in this SubTask. Detailed drawings of end fitting components shall be deferred until approval to proceed with Phase 2.

The Subcontractor shall specify the riser top bend stiffener. The buoyancy and/or ballast modules and other ancillary equipment, if determined necessary, based on the system configuration design shall also be specified. There are two new standards that are in the DIS stage, targeted for publication Q3 2012, that are relevant to these components: ISO 13628-16 / API 17L1, specification for flexible pipe ancillary equipment and ISO 13628-17: API 17L2, recommended practice for flexible pipe ancillary equipment. These components are manufactured by subcontractors, and the Subcontractor shall specify conformance with these standards in the specifications.

The DeepFlex end fitting is an assembly of metallic components designed to sustain the applied loads, including internal and external pressures, tension, bending, torsion and shear loads. Various sub-assemblies are positioned to seal polymer layers, anchor the tensile reinforcement, anchor the hoop layers and maintain hoop strength, properly secure carcass and prevent polymer layer blow through in the transition from the hybrid pipe body to the metallic end fitting structure.

Each end fitting is custom designed based on the pipe structure layer configurations, dimensions, structural capacity and design requirements. The end fitting structural analysis, allowable utilization for the metallic force containing components, and polymer layer seal design methodology are in accordance with API 17J. A simplified drawing of the end fitting assembly is provided in Figure 2-4. The Design Report presents classical and finite element analyses which were conducted to verify the material selection and design.

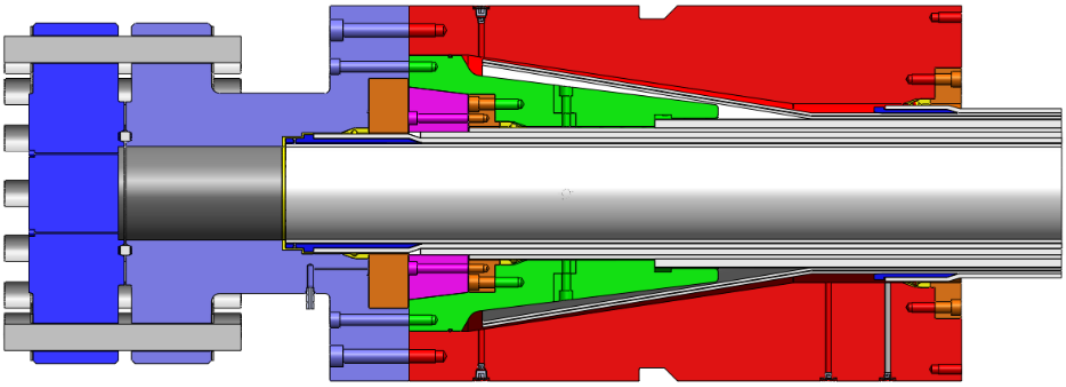

Figure 2-4 End Fitting Assembly

Ancillary equipment for the project are the bend stiffener attached to the I-tube at the riser top to prevent over bending and distributed buoyancy modules for the low-lazy wave riser configuration. The designed bend stiffener is a tapered beam made of 60D polyurethane material that prevents the violation of the MBR at the top side of the riser. The side view of the designed bend stiffener is plotted in Figure 2-5.

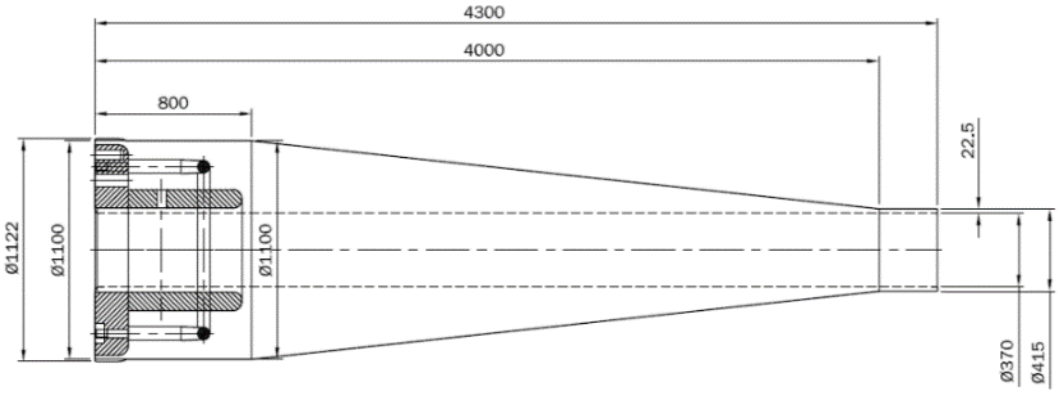

Figure 2-5 Bend Stiffener

Due to the high thermal resistance of the bend stiffener there is a potential for both riser and bend stiffener to exceed temperature limits. Analyses were conducted to confirm that free convection heat transfer from the pipe wall to the water in the gap between the pipe and bend stiffener is sufficient to maintain the temperature of the pipe layers and bend stiffener within allowable values. In order to verify the effectiveness of free convection, two basic analytical and a more sophisticated numerical model was developed to calculate the heat dissipation in the vicinity of the region where the pipe is supported by the bend stiffener. The results of this work is published as Reference [16].

Figure 2-6 shows the buoyancy module as well as the clamp system that is used to attach the module with body of the riser. The low lazy wave configuration of the riser is maintained by utilizing 80 buoyancy modules near the touchdown point of the pipe.

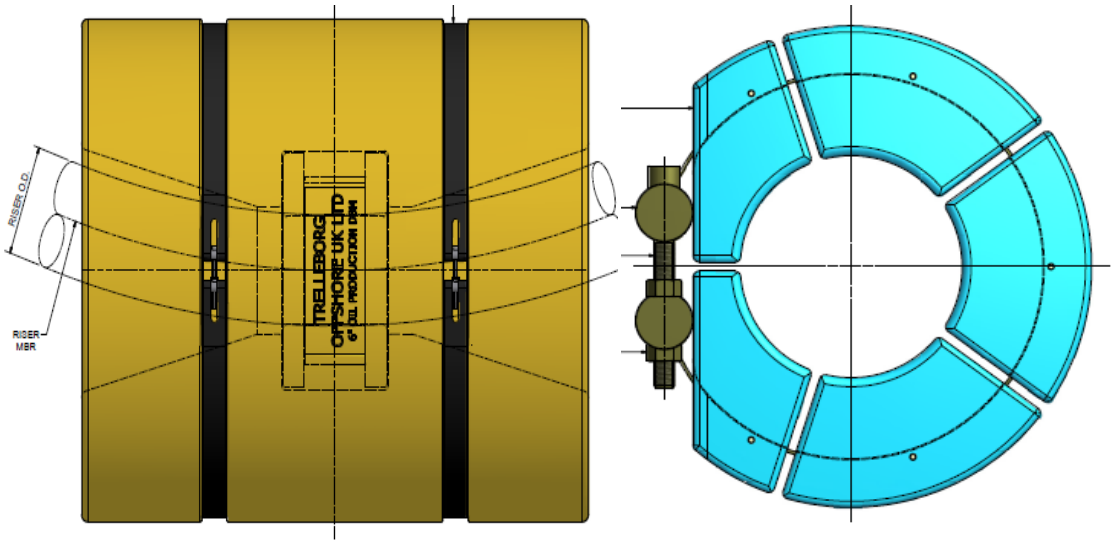

Figure 2-6 Distributed Buoyancy Module (Left) Internal Clamp General Arrangement (Right)

2.3.5 SubTask 6.5 – Design Report

The Subcontractor shall prepare a Design Report that presents a detailed description of the product design and documents the analysis work conducted in SubTask 6.1 and component analysis in SubTask 6.4. The design report shall be prepared in compliance with Section 8.3 and 8.4 of API 17J. The Subcontractor shall submit the report to the RPSEA working committee for review and approval.

Reference [9] is the Design Report in accordance with the noted requirements.

2.3.6 SubTask 6.6 – Dynamic, Service Life and Installation Analysis Report

The Subcontractor shall prepare a single report that presents the results of the riser configuration system dynamic and fatigue analysis work conducted in SubTask 6.2, 6.3 and 6.4. The Subcontractor shall submit the report to the RPSEA working committee for review and approval.

The Subtasks 6.5 and 6.6 reports were combined into the Design Report.

To accomplish the service life analysis, the fatigue seastates and the probability of occurrence to be used in the fatigue analysis are extracted from the design premise document. Since the FPSO is fully weathervaning, similar to the global analysis, head seas are considered for the fatigue load matrix. It is assumed that vessel offset and current would not substantially effect tension and curvature ranges.

Thus the vessel is assumed to be in the mean position, with zero current for all load cases and we have 42 load cases as listed in Table 2-6.

Table 2-6 Fatigue Analysis Load Case Matrix

Load Case	Probability of occurrence (1 = 100%)	Wave		
		Height, Hs (m)	Period, Tp (sec)	Direction (deg)
FTG1	0.18038	0.23	4.5	157.5
FTG2	0.39255	0.76	5.5	
FTG3	0.11887	1.37	5.5	
FTG4	0.12406	1.37	7.5	
FTG5	0.05908	1.98	6.5	
FTG6	0.05082	1.98	8.5	
FTG7	0.04211	2.59	8.5	
FTG8	0.02162	3.35	9.5	
FTG9	0.00518	4.19	9.5	
FTG10	0.00473	5.33	11.5	
FTG11	0.00068	6.86	12.5	
FTG12	0.00014	8.38	12.5	
FTG13	0.00003	9.91	14.5	
FTG14	0.00003	11.43	14.5	
FTG15	0.18038	0.23	4.5	180
:	:	:	:	
:	:	:	:	
FTG28	0.00003	11.43	14.5	
FTG29	0.18038	0.23	4.5	202.5
:	:	:	:	
:	:	:	:	
FTG42	0.00003	11.43	14.5	

All elements used to develop the global analysis model such as bend stiffener, buoyancy modules and mid-line end fittings are considered for the fatigue analysis. The stress responses in pipe cross section are analysed by DeepFlex In-house software, which includes an axisymmetric model and a bending model. For each load case, the maximum stress is calculated with maximum effective tension and maximum bend curvature, and the minimum stress is calculated with minimum effective tension and minimum bend curvature. For Z-shape interlocked pressure armor and composite tensile stacks near the end fitting, stress concentration factors are obtained from an FEA model and applied in the stress analysis. The analysis demonstrated that the 25 year service life requirement was met for the composite and metallic armor layers.

The service life evaluation of the PA-11 jacket is based on API 17 TR2 [20]. Figure 2-7 provides the time to reach the initial acceptance criterion of CIV 1.2 dl/g for the material inherent viscosity.

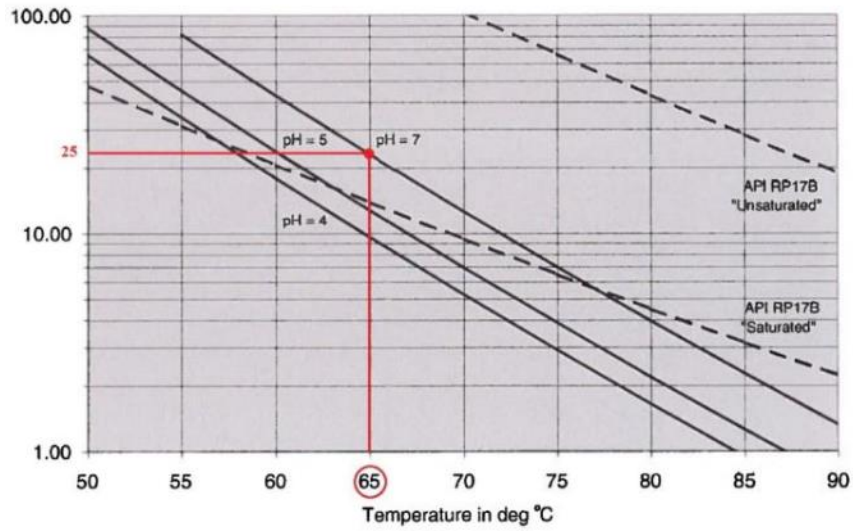

Figure 2-7 PA-11 Jacket Service Life Evaluation

Based on the maximum jacket temperature of 36.6°C, the time to reach the initial acceptance criterion is more than 100 years, which exceeds the required service life of the pipe. Therefore the PA-11 jacket service life does not govern the service life of the pipe.

The content of the final design report is not limited to the defined scope of the work as mentioned above. Other studies such as gas permeation and venting system analysis and thermal modeling of the system were also conducted to better understand and predict the behavior of the riser system and to address the potential uncertainties as listed in the next task- FMECA.

2.4 Task 7.0 – Failure Mode, Effects and Criticality Analysis (FMECA)

Scope of Work:

The Subcontractor shall conduct the FMECA in accordance with Section 7 of DNV RP A203. DNV will be subcontracted to facilitate the FMECA workshop using their Failure Mode Identification and Risk Ranking (FMIRR) process. The subcontractor, having been through the FMIRR process with DNV on a similar FFRP structure, shall customize the FMIRR template based on the proposed design. RPSEA working committee, Operator Participants and subcontractor representatives shall be invited to attend the workshop to assure that all known failure modes and mechanisms are addressed considering broad based knowledge from previous qualification programs and field experience. The FMECA report shall be prepared and submitted to the RPSEA working committee for review and approval.

Summary of work completed:

The FMECA was conducted in accordance with DNV RP A203, which provides guidelines for the process to follow for qualification of new technology. A two day FMECA workshop was facilitated by DNV, with representatives of the RPSEA Project Working Committee and Project Subcontractors attending. The qualification basis consists of the design premise and design report which have been prepared in accordance with API 17J. For the Technology Status assessment and risk ranking, the riser was broken down to the component level – the riser system, the pipe, pipe layers, the end fittings and the ancillary equipment. About 125 failure modes/mechanisms were evaluated. These were based on API 17B Chapter 11 and Annex H, DNV OS-C501 and the collective experience of the workshop team members which included both Working Committee and Subcontractor representatives. For each failure mode/mechanism, the probability and consequence of failure and associated risk ranking were evaluated. An action plan for each item to mitigate the risk was then proposed, with some items to be

addressed in the Engineering Study, some in material and layer small scale qualification tests, some in full scale prototype tests and some during installation and performance monitoring during the 6 months field trial after installation. The final task report [10] has the FMECA matrix. A summary of the FMECA process is also published in OTC 25092 [22], with examples from the RPSEA Project FMECA and qualification plan.

2.5 Task 8.0 – Manufacturing Documentation for Phase 2 Prototype

Scope of Work:

This task is divided into four subtasks as described in the following subsections, which also present a summary of the work completed for each subtask.

2.5.1 SubTask 8.1 – Pipe Construction Report (PCR)

The Subcontractor shall prepare a Pipe Construction Report. The PCR shall provide the instructions from Engineering to Operations to manufacture the pipe; Layer by layer dimensions, materials and tolerances shall be specified.

2.5.2 SubTask 8.2 – Plant Upgrades Evaluation

The Subcontractor shall conduct an evaluation of the product design relative to current manufacturing process capabilities on a layer by layer and overall pipe structure basis to define plant upgrade requirements and timing. The Subcontractor notes that the Phase 2 milestone dates are subject to variance based on the plant upgrades evaluation. If the Phase 2 variance does not meet RPSEA working committee expectations, the Subcontractor, with DOE/NETL/RPSEA approval will consider subcontracting manufacture of some non-composite armor pipe layers to others.

2.5.3 SubTask 8.3 – Quality Plan

The Subcontractor shall prepare a quality plan, which defines the Operational procedures to be followed, the accountability for assuring procedures are followed, the hold and witness points for each process employed in the design activities in Phase 1, the manufacturing, non-destructive inspection and testing, and supply and test of the pipe assemblies for Phase 2.

2.5.4 SubTask 8.4 – Manufacturing Documentation Report

The Subcontractor shall prepare a single report which documents the work conducted in SubTasks 8.1, 8.2 and 8.3 and submit the report to the RPSEA working committee for review and approval. The Subcontractor shall document the variance to Phase 2 and 3 milestones to the RPSEA working committee in the Manufacturing Documentation Report

The work conducted under each subtask described above are collected in the comprehensive final manufacturing documentation report [11].

2.6 Task 9.0 – Phase 2 Qualification Test Plan

Scope of Work:

The Subcontractor shall prepare and submit a Phase 2 Qualification Test Plan which includes sample and test apparatus descriptions, and test procedures to be followed. The test plan for the full scale dynamic testing, Task 14.0 shall be prepared in accordance with Figure 27 in API 17B, 4th Edition (Figure not included in the 5th Edition). The Subcontractor shall include a brief description and photograph of each test set up in the Qualification Test Plan. The deliverable for this Task shall be provided to the RPSEA working committee in Task 11.0.

Summary of Work Completed:

The threat assessment conducted in Task 7 identified the failure modes and mechanisms for the FFRP riser system, pipe structure, pipe components (layers and end fittings) and ancillary equipment. For each failure mode/mechanism group, an action plan to mitigate risk was agreed at the workshop. The action plan consisted of activities which would be conducted to mitigate normal and high risk items during each phase of the project as follows:

- Phase 1 – Engineering Study – Design Aspects
- Phase 2A – Pre-Prototype Activities – Actions taken prior to manufacturing and testing the full scale prototype to qualify the new technology employed in the project.
- Phase 2B – Prototype Manufacture and Testing
- Phase 3 - Installation and Field Deployment

The objective of Phase 2A is to mitigate all identified risks from the threat assessment and qualify the new technology being employed in the pipe design, including the metallic / composite hybrid pressure armor reinforcement and composite tensile armor reinforcement layers. Phase 2A includes activities to be completed prior to manufacture and testing of the full scale prototype of the 7-inch ID riser. Additional material qualification testing at 110 °C in seawater was also added to the test program, to characterize material performance under potentially abnormal and accidental thermal loading conditions. Phase 2A consists of Tasks 12 through 16. Phase 2B consists of continuing Task 12 and 15, and conducting Tasks 17.0 through 22.0, which include the manufacturing of a prototype of the RPSEA pipe, fabrication of end fitting parts, assembly of pipe samples, and conducting full scale tests in accordance with API RP 17B. All of the Factory Acceptance Tests (FAT) and full scale qualification tests listed in Task 17.0 through Task 22.0 shall be witnessed by an Independent Verification Agent (IVA). The statement of work for each task is provided in Sections 3 and 4, which present the scope and progress of Phases 2A and 2B respectively.

2.7 Task 10.0 – Field Development Cost Estimates

Scope of Work:

The Subcontractor shall prepare field development cost estimates based on supply and installation of a single FFRP riser system based on the installation and operating vessel and field location specified in the Design Premise. This task is divided into three subtasks as described in the following subsections, which also present a summary of the work completed for each subtask.

2.7.1 SubTask 10.1 – Packaging, Shipping and Installation Plan

The Subcontractor shall prepare calculations and drawings to define the packaging. Due to the pipe length and diameter, carousel packaging, or packaging on reels with mid-line end fittings is expected. Detailed installation procedures are not in the scope of work, but the riser system installation process shall be sufficiently defined to estimate installation cost.

The upper section of the riser starts from the top side end fitting and passes through the bend stiffener and finishes at the upper mid-line connection end fitting. The lower part is between the subsea and the lower midline connection end fittings. To facilitate the manufacturing process as well as the storage/transportation requirements, the riser is fabricated in two sections – upper and lower, which are connected at the mid-line connection during installation. The inner annulus between the upper and lower section are connected so that the entire riser system annulus is vented to the surface. Each pipe

section is packaged on a single reel, for storage, installation and factory acceptance testing. Table 2-7 provides data regarding the two selected reels.

Table 2-7 Reel Sizes

	Pipe length	Flange Dia.	Barrel Dia.	Inside Width	Partition	Empty Space on the Diameter	Total Weight
Reel 1: Upper section	1930 m	11.4m	6 m	5.0 m	1.1 m	0.4 m	410 MT
Reel 2: Lower section	2070 m				0	1 m	434 MT

2.7.2 SubTask 10.2 – Integrity Management and Data Gathering Plan

To ensure that the necessary valuable data will be obtained during field trials, the Subcontractor shall prepare a clear plan defining instrumentation, passive and active measurements to be made with clear responsibilities. The Subcontractor shall develop an Integrity Management Plan to define the instruments and measurements to be made over the service life on a permanent installation basis. Costs for instrumentation, measurement and integrity management shall be estimated.
This work was conducted largely under subcontract from DeepFlex to Wood Group Kenny (WGK) with DeepFlex oversight and participation. DeepFlex defined the scope of work and summary of the pipe structure, riser system and FMECA results to WGK. The Integrity Management Plan is developed in accordance with an industry recognized corporate methodology, developed through Joint Industry Projects, and extensive project experience. Wood Group Kenny used best industry practices and its up-to-date knowledge of monitoring techniques and procedures when recommending this plan. The plan consists of 5 main categories:

- Inspection: observation by inspectors, divers and ROV cameras; crawlers) and non-destructive evaluation (ultrasonic and, acoustic emission);
- Monitoring: acquisition of operational data remotely (e.g. pressure, temperature, sand monitoring, etc);
- Testing and Analysis: methods of analyzing and testing data gathered through various inspections and monitoring techniques (e.g. riser response analysis and erosion analysis); bore fluid sampling and analysis is also a testing and analysis activity;
- Procedures: IM procedures that should be followed by the operator for efficient and safe management of field (e.g. shut-down and start-up procedures and deck lifting and handling);
- Preventative Maintenance & Remediation: activities to be implemented in case there is evidence that the component requires maintenance; it could be marine growth cleaning, anode replacement, etc. Recommendations will depend on operational history.

The base recommendations considers field proven technology and monitoring devices that Operators already have provision to implement as part of an overall subsea field assessment as shown in Table 2-8.

Table 2-8 Integrity Management Plan Base Recommendations

Activity	Equipment	Interface	Justification
Annulus Vent System	Annulus Gas Vent System	– Control system	Assess Annulus condition and free /flooded volumes-

Activity	Equipment	Interface	Justification
Monitoring		– Topside	identify any failure of the E0 Liner or E1 Membrane Annulus gas sample connections and pressure monitoring.
Metocean Monitoring	Vessel integrated recording equipment (buoy and ADCP)	– Topside – Hull	To record wave and current measurements for fatigue and strength analysis response.
Pressure & De/Re-pressurization monitoring	Pressure sensors (topside and subsea)	– Control system – Topside	To monitor the pressure to ensure it does not exceed design limits.
Riser Motion Monitoring	Accelerometer Inclinometer	– Topside – Hull – Environ ment	To measure bending variations and angular variations at the top of a riser as a verification measure for maximum loads/ motions.
Sand Monitoring	Sand Detector (topside and subsea)	– Control system – Topside	To measure sand rate production from wells.
Temperature monitoring	Temperature sensors (topside and subsea)	– Control system – Topside	To monitor the temperature to ensure it does not exceed design limits.
Vessel Excursion Monitoring	DGPS	– Control system – Topside	To monitor low frequency motions in the translational degrees of freedom (heave, surge and sway).
Vessel Motion Monitoring	Motion Measuring Unit	– Control system – Topside	To monitor the high frequency motions of the vessel in 6 degrees of freedom (heave, surge, sway, pitch, roll and yaw).
Visual Inspection (External)	– ROV	– Hull – Environ ment	To detect any gross damage, distortion or specific component condition.
Visual Inspection (Internal)	– Crawler	– Topside – Hull	To inspect R0 carcass collapse, damage or failure.
Volume Flow Rate monitoring	Flow rate sensors (topside and subsea)	– Process – Topside	To determine the flow rate of fluids and determine any blockage on the line.

The field development concept report [13] also includes Integrity Management measures as well as the optional recommendations along with inspection schedule.

2.7.3 SubTask 10.3 – Field Development Concept Report with Cost Estimates

The Subcontractor shall prepare and submit a report consolidating the work conducted in SubTasks 10.1 and 10.2 to the RPSEA working committee for review and approval.

The field development concept report including cost estimates was prepared and submitted [13].

2.8 Task 11.0 – Proposal for Phase 2

The Subcontractor shall update the Phase 2 plan from the original proposal with the results from Tasks 1.0 to 10.0 and submit the proposal to the RPSEA working committee.

As noted, Phase 2 is divided into two sub-phases, Phase 2A and Phase 2B. Phase 2A consists of Tasks 12 through 16, which are presented in Section 3 of this report. Phase 2B consists of Tasks 17 through 22, which are presented in Section 4 of this report, and continuing Tasks 12 and 15.

2.9 Conclusions from Phase 1

DeepFlex successfully completed Phase 1 in accordance with the scope of work as defined in the Subcontract and further detailed in the Project Management Plan.

A design premise for the 7-inch ID, 10,000 psi design pressure, 10,000 ft water depth, 120 °C design temperature riser system has been agreed with the RPSEA working committee.

Detailed design of the pipe structure and riser system has been completed in accordance with Specification API 17J and Recommended Practice API 17B requirements. Analyses to verify the suitability of the composite armor layers in accordance with DNV OS-C501 was completed. Material qualification tests to verify the suitability of the composite armor material system are underway with successful initial results.

A comprehensive failure mode effects and criticality analysis (FMECA) has been completed which identifies all known failure modes and mechanisms and identifies risk control measures in an action plan leading to a qualification test plan which addresses the known uncertainties.

The qualification test plan has been completed, which identifies the material and pipe structure qualification tests which are planned to be completed in Phase 2. Phase 2 was split into two sub phases, Phase 2A which includes tests to qualify key aspects of the new technology – specifically new structural elements and upgraded pipe manufacturing processes, and Phase 2B which includes manufacture of a full scale prototype and qualification testing in accordance with API RP 17B requirements.

A manufacturing plan for the Phase 2 prototype has been prepared, which provides the documentation for manufacture of the prototype. At the completion of Phase 1, DeepFlex was undergoing a major plant expansion with the upgrades necessary to manufacture the pipe structure which is the subject of Phase 1.

A field development plan has been completed which presents the scope of field installation and options for performance monitoring during the 6 month Gulf of Mexico field trial and over the service life for integrity management.

Figure 2-8 presents how DeepFlex is following the DNV RP-A203 new technology qualification process in executing this project.

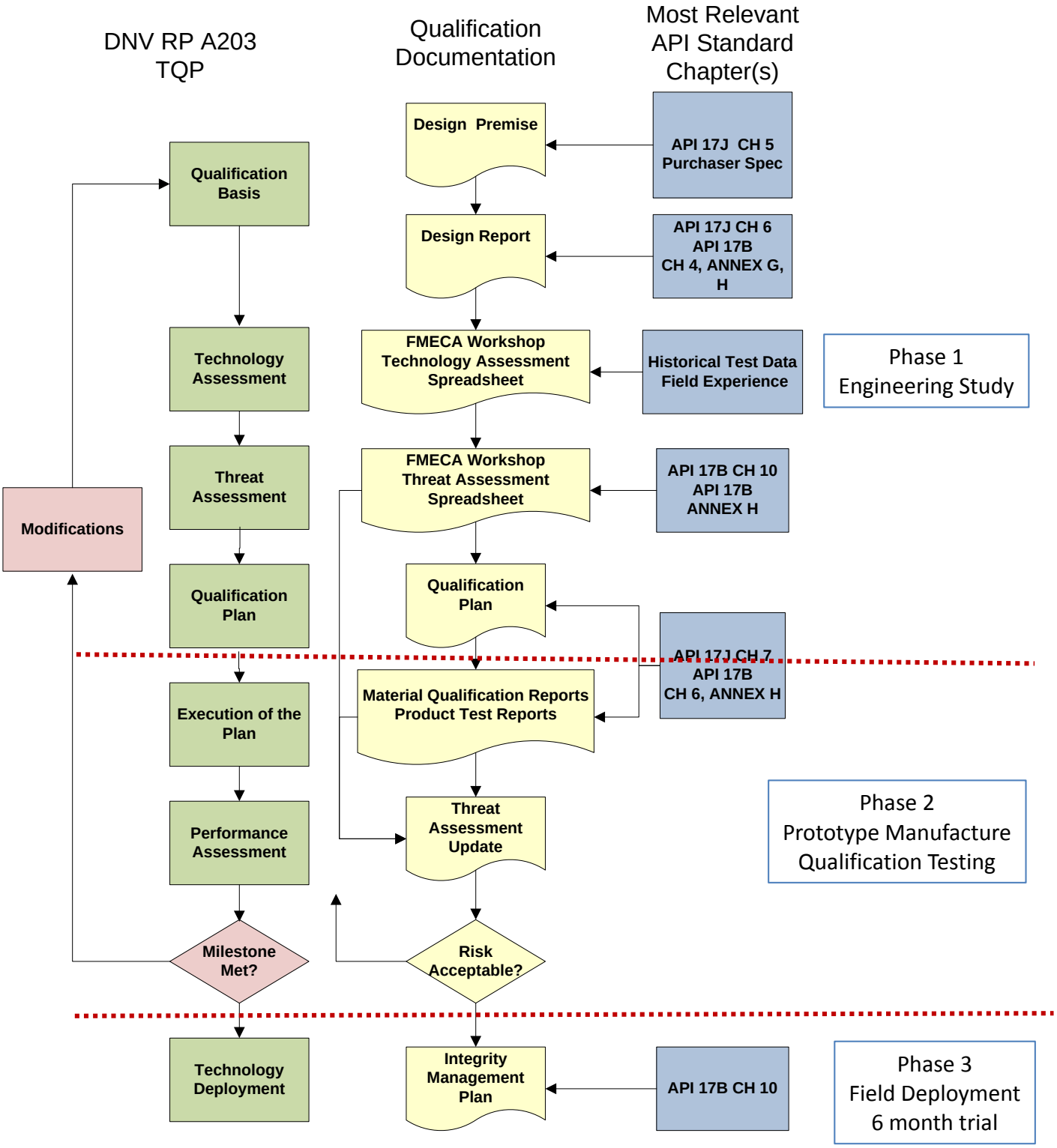

Figure 2-8 Implementation of DNV RP-A203 Technology Qualification Process in RPSEA Project 10121-4402-02

Table 2-9 presents the API 17N Technology Readiness Level (TRL) achieved at each Phase of the Project.

Table 2-9 Technology Readiness Levels associated with each Phase
in RPSEA Project 10121-4402-02

Phase	Description	TRL at start	TRL at finish
1	Engineering Study	0	1 – 2
2A	Qualification of the new Technology	1-2	3
2B	Qualification of the overall structure with API 17B tests	3	4-5
3	Pipe Manufacture/Field Installation	4-5	6
3	After 6 months field monitoring	6	6 3 years service required to achieve TRL 7

Note: Phase 3 was deleted from the Project, per [4].

3.0 PHASE 2A – MATERIAL AND PIPE LAYER DEVELOPMENT AND QUALIFICATION, PRE-PROTOTYPE MANUFACTURE AND TESTS

3.1 TASK 12.0 Composite Material Qualification Extension

3.1.1 Scope of Work:

The Subcontractor shall complete the material qualification testing for the composite materials used in R2, R3, R4, R5 and R6 layers (see figure in Task 17.0) in accordance with Attachment 2 of 10121-4402.08.FINAL. The material qualification work includes:

- Continuation of qualification tests on the composite material for R3 to R6 layers, including ageing at 110 °C;
- Qualification tests on the composite material for R3 to R6 layers with wear resistance surface up to 90 °C and 40 weeks of ageing;
- Qualification tests on the composite material for R2 layer up to 90 °C and 40 weeks of ageing;

The subcontractor shall conduct end fitting potting/anchoring pullout and fatigue tests, ring crush tests and CGS tests as defined in Section 3.1 of 10121-4402.08.FINAL [12].

Any revisions to the material qualification plan shall be approved by the DOE/NETL/RPSEA working committee.

3.1.2 Test Description

The test matrix for the composite material qualification was developed in accordance with the requirements API 17B Annex H, Section H.5 Material Qualification Guidelines [18]. Most of the tests specified are being conducted outside the scope of the RPSEA project. Additional tests proposed for the RPSEA project, are those with ageing at temperature of 110 °C. For the RPSEA pipe design, only seawater ageing tests are relevant, since permeated gases from the bore will not be in contact with the composite armor layers.

3.1.3 Test Results – Tape and reinforcement stack material property characterization

Figures 3-1 to 3-16 summarize the results of tests conducted on the composite tensile armor material for layers R3 through R6 with up to 30 weeks of ageing in seawater.

At the time of this writing, the material for the wear resistant surfaces of the composite tensile armor layers R3 through R6, and the improved material for the R2 composite hoop layer are not yet available.

Figures 3-1 to 3-3 provide unaged material properties at test temperatures from -20 °C to 110 °C.

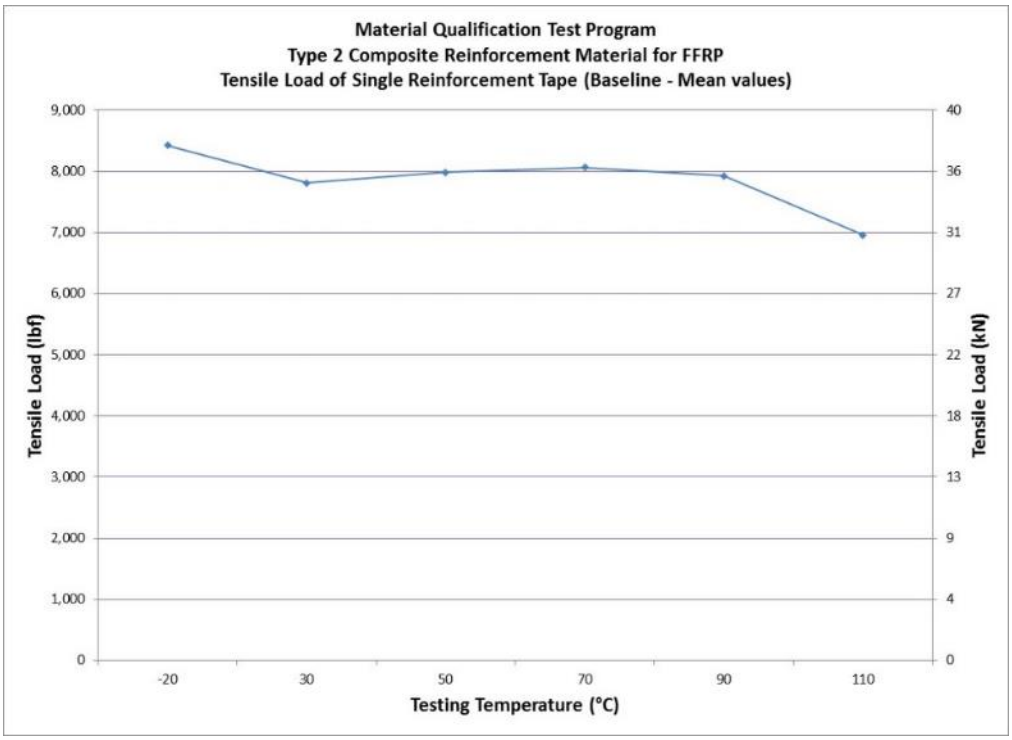

Figure 3-1 Single Tape - Ultimate Tensile Load of un-aged Type 2A Reinforcement versus Temperature

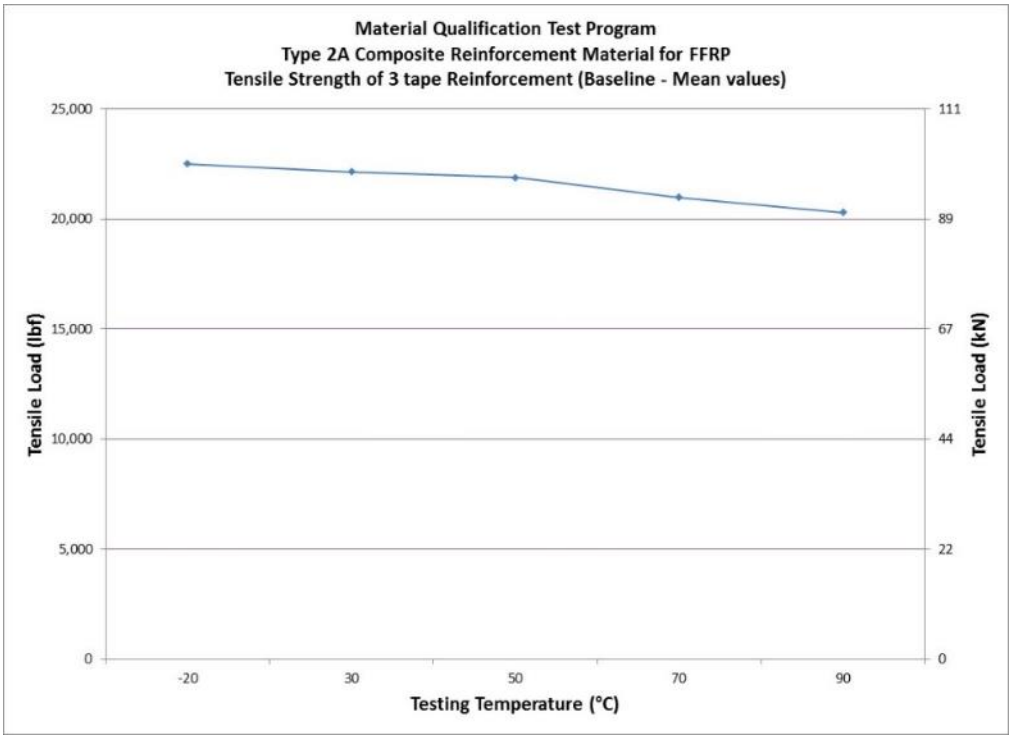

Figure 3-2 3-Tape Stack - Ultimate Tensile Load of un-aged Type 2A Reinforcement 3-Tape stack vs Temperature

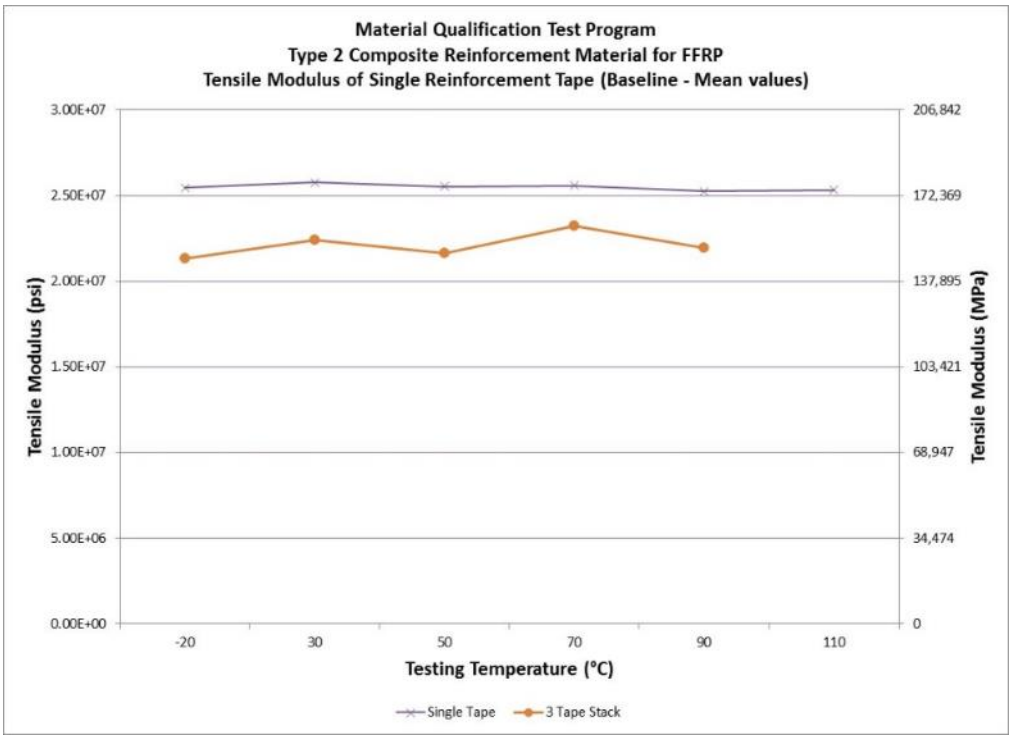

Figure 3-3 Young's Modulus of un-aged Type 2A Reinforcement single and 3-Tape stack versus Temperature

Figure 3-1 and

Figure 3-2 show that the Type 2A reinforcement tape maintains its tensile load capacity for both single and 3-tape configuration for up to 90°C. The tensile capacity reduction for the single tape is only 9% between 110 °C and 90 °C (mean values).

Figure 3-3 shows that the Young's modulus for both single tape and 3-tape configurations maintains its value from -20 °C to 110 °C.

The tensile strength and modulus of Type 2A reinforcement tape after 4, 8 and 20 weeks of seawater ageing are plotted in Figure 3-4 and Figure 3-5. All tests on the aged samples are conducted at 90°C.

The tensile strength ageing in seawater decreases up to 4 weeks followed by a stabilization period where the ageing follows a secondary slope.

In addition, the Young's modulus ageing in seawater, with the exception of 50°C, maintains its value from 30°C to 90°C up to 20 weeks and 8 weeks for 110°C. The reason behind the 50°C variation is related to a high COV (between 15%-23%).

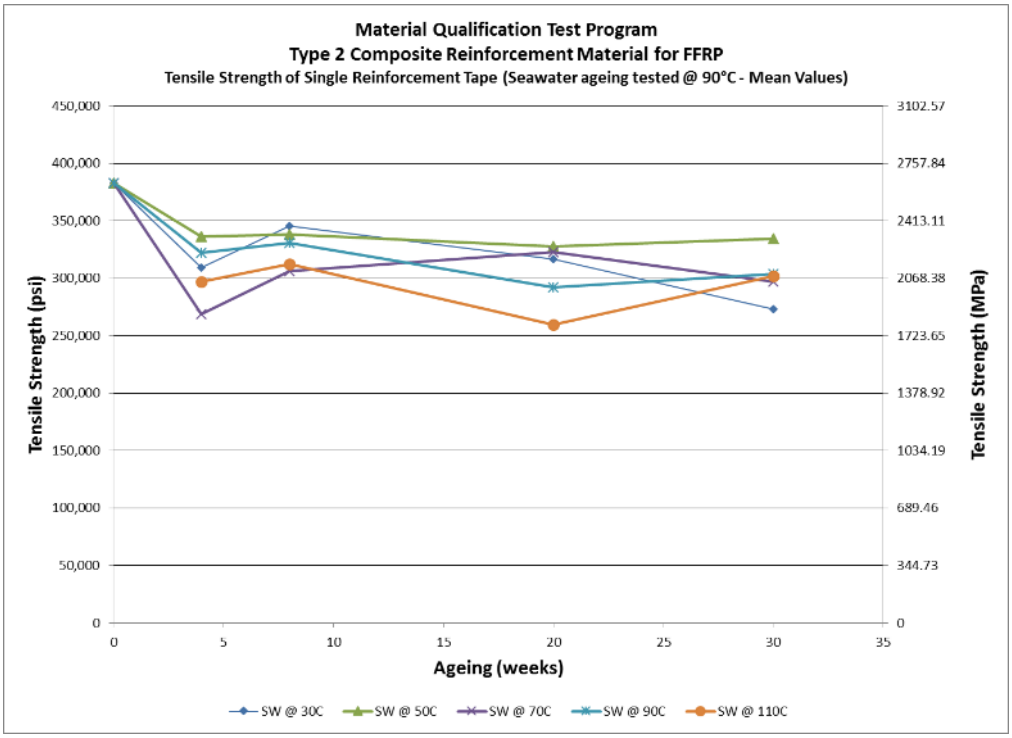

Figure 3-4 Tensile Strength of Type 2A tape after 4, 8, 20 and 30 weeks ageing in seawater

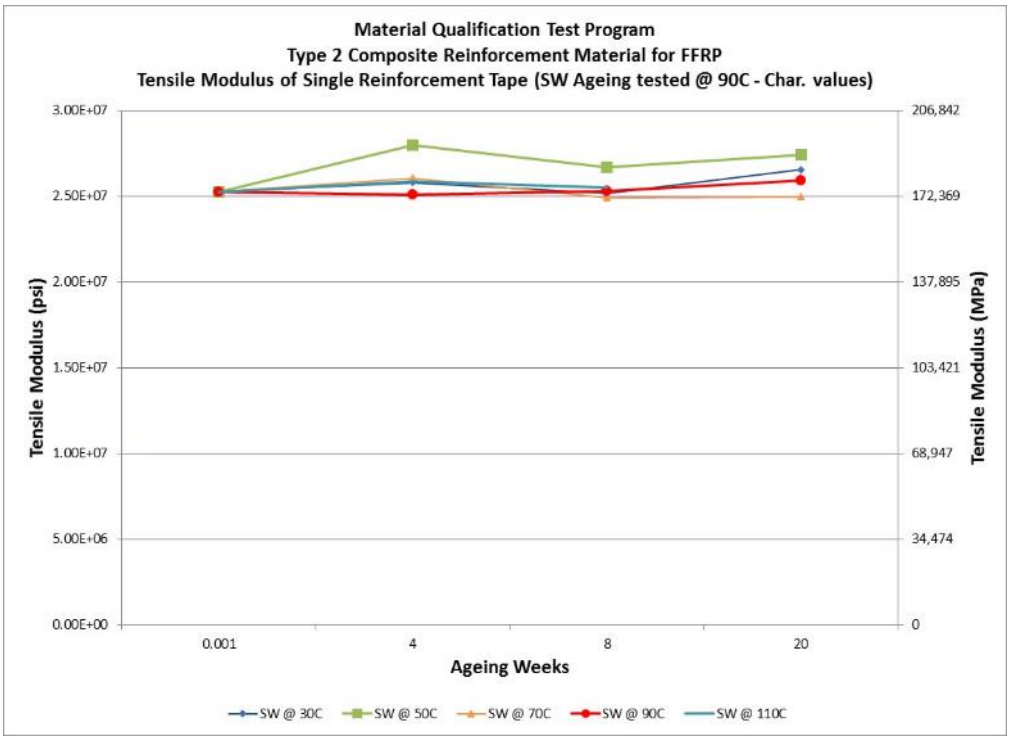

Figure 3-5 Young's Modulus of Type 2A tape after 4, 8 and 20 weeks ageing in Seawater

Figure 3-6 is the same data as Figure 3-4, but plotted on log-log scale, with extrapolation to 25 years, or the end of service life. Based on the extrapolation as shown, a reduction in strength to between

66% and 81% of initial strength is predicted at end of service life, depending on the temperature. This representation, which is also employed with the other mechanical properties in the principal directions is used in the design process to verify that design requirements are met.

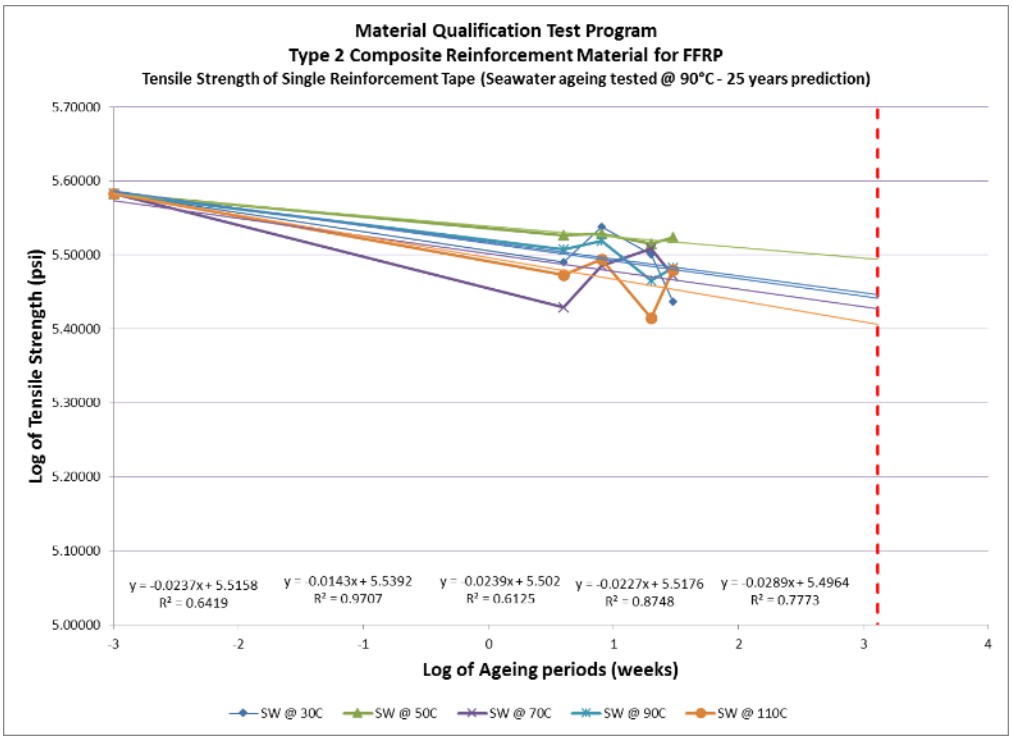

Figure 3-6 Tensile properties versus temperature extrapolation to 25 years service life

Figure 3-7 shows the tensile strength of a 3-tape stack, which has 1 tape with manufacturing splice, baseline properties at temperatures from -20°C to 90°C. The graph also shows the equivalent single tape load and 3 tape laminate extrapolated to a 2 tape laminate equivalent. The criterion for a successful test is that the 3 tape configuration (1 spliced tape) will have the equivalent strength of a 2 tape stack. The approximate breaking load of a single tape (at 90°C) is between 6,800 and 8,400 lbf for baseline 90°C values, therefore 2 tape strength, at 90°C, is between 13,600 and 16,800 lbf, so the criterion has been met.

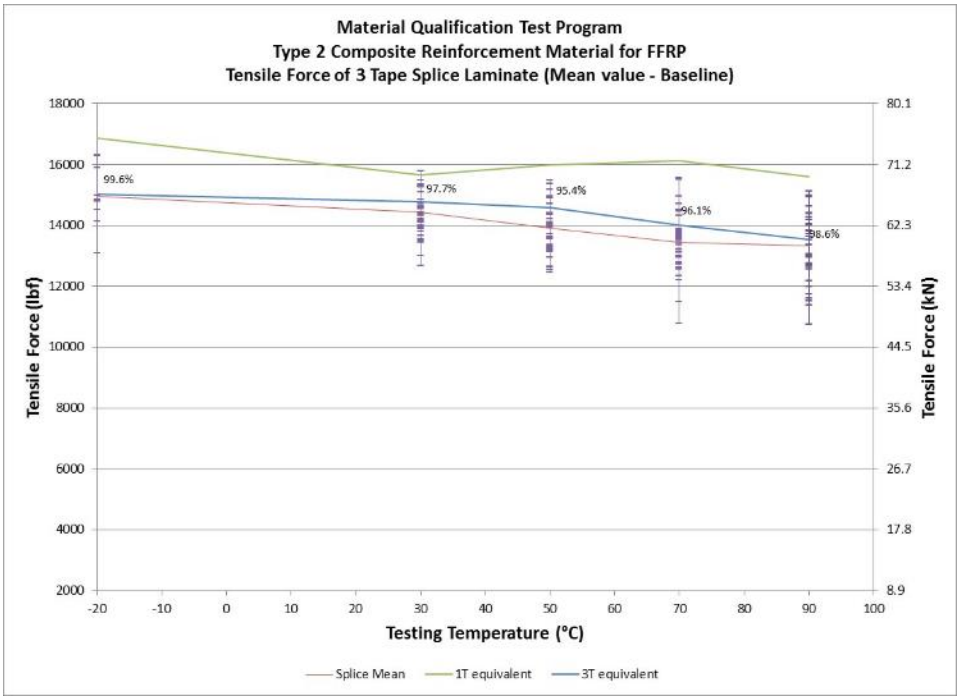

Figure 3-7 Spliced Type 2A 3-tape stack at different temperatures

Figure 3-8 shows the DLS strength baseline properties at temperatures from -20°C to 110°C. Due to the nature of the DLS test, which combines a shear failure with peel, higher temperatures will reduce the bending stiffness of the reinforcement tape and minimize the peel effect and shear will be predominant. Therefore, the DLS strength follows an expected strength increase path.

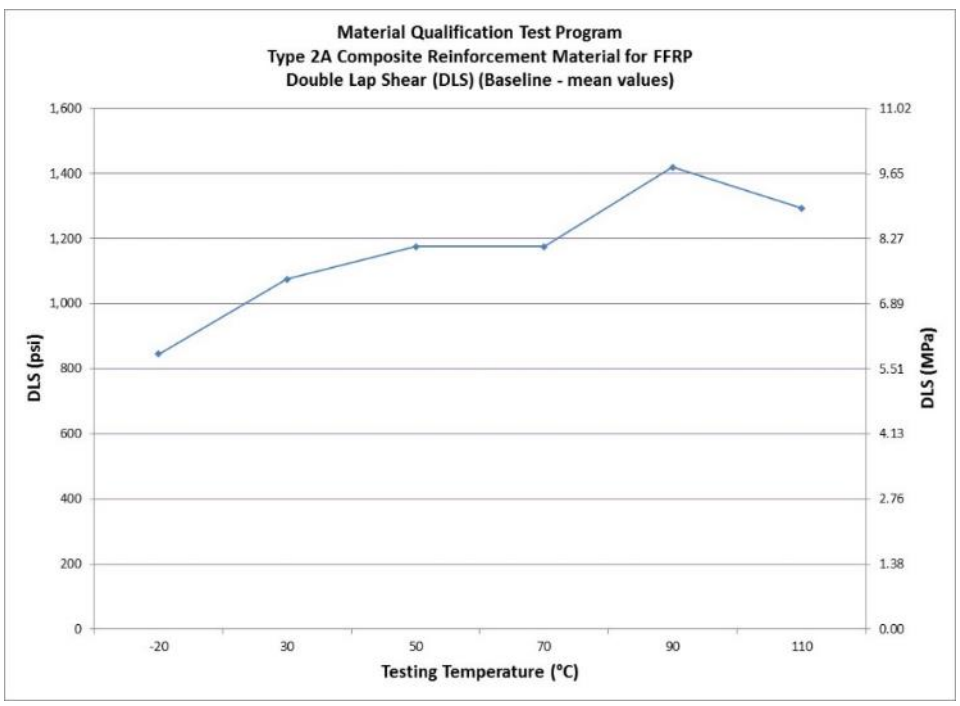

Figure 3-8 Double Lap Shear (DLS) Strength of un-aged stack at different Temperatures

Figure 3-9 shows the mean DLS strength of Type 2A reinforcement tape post ageing at different temperatures in seawater. This curve shows several points breaking the expected behavior. At 30°C 4 and 20 weeks ageing and 90°C 8 weeks ageing results show an above normal COV (%) which causes the deviation of the values.

With ageing at 110°C, there is a drop in lap shear strength up to 20 weeks, then an increase at 30 weeks. The DLS test has a natural high variation (5-10%), predicting long term behavior accurately requires additional points for evaluation.

Note that DLS properties are not used in design, however, they are a useful indication of the resistance to degradation of the adhesive bond between the reinforcement stack tapes and interlaminar adhesive.

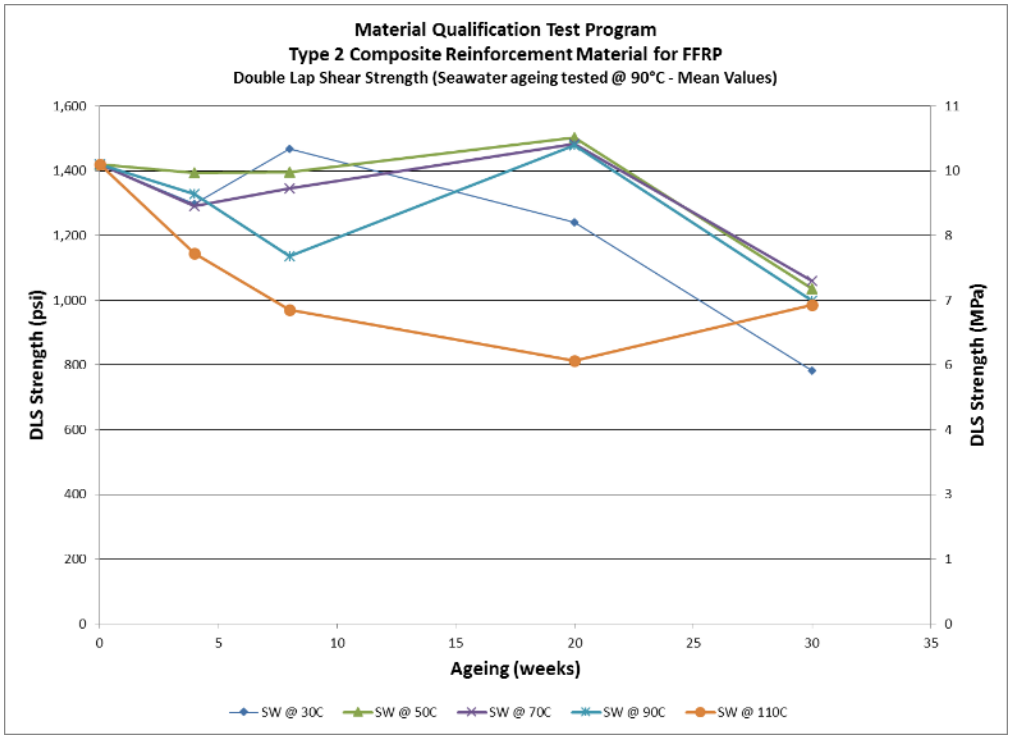

Figure 3-9 Double Lap Shear Strength after 4, 8 and 20 weeks ageing in Seawater

Figure 3-10 shows the mean Through-Thickness Compressive strength of un-aged material at temperatures ranging between 30°C to 110°C. Figure 3-11 shows the mean Through-Thickness Compression strength of Type 2A reinforcement 4 tape stacks post ageing at different temperatures in seawater respectively. This curve shows a typical behavior of an initial drop at 4 weeks and stabilized between 8 weeks and 20 weeks.

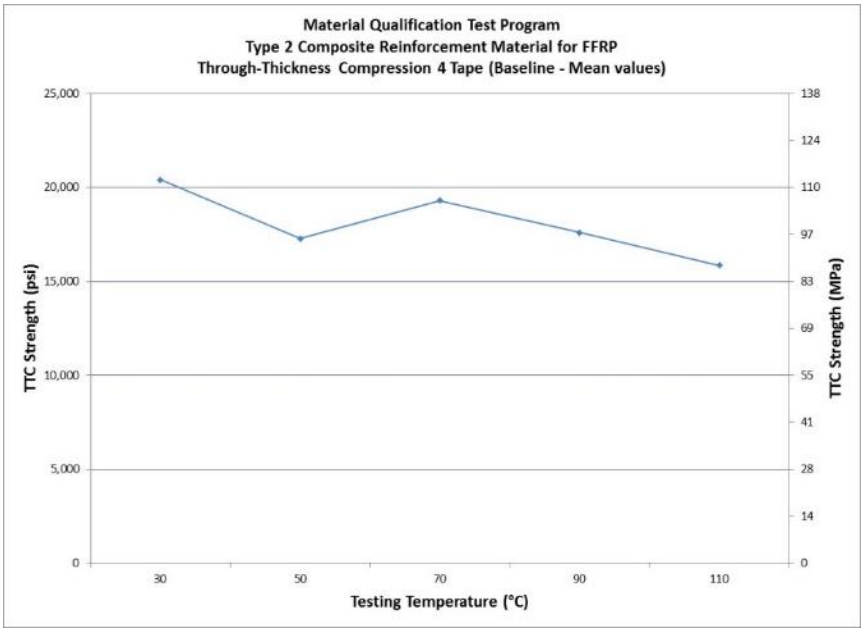

Figure 3-10 Through-Thickness Compression Strength of un-aged stack versus Temperature

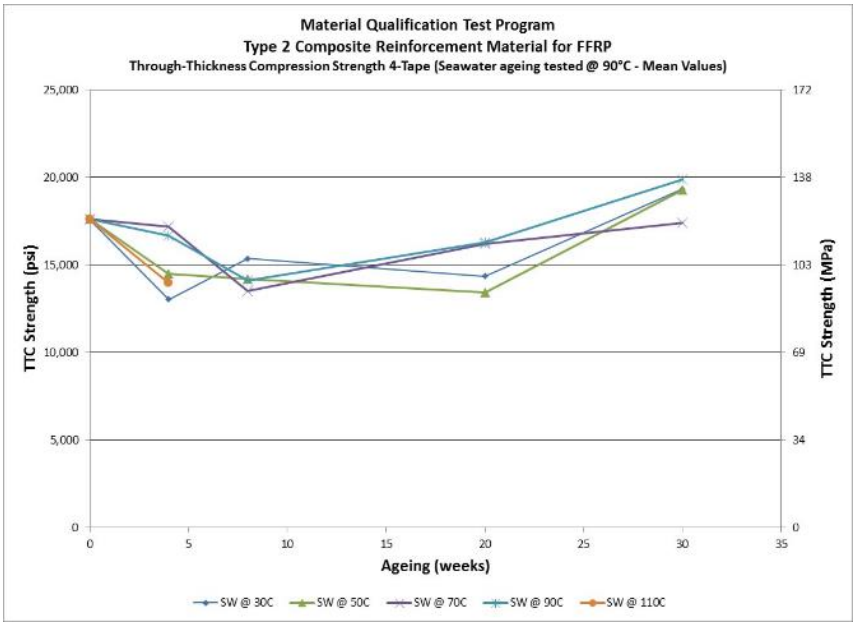

Figure 3-11 Through-Thickness Compression Strength after 4, 8, 20 and 30 weeks ageing in Seawater

Figure 3-12 shows the Through-Width Compression strength baseline properties at temperatures from 30°C to 90°C. Even due to the high COV, the temperature effect on the composite matrix can be appreciated.
The Through-Width Compression test has an inherent high COV values due the coupon geometry simulating tensile reinforcement stacks. This property is not employed in pipe design and used only as a reference for matrix degradation.

Figure 3-13 shows the mean Through-Width Compression strength of Type 2A reinforcement tape post ageing at different temperatures in seawater. This curve shows the slight drop (4 weeks) and

stabilization period on (8 and 20 weeks ageing) with well-established ageing trends. The 110°C ageing curve shows a low value for the property, although it seems to be also in the stabilized region. It should be emphasized that the test carries high variability and to perform a better prediction (for reference) will require additional ageing periods.

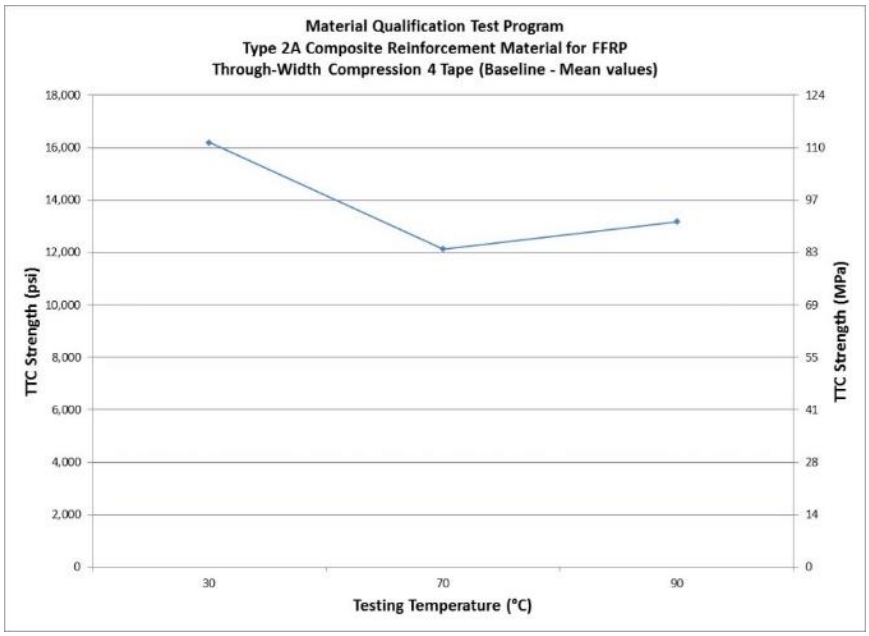

Figure 3-12 Through-Width Compression Strength of un-aged stack versus Temperatures

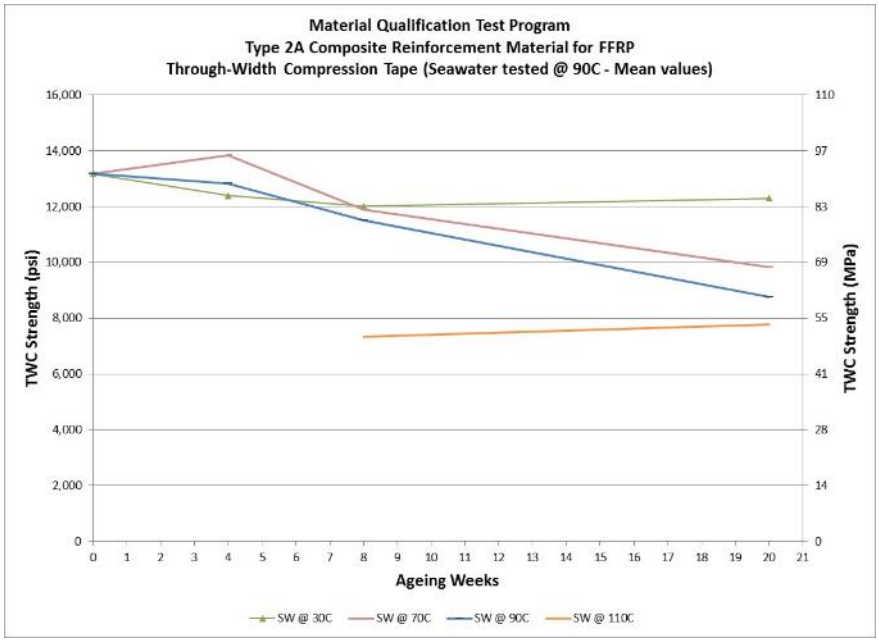

Figure 3-13 Through-Width Compression Strength after 4, 8 and 20 weeks ageing in seawater

Figure 3-14 shows the axial compression strength, tested at 90 °C versus ageing time. The axial compressive strength shows limited degradation up to 90 °C, but at 110 °C, an accidental condition, there is some loss of strength with ageing.

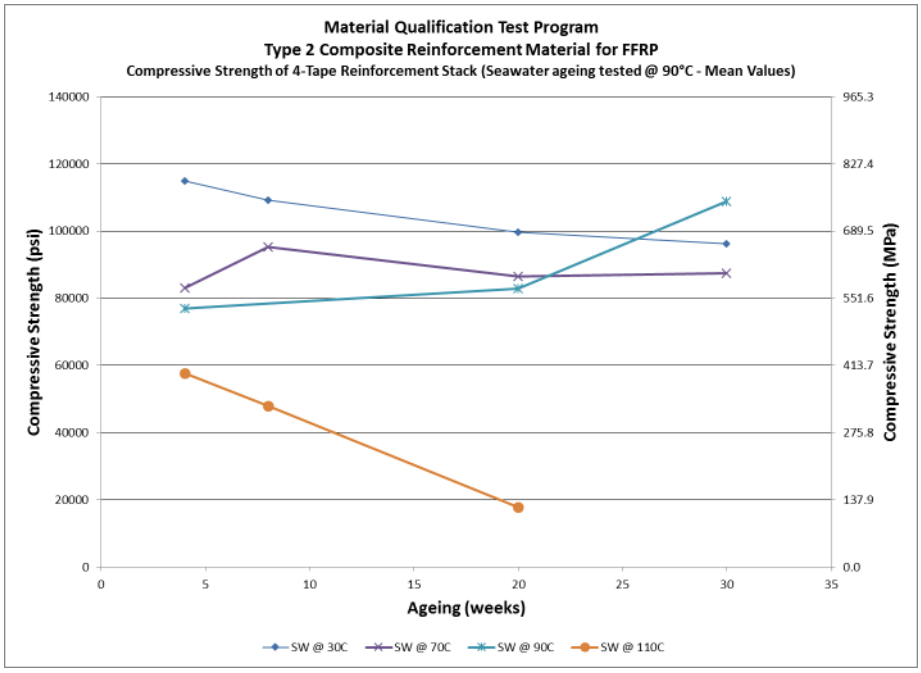

Figure 3-14 Axial compression strength of 4-tape stack after 4, 8, 20 and 30 weeks ageing in seawater

Figure 3-15 and Figure 3-16 present the glass transition temperature (Tg) of the interlaminar adhesive, measured by differential scanning calorimetry (DSC), and of the composite matrix material, measured by dynamic mechanical analysis (DMA). These tests demonstrate limited or no change in the molecular structure of these material, with ageing up to 30 weeks in seawater up to 110 °C.

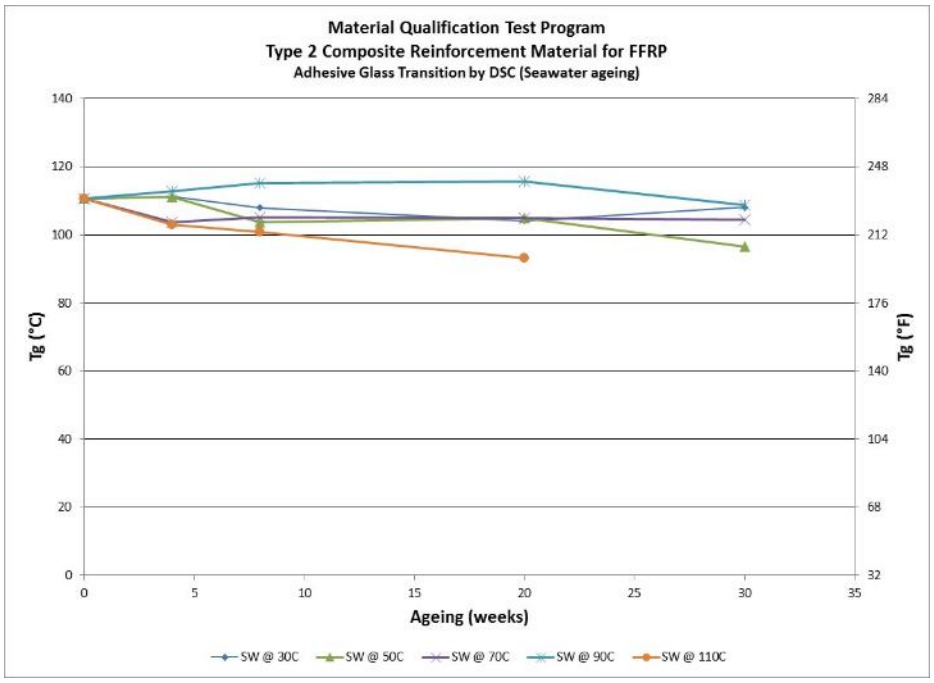

Figure 3-15 Tg of interlaminar adhesive measured by DSC – ageing up to 30 weeks

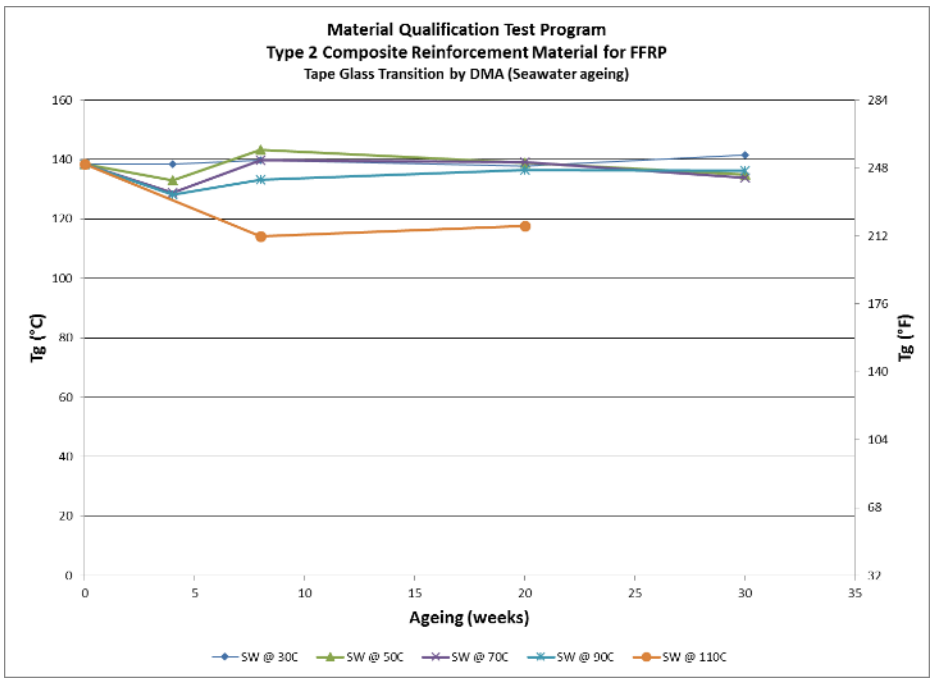

Figure 3-16 Tg of Type 2A reinforcement tape matrix measured by DMA – ageing up to 30 weeks

This phase also includes the testing of the adhesive bond strength between the end fitting potting and the reinforcement tape stack. A 4-tape stack is embedded into a small cup filled with the potting

compound used in pipe termination. The embedment length is 1.5 inch and the total length of the 4 tape stack is 6.5 inch. Figure 3-17 illustrates the assembly including two of 90° aluminum angles to assure perpendicularity between the tape and the finish surface of the end fitting compound while curing. Additionally, the lid provides a flat curing surface for the contact face of the end fitting compound.

As illustrated in Figure 3-17, the aluminum tabs, the lid and cup are removed and the specimen is in testing configuration. The supporting face of the end fitting compound is the fixed side of the test and the tape is pulled to evaluate the shear adhesion strength.

The initial value of the shear adhesion strength is **1,552 psi** which is about 10% higher than the assumed value used for the end fitting design.

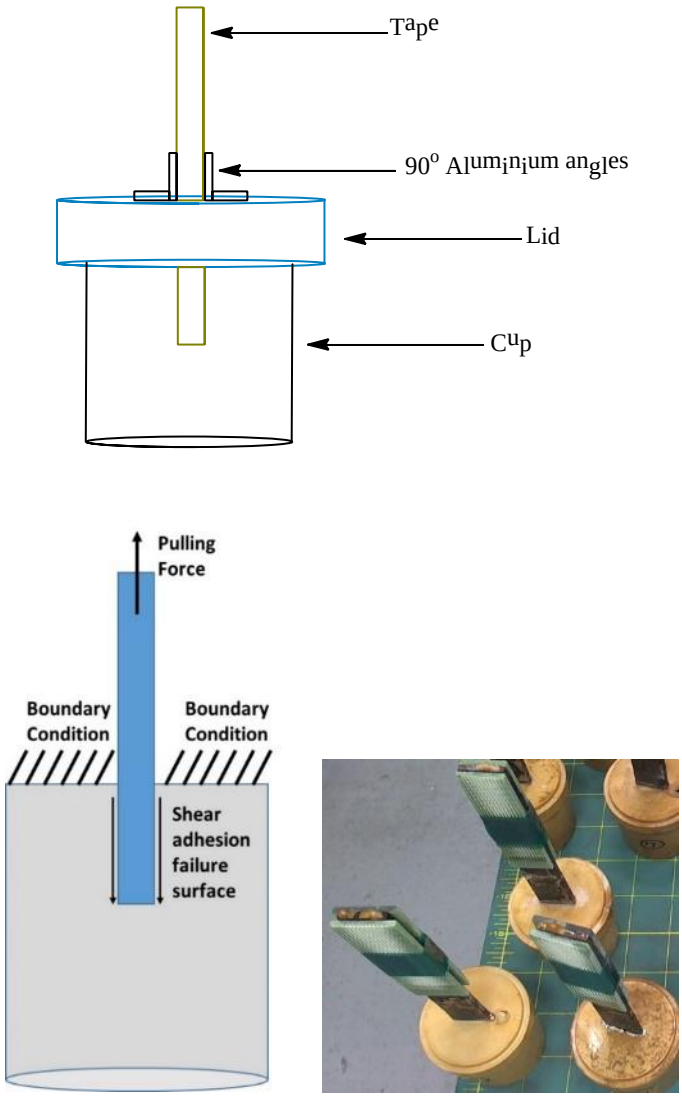

Figure 3-17 End Fitting potting adhesive bond test specimen

Figure 3-18 presents the results of the end fitting potting adhesive bond tests with ageing in seawater up to 20 weeks at 110 °C and up to 30 weeks at 90 °C. At 90 °C aged properties demonstrate long term and stable ageing resistance of the adhesive bond between the end fitting potting and the

reinforcement tape surface. However, at 110 °C, an accidental condition, bonding capacity has dropped about 45% after 20 weeks.

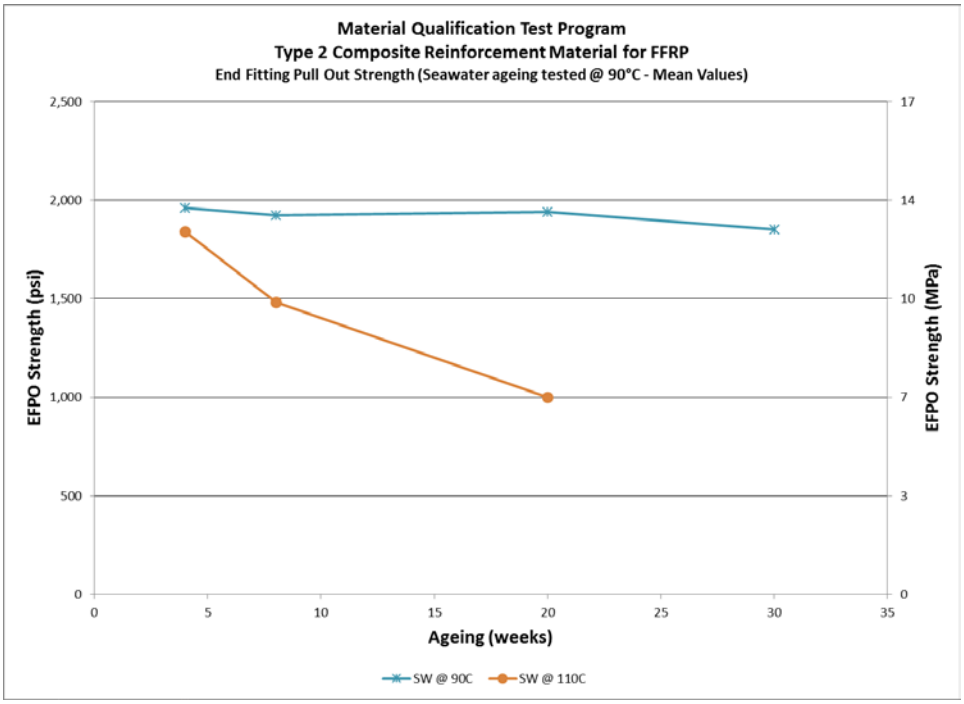

Figure 3-18 End fitting potting adhesive bond strength tested at 90 °C, with ageing at 90 °C and 110 °C

3.1.4 Ring Crush Test

Scope of work

As discussed in Section 2.3.1, the composite hoop layer (R2) consists of helical reinforcement stacks that provide additional internal pressure capacity and crush load resistance. The small-scale ring crush test is conducted to confirm the interlaminar shear strength.

Test Description

The helix is at a typical lay angle above 80 degrees to the pipe axis, so the performance of the composite hoop layer can be tested by applying loads to reinforcement stack rings of similar thickness and diameter. The ring crush test setup is illustrated in Figure 3-19. Two point loads are applied to the ring. Load versus displacement is measured until failure occurs. This test is used to determine the interlaminar shear capacity of the laminate, which is used in the design methodology to evaluate the resistance of the layer to external loads, such as applied by a hydraulic tensioner. The rings are made of Type 2B tape with the interlaminar adhesive cured according to the designed cure schedule. Note that the tests presented herein are on the Type 2B tape that was used for the Task 16 prototype. As discussed in Section 4.1.4, tape and stack design improvements were underway in Subtask 17.4, prior to making the Task 18 full scale prototype.

Figure 3-19 Ring Crush Test

Results

Table 3-1 shows the obtained results.

Table 3-1 Type 2B Ring Crush Test

Specimen	Ring Thickness (inch)	Ring OD (inch)	Peak Load (lbf)
#1	0.60	9.19	1383
#2	0.60	9.19	1409
#3	0.62	9.17	1179

The much lower crush load for the third specimen can be attributed to defects associated with sample preparation process, such as insufficient tape tension which may cause a gap between layers. In the presence of sample defects, the crush load is significantly reduced if the load is applied right above or near the defect area.

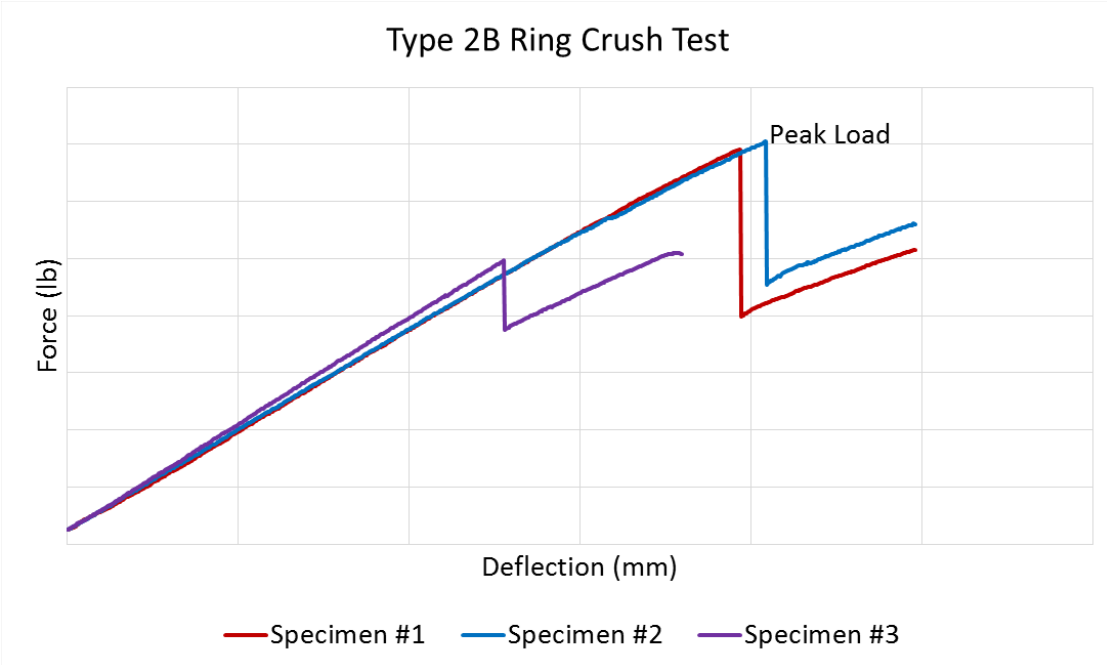

Figure 3-20 Ring Crush Test Results

The interlaminar shear strength can be calculated from the failure load for each ring crush test, which is summarized in Table 3-4.

Table 3-2 Calculated interlaminate shear strength from ring crush tests

Specimen	Ring Thickness (in)	Ring OD (in)	Peak Load (lbf)	Calculated interlaminar shear strength (psi)
#1	0.60	9.19	1383	2301
#2	0.60	9.19	1409	2344
#3	0.62	9.17	1179	1899

3.1.5 CGS test

Scope of work

The Cylindrical Gap Span (CGS) test is designed to confirm the capacity of the R2 hoop layer to resist against internal pressure loads. For this purpose, a single ring test will be conducted to assure structural rather than blow through failure, which is the expected structural failure mechanism for the R2 hoop layer under internal pressure loading. The gap spanning capability of the internal pressure sheath (E0) layer under internal pressure loading is addressed in Task 13.

Test Description

The test set up is illustrated in Figure 3-21. The test specimen consists of a short piece of thermoplastic pipe, an anti-extrusion layer and single hoop reinforcement stack ring. This test simulates the loading experienced by the hoop layer due to internal pressure loading. The test sample is contained in a bolted cylindrical apparatus which is rated up to 25000 psi. Strain gages are applied so that the stresses in the

hoop layer under internal pressure loading can be evaluated. This test simulates the combined loading in the hoop layer. Identical to crush test samples, the rings are made of Type 2B tape and Type 2B adhesive cured in accordance with manufacturing requirements. A pull force of 100 lbf is used in the winding process to apply the tape tension.

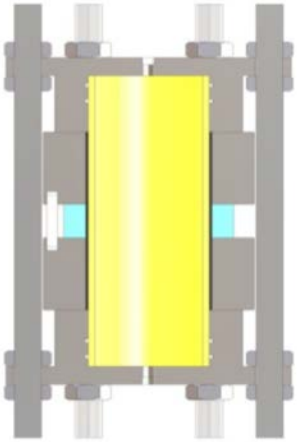

Figure 3-21 Type 2B Ring Crush Sample and fixture

Results

Obtained results are summarized in Table 3-3. The lowest burst pressure in CGS 75C specimen is representative of the material performance.

Table 3-3 Type 2B Single Ring CGS Test

CGS Specimen	Burst Pressure (psi)	Maximum Strain	Remark
75A	24304*	0.0055	Strain at pressure 17768 psi
75B	24138*	0.0053	Strain at pressure 17922 psi
75C	17379*	0.0046	Strain at burst pressure 17379 psi

* Other structural elements such as anti-extrusion tapes that are required to setup the fixture are also contributing to the obtained burst resistance.

Moreover, as could be observed in Figure 3-22, the failure mode which is the carbon fiber breakage is in agreement with the prediction model.

Figure 3-22 CGS (Cylindrical Gap Span) test

Post-processing

The pressure supported only by Type 2B ring in CGS test can be calculated with the measured strains from strain gauges, as summarized in Table 3-4. The expected pressure of CGS ring calculated with type 2B tape base properties by using Tsai-Wu failure criteria, is also summarized in Table 3-4.

Table 3-4 CGS results compared with Tsai-Wu analysis results

CGS Specimen	**Pressure taken by type 2B ring at Burst Pressure (psi)**	**Predicted type 2B ring burst pressure from Tsai-Wu criteria (psi)**
75A	19442	17632
75B	18447	
75C	11968	

The lowest CGS burst pressure result (CGS 75C) will be utilized in prediction of the burst pressure for the phase 2A prototype (Task 16, discussed in Section 3.5.4.)

3.1.6 End fitting Potting/anchoring Pullout and Fatigue Tests

Scope of work

End fitting potting anchoring pullout and fatigue tests are designed to confirm the anchoring capacity and fatigue resistance of the tensile armors within the end fitting. It confirms the anchored length and termination enhancement as described in Section 2.3.4. The fatigue testing was not completed during Phase 2A and will be conducted in Phase 2B.

Test Description

The test set up is illustrated in Figure 3-23Figure. A single tensile reinforcement stack per the RPSEA pipe design is potted into a wedge shaped cavity to simulate the potted cavity in the end fitting. Tensile load is applied to the wedges. A test to failure determines the anchoring capacity of the end fitting termination. The test samples are immersed in water for 7 days prior to the test to confirm that water ingress into the potted cone does not affect the pullout resistance. Strain gauges are installed on the tensile stack prior to the test. The fatigue test is conducted to compare the stress range to failure with that of unpotted tensile armor stacks away from the end fitting. High stress range, low cycle fatigue tests will be conducted at the stress range which results in 10^3 to 10^4 cycles to failure based on unanchored tensile reinforcement stack fatigue test data. 5 samples will be tested at one stress range.

Figure 3-23 Pullout Test Fixture and Setup

Results

Figure 3-24 provides the sample tension and elongation graph. As shown, when the load was increased from 2% ~ 25% and 2% ~ 50% target failure load, the end fitting compound within the steel fixture displaced. This is the result of the mold release, which allows relative motion between potting compound and the steel fixture, and the deformation of the steel fixture itself.

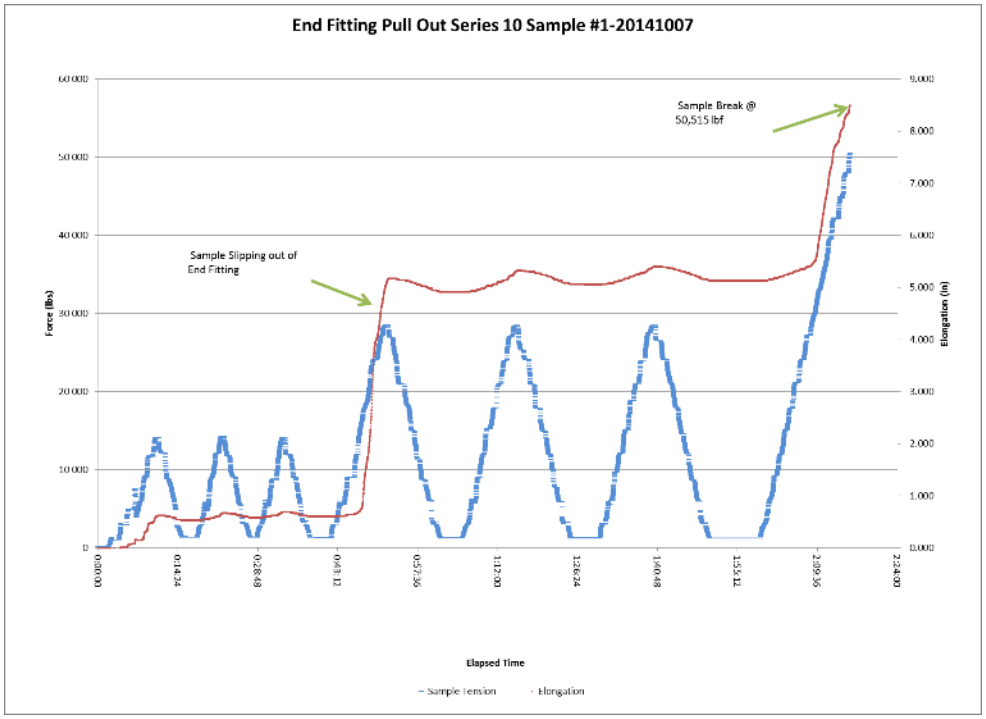

Figure 3-24 End Fitting Pullout Test – Load and Displacement versus elapsed time

However, successful results are obtained as failure occurred in the tape outside the wedge (see Figure 3-25).

The sectioning of one end of the end fitting pullout test, Figure 3-26, indicates that the bonding between the tape and the end fitting compound maintained intact throughout the test. The composite tensile stack did not have any observable failures within this end. The end fitting compound ruptured at two locations. One was located at the very end of the embedded carbon fiber stack (see left image Figure 3-26). The other location appeared to be near the first split in the carbon fiber tape. There were additional hair line cracks through the tape. It was difficult to determine if these cracks were from the testing or the post-test dissection process.

Figure 3-25 Pullout sample failure

Table 3-5 compares the experimental finding versus model prediction for this test.

Table 3-5 Pullout Test Summary

Number of Samples	Expected Failure Tension Value	Obtained Failure Tension Value
2	56,700 lbs	50,503 lbs

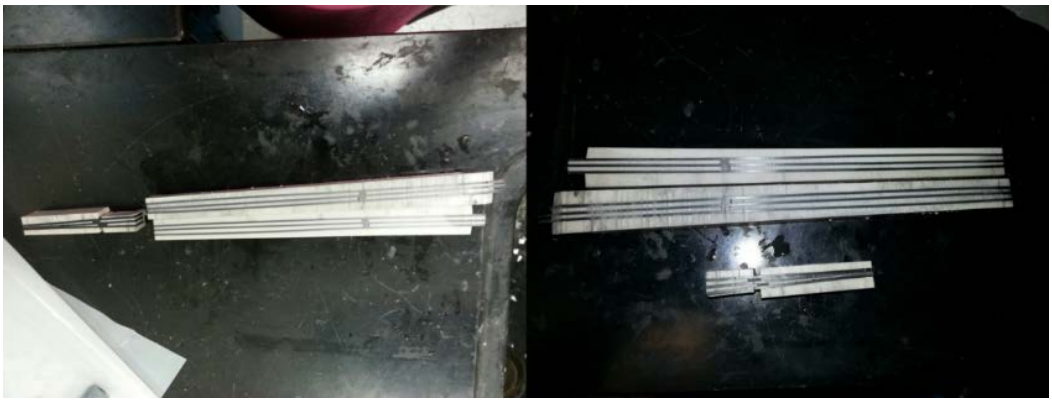

Figure 3-26 Pullout Test Specimen Dissection

3.1.7 Tensile Armor Bend Back Test

Scope of work

During the end fitting termination procedure, tensile stacks are required to be bent back such that sufficient room for installation of underlying end fitting structural components and seals is provided. The bend back imposes a combined bending and torsion loading on the tensile armors. If the extent of bend

back exceeds the limits, matrix cracking may be initiated in the stacks. This will have potential impact on the aforementioned failure mechanisms during end fitting installation, the maximum shear stress and strain in the composite tensile armor stacks are controlled within the allowable value, determined as the ultimate shear stress and strain divided by a factor of safety. For this purpose, in this study, a combined numerical and experimental approach is developed as follows; a single stack torsion test is conducted to obtain the shear modulus, interlaminar shear failure and matrix cracking onset shear. The experimental data is then input to a 3D finite element model to confirm that the tensile reinforcement stacks will not be subjected to unacceptable matrix cracking during end fitting installation.

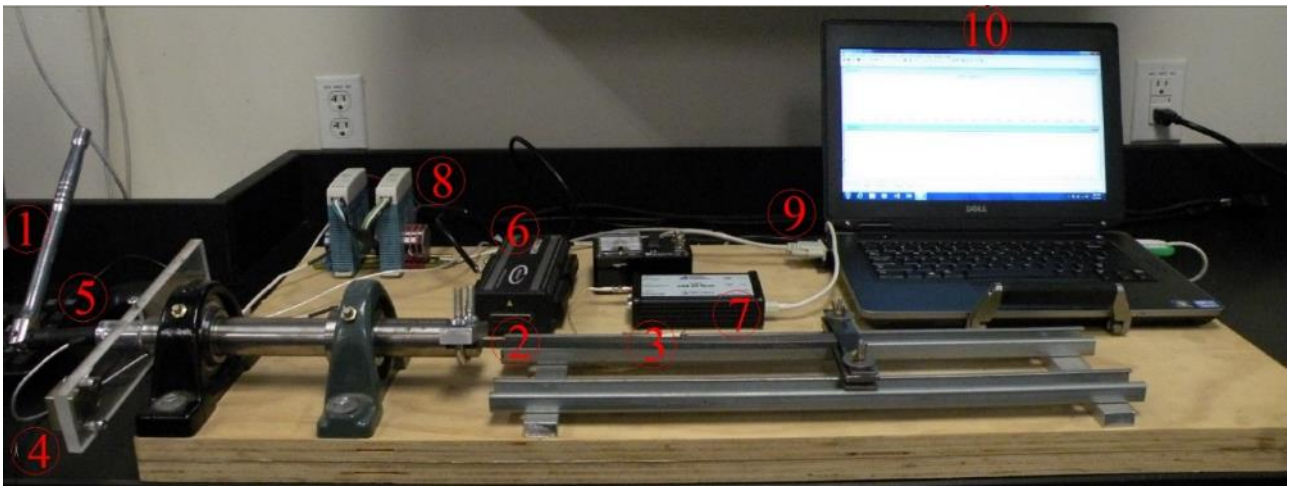

Figure 3-27 Test Setup – (1) torque handle (2) Composite Stack (3) Acoustic Emission Sensor (4) Inclinometer (5) Torque meter (6) Low band-width Data Acquisition System (7) High band-width Data Acquisition system (8) Sensor Power Supply (9) Serial Port (10) Software Interface

Test Description

The allowable torsion test is conducted using the test apparatus illustrated in Figure 3-27. Fixing both ends of the composite stack (2) and applying the input torque using the load handle (1), the structural response of the specimen to the pure torsion loading is monitored. There are three major sensing modalities embedded in the experimental setup; a torque meter (5) to record the applied moment, an inclinometer (4) to measure the twist angle and the acoustic emission sensor (PICO, Ultra-mini WB AE Sensor produced by Mistras) (3) to capture the acoustic signals generated inside the stack structure.

Test Results

Ten samples are tested in this study. Obtained results are illustrated in Figure 3-28 and Figure 3-29. As expected, by increasing the applied torque, twist angle increases in a relatively linear manner, up to a point where the torque meter indicates a sudden drop. This indicates the occurrence of brittle failure and the shear stresses reaching their ultimate value($\widehat{\sigma_{12}}$). The stack torsional stiffness as well as the ultimate shear strength of the laminate could be extracted from this result. In order to obtain a more precise understanding of the tensile armor structure behavior near the end fitting where it is subjected to maximum tension loads, as part of the experimental setup, the acoustic emission sensor is used to capture the elastic waves as the loading is in progress. Figure 3-28 plots the average frequency-average amplitude envelope for the recorded signals: 1-As the loading begins, the captured acoustic data remain in a low frequency-low amplitude region (less than 200 KHz and 50 dB). 2-Prior to the drop of applied torque, there is a jump in the average frequency of the received signals (up to 1000 KHz) while the average amplitude remains almost the same. An average crack size of 1.5 ply thickness produces the

peak frequency of 900 kHz to 1200 KHz. Therefore, considering the generation of elastic waves inside anisotropic materials, this sudden signal frequency variation suggests a major internal structure variation indicating initiation of micro-cracks inside the composite matrix prior to exceeding the ultimate structural failure. 3-As the loading continues, high frequency signals are more frequently recorded which could be interpreted as formation of more micro-cracks in the stack matrix. As the applied torque increases, there is a second frequency jump (2000 KHz) that coincides with the ultimate failure of the stack.

Following the torque drop, the acoustic emission sensor also detects several low frequency signals with relatively high amplitudes. These correspond to the post-damage waves that are low frequency-high amplitude audible signals.

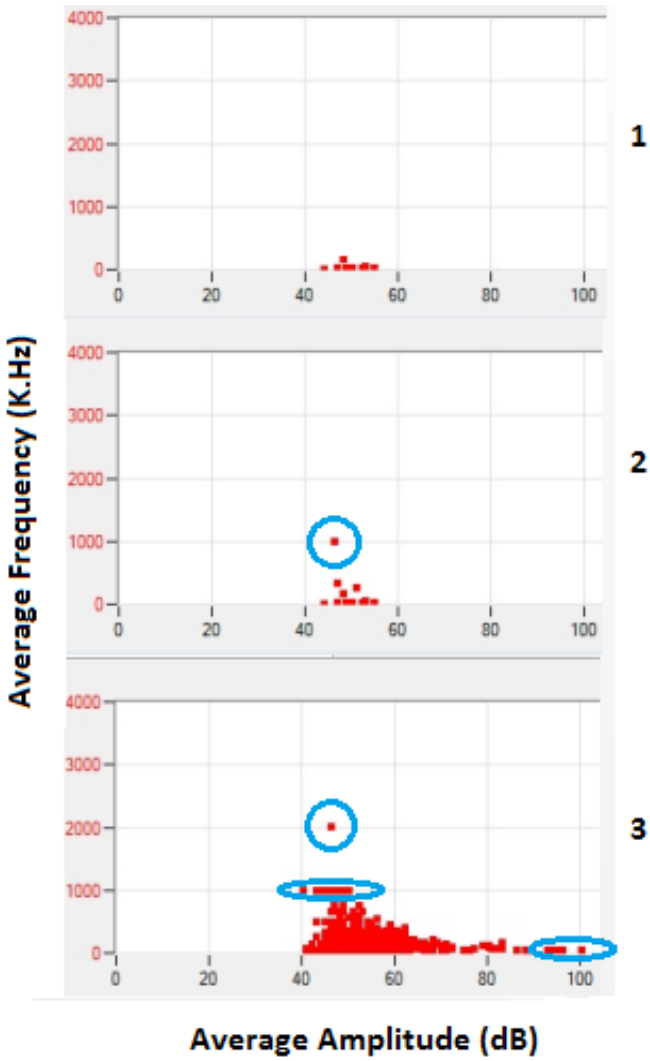

Figure 3-28 Acoustic Signals

Figure 3-29 maps the mentioned signal pattern to the structural response of the stack. In order to have a more precise understanding of the acoustic emission waves and how each internal structure alteration could be uniquely mapped to the detected signals, one can study the complete frequency response of the structure rather than looking at the average values. In the current case however, since the average amplitude of the received signals remained within a relatively narrow window (50 dB), utilization of average frequency results in reliable interpretation of events.

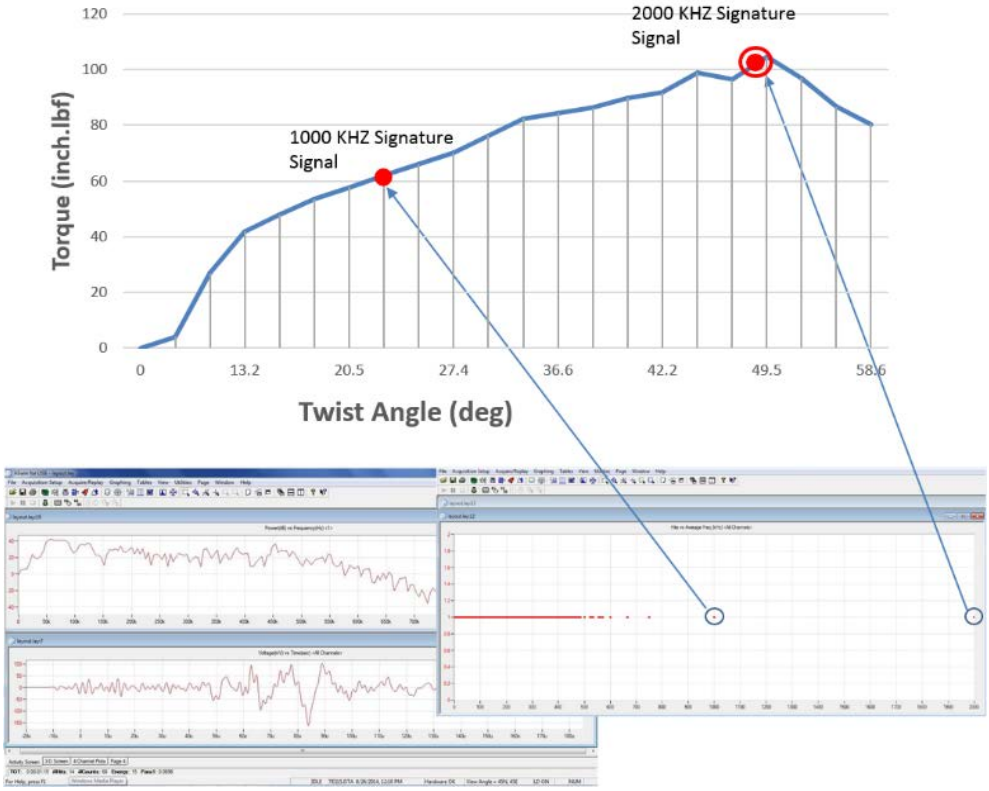

Figure 3-29 Crack Onset Detection

Table 3-6 summarizes the results of the test. As shown, there are two outliers observed among all specimens, which could be indicative of either sample preparation issues or measurement errors. From data provided in Table 3-6, the cracking shear stress is considered as the failure criterion in the bend back finite element model to obtain the extent of bend back. The FE model utilizes 3D 8-node linear brick elements to simulate the tensile armors. In addition, including the contact elements between the tensile layer and adjacent layers provides more realistic numerical outputs. Figure 3-30 illustrates the final configuration of the tensile armors. This model provides a design methodology to prevent matrix cracking in the tensile armors bend back process, meeting the requirements of API 17B Annex H [18].

Table 3-6 Tensile Armor Bend Back Test Results

Sample	Cracking torque	Break Torque	Cracking Shear stress	Break shear stress	Shear modulus (Cracking)
	(ft-lbf)	(ft-lbf)	(ksi)	(ksi)	ksi
1	2.98	8.41	3.69	10.40	706.11
2	4.13	7.4	5.11	9.15	611.63
3	4.07	7.99	5.03	9.88	688.85
4	3.00	8.41	3.71	10.40	710.85
5	3.09	7.93	3.82	9.81	610.15
6	1.89	5.32	2.34	6.58	746.39
7	3.38	7.29	4.18	9.02	667.41
8	2.40	8.41	2.97	10.40	947.80
9	6.86	8.72	8.48	10.78	580.53
10	2.98	7.69	3.69	9.51	882.64
Allowable			3.6		

*Allowable value is based on 90% AVERAGE VALUE.

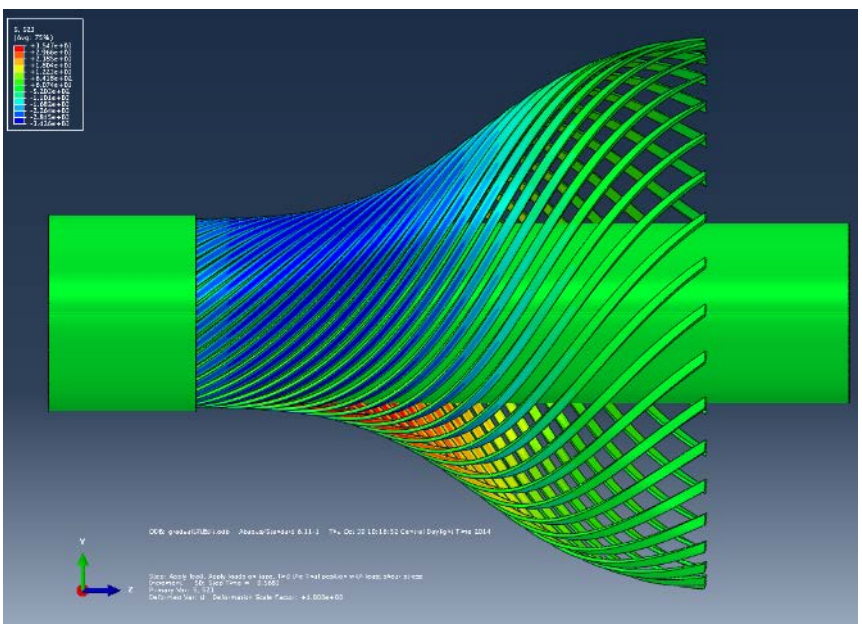

Figure 3-30 Finite Element Bend Back Model

3.2 Task 13 – Gap Span Tests

3.2.1 Scope of Work

The Subcontractor shall conduct gap spanning tests in accordance with Section 3.2 of 10121-4402.08.FINAL to provide an evaluation of the polymer layers thinning against the acceptance criteria.

Section 3.2 of 10121-4402.08.FINAL states: "

The purpose of the gap spanning tests is to confirm the minimum thickness tolerance of the E0 liner and E1 membrane layers, and the maximum gap tolerances between adjacent wraps of the adjacent pressure armor and hoop reinforcement layers R1 and R2. In particular, this test is designed to:

- Simulate maximum gap in pressure armor and test liner at maximum design conditions.
- Simulate maximum gap in composite hoop layer and test membrane at maximum design conditions.

3.2.2 Test Description

The gap spanning test apparatus as well as the Z-interlock sample is illustrated in Figure 3-31.

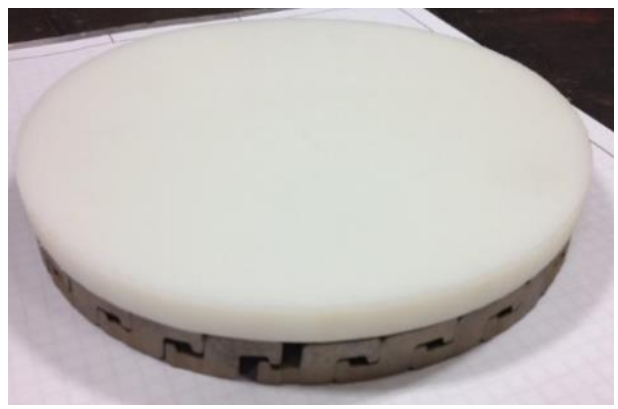

Figure 3-31 Gap Spanning Test Apparatus and Test Specimen

The test apparatus simulates the extrusion of liner material (PVDF) in flat sheet form, supported by Z interlocking pressure armor sections. The pressure load is simulated by a soft viscoelastic pad. The use of the viscoelastic material to simulate the internal pressure makes the test protocol much easier and safer than loading with a liquid pressure source. The small amount of pressure load taken by the rubber pad is adjusted from the test results. The flat liner material is pressed against a flat weldment or composite layup that is made from R1 hoop layer 1 Z interlocked wires or R2 hoop layer 2 composite reinforcement stacks. The liner pad thickness is the minimum tolerance thickness for the layer. The hoop layer sections are configured so that they have the maximum gap between adjacent wraps (fully extended for the metallic interlocked hoop layer 1, maximum gap tolerance plus expected opening due to pipe bending to MBR for composite hoop layer 2). The pressure loading and duration simulates the factory acceptance testing followed by design pressure and temperature conditions for a sufficient period to take into account creep of the liner layer. The change in polymer thickness and flow of polymer material into the gaps is used to validate the gap spanning model and confirm the minimum thickness

tolerance for the E0 liner and E1 membrane. Figure 3-32 shows the schematic of the setup when liner is tested against metallic Z-interlock layer.

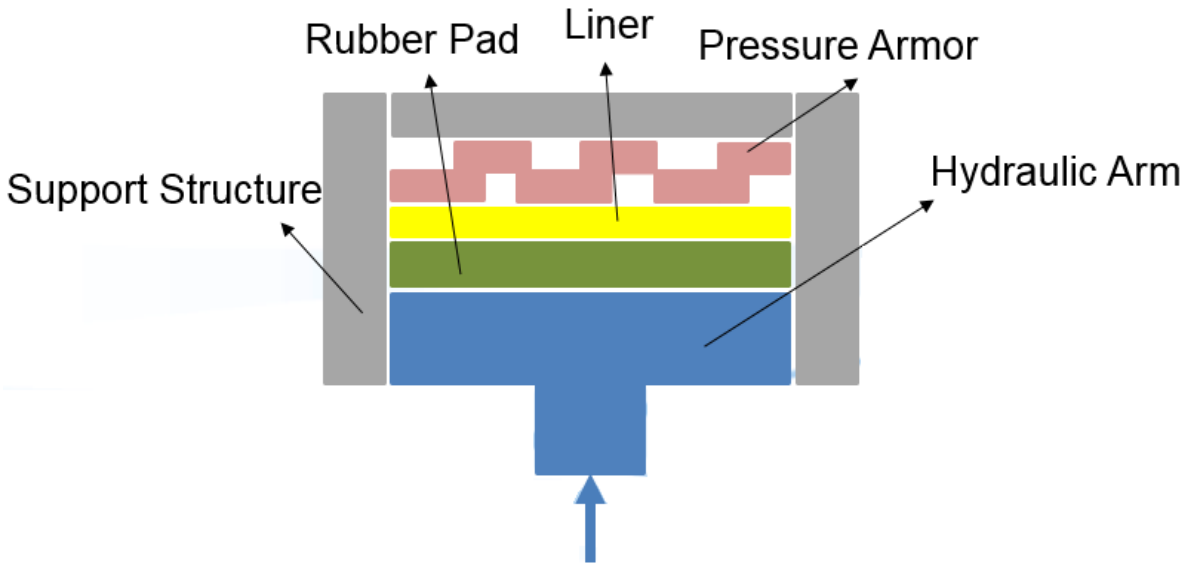

Figure 3-32 Schematic of the Creep test fixture

3.2.3 Results

Table 3-7 shows the load cases considered for this test. The most critical case in terms of layer thickness reduction is found to be case 6 where the liner thickness is the minimum value and the high bore temperature maximizes creep of PVDF inside the Z-interlock armor gaps.

Table 3-7 Gap Span Load Cases

	Polymer layer	Polymer layer Thickness	Armor Layer	Pressure (psi)	Temperature (F)	Test Condition
1	Liner	Nominal	Metallic Hoop	17165	77	FAT
2	Liner	Nominal	Metallic Hoop	11065	233	Max Operation
3	Membrane	Nominal	Composite Hoop	7133	77	FAT
4	Membrane	Nominal	Composite Hoop	4742	205	Max Operation
5	Liner	Minimum	Metallic Hoop	17165	77	FAT
6	Liner	Minimum	Metallic Hoop	11065	233	Max Operation

The results corresponding to the load case 6 are shown in Figure 3-33. As indicated, approximately at 800 seconds, the PVDF liner fills the gap completely and so no more creep occurred after.

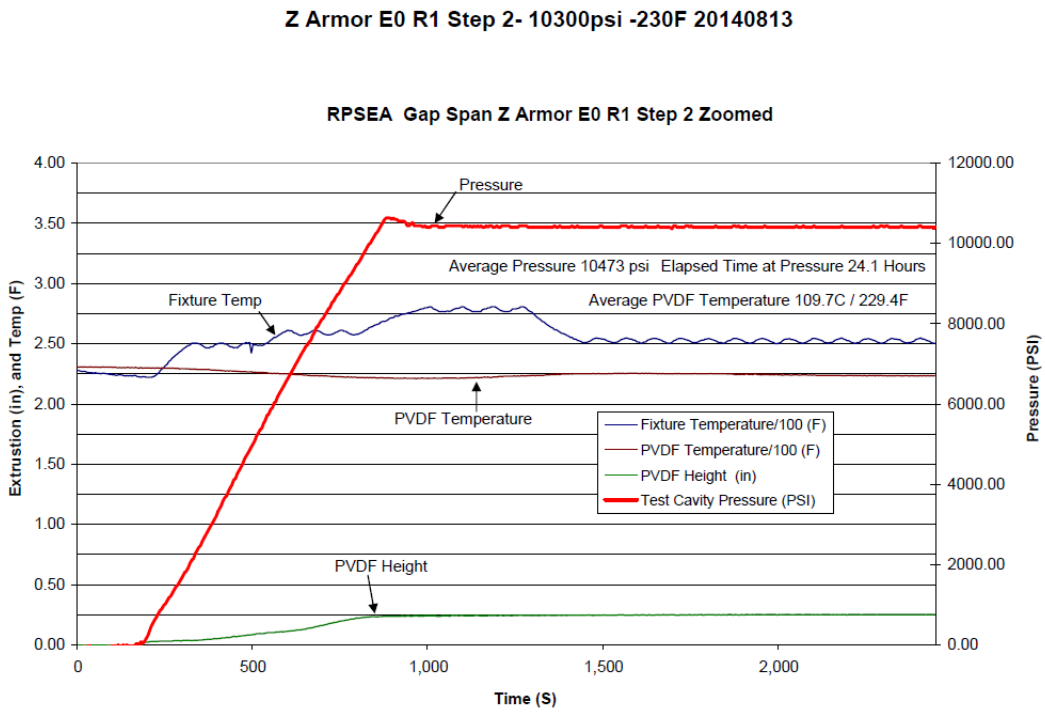

Figure 3-33 Load Case 6 results

The post-creep cross section of sample is investigated to confirm that the reduced liner thickness is still within the acceptable range per the API 17J requirement. The data also is used to calibrate the numerical model generated during phase 1. Figure 3-34 shows the calibration process as discussed. A quick comparison between the FE result and test output suggest that the numerical model is conservative in predicting the final thickness of the layer.

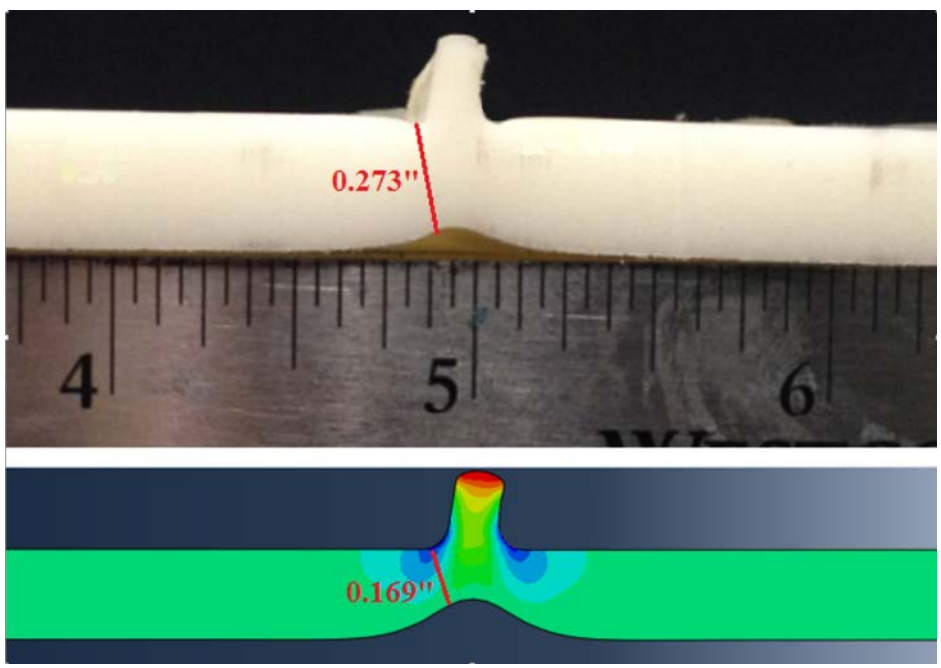

Figure 3-34 Numerical versus Experimental Results

The data obtained from the gap spanning tests was used to calibrate a creep model to provide more precise prediction for creep behavior of the layer. Figure 3-35 presents the creep material property model for PVDF which is obtained by curve fitting the coupon test results. The results of the gap span tests, supported by the creep model analysis verified that the liner and membrane wall thicknesses in the design meet requirements.

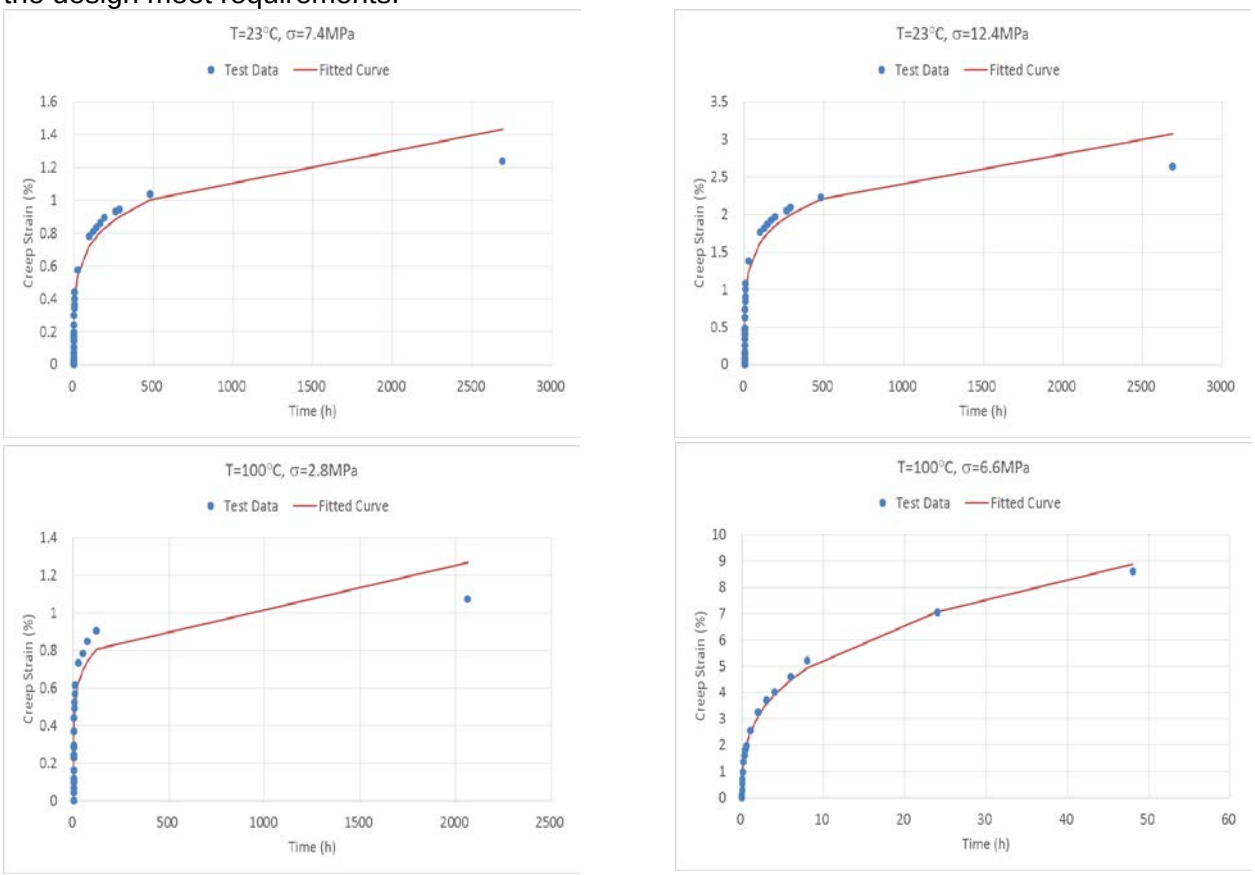

Figure 3-35 Creep Model Calibration

3.3 Task 14 Wear Test

3.3.1 Scope of Work

This task consists of wear and friction tests between the tensile reinforcement stacks and the anti-wear tapes. The friction tests are to confirm the friction coefficient between the anti-wear tape and the tensile reinforcement stacks, which is used in the analyses to evaluate the alternating stresses in the tensile armor layers for the service life analysis. The wear tests are also to confirm that the tensile reinforcement stack will not be subject to significant wear from the relative movement and contact pressure between the stack and the anti-wear layer, and to confirm that the anti-wear layer will not wear through over the service life of the pipe. The potential wear due to relative motion between the adjacent stacks in the same layer will be analyzed and evaluated during the test if it is relevant.

3.3.2 Test Description

A test apparatus which has been employed by DeepFlex for previous wear tests is illustrated in Figure 3-36. This fixture has the capability to simulate reciprocating relative motion, contact pressure, temperature and the environmental condition at the tensile armor/anti-wear layer interface. The contact pressure is applied by the weighted level arm reacting against a platen to which the reinforcement sample is fixed. Relative movement between the reinforcement sample and anti-wear sample is

achieved by a motor, crank and slider arm assembly which reciprocates the anti-wear sample holder relative to the reinforcement sample.

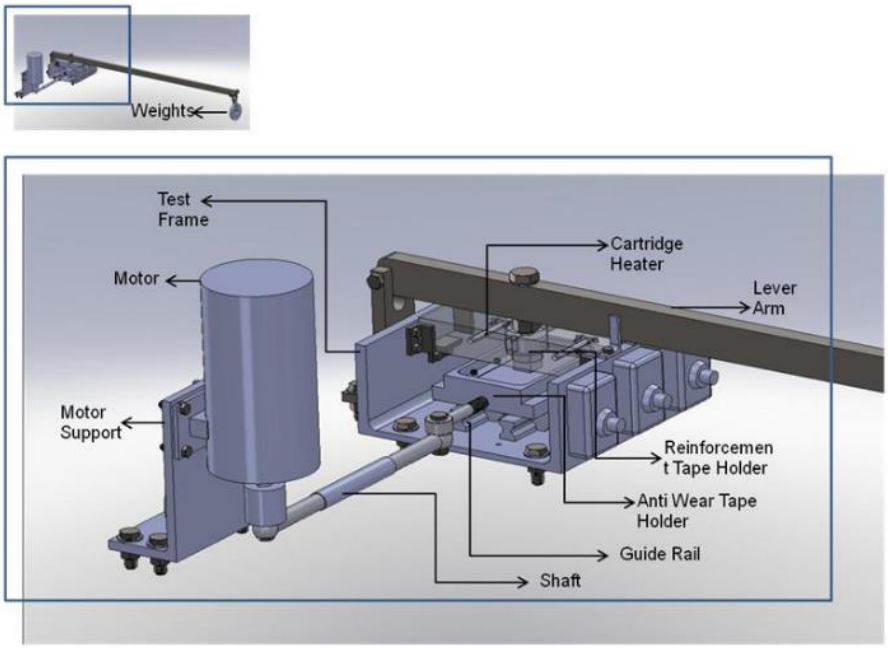

Figure 3-36 Wear Test Setup

Results

Table 3-8 summarizes the load cases and samples considered for this task.

Table 3-8 Wear Test load cases

Case	Reinforcement stack	Contact Pressure	Sacrificial Outermost tape	Temperature	Environment	Test duration
1	4 tape 2A carbon stack	1200 psi	None	Ambient	Air	250,000 cycles
2				Ambient	Water	
3				140 F	Water	
4			Type 1A glass fiber tape	Ambient	Air	
5				Ambient	Water	
6				140 F	Water	
7			Aramid Fabric	Ambient	Air	
8				Ambient	Water	
9				140 F	Water	
10	UD aramid tape		None	140 F	Water	

The four different samples mentioned in Table 3-8 are shown in Figure 3-37. To simulate the entire service life of the pipe, the number of test cycles are calculated as follows: Design premise document [6] provides 14 fatigue bins along with the corresponding probabilities and wave periods. Considering 3 different wave directions and two regions on the pipe (top section and TDP), 84 load cases were defined in global fatigue analysis. The maximum curvature for these load cases was obtained during phase 1 study as provided in the design report [4]. A full –MBR to +MBR bending results in 0.0315 m sliding length. Utilizing a linear correlation, the associated relative motion for each load case is calculated. Summation of all these values for each load case, considering their probability, it is

estimated that during 25 year service life of the pipe, the maximum relative motion for each stack is found to be 8720m. Finally, considering the 0.035 m sliding stroke of the test fixture, it could be concluded that 250,000 test cycles would simulate the wear behavior of the tensile layer-wear tape interaction during the full service life of the riser system.

Figure 3-37 Wear Samples

For load cases 1 to 3, without a sacrificial outermost tape on the reinforcement stack, the anti-wear tape was torn apart in less than 10,000 cycles suggesting that the PVDF anti-wear tape will not survive through the service life of the pipe. Figure 3-38 shows the surface of the anti-wear tape after 4,000 cycles.

Figure 3-38 anti wear tape surface after 4000 cycles (load case 1)

In addition to tear issue with the anti-wear tape, it is also observed that the relative motion causes the reinforcement stack to lose a considerable amount of material as shown in Figure 3-39.

Figure 3-39 Reinforcement Material Loss after 4000 Cycles (load case 1)

While the load cases corresponding to the sample coated with glass fiber tape (4, 5 and 6) survived throughout the pipe service life, a considerable amount of reinforcement material is observed to be removed from the tensile stack. In contrast, the results of load cases 7, 8 and 9 where the tensile stack had a woven aramid fabric as the outermost layer showed that not only the reinforcement material won't be removed from the tensile stack, but also the wear foot print on the surface of the anti-wear tape is limited and minimal. Figure 3-40 shows the results of load case 9 which resembles the most critical condition for the aramid coated sample. The results of load case 10, for which the sample was a unidirectional aramid tape pultrusion were similar, as illustrated in Figure 3-40.

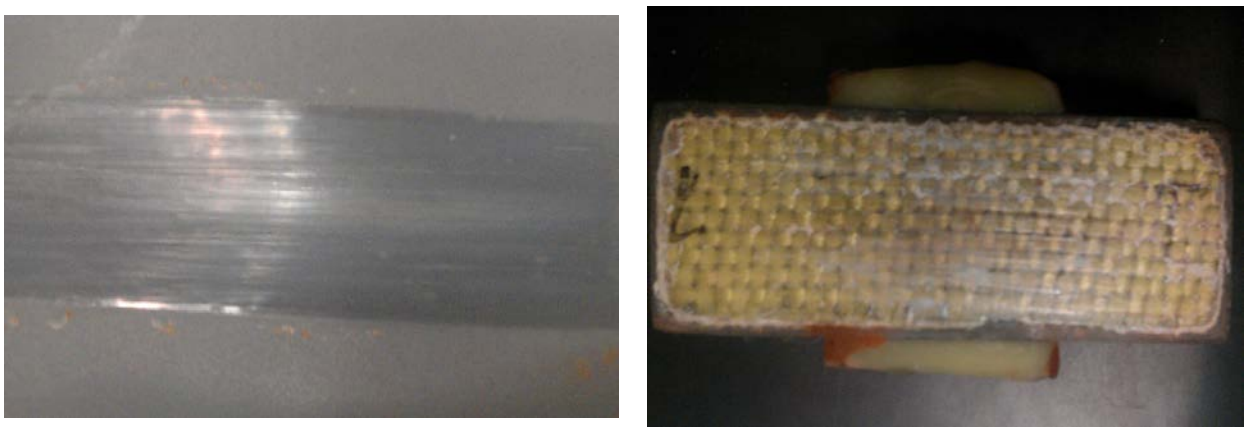

Figure 3-40 Results after 250,000 Cycles (load case 9)

During the execution of the test, applied normal load as well as the push/pull forces are recorded real-time utilizing the load cells included in the fixture. This data was used to validate the coefficient of friction which is selected for the tensile armor layer bending stress analysis conducted as part of the service life analysis.

Figure 3-41 shows the frictional forces and contact force between anti-wear tape and reinforcement stack after 225,000 cycles.

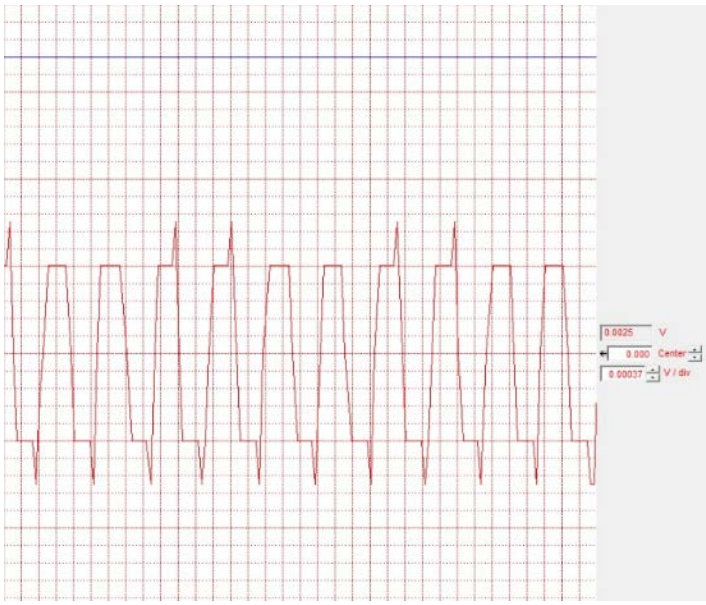

Figure 3-41 Push/pull Forces (in red) and Normal load (blue) after 225,000 Cycles

Table 3-9 summarizes the sensor readings and the calculated coefficient of friction.

Table 3-9 Frictional Forces and Frintional Coefficient

Average push Force (lbf)	Average pull Force (lbf)	Average Normal Load (lbf)	Coefficient of Friction (Associated with push)	Coefficient of Friction (Associated with pull)	Average Coefficient of Friction
102.5	85.1	1471.1	0.069	0.057	0.063

These readings are used to estimate the coefficient of friction which results in re-evaluation of the alternating stresses in the tensile armor layers for the service life analysis.

In summary, per load cases 7 through 10, the aramid fabric and the unidirectional aramid provided acceptable results. The dominant phenomenon is the migration of PVDF material from anti-wear tape to the aramid sample. The tests clearly demonstrate that a wear resistant surface on the tensile armor stacks is needed. One option under consideration for the tensile armor reinforcement stacks is illustrated in Figure 3-42. The top and bottom tapes of the reinforcement stack have aramid fibers on one of the outer surfaces of the tape. At the time of this writing, DeepFlex is working with a potential supplier to develop and screen this and other potential configurations of tensile armor reinforcement tapes with a single anti-wear surface.

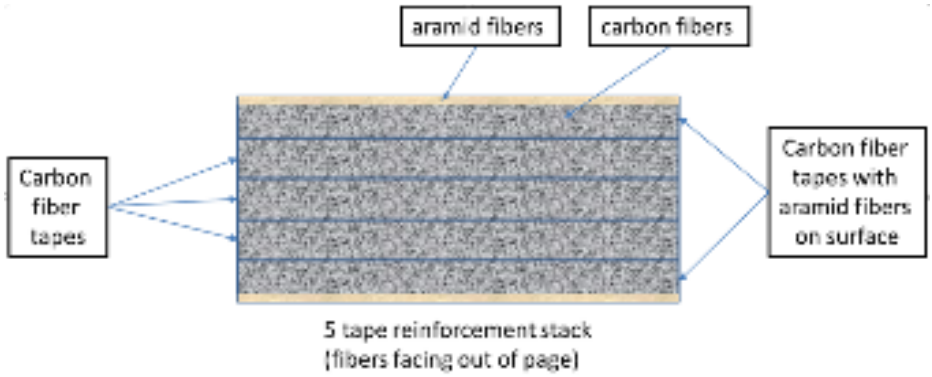

Figure 3-42 Tensile Reinforcement Stack Configuration

3.4 Task 15 Permeation Test

3.4.1 Scope of Work

The Subcontractor shall conduct wear tests in accordance with Section 3.3 of 10121-4402.08.FINAL [12].

Permeated gases are vented to the topside end fitting via the inner annulus helical flow path. Therefore one of the most critical aspects in confirming the feasibility of the pipe design is to assure that the inner annulus pressure will not exceed the collapse pressure of the carcass with sufficient margin of safety. During phase 1, a numerical model was generated to predict the permeation flow rate, composition and annulus pressure. This task is conducted to validate the permeation rate and calibrate shielding factors presented in the design report [9].

3.4.2 Test Description

A short section of a PVDF tube simulating the E0 Liner layer (approximately 1 meter in length) is terminated by end fittings which seal the liner and provide force containment at the ends. Threaded rods surrounding the end fittings are used to react the end cap load due to internal pressure. The simulated pressure armor is machined with a helical gap, with the gap and pitch similar to the R1 Hoop Layer 1 (See Figure 3-43 left). High pressure carbon dioxide is introduced into the bore of the pipe sample. The rate of pressure buildup in the sealed annulus is measured while the pressure in the bore remains constant. Based on the rate of pressure buildup, the flow rate over the exposed length of annulus as a function of the pressure difference between the bore and annulus is calculated.

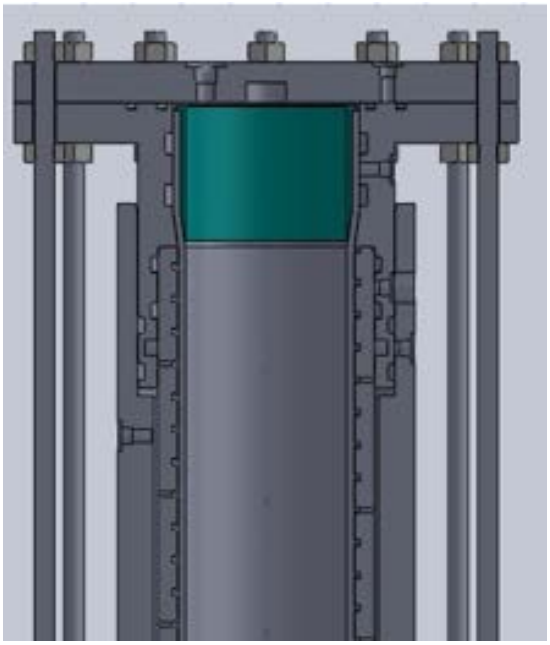

Figure 3-43 Permeation Test Fixture

Four load cases are designed for the permeation test to determine the shielding factor as well as to evaluate the permeability data. Two of them are bare liner permeation tests to check the permeability data and analysis model at 60 °C and 90 °C respectively; two of them are permeation tests with liner and pressure armor to determine the shielding factor. The test load cases are summarized in Table 3-10.

Table 3-10 Permeation Test load cases

Load Case No.	Permeation Cell	Test Pressure (psi)	Test Temperature (F)	Test Duration (hrs)
1	Bare Liner	50	140	480
2	Bare Liner	50	194	240
3	Armored	725	140	120
4	Armored	725	194	72

3.4.3 Results

The permeability data for CO2 through liner material PVDF is extracted from Solvay MQ data as shown in Table 3-11. The permeability data against the reverse of temperature has a log-linear relation, as shown in Figure 3-44.

Table 3-11 Permeability data for CO2 through PVDF

Temperature	Permeability for CO2 through PVDF
(°C)	($x10^{-8}$ cm^3/cm*sec*bar)
75	8.403
90	15.53
105	26.98
135	69.89

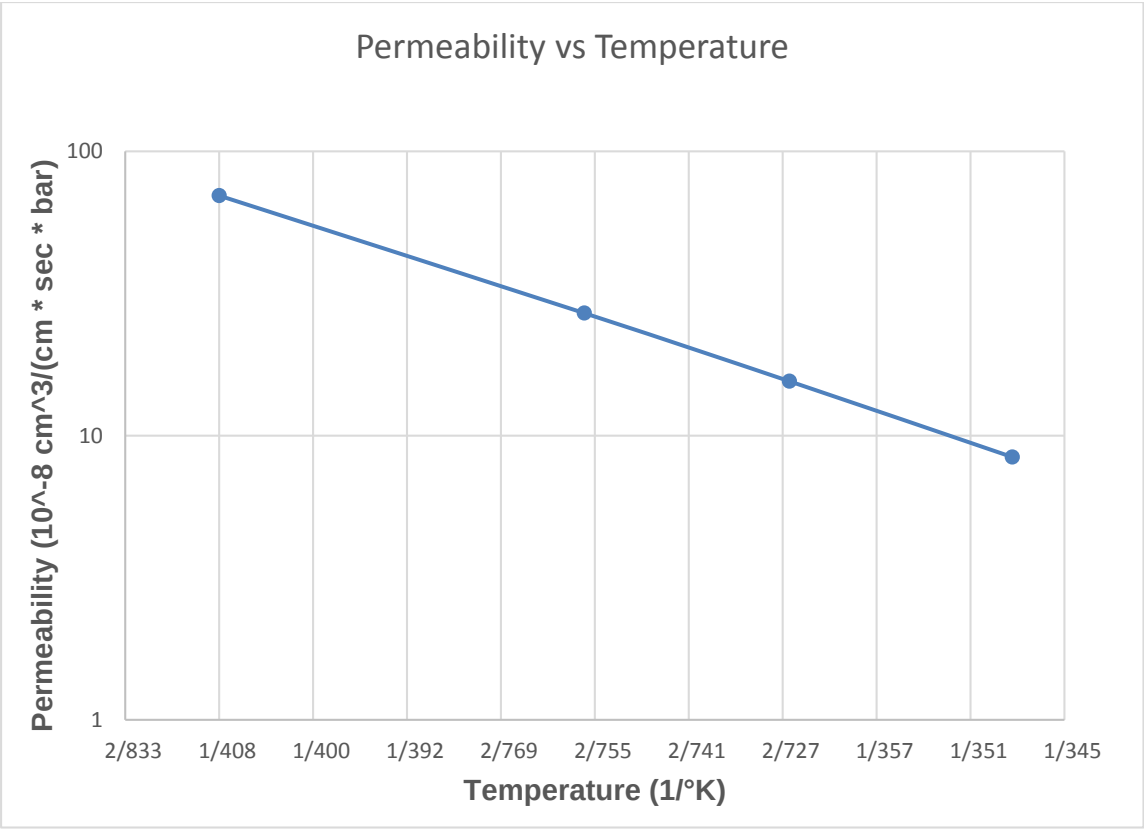

Figure 3-44 Permeability of CO2 through PVDF

The first load case was tested with bare liner under the environment temperature of 60 °C, with the bore pressure set to 50 psi to reduce the liner creep and avoid bursting the liner. The test results are shown in Figure 3-45. The dip on the curve is due to a pressure excursion on the bore pressure caused by improper regulator adjustment. By shifting the test data curve to left by 2.5 days to consider the liner absorption and saturation time (lag time), it is found that the slope of test curve is almost same as the slope on the model prediction curve. The slope of the curve is linear to the permeability, so the bare liner test results show the permeability data used in analysis is valid.

The second test is being executed utilizing the identical test setup under the elevated temperature 90 °C, while the bore pressure is kept the same compared to load case 1. The test results are shown in Figure 3-46. The liner absorption and saturation period related data is already trimmed in the graph. At the beginning, the slope of test curve is found to be almost the same as the slope on the model prediction curve. As the test progresses, the permeation rate drops suggesting the relatively lower annulus pressure toward the end of the test.

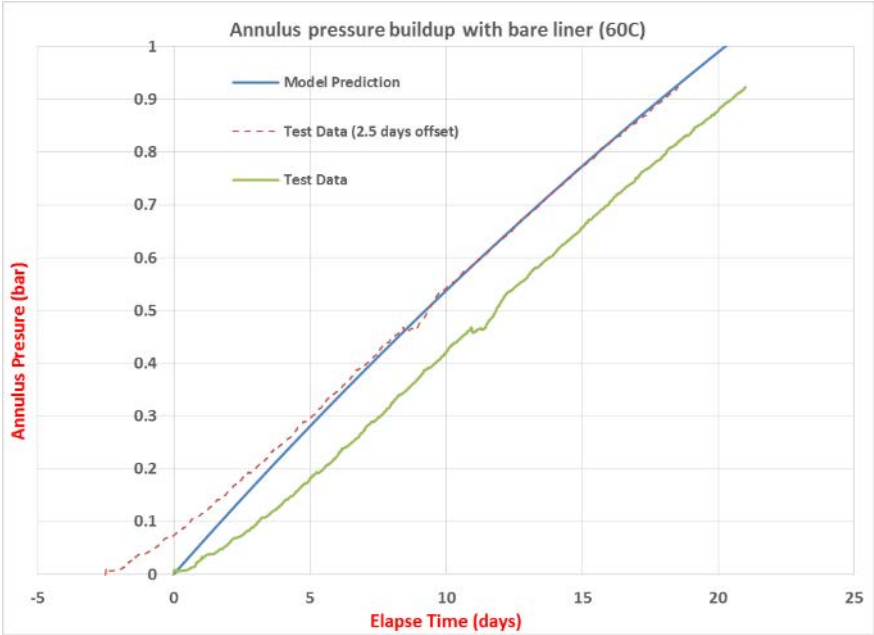

Figure 3-45 Bare Liner permeation test results at 60 °C

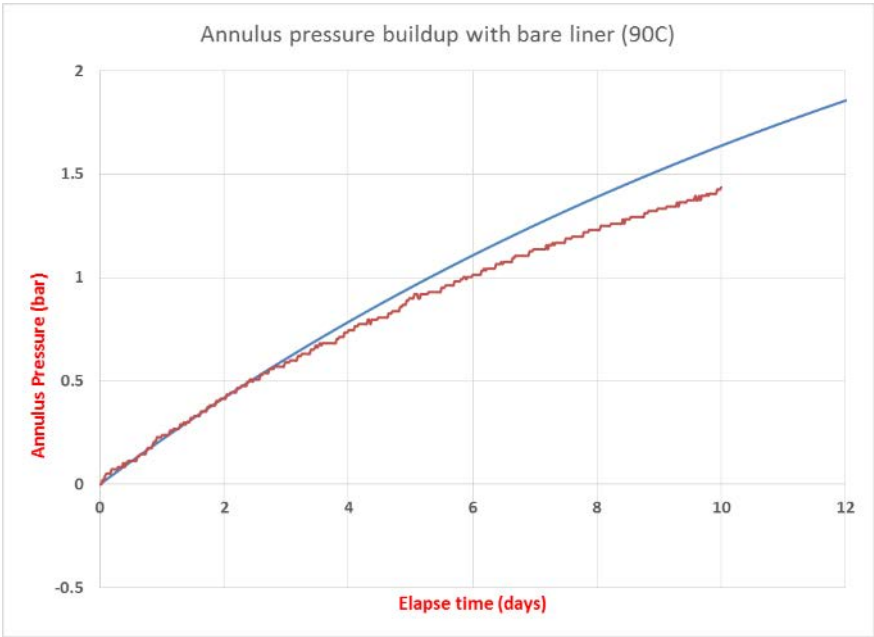

Figure 3-46 Bare Liner permeation test results at 90 °C

The third load case was tested with liner and pressure armor at 60 °C. This load case is repeated twice, with one test performed from the beginning after the test setup was assembled, and another right after load case 4' is finished so the lag time is not observed. The test data are plotted with model prediction under different shielding factors in Figure 3-47. The first time test curve is shifted by 3 days to compensate for the lag time. The curves from both tests have similar slope to the model prediction with 0% shielding factor.

The tests are performed with bore pressure 725 psi. From the test results, it seems that this bore pressure cannot produce enough contact pressure between liner and pressure armor so as to prevent gas from diffusion through the contact area.

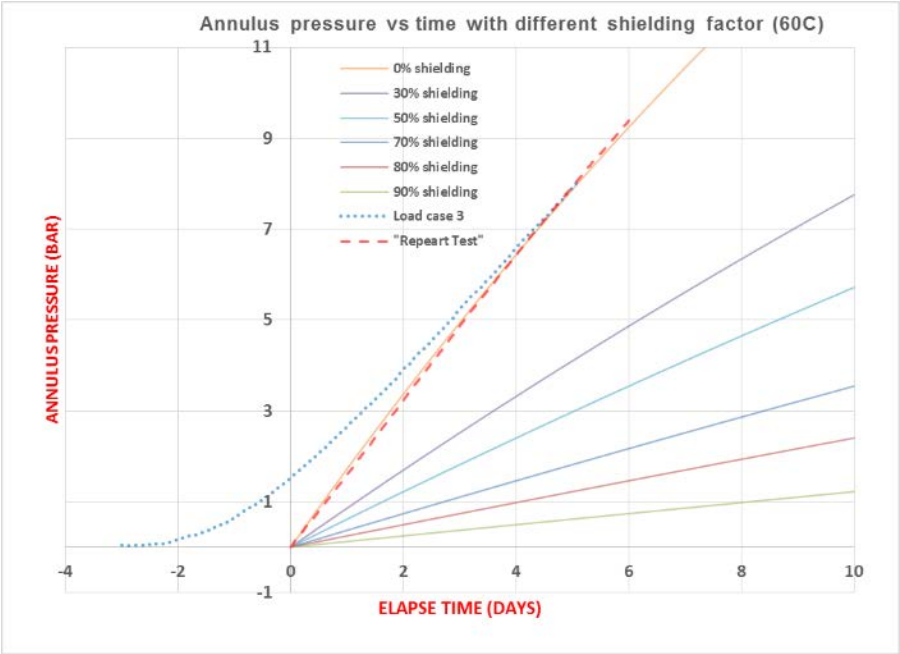

Figure 3-47 Permeation test with Liner and Pressure armor at 60 °C

The third test (Load case 4) was performed with liner and pressure armor at 90 °C. The test was performed after the liner was pressurized for a few days at 90 °C before data was recorded, so the lag time is not shown on the curve, see Figure 3-48. The test data is between the 30% to 40% shielding factor model prediction curves.

To further quantify the shielding factor from pressure armor, load case 4 was repeated increasing the bore pressure to 1000 psi (Load case 4'). Again the lag time is not shown in the test data because load case 4' was performed right after load case 4 finished. The results of load case 4' compared to model prediction is plotted in Figure 3-49. A shielding factor of about 20% is obtained from load case 4'.

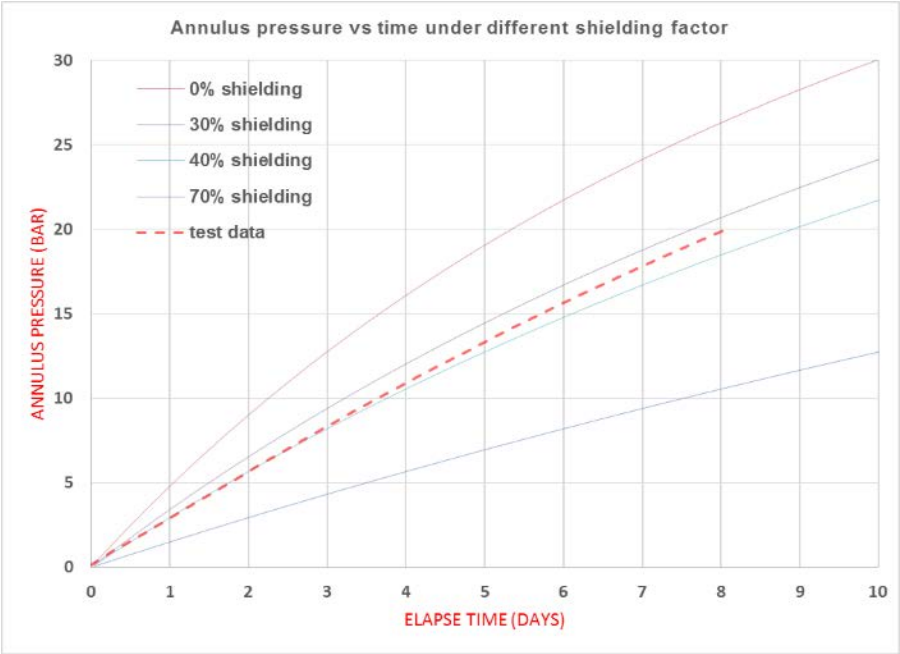

Figure 3-48 Permeation test with Liner and Pressure armor at 90 °C (bore pressure is 725 psi)

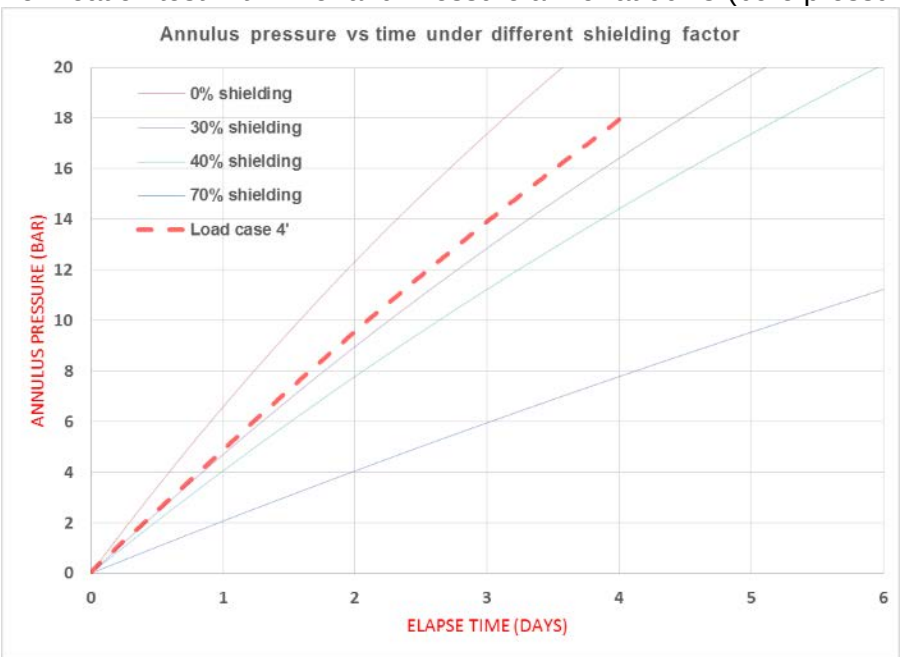

Figure 3-49 Permeation test with Liner and Pressure armor at 90 °C (bore pressure is 1000 psi)

Comparing the test results with pressure armor under 60 °C and 90 °C, shielding is observed at 90 °C. It is concluded that the high temperature increases the contact between liner and pressure armor thus providing some shielding. However, the shielding factor obtained from tests is not close to the theoretical shielding factor calculated with the coverage ratio (~80%). Further analysis of the test results and model refinement, and additional tests if considered necessary were planned to be conducted during Phase 2B to verify or update the conclusions of the permeation and annular pressure drop analyses conducted during Phase 1. This work was not started.

3.5 Task 16 – Phase 2A Prototype Manufacturing and Test

3.5.1 Prototype Manufacturing

Scope of Work

The Subcontractor shall procure the pipe sample materials and construct the pipe layer by layer as specified in Table 3-12, at their manufacturing facility. Subcontractor shall manufacture two 10 meter length of the prototype pipe and two end-fittings.

Table 3-12 Phase 2A Prototype sample

Layer	Material
Liner	PA-11
Pressure Armor	Carbon steel-sour service grade
Membrane	HDPE
Burst Reinforcement (Composite Hoop)	Type 2B
Tensile Reinforcement	2 layers - Type 2A

The subcontractor shall conduct a burst pressure test as per DeepFlex Burst Pressure Test Procedure (A-ENG-SOP-10102) and a tensile test per DeepFlex Axial Tension Test Procedure (A-ENG-SOP-10103).

Subcontractor shall prepare and submit a report to the DOE/NETL/RPSEA working committee for review and approval documenting the results of the Phase 2A Task 12 through Task 16 tests. The report will reference the test procedure and provide an evaluation of the material, layer and prototype pipe performance against the acceptance criteria.
The prototype was manufactured in the DeepFlex Manitowoc manufacturing facility. The cross section of the Phase 2A prototype is illustrated in Figure 3-50.

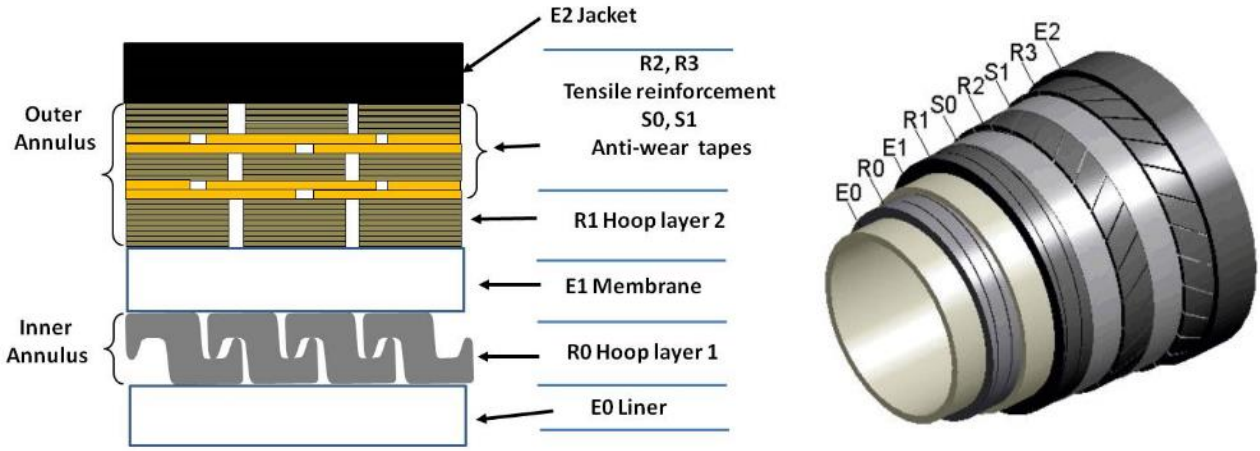

Figure 3-50 Phase 2A pipe cross section design

The prototype for Phase 2A is manufactured using the smooth bore liner due to lack of availability of a carcass forming machine at DeepFlex. The differences in the pipe composition for phase 2A and 2B are listed in Table 3-13.

Table 3-13 Layer by Layer Comparison of Phase 2B and 2A Prototype

Layer	Prototype - Phase 2B Materials	Prototype – Phase 2A Materials
Carcass	Duplex	Not included
Liner	PVDF	PA-11
Pressure Armor	Carbon steel	Carbon steel
Membrane	PVDF	HDPE
Burst Reinforcement (Composite Hoop)	Type 2B	Type 2B
Tensile Reinforcement	4 layers – Type 2A	2 Layers –Type 2A
Outer Sheath	PA-11	HDPE

3.5.2 Pipe Design and Construction

Figure 3-51 illustrates the different stages of manufacturing the pipe.

Figure 3-51 Phase 2A pipe manufacturing

During manufacturing of the pipe, several challenges were faced that need to be addressed for successful delivery of phase 2B goals. Table 3-14 summarizes some of these challenges along with the proposed solutions.

Table 3-14 Pipe Construction Challenges

Issue	Solution	Phase 2B considerations
Concentricity and diameter variance issues with manufactured metallic layer (prototype Z-interlock machine)	Subsequent layer manufacture and test predictions took into account the non-conformances.	The layer will be made with the production Z-interlock pressure armor line, rather than prototype equipment. Using the proper machinery and properly adjusted equipment, all the manufacturing tolerances will be inside the acceptable range. Trials will be conducted prior to manufacture to verify.
Intra-tape delamination of 2B tapes	On-going collaboration with the material supplier to resolve the issue in future tapes.	Quality related issues of the materials need to be discussed with suppliers and resolved prior to the construction of the Phase 2B prototype pipe.
Insufficient interlaminar adhesive bonding in carbon reinforcement stacks	Contributing factors of insufficient cure, lack of tape tension control and surface finish of tape are being addressed.	The composite armor layers will be made with the new composite armor line and adhesive curing oven which is being designed and constructed to address these factors.

3.5.3 End Fittings

In this task, two full scale end fittings are constructed considering an extra set of consumable parts to facilitate the end fitting re-termination for the second pipe sample. The process for tensile armor bend back, anchoring, potting and curing the tensile armors in the end fitting per the end fitting installation procedure is followed. Figure 3-52 shows the cross section of end fitting.

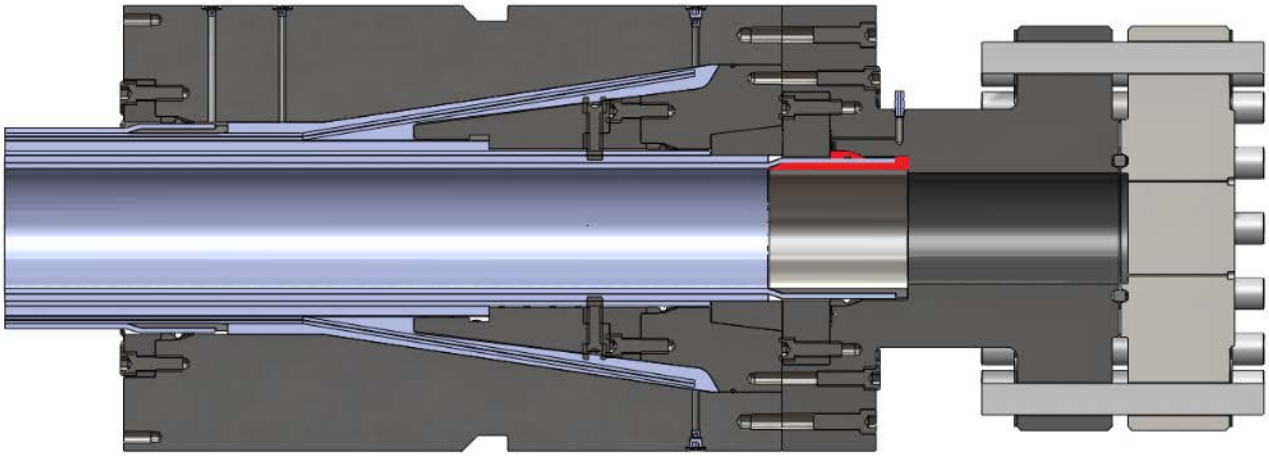

Figure 3-52 Phase 2A end fitting cross section

Figure 3-53 shows the termination of the end fitting in various stages.

Figure 3-53 Phase 2A end fitting installation process

The first test prototype sample shown in Figure 3-54 passed FAT successfully.

Figure 3-54 Burst Sample

3.5.4 Full Scale Burst Pressure test

Scope of Work

In order to characterize the performance of the structural layers and determine the burst pressure capacity, the prototype was subjected to a burst pressure test.

Test Setup

The burst pressure test sample was assembled with two full scale end fittings. Figure 3-55 shows the setup of the burst test with the instrumentation mounted to monitor the pipe behavior

- Two string potentiometers were used to measure overall axial elongation
- Two inclinometers were used to measure the twist during the test
- Pressure and temperature of the internal fluid were measured by pressure transducer and thermocouple

This test was performed in accordance with the DeepFlex Burst Pressure Test Procedure [23]

Figure 3-55 Burst Test setup

Test Result – First Attempt

Prior to conducting a burst pressure test, the sample was subjected to 24 hour FAT (Factory Acceptance Test) hydrotest. The FAT hydrotest was conducted as per Deepflex FAT procedure [25]. The sample passed FAT successfully.

Due to technical issues with the pump system the sample was depressurized. Following repairs, the sample was pressurized to 20149 psi, however further technical issues required conclusion of the test before achieving burst.

Figure 3-56 shows the pipe internal and relative twist between the end fittings versus axial strain. To maintain schedule, this pipe sample was sent to Stress Engineering Inc. Houston for the axial tension to failure test.

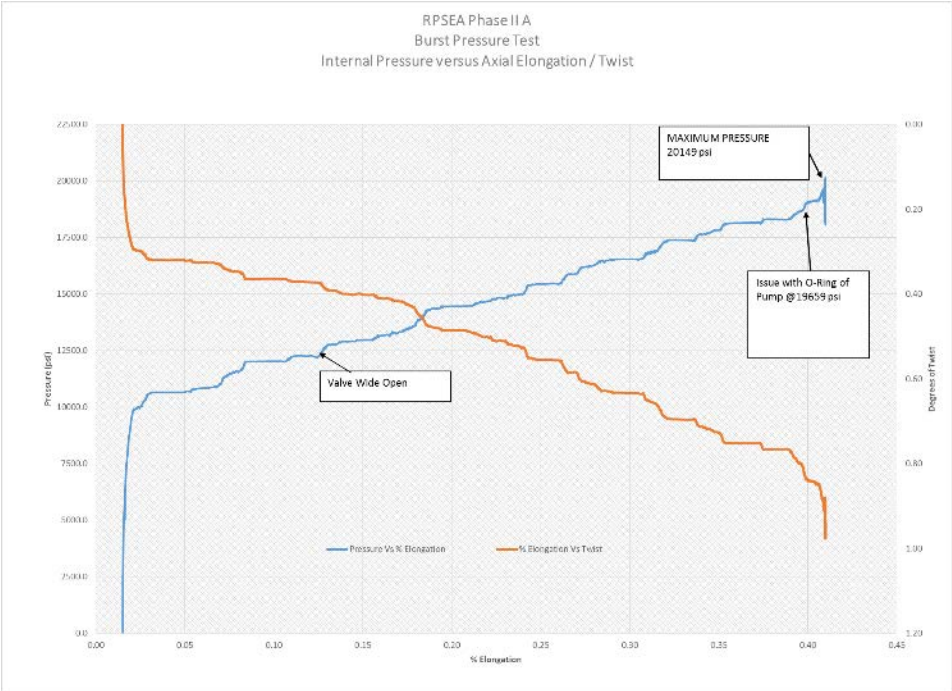

Figure 3-56 Internal Pressure and Twist versus Axial Elongation – 1st Attempt

<u>Test Results (2nd Attempt)</u>

After resolving the technical issues experienced in the 1st attempt at the burst test, the second pipe sample was assembled and subjected to 24 hour FAT (Factory Acceptance Test) hydrotest. The FAT hydrotest was conducted as per Deepflex FAT procedure [25].

Upon successful completion of FAT hydrotest the sample was then subjected to the burst pressure test. During the burst pressure cycle the sample burst at 22423 psi. The burst failure location was in the middle of the pipe sample, outside of the end fittings as show in Figure 3-57. Figure 3-58 plots the pipe internal pressure and relative twist between the end fittings versus axial strain.

Figure 3-57 Burst failure location

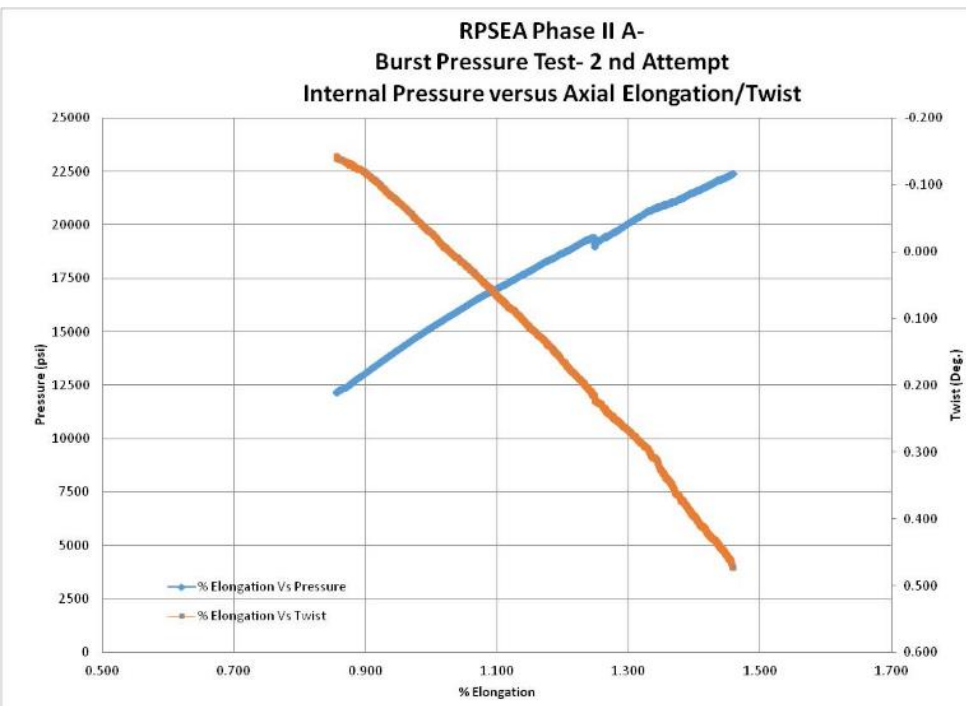

Figure 3-58 Internal Pressure and Twist versus Axial Elongation – 2nd Attempt

Based on the results of a burst test sample built through steel interlock pressure armor only (conducted outside the RPSEA project) and the CGS test results of composite type 2B tape (see Section 3.1.5), the predicted burst pressure on phase 2A prototype is estimated to be 21312 psi. Table 3-15 summarizes these values.

Table 3-15 Burst Test Summary

Test	Predicted Burst Pressure	Actual Burst Pressure
Burst test on pressure armor only	8,490 psi	9,305 psi
RPSEA Phase 2A Burst Test (1st Attempt)	21,312 psi	20,149 psi (did not burst due to pump problem)
RPSEA Phase 2A Burst Test (2nd Attempt)	21,312 psi	22,423 psi

The test pipe has demonstrated that the observed burst pressure has exceeded the predicted burst pressure.

3.5.5 Tension Test

Scope of Work

The purpose of this test is to confirm the tensile capacity of the R2-R3 tensile reinforcement layers and the design of the anchoring system in the end fitting.

Test Setup

The sample used in the first attempt at the burst pressure test was subjected to the axial tension test. Figure 3-59 shows the axial tension test setup. String potentiometers were mounted on the sample to measure the overall axial elongation. This test was performed in accordance with DeepFlex axial tension test procedure [24].

Figure 3-59 Axial Tension Test Setup

Test Results

Figure 3-60 shows the plot of axial tension versus elongation. The pipe sample showed a linear behavior throughout the test. The sample ultimately failed at 2197 kips tension without the end fitting failure. The test sample was then dissected to determine the sequence of failure in the reinforcement layers and to confirm that there was no tensile reinforcement anchoring pullout from either end fitting.

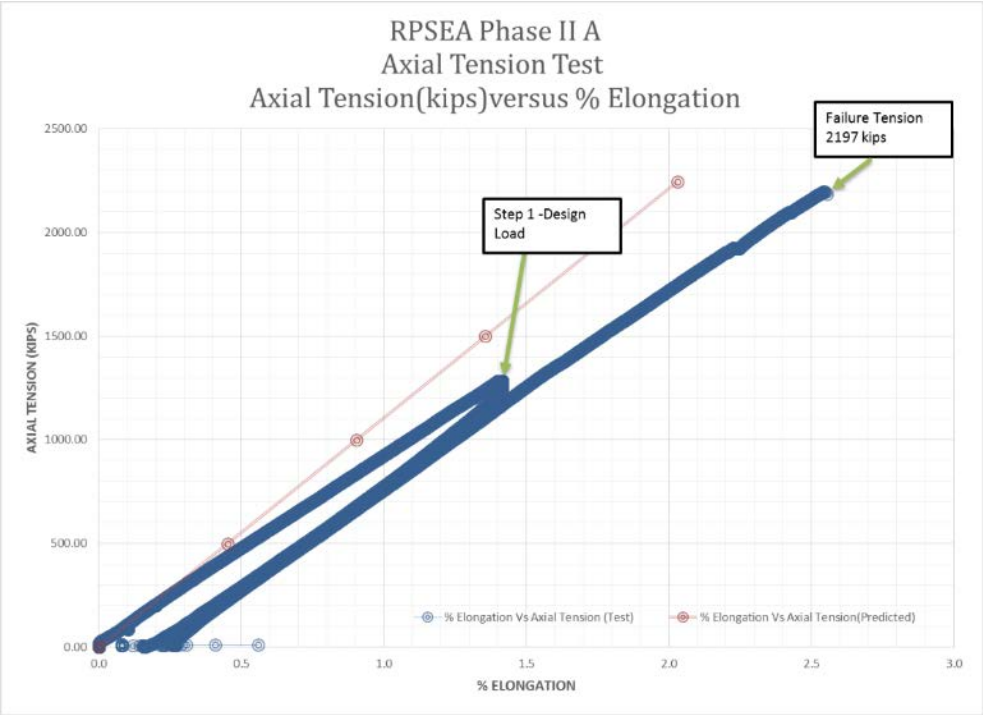

Figure 3-60 Axial Tension versus Elongation

Table 3-16summarizes the tensile test results versus prediction.

Table 3-16 Tensile Test Summary

Tensile Test	Pipe Data Sheet Predicted Tensile Failure	Observed Tensile Failure
RPSEA Phase 2A- Axial Tension Test	2246 kips	2197 kips

No tensile armor pullout from the end fitting confirms the successful anchoring of the tensile armors.

3.6 Task 17.0 – Carcass and Liner Tests

Scope of Work:

3.6.1 Subtask 17.1 – Carcass and Liner End Fitting Tension Test

Scope of Work:

The Subcontractor shall conduct two tests to verify that there is no loss of tensile capacity of the liner due to crimping effect of the seal as well as to measure the axial load capacity of the carcass. A test procedure shall be written and the test shall be conducted in accordance with the procedure.

Progress:

No work has been conducted on this task within the scope of the project.

3.6.2 Subtask 17.2 – Carcass and Liner End Fitting Collapse Test

Scope of Work:

The Subcontractor shall conduct a test to measure the collapse resistance of the carcass and liner. The test shall be conducted in accordance with DeepFlex collapse test procedure A-ENG-SOP-10105.

Progress:

No work has been conducted on this task within the scope of the project.

3.7 Conclusions from Phase 2A

Table 3-17 summarizes the conclusions from Phase 2A, in terms of design modifications to the Phase 2B full scale prototype.

Based on the largely successful results, an API 17N TRL of 3 has been achieved at the end of Phase 2A and DeepFlex was authorized to proceed with Phase 2B.

Table 3-17 Summary of Phase 2B design modifications based on Phase 2A Test Results

Task #	Test	Phase 2B Prototype Design Modifications
Task 12	Ageing up to 90 °C	Results to date indicate that the thickness of tensile armor layers should be slightly increased for the design to meet the Phase 1 design premise conditions. Longer term tests as scheduled are needed for re-evaluation and to confirm long term performance and characteristic properties at end of service life.
	Ageing 110 °C	Results to date indicate that short exposure at temperatures up to 110 °C are acceptable.
	Pullout Test	Results indicate that the adhesion strength used in design is conservative.
	CGS Test	Results used for calibration of the burst pressure model
	Crush Test	Results used for evaluation of interlaminar shear strength
	Torsion Test	Results used for input to the Finite Element model to determine allowable tensile armor stack bend back.
Task 13	Gap Span Test	Results to be used for calibration of Creep Model
Task 14	Wear Test	An anti-wear tape is needed on the tensile armor stacks external surfaces.
Task 15	Permeation Test	Material permeation data validated by unshielded tests. Shielded tests require further evaluation of results to confirm conclusions of permeation and annular pressure drop analysis
Task 16	Burst Test	Burst pressure above prediction - Validation point and confirms acceptance of overall structural performance of pipe and end fitting design
	Tension Test	Failure tension slightly lower than prediction – Model needs some minor calibration, however structural performance of pipe and end fitting design are acceptable.

4.0 Phase 2B – Full Scale Prototype Manufacturing and Qualification Tests

4.1 Task 18.0 – Phase 2B Prototype Manufacture

Scope of Work:

The Phase 2B prototype is in accordance with the design which was the subject of the Phase 1 work. The results of Phase 2A in validating the analyses conducted during Phase 1 design were considered in modifying the Phase 2B design to assure that the design requirements were met. Subtasks to accomplish the activities specified below.

4.1.1 Subtask 18.1 – Pipe Layer Material Procurement

Scope of Work:

The Subcontractor shall procure the pipe sample materials.

Progress:

No work has been conducted on this task within the scope of the project.

4.1.2 Subtask 18.2 – Pipe Manufacturing

Scope of Work:

The Subcontractor shall construct the pipe layer by layer at their manufacturing facility and the Subcontractor's material specifications and manufacturing procedures. Subcontractor shall manufacture a 120 meter length of the prototype pipe.

Progress:

No work has been conducted on this task within the scope of the project.

4.1.3 Subtask 18.3 – End Fitting Procurement

Scope of Work:

The Subcontractor shall issue drawings and procure end fitting components from qualified suppliers. The subcontractor shall procure four full scale end fittings, four mid-scale end fittings for the thermal cycling tests, and additional parts to reuse the end fittings as necessary to complete the Task 19 through 23 tests.

Progress:

The design drawings were to be developed in accordance with the design concept developed in the Phase 1 engineering study (see Chapter 8.0 of the Final Design Report (10121-4402-02 - Final Design Report) with design improvements based on the learnings from Tasks 12 and 16. Analyses to verify part sizes and design models were completed. The material procurement package for forgings and SolidWorks models of parts was completed.

4.1.4 Subtask 18.4 – Verification of Ancillary Equipment Qualification and Bend Stiffener Procurement

Scope of Work:

The Subcontractor shall prepare and issue the bend stiffener specifications, and obtain documentation of certification of the ancillary equipment specified in 10121-4402.05.FINAL, Section 9 to API 17L1.

Progress:

No work has been conducted on this task within the scope of the project.

4.1.5 Subtask 18.5 – Pipe Sample Assembly and Factory Acceptance Tests

Scope of Work:

A pipe assembly and test plan documenting the lengths, end fitting usage and testing sequence shall be provided to the DOE/NETL/RPSEA working committee for review and approval prior to the conduct of the specified qualification testing.
One or more of the prototype pipe sections shall be subjected to a series of Factory Acceptance Tests (FAT) as described in 10121-4402.08.FINAL, Table 4-1, including

- Annulus Venting Test,
- Gauge Test,
- Electrical Isolation of carcass,
- Annulus Sealing Test, and
- Hydrostatic Pressure Test.

Upon successful completion of FAT's the subcontractor shall cut and assemble pipe samples for the prototype testing to be conducted in Tasks 19.0 – 22.0. Pipe sample lengths shall be in accordance with the requirements of API RP 17B.

Progress:

No work has been conducted on this task within the scope of the project.

4.2 Task 19.0 – Prototype Tests (Static)

Scope of Work:

The Subcontractor shall conduct static tests in accordance with API 17B, Fifth Edition, Chapter 7. The details of the following subtasks 19.1 through 19.11 are provided in 10121-4402.08.FINAL, Section 4. The Subcontractor shall prepare and submit a test report to the DOE/NETL/RPSEA working committee for review and approval documenting the results of the tests. The report shall provide the results of pipe dissection and comparison with predicted results and failure modes/mechanisms.

Progress:

Planning activities were conducted to evaluate the timing, equipment and logistics for assembling samples and executing the tests.

4.2.1 Subtask 19.1 - Burst Pressure Test

Scope of Work:

The Subcontractor shall conduct burst pressure test to determine the burst resistance of the flexible pipe. The report will reference the burst pressure test procedure (A-ENG-SOP-10102) and provides the axial strain and relative twist as a function of internal pressure.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.2 Subtask 19.2 – Radial Crush Test

Scope of Work:

The Subcontractor shall conduct radial crush test to determine the capacity of the pipe under the compression load applied by tensioner during the deployment and retrieval. The report will reference the radial crush test procedure (A-ENG-SOP-10672) and provides the pipe diameter change under the load and after unloaded.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.3 Subtask 19.3 – Collapse Test

Scope of Work:

The Subcontractor shall conduct collapse test to evaluate the pipe resistance to external hydrostatic pressure. The report will reference the collapse test procedure (A-ENG-SOP-10105) and provides the collapse pressure values.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.4 Subtask 19.4 – External Hydrostatic Pressure with Supporting Rod

Scope of Work:

The Subcontractor shall conduct the test to verify the axial compression resistance of pipe and failure mode under reverse end cap load when the pipe is empty. The report will reference the test procedure (A-ENG-SOP-10105) and provides the result of the pipe dissection analysis for the axial compression failure mechanisms described in Task 6 Report.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.5 Subtask 19.5 - Axial Tension Test with Internal Pressure Test

Scope of Work:

The Subcontractor shall conduct the test to verify the axial compression resistance of pipe and failure mode under reverse end cap load when the pipe is empty. The report will reference the test procedure (A-ENG-SOP-10105) and provides the result of the pipe dissection analysis for the axial compression failure mechanisms described in Task 6 Report.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.6 Subtask 19.6 – Axial Tension Test

Scope of Work:

The Subcontractor shall conduct axial tension test to verify the axial tension capacity of the pipe. The report will reference the test procedure (A-ENG-SOP-10103) and provides the axial tension versus axial elongation of the pipe.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.7 Subtask 19.7 – Membrane Seal Test

Scope of Work:

The Subcontractor shall conduct membrane seal test to confirm the integrity of the seal against the external fluid ingress at external hydrostatic pressure in the event of a jacket breach. The report will reference the test procedure (A-ENG-SOP-10115).

Progress:

No work has been conducted on this task within the scope of the project.

4.2.8 Subtask 19.8 – Bending Stiffness Test

Scope of Work:

The Subcontractor shall conduct bending stiffness test to determine the bending stiffness and bending moment of the pipe versus pipe bending radius. The report will reference the test procedure (A-ENG-SOP-11163-Rev 2) and provides pipe's bending moment and curvature calculated from the measured load and deformation of the test sample.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.9 Subtask 19.9 – Impact Test

Scope of Work:

The Subcontractor shall conduct impact test to verify the impact resistance of the pipe. The report will reference the test procedure to be written based on NORSOK U-001 for dropped objects and provides the result of pipe dissection for observing the failure mechanisms.

Progress:

No work has been conducted on this task within the scope of the project.

4.2.10 Subtask 19.10 – Torsional Stiffness Test

Scope of Work:

The Subcontractor shall conduct torsional stiffness test to verify the resistance of flexible pipe to the rotation around its axis under torsional moment. The report will reference the test procedure to be prepared by DeepFlex and provides pipe's torsional stiffness and angular deformation data. .

Progress:

No work has been conducted on this task within the scope of the project.

4.2.11 Subtask 19.11 – Outer Sheath Holding Test

Scope of Work:

The Subcontractor shall conduct outer sheath holding test to check the outer sheath/end fitting interface under high tension. The report will reference the test procedure to be prepared by DeepFlex.

Progress:

No work has been conducted on this task within the scope of the project.

4.3 Task 20 – Prototype testing – Dynamic Fatigue Test

Scope of Work:

The Subcontractor shall conduct a service simulation test as defined in API 17B. The dynamic testing simulates the fatigue loading experienced at the riser top connection due to combined bending, tension, fluid temperature and internal pressure. The Subcontractor shall prepare a test procedure defining the test setup, specified loading, instrumentation, measurements to be taken, and acceptance criteria. The Subcontractor shall prepare and submit a test report to the RPSEA working committee for review and approval documenting the results of the dynamic test. The report will reference the test procedure and provide an evaluation of the pipe performance against the acceptance criteria.

Progress:

No work has been conducted on this task within the scope of the project.

4.4 Task 21 – Prototype Testing – Thermal Cycling Test

Scope of Work:

The Subcontractor shall conduct thermal cycling testing to confirm the suitability of the liner seal in the end fitting to withstand thermal cycling between minimum and maximum design temperature (defined in 10121-4402-02.04.FINAL) as expected over the service life. The testing will be conducted in accordance with Annex C of API 17B. The Subcontractor shall prepare a test procedure defining the test setup, specified loading, instrumentation, measurements to be taken, and acceptance criteria. The Subcontractor shall prepare and submit a test report to the RPSEA working committee for review and approval documenting the results of the thermal cycling test. The report will reference the test procedure and provide an evaluation of the pipe performance against the acceptance criteria.

Progress:

No work has been conducted on this task within the scope of the project.

4.5 Task 22 – Prototype testing – Bending with External Pressure/Curved Collapse

Scope of Work:

The Subcontractor shall perform tests to simulate the loading experienced near the touchdown point and confirm the resistance of the tensile reinforcement against lateral buckling. There is currently no standard in place for this test, however one is being considered for inclusion in the next revision of API 17B for ultra-deep water applications. The test will be conducted similarly to as presented in OTC 21490 "Qualification Testing of Flexible Pipes for 3000m Water Depth". The Subcontractor shall prepare a test procedure defining the test setup, specified loading, instrumentation, measurements to be taken, and acceptance criteria. The Subcontractor shall prepare and submit a test report to the RPSEA working committee for review and approval documenting the results of the bending with external pressure test. The report will reference the test procedure and provide an evaluation of the pipe performance against the acceptance criteria.

Progress:

No work has been conducted on this task within the scope of the project.

4.6 Task 23 – Phase 3 Proposal

The FMECA report attachment 4 (10121-4402-02.06.FINAL – Failure Mode Identification and Risk Ranking) will be updated based on the results of Phase 2. Columns N through Q, documenting the completion of the action plan and verifying that all failure modes and mechanisms with risk ranking of critical and normal have been addressed in the qualification program will be updated.

The Subcontractor shall update the proposal for Phase 3, Field Deployment supply and submit the proposal to the RPSEA working committee, taking into account the learning from the Phase 1 and Phase 2 work.

Progress:

The field deployment was proposed to be conducted in accordance with the Field Development Concept report [13], prepared in Task 10. The riser system was to be instrumented in accordance with the Integrity Management and Data Gathering Plan developed in Subtask 10.2. The data from the field trial was to be analyzed, and in particular compared with design data developed in Phase 1. In particular, the global analysis and service life analysis results was to be validated using best available methods.

Due to the delays in completing the DeepFlex manufacturing facility in time to complete Phase 2, and be prepared to manufacture the riser system in time to meet the RPSEA project sunset date, no work was conducted on Phase 3 within the scope of the project.

5.0 REFERENCES

No.	Reference	Task	Applicability
1	RPSEA Document RFP2010UDW004 UDW Need 4 Technical Areas of Interest	N/A	RPSEA Request for Proposal for Project – Specifically, Technical Area of Interest 4402
2	DeepFlex Document RFP2010UDW004 Need 4 Technical Area of Interest – 4402 Qualification of Flexible Fiber Reinforced Pipe for 10,000-Foot Water Depths Technical Volume	N/A	DeepFlex Proposal in response to RFP
3	RPSEA Cost Reimburseable Cost Share Contract, Subcontract # 10121-4402-02	N/A	Governing document between DOE/NETL/RPSEA and DeepFlex
4	Modification Agreement Mod No. 3 Subcontract No. 10121-4402-02	N/A	Revision of Governing Document, Reference [3]
5	10121-4402-02.01 – Project Management Plan Modified 01-30-14	N/A	Presents the latestscope of work for the project approved by RPSEA and the WPG
6	10121-4402-02.02 – Qualification of FFRP for 10000 ft water depth – Technology Status Assessment	2	Presents the state of the art of FFRP technology prior to the start of the project
7	10121-4402-02.03 – Technology Transfer Plan	3	Presents the Technology Transfer Plan for the project.
8	10121-4402-02.04 – Qualification of FFRP for 10000 ft water depth – Design Premise Report	5	Presents the functional and design requirements that the DeepFlex down line will have to satisfy for GOM ultra deep fields.
9	10121-4402-02.05 – Qualification of FFRP for 10000 ft water depth – Design Report	6	Provides the pipe layer by layer material and structure descriptions, global dynamic analysis of the riser system, pipe cross section design, gas permeation / venting system design and analysis, end fitting design, service life analysis and ancillary equipment design.
10	10121-4402-02.06 – Qualification of FFRP for 10000 ft water depth – FMECA Report	7	Presents the Qualification Basis, Technology Assesssment and FMECA Threat Assessment
11	10121-4402-02.07 – Qualification of FFRP for 10000 ft water depth – Manufacturing Documentation Report	8	Presents the results of Task 8.0 – Manufacturing Documentation for Phase 2 Prototype
12	10121-4402-02.08 – Qualification of FFRP for 10000 ft water depth – Phase 2 Qualification Test Plan	9	Presents the Phase 2A and Phase 2B Qualification Test Plan based on the FMECA output.

13	10121-4402-02.09 – Qualification of FFRP for 10000 ft water depth – Field Development Concept Report	10	Presents the Packing, Shipping, Installation and Integrity Management Plans and Cost Estimates.
14	M. Kalman, L. Yu, A. Salimi, J. Liu. Qualification of Flexible Fiber-Reinforced Pipe for Ultradeepwater Applications. Presented at Offshore Technology Conference, Houston, Texas, May 6-9, 2013. DOI: 10.4043/23931-MS	3	Technology Transfer
15	M. Kalman, L. Yu, A. Salimi, J. Liu. Qualification of Flexible Fiber-Reinforced Pipe for Ultradeepwater Applications – Update on Phase 1 Engineering Study and Phase 2 Prototype Testing. Presented at Offshore Technology Conference, Houston, Texas, May 5-8, 2014. DOI: 10.4043/25084-MS	3	Technology Transfer
16	Salimi, M. Kalman, L. Yu. Flexible Hybrid Reinforced Pipe-Bend Stiffener Interface Design with Optimized Thermal Performance, Proceeding of the 14th International Conference on Ocean, Offshore and Arctic Engineering, San Fransisco, California, June 8-13, 2014	3	Technology Transfer
17	API 17J Fourth Edition, Specification for Unbonded Flexible Pipe, Fourth Edition, May 2014	ALL	Governing standard, defining technical requirements for design, material selection, manufacture, testing, marking and packaging the flexible pipe. Metallic armor material requirements are not relevant to the composite armor layers.
18	API 17B Fifth Edition, Recommended Practice for Unbonded Flexible Pipe, Fifth Edition, May 2014	ALL	Provides guidelines for design, analysis, manufacture, testing, installation and operation of flexible pipes. .Annex H is the governing standard for the composite armor layers.
19	DNV OS C501 Composite Components	ALL	Governing standard for the composite armor materials in lieu of the metallic armor material requirements in Reference 16, based on the guidelines provided in Annex H of Reference 17.
20	API 17 Technical Report TR2, The Ageing of PA-11 in Flexible Pipes, First Edition	6	PA-11 jacket service life analysis
21	DNV RP A203 Qualification New Technology, Det Norske Veritas AS	7	FMECA analysis and qualification plan development guidance document.

22	M. Kalman, L. Yu, A. Salimi, C. Durr. J. Suarez Qualification of Unbonded Flexible Pipe to API and DNV Standards. Presented at Offshore Technology Conference, Houston, Texas, May 5-8, 2014. DOI: 10.4043/25092-MS	N/A	Presents a summary of the FMECA process leading to development of an unbonded flexible pipe qualification plan.
23	A-ENG-SOP-10102- Standard Operating Procedure for Burst Pressure Test	16	DeepFlex procedure used for Burst Test of Task 16 Prototype
24	A-ENG-SOP-10103-Standard Operating Procedure for Axial Tension Test	16	DeepFlex procedure used for axial tension test of Task 16 Prototype
25	A-ENG-SOP-10100- Standard Operating Procedure- Factory Acceptance Test (FAT) Hydrotest	16	DeepFlex procedure used for FAT of Task 16 Prototype