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FINAL REPORT

MAY 18TH, 2009

SBIR PHASE I

"New In-field Composite Repair Techniques for Transmission or Distribution Pipelines"

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SBIR PHASE I

1.0 PROGRAM INTRODUCTION

In-field repair of a damaged pipeline must be performed safely, efficiently, rapidly and reliably. Reinforcement of damaged pipelines is typically accomplished by welding a repair patch and then recoating the repaired area. The welded full-encirclement sleeve is still the most common repair system due to the lower risk, potential cost savings, and simplicity of the repair. Recent developments in fiber reinforced composite repair patches have led to their increased usage across other industries. A composite repair offers an alternative to welding as the strength is claimed to be comparable. The pipeline surface conditions play a role in the long term performance of the composite patch.

Odyssian Technology will introduce a new composite repair technology that uses thermoplastic as the composite matrix in place of the conventional thermoset. A thermoset polymer sets up under heat or when mixed with a two part system having chemical hardeners. The elevated cure thermoset systems require exposure to heat over prolonged periods of time. This can be problematic during in-field repair under harsh weather conditions. A two part system can be used that significantly reduces the time of cure of the thermoset resin, yet typically at a cost to the structural performance of the polymer matrix material. Two part system achieve cross-linking or cure through the addition of hardeners. These hardeners act as catalysts to promote and accelerate cross-linking of the polymer system. The disadvantage is that they typically cause a significant reduction in mechanical properties, which can cause a corresponding reduction in compressive strength of the composite material system.

The advantage of thermoplastic over themoset is that a thermoplastic melts and fuses when heated. This process does not rely upon extended heating to cause complete cross-linking and full realization of mechanical properties. In addition, thermoplastics can be recycled which may allow the thermoplastic composite repair materials to be made from lower cost recycled plastics. Odyssian Technology will perform a design study of a composite repair wrap using layered cover that includes the use of hybrid fiber composite material with an embedded thick film of HDPE for improved toughness and sealing. A high flow bonding adhesive would be used to assure adequate fill and bonding to the aged or damaged pipe. This is a two piece configuration, with the advantage of this concept being reduced time and improved ease in repair.

The official start of this program was September 18, 2008 with completion of the scheduled technical tasks by May 1, 2009 and final reporting and documentation by May 18, 2009.

2.0 PROGRAM OBJECTIVES

During this SBIR program Odyssian Technology will study, develop and demonstrate new repair techniques for Transmission and or Distribution Pipelines. Anticipated results would provide data in support of long term performance and or recommended method/practices for their application. The scope of phase I will include studying other related methods of composite repair (see related work section) and developing concepts and designs for Odyssian Technology's new repair technique. Phase I will be focused on accomplishing the following objectives.

(i) Develop a new composite repair that improves safety

(ii) Develop a new composite repair that will support long term performance

3.0 PHASE I ACCOMPLISHMENTS

The status of this program is provided in the subsequent sections. Program management status, schedule status, and financial status are discussed.

3.1 – SCHEDULE

Phase I of this program is on schedule.

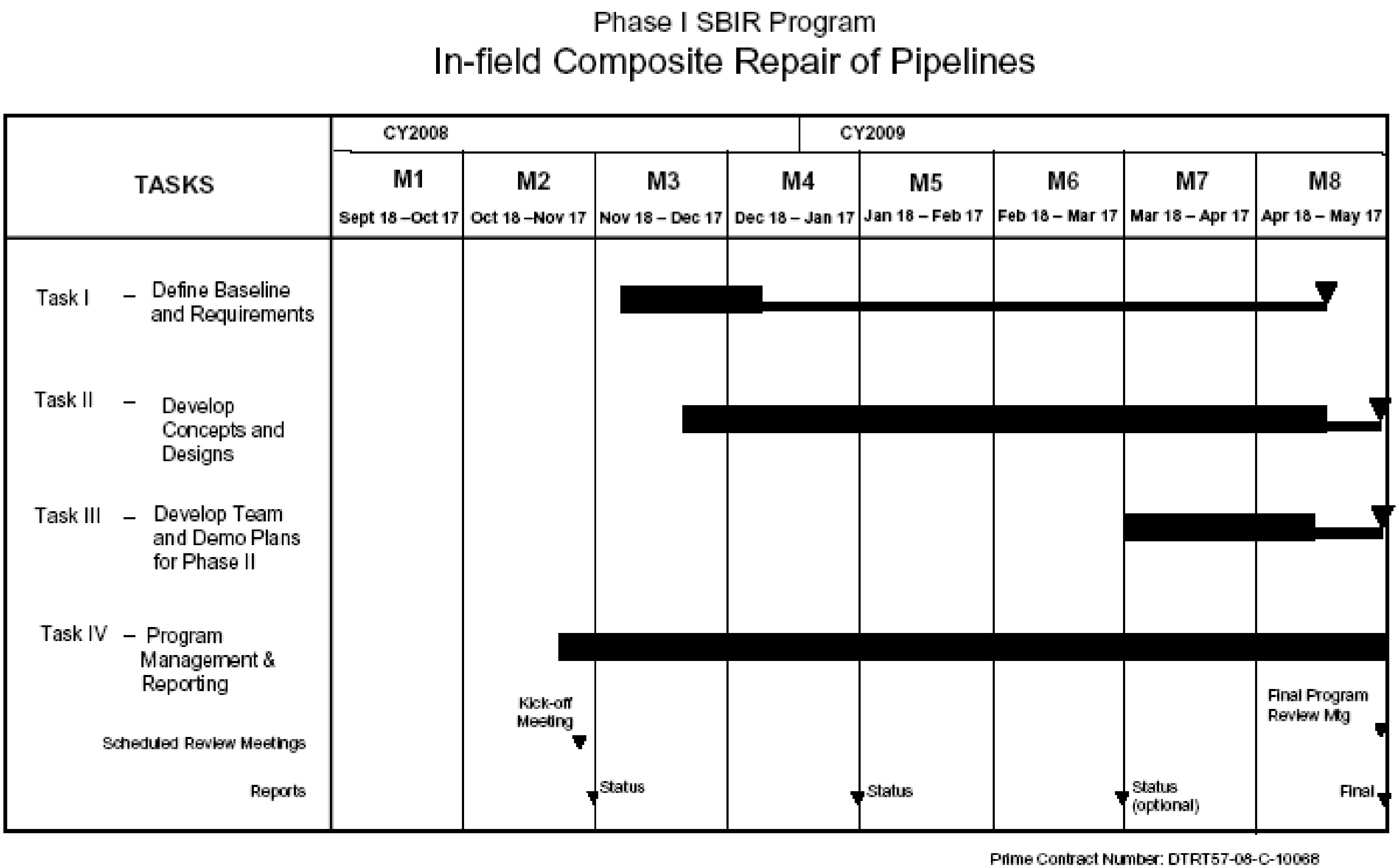

Figure 1: Revised Phase I Program Schedule

3.2 – TECHNICAL ACCOMPLISHMENTS

Task I – Define Baseline and Requirements

Project Definition and Rationale

A study was done into the history and current state of the pipeline infrastructure in the United States. Figure 2 below shows the location of various hazardous liquid and natural gas pipelines in the US, a large amount is located on and around the Gulf of Mexico coastline. The statistics released by the Department of Transportation's Pipeline and Hazardous Material Safety Administration shows that out of the total mileage of pipelines as of 2003 (2,307,981 miles), only 7% constituted hazardous liquid pipelines (160,868 miles), of which pipelines carrying oil and petroleum are included, while 13% made up of interstate natural gas transmission lines (298,133 miles), and the majority 80% makes up smaller intrastate natural gas distribution lines (1,848,980 miles). A table of the mileage statistics is available in Appendix A.

A current incident report (accidents involving damaged or breached pipelines) filed by pipeline operators were compiled by the PHMSA and details the consequences to the public and pipeline industry, in terms of monetary costs and lives. The consequence statistics showed that in the time frame of 2003-2007, roughly ~$500 million in total property damage was caused by hazardous liquid pipelines with 11 fatalities and 35 injures. During this same time, natural gas gathering, distribution and transmission pipelines were responsible for ~1.2 billion dollars in total property damages with 58 fatalities and 162 injuries. The majority of cost and fatalities/injuries were the result of accidents involving natural gas distribution pipelines (~$600 million with 52 fatalities and 132 injuries). The majority of all total property damage across the four categories occurred in 2005, possibly due to Hurricane Katrina. Tables on costs and consequences of hazardous liquid and natural gas pipelines are available in the Appendix A.

The study showed that the majority of pipelines in the United States are natural gas distribution pipelines and that the majority of property damage cost and fatalities and injuries are resulting from accidents involving natural gas distribution pipelines. Due to the results of this study, the focus of the design is on the repair of natural gas distribution lines and to an extent natural gas transmission lines.

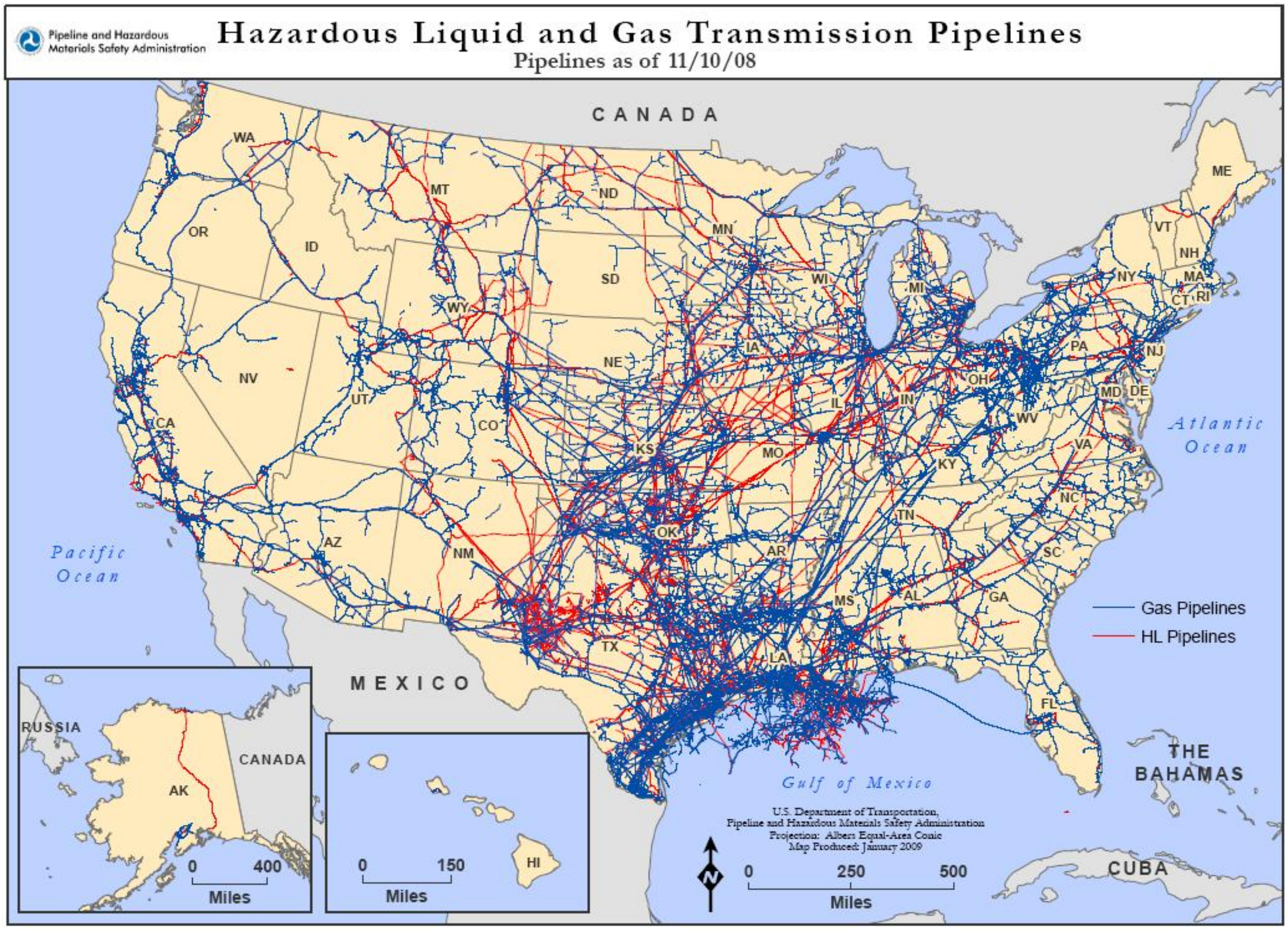

Figure 2: Hazardous liquid (i.e. petroleum) and natural gas transmission pipelines in the US

The sizing, materials, and operating pressures of natural gas transmission and distribution lines covers a wide range. Transmission pipelines for natural gas were found to have varying diameters from 6 to 36" (measured from OD) and are typically made from carbon steel material. The internal operating pressures of a NG transmission line ranges from 300 to 1500 psi. Distribution lines have smaller diameters that range from 2 to 16", and are made from steel, plastic or cast iron material. The typical operating pressures of a distribution line typically range from a quarter to 200 psi. Based on this information, a good starting point for the design of the composite repair system is decided to be a 6" steel natural gas pipe that can handle an operating pressure of up to 1500 psi.

Standards and Testing Methods

The standards pertaining to the non-metallic and bonded repairs for pipes include the federal standard released by the DOT Office of Pipeline Safety 49 CFR 192 and the ASME PCC-2. Testing standards include the ASTM standards listen below in figure 4.

Although the federal regulation standards do not list specific numbers, it does state that a composite repair system must be able to permanently restore the serviceability of the pipe. Two sections of the CFR 192 regulation address this in the repair of dents and corrosions. For repair of dents in a steel pipe, it states: "Each of the following dents must be removed from steel pipe to be operated at a pressure that produces a hoop stress of 20 percent, or more of SYMS (specified yield minimum strength), unless dent is repaired by a method that reliable engineering tests and analysis show can permanently restore the serviceability of the pipe." (49 CFR 192.309) For corrosion on a steel pipe, it states: "General corrosion. Each segment of transmission line with general corrosion and with a remaining wall thickness less than that required for the MAOP of the pipeline must be replaced or the operating pressure reduced commensurate with the strength of the pipe based on actual remaining wall thickness. However, corroded pipe may be repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe." (49 CFR 192.485)

There are currently no minimum specified standards concerning mechanical and performance properties of composite repair system. However, for the repair and reinforcement of steel pipelines to be effective, composite materials must have adequate stiffness. A good rule of thumb is to have a material with a tensile modulus on the order of 2.5 Msi and tensile strength on the order of 50 ksi. Design considerations must also consider long-term performance as well as time and temperature-dependant material degradation issues.[1] Additional guidelines and requirements for composite repair delivered by the International Pipeline Conference are shown in the Appendix A, which are further extrapolated in the ASME PCC-2-2006 standards document.

When bonded composite repair systems were introduced into the oil and gas pipeline industry, Clock Spring set the standard for composite repair development. Clock Spring was recognized as the first developed composite repair system that was widely used on transmission pipelines. The repair system is made up of E-glass/polyester material and methacrylate adhesive and have typical mechanical properties shown below (figure 3). Due to the Clock Spring system being the de-facto "industry standard", its mechanical properties will be used as a guide for designing the composite repair system.

Property	***Value***
Elastic Modulus	5 Msi (0), 1.4 Msi (90)
Tensile Strength	75-100 ksi
Coefficient of thermal expansion (CTE)	6.0e-6 in/in/F (0), 3.2e-5 in/in/F (90)
Percent Strain (Elongation)	1.5 to 2%
Glass fiber content	60-70% (weight), 45-55% (volume)
Nominal thickness per ply	0.065"

Figure 3: Mechanical and physical properties of Clock Spring repair system

Testing standards for the mechanical and material properties of the composite repair system are listed in full in the figure below (figure 4). These are based upon the international ASTM standard. The most important properties to test, as listed on the ASME PCC-2 standard, are tensile, flexural,

[1] Alexander, Chris and Francini, Bob. "State of the Art Assessment of Composite Systems Used to Repair Transmission Pipelines" 6th International Pipeline Conference, 2006. IPC2006-10484

Young's modulus and Poisson's ratio, Shore hardness, CTE, and adhesive shear. Mechanical property such as tensile and shear were tested using MTI-50K Universal Testing System available in the Odyssian Technology facility (see figure 5).

Standard	***Description***	***Alternative***
ASTM D-695	Compression Strength and Modulus	
ASTM D-3039	Young's Modulus and Poisson's Ratio	
ASTM E-831	Coefficient of Thermal Expansion	ASTM D-696
ASTM D-790	Flexural Strength and Modulus	
ASTM D-638	Tensile Strength and Modulus	ASTM D-3039
ASTM D-1002	Composite Lap Shear Strength (Adhesion)	ASTM D-3165
ASTM D-5379	Shear Strength and Modulus	
ASTM D-6604	Composite Transition Temp of Resin	
ASTM D-2583	Shore Hardness	
ASTM G 8-96	Cathodic Disbondment	
ASTM G-14	Impact Test - Modified Gardner	
ASTM D-648	Heat Distortion Temperature	

Figure 4: List of ASTM testing standards

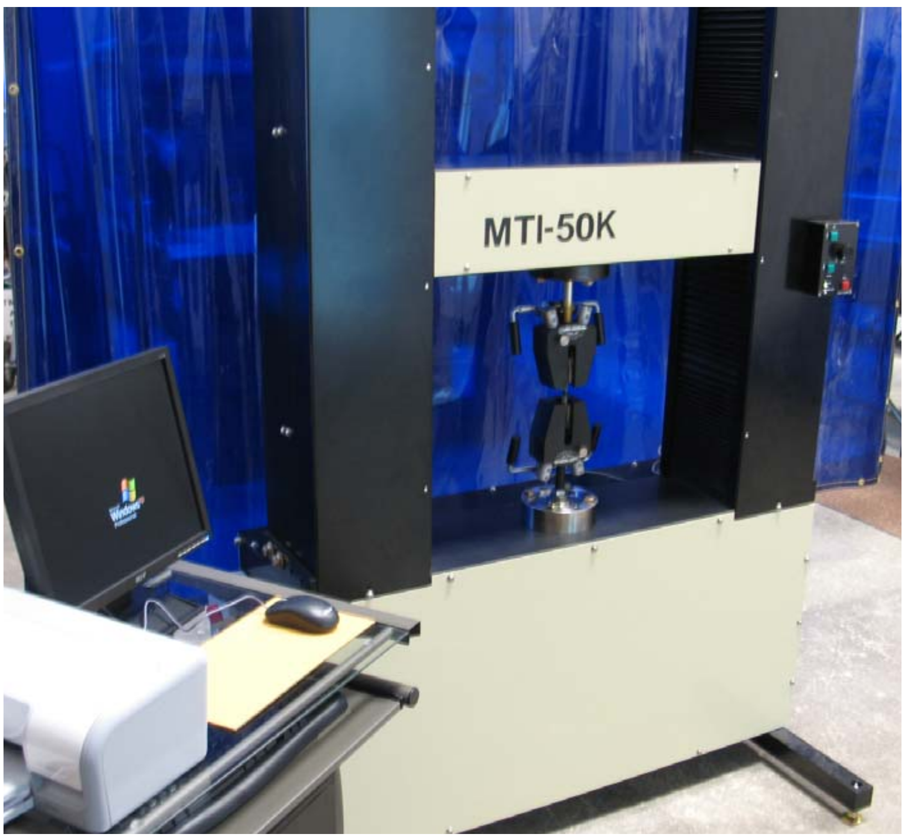

Figure 5: In-house mechanical testing system, with tensile grip tooling.

Task II – Develop Concepts and Designs

Material System Selection

Research was done into the different thermoplastic composite material systems that could be used in designing the final repair system. A typical composite repair system consists of a fiber reinforcement, typically glass or carbon fibers that provide strength and stiffness and a resin matrix system, consisting of a thermoplastic or thermoset that is used to transfer load between fibers. An adhesive is often used to bond the composite, made up of multiple layers of fiber-resin sheets, to the pipe structure. The fiber material form can be either unidirectional or woven 0-90 bi-directional.

There were many different material systems researched with cost, ease of installation, and minimum performance requirements in mind. A chart of some of the material systems researched and their performance data is listed in Appendix A. Once data for all the different material systems were compiled, a down selection process was used to determine the most desirable material. Consideration was given to cost and ease of processing while satisfying the design parameters mentioned in Task I.

The first and easiest selection was any material system that uses thermoplastics. To reiterate from past reports and the original proposal, the advantage of thermoplastics over themosets is that a thermoplastic melts and fuses when heated. This process does not rely upon extended heating to cause complete cross-linking and full realization of mechanical properties. In addition, thermoplastics can be recycled which may allow the thermoplastic composite repair materials to be made from lower cost recycled plastics. Other advantages include the fact that thermoset materials expire after a certain amount of time whereas thermoplastics have no shelf life. And while thermosets have higher overall material performance, it requires a more complicated curing process, such as chemical reaction (i.e. two-part epoxy, or heat induced single-part epoxy) or irradiation (i.e. electron beam processing) which increases the time to process, and cost of processing equipment. Compare this to thermoplastics, which only require a relatively short application of heat.

The second selection was the HDPE resin. There were a variety of thermoplastics to choose from, with a range of different performance values and processing parameters. The table below (figure 6) shows the various thermoplastic resins and their mechanical performance properties, which shows a strong correlation between process temperature and performance. The higher the processing temperature, the higher the tensile strength and modulus. And while higher strength and modulus is ultimately desirable, the higher processing temperature means more powerful heating apparatus and a longer heat exposure time, which raises the equipment/fuel cost and time of labor. The HDPE resin has shown to satisfy the "rule of thumb" requirement in Task I for tensile strength and modulus while having the lowest required process temperature. Tensile strength can match the Clock Spring standard by raising the fiber count to 60% (by weight) from 45% listed in Appendix A data table. HDPE has also shown to be common, and relatively inexpensive, which reduces the composite material system cost.

Thermoplastic Resin	***Process Temperature***	***Tensile Strength (ksi)***	***Tensile Modulus (Msi)***
High Density Polyethylene (HDPE)	350 F (175 C)	65	2.5
Polypropylene (PP)	400 F (205 C)	108	4.1

Polyamide (Nylon 6)	525 F (275 C)	--	--
Polyetherimide (PEI)	600 F (315 C)	--	--
Polyphenylene Sulfide (PPS)	625 F (330 C)	162	6.3
Polyetheretherketone (PEEK)	715 F (385 C)	175	6.5

Figure 6: List of various thermoplastic resins and their processing temperatures, E-glass reinforced and based off the values taken from the material systems data table in Appendix A

The next selection was choosing E-glass continuous fiber reinforcement over carbon fibers. The table below (figure 7) shows the various fiber materials and their mechanical performance parameters. As the data shows, carbon fibers perform much better than E-glass under the same conditions and resin matrix. However, the cost of carbon fibers is approximately $20-30 per pound, while the cost of E-Glass is approximately $1 per pound, an order of magnitude less.

	50% Carbon Fibers	**47.5% E-Glass**	**50% Carbon Fibers**	**50% E-Glass**
Tensile Strength (psi)	109800	49300	95100	70200
Tensile Modulus (psi)	8100000	3100000	8100000	3800000
Flexural Strength (psi)	148900	74200	126200	97000
Flexural Modulus (psi)	8700000	3300000	7300000	4100000
Compression Strength (psi)	93300	61600	108000	105400
Compression Modulus (psi)	7500000	3700000	7500000	4200000
Resin Type	Polyphylene	Polyphylene	Polythermide	Polytherimide
Thickness	0.0122”	0.0098”	0.0122”	0.0094”
Cost	~$20-30/lb	~$1/lb	~$20-30/lb	~$1/lb

Figure 7: List of various fiber materials and their performance parameters and cost, values taken from the material systems data table in the appendix

The material system down-selection process resulted in the selection of a material repair system consisting of unidirectional E-Glass fibers (60%-70% by weight) with an HDPE resin matrix. The initial data suggests that this material system is the most cost-effective and easy to use, and satisfies both the “rule of thumb” and Clock Spring standards discussed in Task I. Further analysis and testing was done to verify proper selection of the composite repair material system. The selection of the adhesive was performed and discussed in the evaluation section later on this report.

Evaluation of Material Fabrication Process – Indiana Match Grant

During the final phase of the program fabrication and evaluation of the continuous glass-reinforced HDPE material system was performed. Fabrication and tensile testing were done on two different types of fiberglass reinforced thermoplastic composites: a bi-directional woven S-Glass fabric wetted through with HDPE (a process called resin-film infusion, done in-house), and a unidirectional E-Glass fiber-reinforced HDPE prepreg from Ticona. Figure 8 below shows the wide range of material systems fabricated and evaluated during this period.

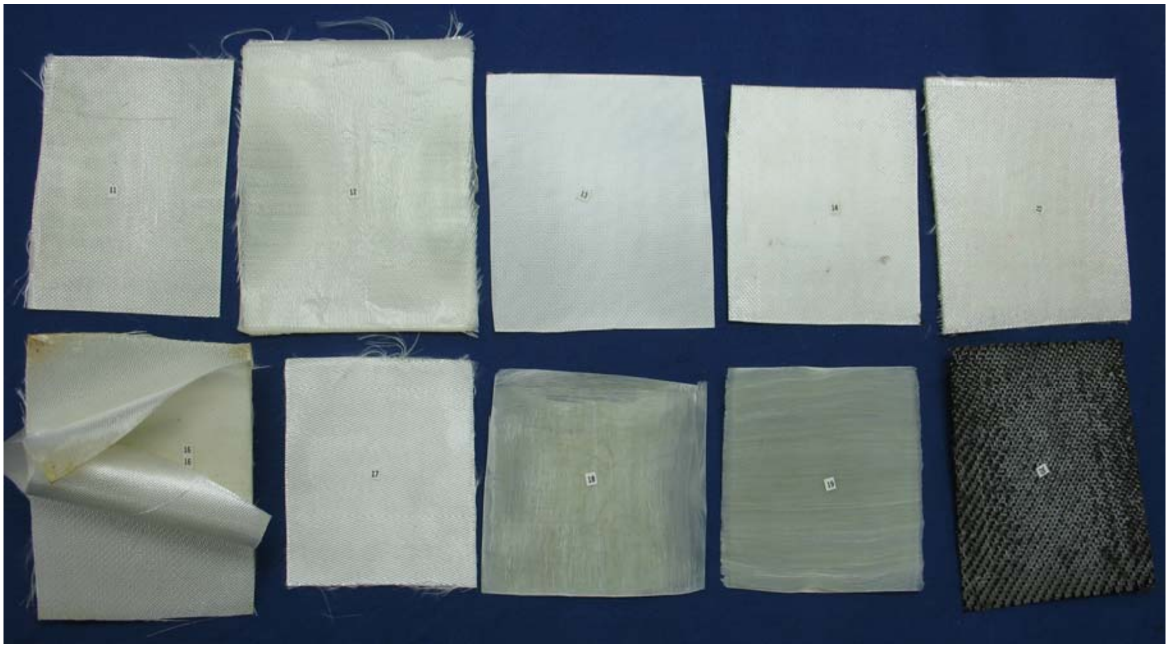

Figure 8: Various attempts at fabricating and consolidating thermoplastic/fiber composite laminates

The decision to evaluate the resin film infusion process was due to the availability of dry S-Glass fabric material in-house as well as to test the viability of impregnating glass fiber with HDPE under heat and pressure. The available in-house fabric is made up of 1.4 Oz / sq yard woven S-2 glass fibers from Aerospace Composite Products Inc., loosely woven to allow for better infusion by the thermoplastic HDPE through the fabric. S-Glass is a fiberglass material with a higher tensile strength and modulus than E-glass (see figure 9), but more expensive and less readily available.

Materials	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (GPa)
E-Glass	2.55	2000	80
S-Glass	2.49	4750	89

Figure 9: Typical property values for different fiber materials

The process of infusing S-Glass with HDPE involves stacking plies of both S-Glass fabric and HDPE film or sheets together and placing it under applied heat and pressure for a period of time. The heat will cause the HDPE to "melt" and change into a less viscous phase, the applied pressure will aid the HDPE in flowing through the S-Glass fabric. The tooling for this process and its final product can be seen below in figure 10. The first attempts at impregnation was done by inter-stacking layup of 0.006" S-Glass fabric with 0.005" thick HDPE film, sandwiched between EPDM rubber (with Teflon fabric on each side to prevent the rubber from sticking) and a metal press on the outside. The entire fixture is then placed in an oven and "soaked" at 400 degrees F for 30 minutes. The rubber will expand under the heat, providing additional pressure during the soak. The results showed that, while the HDPE allowed for good consolidation and adhesion between the layers of S-Glass fabric, it did not "wet" through the fabric to the surface. In addition, unidirectional wrinkles were found on surfaces in contact with the rubber and Teflon, which is due to the rubber contracting during the post-soak cool-down. The solution was to add a layer of galvanized steel between the rubber/Teflon and the composite layup and an additional ply of HDPE film to the outer surface of the layup. The galvanized steel allows for the rubber to expand and contract, providing even pressure to the layup without wrinkling its surface. Future processes substituted the galvanized steel for two layers of Teflon.

Figure 10: S-Glass/HDPE resin infusion process in oven (left) and fabricated S-Glass/HDPE laminate (right)

Tests were also done to observe the permeability of the liquid-phase HDPE through multiple layers of S-Glass fabric during the resin film infusion process. The layup was composed of a sheet of 0.062" thick HDPE with five plies of 0.006" S-Glass fabric on each side, sandwiched between layers of rubber, galvanized steel, and metal press. The fixture is allowed to soak in the oven at 400 F for 1 hour. High process temperatures (400 degrees F and greater) was used to allow greater heat flow in the HDPE resin. Results showed consistent and excellent wet-through in most areas, but not thorough at some areas, which can be solved by increasing the process temperature and pressure and adding more HDPE. The percentage of fiber to resin varies amongst process batch to batch, depending on how much HDPE is used and "squeezed out" from the applied pressure during the resin infusion process. Typical values ranged from 45 to 64 percent by weight, and 40 to 65 percent by volume. Other fabrics were also tested, such as a denser woven S-Glass and Carbon fibers, with less success.

The second approach was the use of unidirectional E-glass fiber-reinforced HDPE pre-preg. Pre-preg materials were obtained from various sources, with a large and high quantity roll of E-glass pre-preg obtained from obtained from Ticona (figure 11).

Figure 11: E-Glass fiber-reinforced HDPE prepreg. The large roll is the material sent by Ticona.

The material sent by Ticona is their Celstran CFT HDPE-GF70 fiber-reinforced HDPE composite tape. According to the specification sheet that came with the material, the composite is made up of 70% content by weight (46% by volume) and have a tensile strength of 120526 psi or ~121 ksi (831 MPa) and a tensile modulus of 5395402 psi or ~5.4 Msi (37200 MPa). All list of material data specs are shown below in figure 12, taken from Appendix C. The given tensile modulus is much higher than the general "rule of thumb" requirement (2.5 Msi) and matches with the Clock Spring standard (5.0 Msi). The given tensile strength is high than the "rule of thumb" requirement (~50 ksi) and the Clock Spring standard (100 ksi). Fabrication of the laminate using the pre-preg involved applying heat and pressure to consolidate individual plies into a thicker sheet.

Property	***Value***	***Unit***	***Test Method***
Polymer Resin	HDPE	-	-
Fiber Reinforcement	E-Glass	-	-
Density	1.69	g/cm^3	ISO 1183
Fiber Content	70 (46)	% wt (% vol)	-
Tensile Strength	831	MPa	ASTM D 638
Elongation at break	2.1	%	ASTM D 638
Tensile Modulus	37200	MPa	ASTM D 638
Flexural Strength	270	MPa	ASTM D 790
Flexural Modulus	25600	MPa	ASTM D 790
Melting Temp	128	deg C	-

Figure 12: Preliminary values for Celstran CFT HDPE-GF70 provided by Ticona

The issue with the consolidation of the E-Glass pre-preg involves adjusting the process temperature and pressure to fully consolidate the plies without causing resin overflow and fiber wash. Fiber wash occurs when the resin, under excess heat and uneven pressure, begins to flow too much and ultimately distort the orientations of the fibers. Unidirectional fibers are very susceptible to this type of distortion, which causes the fibers to appear to "bend" towards the direction of the resin flow (as shown in figure 13). Initially, several plies of the pre-preg was sandwiched in between Teflon, EDPM rubber, and a metal press under 80 in-lb of torque, then allowed to soak in the oven at 400 degrees F for 30 minutes. The resulting laminate showed signs of fiber wash in the direction of highest applied pressure in the tooling (near the clamps and bolts) to the lowest (towards the edges). After several attempts, an optimum process temperature of 300 F and a low, evenly-placed pressure was applied to layup for consolidation. The layup is allowed to soak in the oven for a given time, dependent on the thickness of the consolidated laminate.

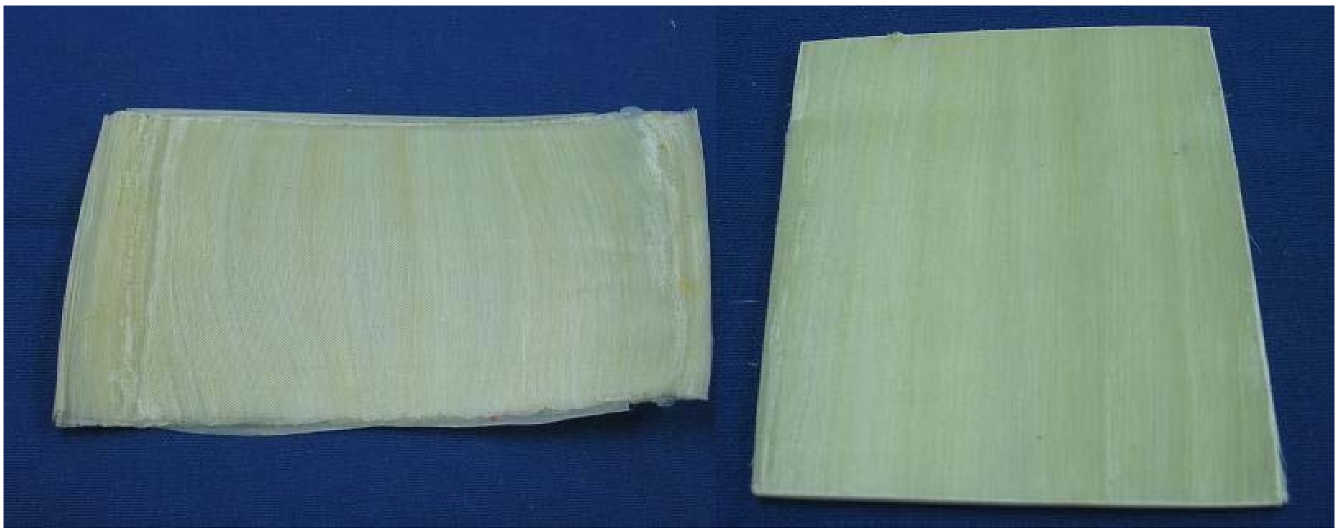

Figure 13: An example of a post-consolidated laminate subject to fiber wash (left) and one that has kept its fiber orientation after the consolidation process (right)

Evaluation of Performance Properties – Indiana Match Grant

The testing of tensile strength and modulus of the S-Glass and E-Glass laminates discussed in the previous section were done in order to perform a final down-selection on the material system to use as well as to verify the data specs on the E-Glass pre-preg sent by Ticona. Thermoplastic hot melt adhesives were also obtained and lap shear tests were performed on its bonding between the down-selected material and steel. Nichrome material used for the in-field heating apparatus was also obtained and evaluated.

Test coupons of the S-Glass and E-Glass materials were made for tensile testing (figure 14) to ASTM D 3039 standards. Testing of the S-Glass composite material was successful though some issues with fabric tearing and uneven load distribution. Problems were more substantial when testing the E-Glass coupons, due to issues with gripping the pre-preg surface using the in-house general tensile grip. The woven S-Glass fabric impregnated with HDPE resin has a softer surface that allows for a good mechanical grip. The E-glass pre-preg, however, has a hard, slippery surface that does not allow the teeth on the grip to "bite" into the material to provide a good mechanical stop. Attempts to enhance the contact between the grip and laminate surface by lightly sanding the surface of the pre-preg laminate to provide grooves for the teeth to grip or using sandpaper wrapping were unsuccessful. Gripping issues were finally solved by bonding G10/FR4 fiberglass epoxy tabs onto the test coupons. G10 is the most commonly used tabbing material for gripping and provides excellent mechanical contact with a variety of tensile grips.

While the gripping issue was solved, the point of failure for the tensile testing was moved from the grip contact to the bond between the tabs and laminate material, rather than the fibers themselves. Attempts were made to solve the problem by making the shear strength of the tab adhesive to be higher than the strength of the fibers. Several adhesive bonding agents were used, including two-stage epoxies, super glue, and the Loctite 401 irregular surface glue. The best performing adhesive was the irregular surface glue, providing the highest peak stress before tab separation, while the worst performing adhesive was the two-stage epoxy. The cross-sectional area of the coupon gage area was also reduced to provide a lower breaking point. As of the end of the program reporting period, not a single unidirectional test coupon provided breaking at the fibers, though test data was conclusive enough to make a final down-selection.

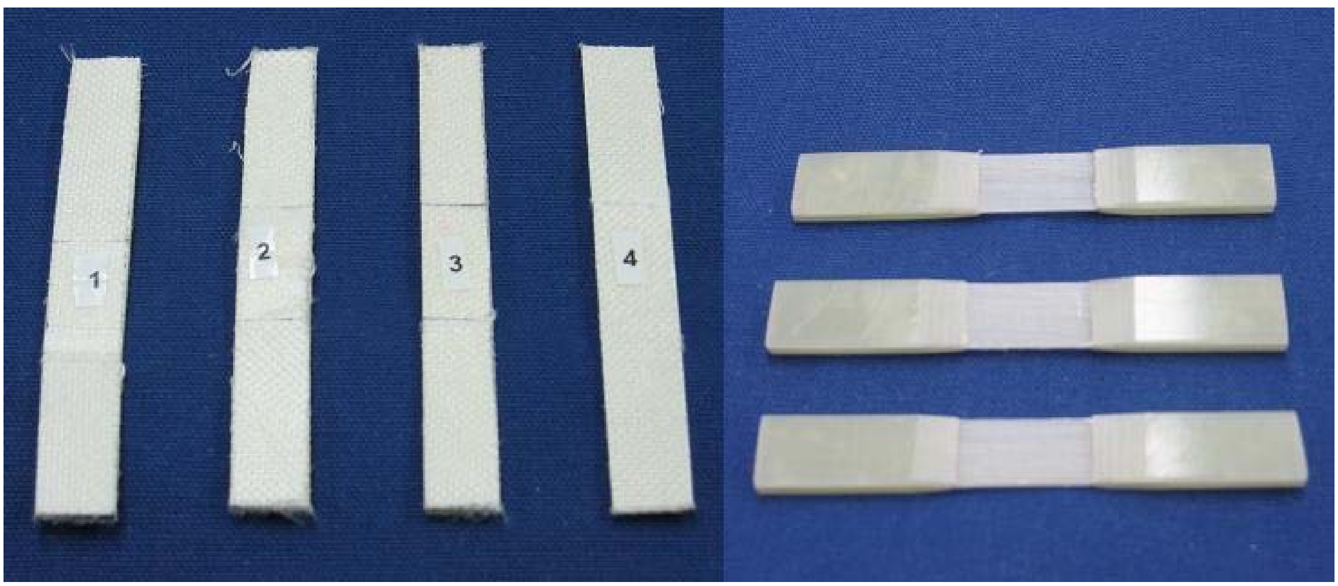

Figure 14: Test coupons made for tensile testing. Test coupons made from bidirectional woven S-Glass (left) and unidirectional E-Glass pre-preg with G10 tabs (right).

Results of the bi-directional woven S-Glass laminate shows the highest tensile strength to be around 25.7 ksi with a tensile modulus of ~200 ksi, performed on a test coupon with a cross-sectional gage area of 0.577" by 0.064" and no tabbing. The results show that the woven S-Glass fabric does satisfy neither the "rule of thumb" requirement nor the Clock Spring standard. This is perhaps due to the fact that density of the fibers are equally distributed in two directions, which provides equal tensile strength in both the 0 and 90 orientations but effectively halving the strength in one direction. The S-Glass fabric is also loosely woven, and thus have a much lower fiber density than standard unidirectional (or even some bi-directional) pre-preg.

The testing data taken from tensile testing of the unidirectional E-Glass pre-preg laminate, though not conclusive, was enough to satisfy the tensile strength requirement "rule of thumb" requirement, though not for the Tensile Modulus. The highest tensile strength recorded was approximately 61 ksi with a tensile modulus of ~660 ksi from a test coupon with relatively straight fiber orientation (unidirectional), cross-sectional gage area of 0.546" by 0.031", and G10 tabs bonded on by Loctite 401 irregular surface glue. Note that the test was concluded due to the failure of the bonding between the tabs and not from the fibers themselves. It is more that likely that the gradual "slipping" of the adhesive bond-line and the eventual shear failure made the recorded tensile strength and modulus of the fibers to be much lower than the actual strength and modulus values. In essence, the recorded tensile strength and modulus was that of the Loctite 401 adhesive, and the pre-preg material can be concluded to have strength and modulus of *at least* 61 ksi and 660 ksi, respectively. Correspondence with Ticona (the manufacturer of the E-Glass pre-preg material) reveals that they used the ASTM D 638 method for their tensile testing[2]. Their testing was successful in breaking the fibers and more conclusive in gauging the mechanical properties of the material (figure 12). Therefore it can be stated with a measure of confidence that the actual tensile strength and modulus values are closer to the Ticona data than the ones obtained in-house.

The most conclusive results of the in-house tensile testing are listen in figure 15 below. A more detailed data are listed in Appendix B. Since the S-Glass fabric failed to meet the requirements while the unidirectional E-Glass meets or exceed a majority of requirements in testing done by both Ticona and in-house, the E-Glass pre-preg is chosen as the final material system in the down-selection process.

Material	***Tensile Strength (psi)***	***Tensile Modulus (psi)***	***Comments***
0/90 S-Glass HDPE	25699.1	199713.1	Breaking of the fibers occurred
0/0 E-Glass HDPE	61073.7	660383.9	Fibers did not break, adhesive tabs slipped

Figure 15: Results of the tensile tests, data taken from the most conclusive results

Once the down-select to the unidirectional E-glass pre-preg was made, lap shear testing was performed on thermoplastic hot melt adhesives used bond the pre-preg laminate to the surface of a steel pipe. Thermoplastic adhesive was chosen over other adhesive types such as thermoset epoxies in order to create a complete thermoplastic system that is high-fill, heat-controlled and does not require cure time. Several thermoplastic hot melts were obtained from Bemis based from polyurethane, polyester, and modified HDPE. The modified HDPE hot melt was used for lap shear testing, being the same material as the laminate resin and providing good adhesion to a variety of polymers and metals, maintaining structural adhesion in the presence of moisture and most chemical solvents. The listed bond strength for the modified HDPE hot melt is 2200 psi, comparable to many two-party epoxies out on the market. High performance epoxies such as the Loctite 120-HP have bond strength of 3400 psi to stainless steel.

Test coupons were made by bonding galvanized steel to the E-Glass pre-preg using a square inch of 0.006" thick modified HDPE (figure 16), made to ASTM D 5379 standards. The coupons were

[2] It was not possible to perform ASTM D 638 testing in-house due to the lack of proper tooling to do so.

processed in the oven at 260 degrees F for 10 minutes to activate the adhesive layer. Lap shear testing was successful as the bond-line was broken. The highest bond stress recorded was 741 psi with a modulus of 13725 psi, with a more detailed report presented in Appendix B. The results were lower than expected (compared to thermoset epoxies), and could be attributed to the fact that the hot melt was not processed long enough for it to completely bond with the two surfaces. Higher bond strength can be achieved by a longer process under greater pressure. Other solutions include better surface prep on the steel such as sand-blasting and chemical etching to promote a better grip. Polyurethane and polyester hot melt lap shear coupons are currently being fabricated and tested. Polyester has higher tensile strength than HDPE while polyurethane has a much lower processing temperature. It remains to be seen whether both these hot melt materials can be bonded onto the steel and pre-preg as well as the modified HDPE.

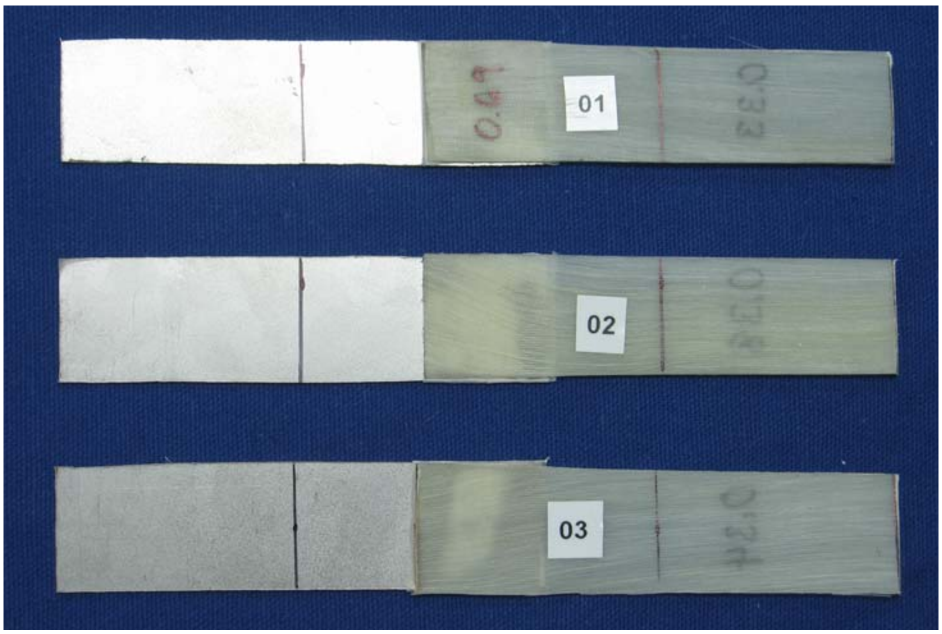

Figure 16: Test coupons made for lap shear testing

Material for the in-field heating apparatus was obtained and evaluated during this period. A sheet of Nichrome wire mesh was connected to various DC and AC power sources and temperature measurements were made on the mesh surface using a thermocouple. The two leads of the power source were connected from one corner of the wire mesh sheet to the opposite corner as well as to two metal rods running along opposite edges of the sheet. The tests were not successful as no temperature increase was observed even with a 700 W AC power source connected to it. This is due to the low resistivity running through the mesh and the electrical current from the power supply having multiple paths of interlinking wire travel through, thereby minimizing heat dissipation by electrical resistance. The solution is to have the electrical current go through a single Nichrome wire, which is placed in a staggered "zigzag" pattern to provide equal heat distribution. The test setup in figure 17 shows the single wire heating apparatus connected to a DC power source. The thermocouple reading shows that, under a 2A current, the temperature reached 300 degrees F in two minutes.

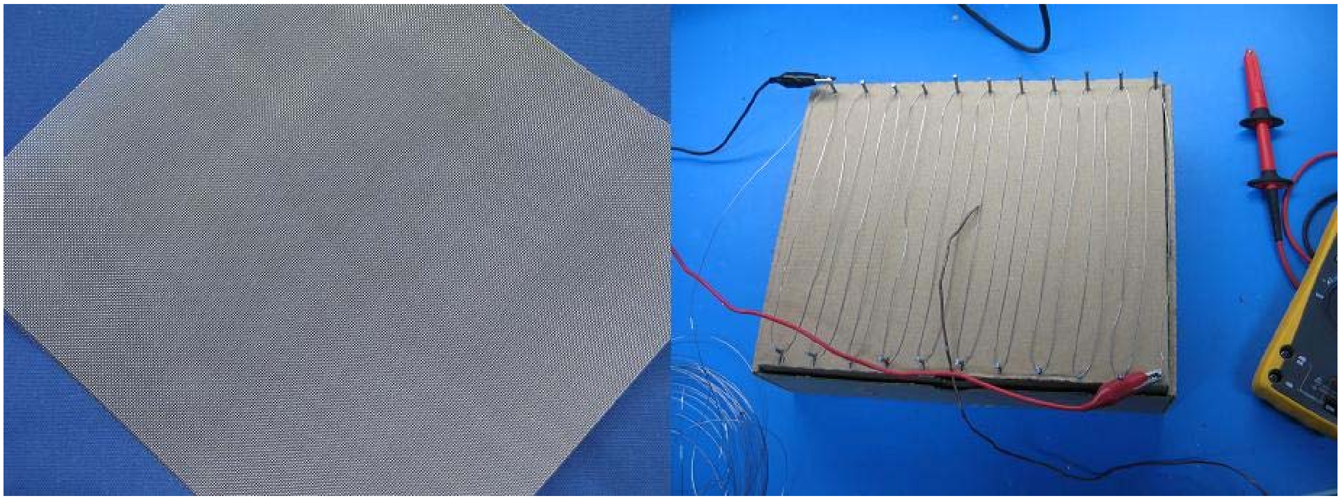

Figure 17: Heat apparatus testing, nichrome wire mesh (left) vs staggered nichrome wire design (right)

Analysis

Analysis of the repair laminate for design and performance was concluded by the end of the program. Calculations for the minimum design thickness were given in the ASME PCC-2-2006 handbook, titled Repair of Pressure Equipment and Piping. Two sets of equations are used to determine minimum repair laminate thickness, one for pipes not leaking, requiring structural reinforcement only, and another for pipes requiring structural reinforcement and sealing of through-wall defects (i.e. leaks).

The equations used to calculate minimum laminate thickness on a non-leaking pipe are given by the following, taken from Article 4.1 of the ASME PCC-2-2006 standards handbook:

$$t_{\min} = \frac{D}{2s}\left(\frac{E_s}{E_c}\right)(P - P_s) \qquad (1)$$

$$t_{\min} = \frac{D}{2s}\left(\frac{E_s}{E_c}\right)\left(\frac{2F}{\pi D^2} - P_s\right) \qquad (2)$$

Equation 1 is the minimum design thickness for hoop stresses due to internal pressure. Equation 2 is the minimum design thickness for axial stresses due to internal pressure, bending, and axial thrust.

The equations used to calculate minimum laminate thickness on a leaking pipe with through-wall defects are given by the following:

$$t_{\min} = \frac{1}{\varepsilon_c}\left(\frac{PD}{2}\frac{1}{E_c} - \frac{F}{\pi D}\frac{\upsilon_{ca}}{E_c}\right) \qquad (3)$$

$$t_{\min} = \frac{1}{\varepsilon_c}\left(\frac{PD}{2}\frac{1}{E_c} - \frac{F}{\pi D}\frac{\upsilon_{ca}}{E_c}\right) \qquad (4)$$

Equation 3 is the minimum design thickness for hoop stresses due to internal pressure. Equation 4 is the minimum design thickness for axial stresses due to internal pressure, bending, and axial thrust.

A table of the equation terms and values used for calculating minimum repair laminate thickness for equations 1-4 are shown below:

Symbols	***Description***	***Values Used***
D	External pipe diameter (in.)	6.625
s	Specified Minimum Yield Strength of pipe (psi)	30000
E_s	Tensile modulus for steel or pipe material (psi)	30000000
E_c	Tensile modulus for the composite laminate in the circumferential direction (psi)	5395402
P	Internal design pressure according to CFR 192.105 (psi)	1127
P_s	Maximum Allowable Working Pressure for the pipe (psi)	150
F	Sum axial tensile loads due to pressure, bending, and axial thrust (lb)	35741
ε_c	Allowable circumferential strain	0.002295
υ_{ca}	Poisson's ratio for the composite laminate in the circumferential direction	0.36
E_a	Tensile modulus for the composite laminate in the axial direction (psi)	145037.7
ε_a	Allowable axial strain	0.00044

Figure 18: List of terms used to calculate minimum repair laminate thickness

Most of the values taken from the table above (Figure 18) comes from the physical and mechanical properties of the Ticona E-Glass laminate and a standard stainless steel pipe. These properties are available in Appendix C. The internal design pressure, *P*, is taken from the Code of Federal Regulations 192.105(a), which states:

```
“The design pressure for steel pipe is determined in accordance
with the following formula:

P=(2 St/D)xFxExT

P=Design pressure in pounds per square inch (kPa) gauge.
S=Yield strength in pounds per square inch (kPa) determined in
accordance with Sec.  192.107.
D=Nominal outside diameter of the pipe in inches (millimeters).
t=Nominal wall thickness of the pipe in inches (millimeters). If this
is
unknown, it is determined in accordance with Sec.  192.109. Additional
```

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wall thickness required for concurrent external loads in accordance
with
Sec.  192.103 may not be included in computing design pressure.
F=Design factor determined in accordance with Sec.  192.111.
E=Longitudinal joint factor determined in accordance with Sec.
192.113.
T=Temperature derating factor determined in accordance with Sec.
192.115."
```

In order to allow the repair laminate to operate for the widest range of applications, parameters were chosen for the 192.105 formula for the highest possible rated internal design pressure. The yield strength was selected to be 24000 psi, outside pipe diameter 6.625", nominal wall thickness 0.27", design factor 0.72, longitudinal join factor 0.8, and temperature derating factor 1.000. The highest internal design pressure was calculated to be about 1127 psi.

The sum axial load, *F*, is calculated by taking the upper limit case in which one of the ends of the pipe is terminated with an end cap. The upper limit sum axial load is determined by taking the internal area of the end cap multiplied by the pressure per unit area from the internal pressure:

$$F = \pi R^2 P \qquad (5)$$

where *R* is the radius of the inner diameter of the pipe and *P* is the internal design pressure. Given a maximum internal pressure of 1127 psi, the calculated sum axial load was 35741 lbs.

The allowable repair laminate strains (circumferential and axial) are taken from section 3.4.4 of the ASME PCC-2-2006 standards book, given by the following equation:

$$\varepsilon_c = f_T \varepsilon_{c0} - \Delta T(\alpha_s - \alpha_c) \qquad (6)$$
$$\varepsilon_a = f_T \varepsilon_{a0} - \Delta T(\alpha_s - \alpha_a) \qquad (7)$$

where f_T is the temperature derating factor, ε_{c0} and ε_{a0} are taken from Table 4 of the handbook, and α_s, α_a and α_c are the coefficient of thermal expansion for the steel pipe and composite in the axial and circumferential direction, respectively[3]. The calculated values for allowable strain are listed in figure 18.

Using equations 1-4 and the values listed in figure 18, the minimum calculated repair laminate thickness are listed below (figure 19). The results show that the minimum thickness required for a non-leaking pipe is three times that of a leaking pipe. This is due to the fact that the design methodology for a non-leaking pipe focuses exclusively on structural reinforcement, and requires the repair laminate to be thick enough to match the stiffness of the underlying steel pipe. The repair of the leaking pipe, however, requires the repair laminate to handle all the load carrying capability, and thus the stiffness-matching of the two materials do not factor into the calculation. Given that

[3] The values of the CTE for composites are taken from http://www.amalgacomposites.com/eng_mp.htm and steel from Matweb.

majority of in-field repairs involve a leaking pipe, design methodology 3 will be used as a model for FEA analysis and design. All listed values and calculations are detailed in Appendix D.

Design Methodology	***Minimum Thickness***
(1) Non-leaking Pipe, Maximum Hoop Stress	0.75”
(2) Non-leaking Pipe, Maximum Axial Stress	0.28”
(3) Leaking Pipe, Maximum Hoop Stress	0.25”
(4) Leaking Pipe, Maximum Axial Stress	0.16”

Figure 19: Minimum repair laminate thickness for the four listed design methodologies under maximum stress conditions on a standard 6.625” OD steel pipe

Finite element analysis was performed using COSMOS to simulate and verify the results of the previous analysis for a 0.25” thick composite repair laminate and a standard 6.625” steel pipe under an internal pressure of 1127 psi. The pipe material used was a plain carbon steel with a tensile modulus of approximately 30 Msi, a tensile strength of 58 ksi, and yield strength of 32 ksi. Under a constant internal pressure 1127 psi, the pipe exhibited a hoop stress of 7.5e7 N/m^2 or 10878 psi and a deformation of 0.03 mm or 0.00118” (figure 20).

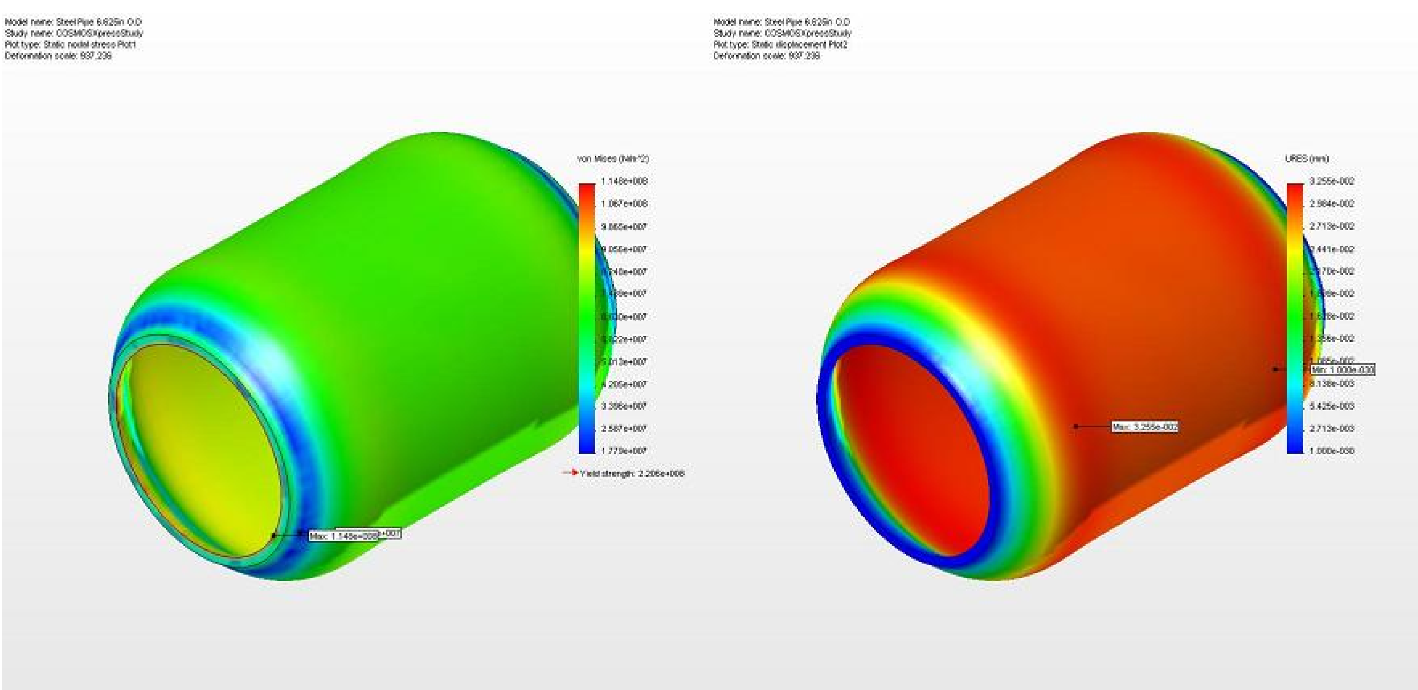


Figure 20: von Mises stress (left) and displacement (right) of a standard 6.625” OD steel pipe under 1127 psi of uniformed hoop stress. Note that the deformation scale is 937.

FEA was performed on the 0.25” thick E-Glass repair laminate that is sized to bond over the steel pipe at the location of the through-wall defect or leak. Due to the fact that in this deign methodology the contribution of load-carrying capability the original pipe is ignored, the pipe was removed for the analysis and a uniform internal pressure was placed on the repair laminate itself. Under this constant pressure, the repair laminate exhibited a hoop stress of 1.0e8 N/m^2 or 14504 psi and a deformation of 0.445 mm or 0.01752" towards the upper and lower edges of the laminate and 0.3641 mm or 0.014" near the center (figure 21). The rate of deformation being higher for the composite than the steel is to be expected, due to its lower tensile modulus. The results show that while the rate of deformation is evenly distributed in the steel pipe, it is unevenly concentrated at the top and bottom of the composite clamshell, away from the clamped ends. This might be potential issue in the future and is presently being looked into.

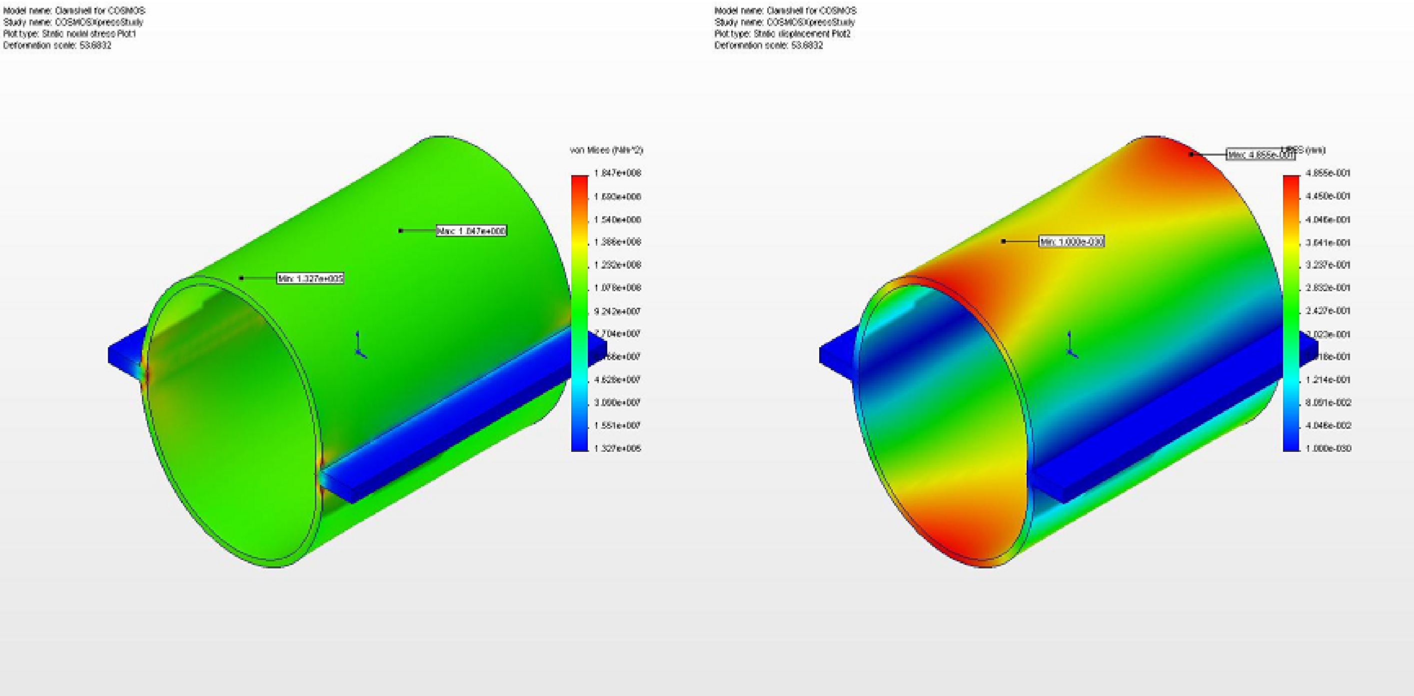


Figure 21: von Mises stress (left) and displacement (right) of the 0.25" thick E-glass pre-preg laminate under 1127 psi of uniformed hoop stress. Note that the deformation scale is 24.

FEA analysis was performed on several other internal hoop pressures, which are listed in Appendix E.

Design Concepts

Designs were made for the repair system and its associated tooling. The following paragraphs describe the design of various components and tooling assemblies for the composite repair system.

High pressure consolidation of the composite material yields a very low void content which maximizes optimum density. Therefore, the use of pre-consolidated thermoplastic panels is being considered. These panels, which are made up of multiple plies or layers of composite sheets, are consolidated under high pressure to minimize void content. Figure 22 shows a composite panel for the repair system that would be pre-consolidated in a flat shape, and subsequently formed to fit the outer diameter of the pipe to be repaired. Continuous fiber reinforcement (CFR) will increase the performance of the thermoplastic composite repair system. Reinforcements could be unidirectional or bi-directional but earlier research showed some concern over a woven fabric having the potential for fiber distortion that may occur during expansion and contraction process cycles.

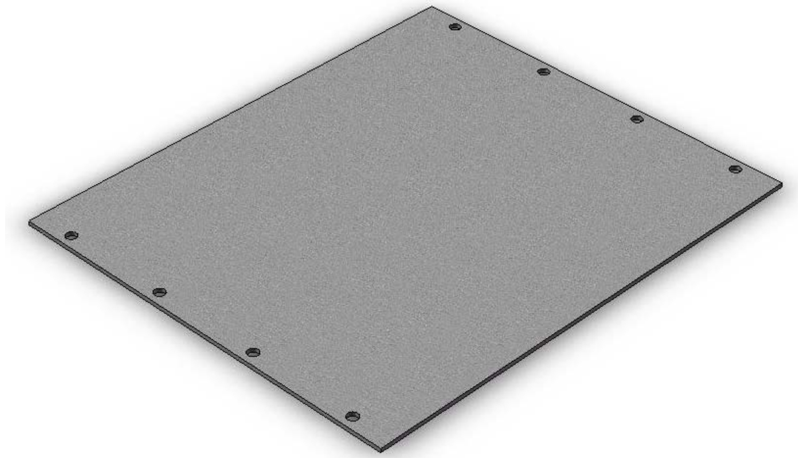


Figure 22: Pre-consolidated composite panel before forming.

Tooling designs for forming the pre-consolidated panels to the proper shape could be constructed from a variety of material. *(see Figure 23)*. The tool itself would not have to as robust because of the initial pre-processing phase. This could allow the use TIG welded aluminum form tools for a greater cost savings over billet stock.

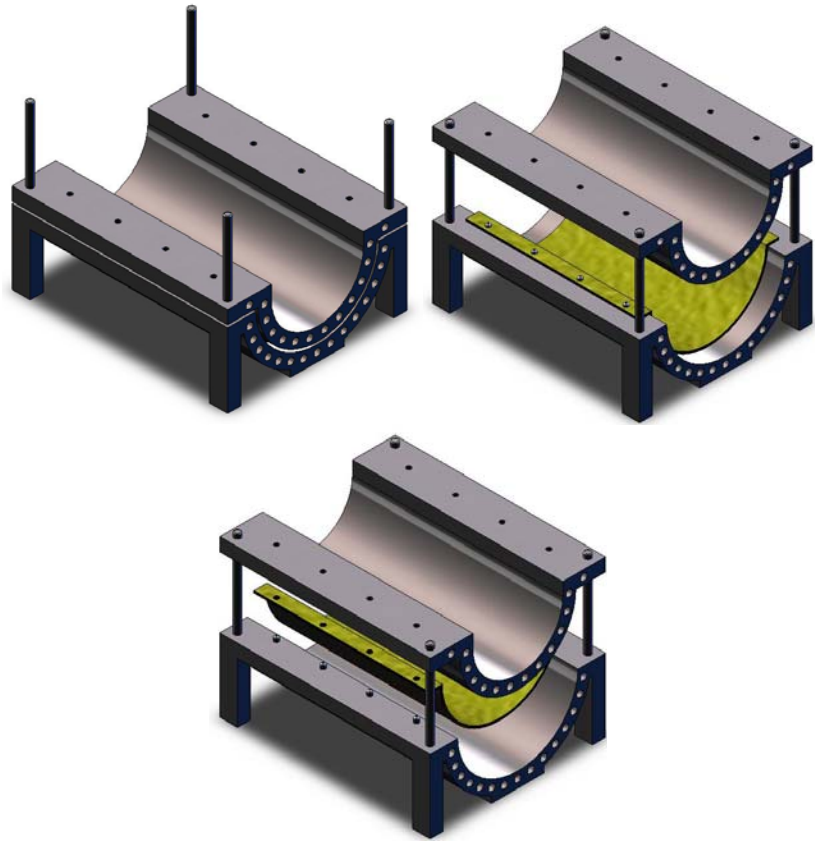


Figure 23: Tooling concept for pre-forming the HDPE pre-consolidated composite panel.

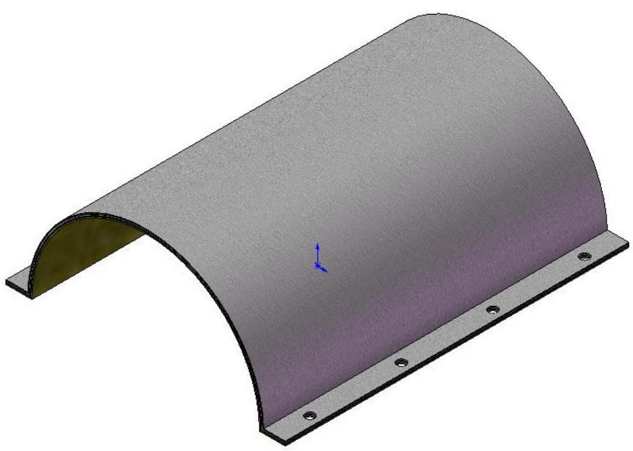


Figure 24: Thermoformed clam-shell half

The composite panels will be formed by preheating the pre-consolidated composite panels until the material becomes flexible enough to be formed. Once properly heated, the panel is formed by placing the heated panel over the correct form, clamping the tool mating halves together, and then allowing the part to gradually cool. The fundamental of heat fusion welding is to heat the HDPE surfaces to an appropriate temperature, changing the resin's molecular structure to an amorphous (pliable state), and then fuse them together by application of prescribed force (torque). During the cooling phase, the material returns to its crystalline state thus creating one homogeneous structure (see Figure 24).

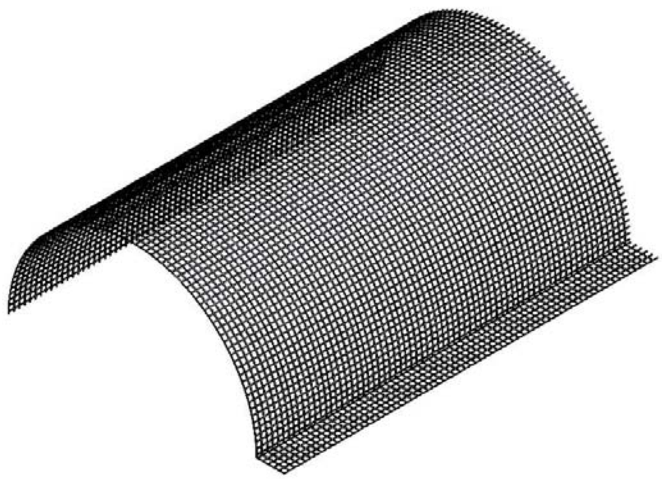


Figure 25: Nichrome heating element.

One method being investigated as a possible heat source involves nichrome wire mesh (see Figure 25). The mesh would be sandwiched in the assembly to uniformly distribute heat to the clamshell surfaces. An electrical current would cause the heating of the wires to the proper temperature after the assembly was installed on the damaged pipe section. The damaged pipe section would have all of the components assembled with a metallic over-press held together with standard fasteners with the required specified torque (see Figure 26). When fusion pressure is applied at the designated temperature and the prescribed force is applied, the thermoplastic molecules from each mating surface mix. As the joint cools, the molecules return to their crystalline form, the original interfaces have been removed, and the two halves have become one monolithic structure *(*see Figure 27*)*.

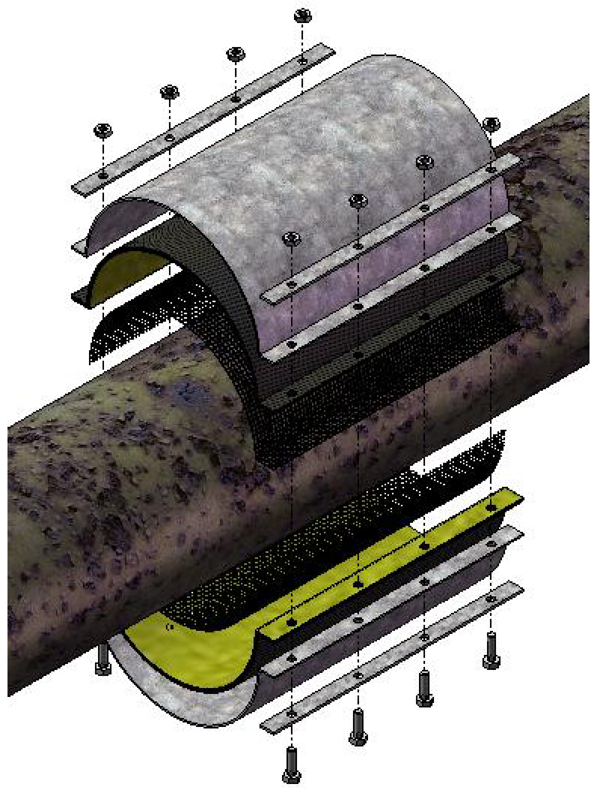


Figure 26: Exploded view of the thermoplastic composite repair system.

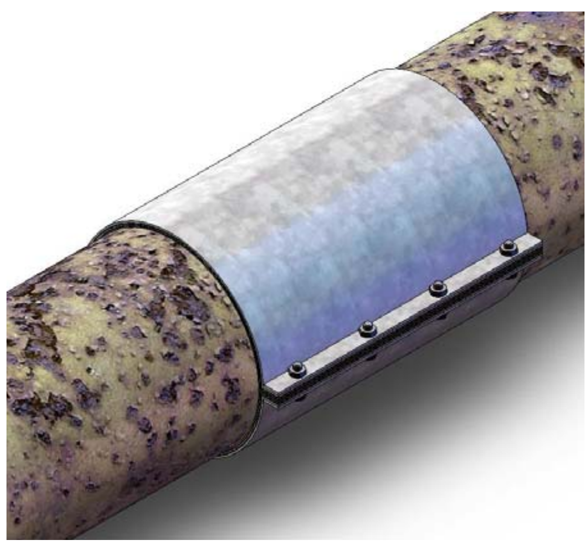


Figure 27: Completed thermoplastic composite repair system.

In-House Prototype

A prototype tooling was made in-house which incorporated an actual 6" schedule 40 pipe section for forming the half clamshell in a vacuum chamber environment. The support frame was constructed with standard 2" x 6" wood joists which were assembled so that the centerline of the pipe was collinear with the underside of the formed clamshell. This simplified approach was taken in lieu of a machined forming tool to prove the concept prior to having a hard form tool being machined. The composite layup consisted of 25 plies of the Celstran E-Glass pre-preg laminate material provided by Ticona. The composite material was then sandwiched between two layers of a Teflon coated fabric to insure that the material would not adhere to the tooling or vacuum bag. (see figure 28) A flexible membrane (stretchable rubber) upper frame was assembled over the composite layup. This creates a vacuum-sealed environment in which the membrane, under vacuum, applies a form-fitting pressure to the layup during the heating process. The fully assembled vacuum chamber was placed into the oven with the vacuum hose attached and heated with the appropriate temperature, time, and pressure required for processing.

Figure 28: The tooling (left) and the E-Glass laminate material (right) before process

Upon removal from the oven, the vacuum pump was re-attached to the vacuum chamber and left running during the cool down cycle to insure no movement of the formed composite clamshell (see figure 29).

Figure 29: Stretchable membrane under vacuum creates a form-fitting pressure on the layup

The pre-formed clamshell halves were assembled onto the repair area with the addition of the metallic over-press, metallic flange reinforcements, and mechanical fasteners. All components went together with a relative ease of assembly. The final assembled prototype is shown in figure 30.

Figure 30: Assembled prototype

Task III – Develop Team and Demo Plans for Phase II

Phase II Proposed Work Plan

The work plan for this proposed program is structured to provide the DOT technical program manager with a clear plan for program execution and review. The following is a list and summary of each program task.

TASK I – Define Baseline and Requirements

The baseline repair techniques will be studied and documented. Odyssian Technology will solicit input from major companies that are well established in maintaining Oil & Gas pipeline systems in an attempt to qualitatively assess the performance and ease of repair of current composite repair systems. Performance needs, requirements, and specifications will be used to define design objectives and requirements.

TASK II – Develop Composite Repair Concepts and Designs

In this task, Odyssian Technology will continue to develop 3D solid model designs of the composite repair system. Analysis of the 3D solid model design will be performed using finite element analysis techniques and tools to guide design and predict performance.

Materials and processing concepts will be further developed that include consideration of cost materials, ease of in-field repair, safety, long term performance, and commercial availability. Tooling design concepts will be developed using 3D solid modeling design software and recommendations for repair method/practices will be documented.

TASK III – Process Development and Evaluation

Process development and evaluation of the composite repair technique will be made. This task will include sourcing and evaluating readily available materials. Subscale piping will be used for early development and evaluation of the composite repair technology. It is anticipated that this will include the purchase of subscale tooling and composite heating and fusing equipment.

TASK IV – Develop Concepts and Designs of Leak Detection Sensor Patch

The composite repair concept will include an integrated sensor and seal system that provides early warning of leak progression. This patented technology will be adapted for use in the new composite repair system. These concepts and designs will be focused on the means for effectively integrating seals and leak progression sensor arrays into the composite repair system. Consideration will be given to ease of installation, cost, and prolonged performance. This task will also include research into sensing methods that satisfy size constraints and environmental conditions. It is anticipated that the design of the circuitry, power supply, and communication network will be started during this time.

Phase II Team

The phase II team is currently being assembled. Some of the parties interested are Chris Alexander from Stress Engineering Services, Inc (a lab/testing house for composite repair systems), Bemis (provider of thermoplastic adhesives), and Ticona (provider of E-Glass/HDPE composites). Some letters of interest are shown in Appendix F.

3.3 – RELATED WORK – INDIANA MATCH

Task I – Process Development and Evaluation

The technical accomplishments of this task are discussed in section 3.2 – Technical Accomplishments in this report, under the heading Evaluation of Material Fabrication Process and Evaluation of Performance Properties.

Task II – Development of Sensor Patch Design

Design and Concepts for Structural Stain-Gauge Patch Sensor

The goal of designing an integrated strain gauge repair patch is to detect leaks by measuring the structural integrity of the composite wrap after the pipe repair in order to monitor the repaired segment for any future corrosion or fractures. To measure the structural integrity, strain gauges must be integrated directly onto the repair patch.

Using the Indiana Match funds provided for this SBIR, Odyssian Technology is currently developing and investigating technology that will ultimately result in a smart patch repair system capable of providing health monitoring and verifying the integrity of composite repairs. To accomplish this, Odyssian Technology is developing smart composite patches having embedded strain gauges. The focus was on developing and determining feasibility of the 'smart repair patches'. Figure 31 shows a 6" diameter composite patch having three printed strain gauges for determination of force loads and primary load path through the patch. These strain gauges will be made using highly conductive and compliant ink made by Creative Materials, Inc. These strain gauges will be embedded within plies of composite material prior to in-place repair. The concept shown in Figure 31 was explored during this Phase I along with repair technique including consideration of low temperature cure prepreg and dry fiber with resin infusion processing.

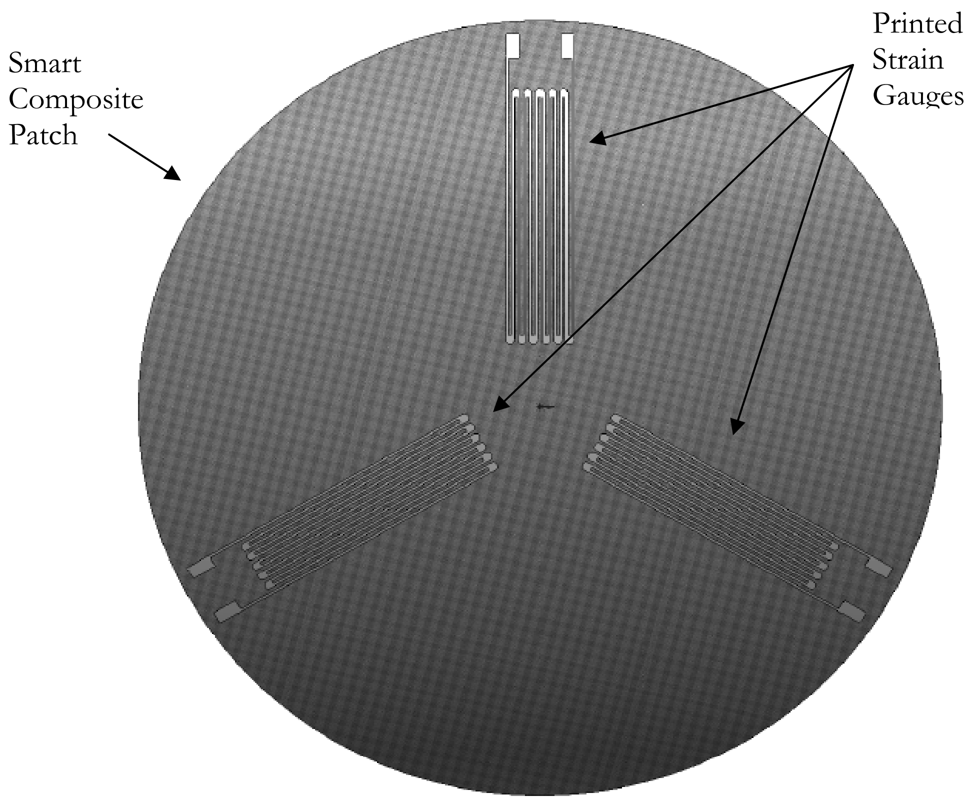


Figure 31: Smart Composite Patch with embedded (direct-write) printed strain gauges. (top composite ply not shown to illustrate printed strain gauges)

Figure 32 shows a concept that measures strain within the center filled patch region and the outer overlay patch region. This concept will be developed and investigated to determine feasibility in measuring strain within and outside the primary composite repair site to determine efficiency in carrying load.

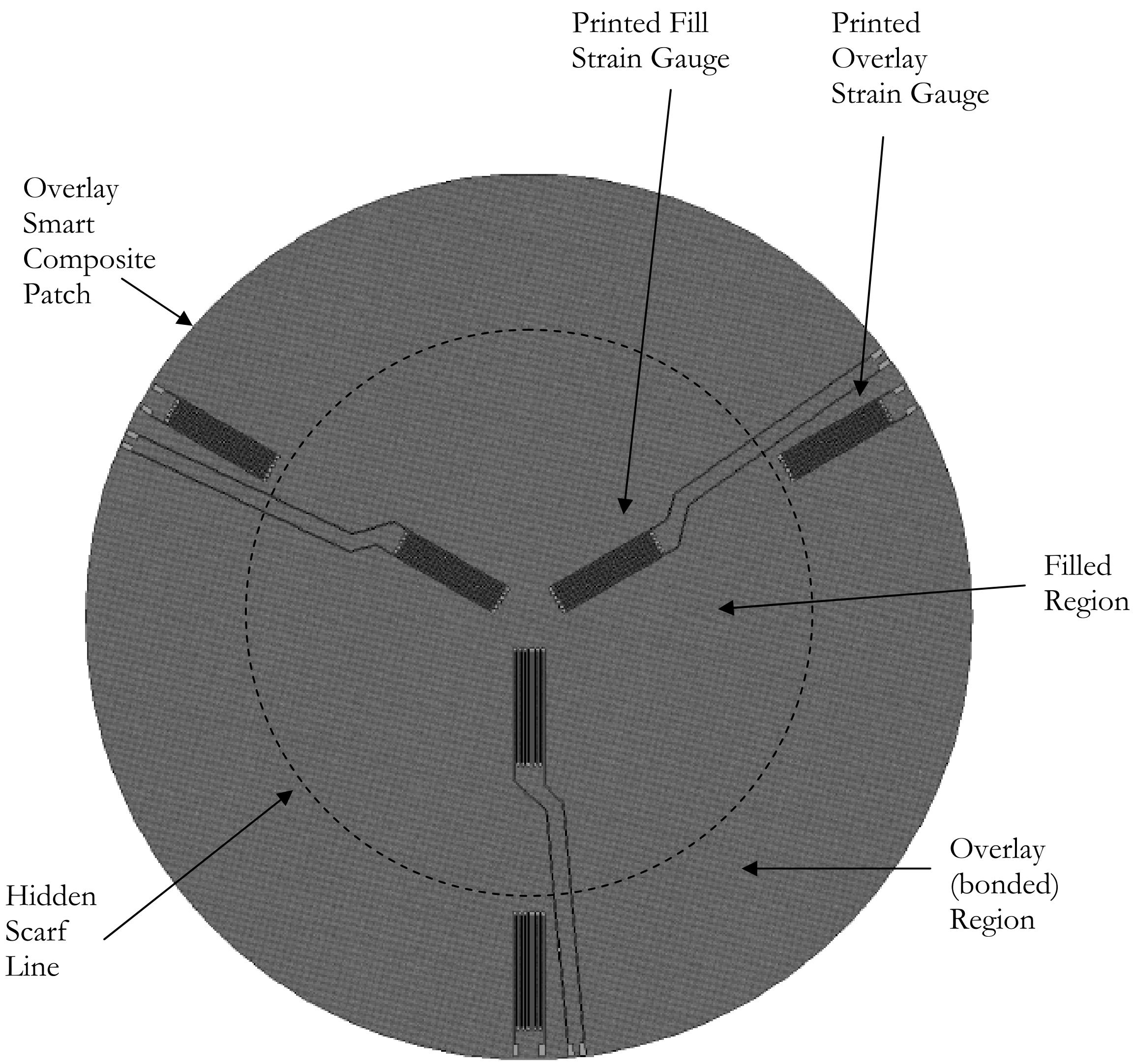


Figure 32: Smart Overlay Composite Patch with embedded (direct-write) printed strain gauges. The outer placed Overlay Strain Gauges in conjunction with inner placed Fill Strain Gauges allow for the measure of patch structural effectiveness. (top composite ply not shown to illustrate printed strain gauges)

A preliminary investigation was conducted into the feasibility of using passive non-contact printed strain gauges that are embedded within the composite laminate. This concept is similar to the NASA Langley non-contact fluid level sensor in which a printed fluid-measuring capacitor-sensor is placed in parallel with an inductor with acts as both a wireless transmittor and power source. Instead of a digitated capacitive sensing element coupled to a inductor coil, Odyssian Technology will use the resistive strain gauge. Figure 33 shows an illustration of this concept.

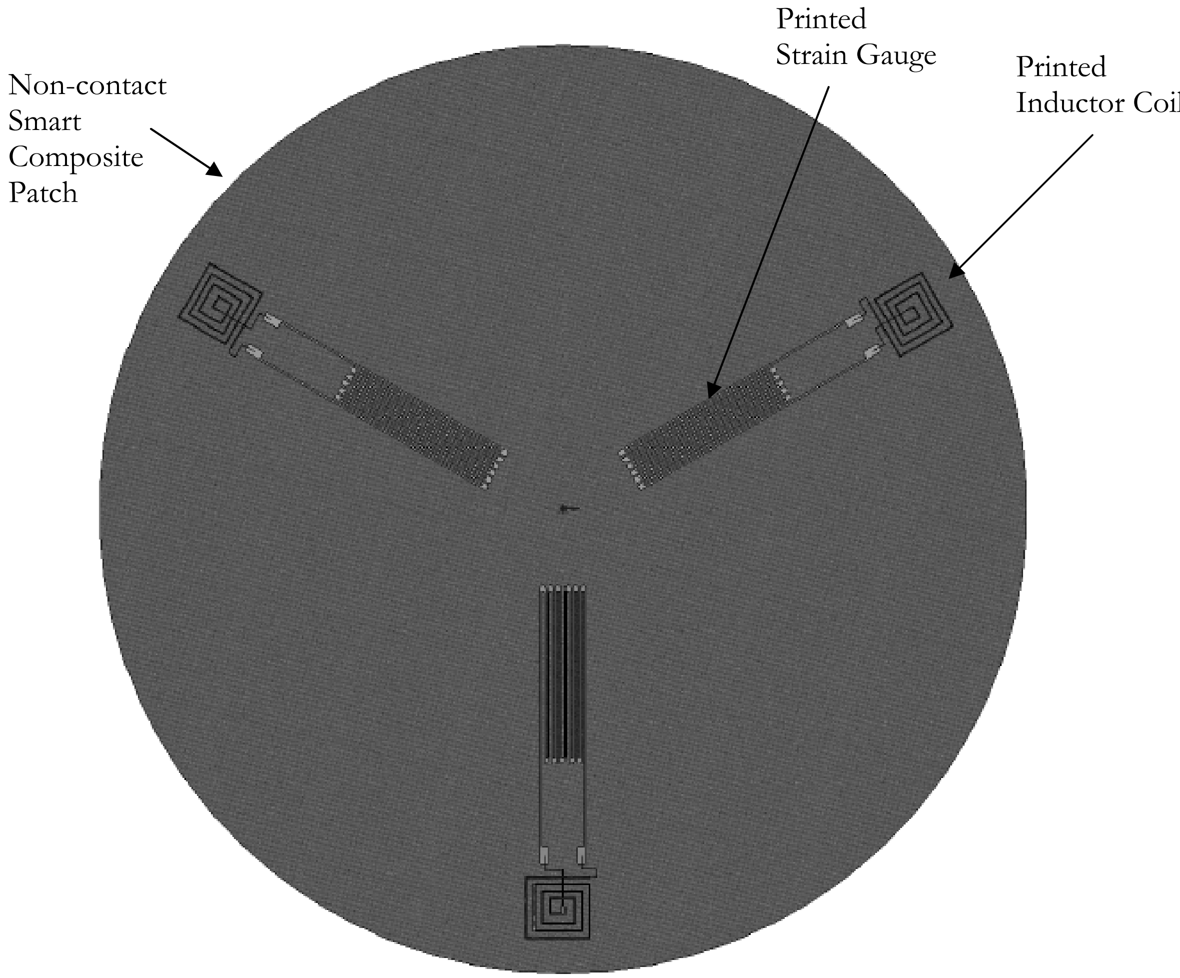


Figure 33: Non-Contact Smart Composite Patch with embedded (direct-write) printed strain gauges. The printed inductor coils allow for non-contact reading of the strain sensors to ease integration within the composite patch laminate. (top composite ply not shown to illustrate printed strain gauges)

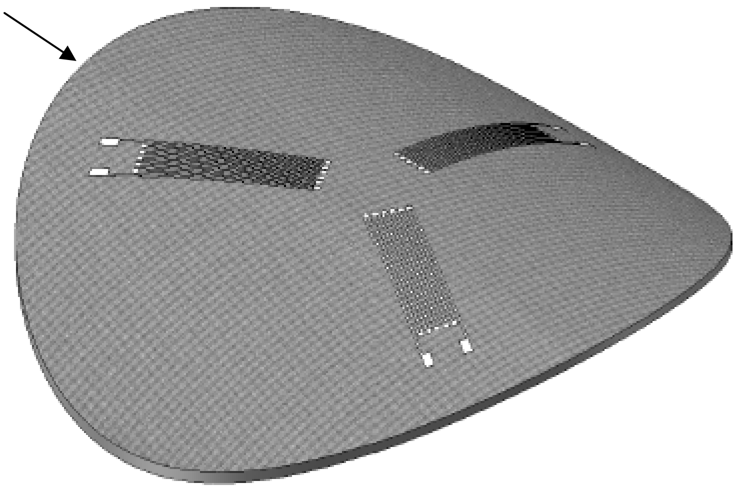


Figure 34: Shaped Smart Composite Patch with embedded (direct-write) printed strain gauges. Rigid shaped composite patches offer the advantage of controlled surface roughness and a rigid substrate that provides stable support of the printed sensors. (top composite ply not shown to illustrate printed strain gauges)

The inner portion of the patch, called the insert will be made rigid through B-staging (partial cure) or full cure of the underlying composite material. After the direct-write printing is completed and tested, the rigid composite insert will be co-bonded within the remainder of the uncured composite patch material. This concept offers the advantage of a smooth substrate surface for possible improvement in printing consistency and a rigid substrate that will protect the printed circuitry from excessive flexing. Pre-forming or shaping of the rigid insert prior to in-place composite repair will allow for more precise layup of the total composite patch when used to repair shaped or contoured structures.

Design and Concepts for Gas Leak Detection Sensors

A flexible gas detection ring sensor is being investigated for use with natural gas transmission and distribution pipelines for accurate sensing of potential ruptures in the repair laminate after the repair is made. The flexible sensor is made up of three layers. The bottom layer is a staggered Nichrome thin-film tracing that acts as a heater. The heater layer acts to provide a constant temperature at the sensor surface. The second layer is a conductive heat-tolerant layer of thin-film nickel in an interdigitated design and a solid layer of reactive tin-oxide which acts as a bridge between the nickel "fingers". The detection process for this sensor is by the diffusion/adsorption method. The gas is diffused within the sealed clamshell before coming into contact with the metal-oxide film on the inner surface. When the gas reacts with the heated tin-oxide film (the metal oxide needs to be heated to a certain degree to promote a reaction to the gas), there is a proportional decrease in electrical resistance based upon the concentration of air/gas mixture. This information will be transmitted through wires to a control enclosure containing an analog data acquisition device and interface (either wireless or wired). This type of gas sensor can be fabricated in-house through the use of the physical vapor deposition machine (Lesker PVD-75) available in the Odyssian Technology facility. Figure 35 and 36 shows the design of the flexible "ring" gas sensor.

Figure 35: Concept for sensor collar incorporation in-house design of a flexible "ring" gas sensor

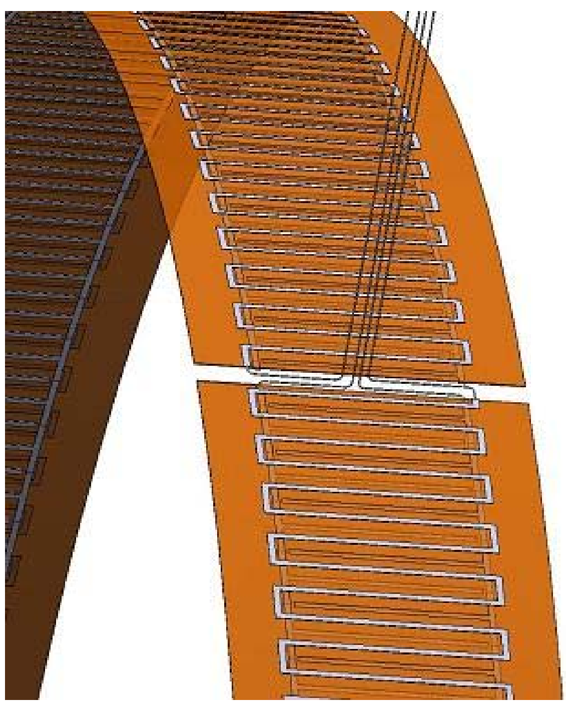


Figure 36: Close-up of flexible "ring" gas sensor

The detection process for figure 37 is also by the diffusion/adsorption method in which the gas and air diffuse within the sealed clamshell before coming onto contact with a commercial off-the-shelf sensor. This sensor could be any commercial circular gas sensor (i.e. solid state, catalytic, electrochemical, etc.), and could be installed into the sensor collar with or without an enclosure. Additionally, the signal could either be transmitted through hard wires to a control enclosure at or above ground level.

Figure 37: Concept for sensor collar incorporating a commercial off-the-shelf sensor

APPENDIX A – REQUIREMENTS DATA

Mileage Statistics of Hazardous Liquid and National Gas Pipelines

http://www.phmsa.dot.gov/portal/site/PHMSA/menuitem.ebdc7a8a7e39f2e55cf2031050248a0c/?vgnextoid=a62924cc45ea4110VgnVCM1000009ed07898RCRD&vgnextchannel=80837e2cd44d3110VgnVCM1000009ed07898RCRD&vgnextfmt=print

Type of pipeline		**Mileage**	**Total**
Hazardous Liquid (2003)		160,868	160,868
Natural Gas Transmission			
	Gathering lines	19,864	
	Transmission lines	278,269	
Total			**298,133**
Natural Gas Distribution (2001)			
	Distribution Mains	1,119,430	
	Distribution Service Lines	729,550	
Total			**1,848,980**
	Grand Total:		**2,307,981**

Consequences Summary Statistics for Natural Gas and Hazardous Liquid Pipelines

http://primis.phmsa.dot.gov/comm/reports/safety/CPI.html?nocache=9757

National Hazardous Liquid: Consequences Summary Statistics: 2003-2007

Year	Public Fatalities		Industry Fatalities		Public Injuries		Industry Injuries		Total Property Damage (B) (C)	Damage to Public Property (D) (B)		Damage to Industry Property (E) (B)		Value of Product Lost (B)	
2003	0	0%	0	0%	0	0%	5	100%	$54,538,762	$31,011,307	56%	$22,034,644	40%	$1,492,811	2%
2004	5	100%	0	0%	15	93%	1	6%	$159,374,542	$33,755,694	21%	$122,841,426	77%	$2,777,421	1%
2005	0	0%	2	100%	2	100%	0	0%	$165,063,016	$84,036,748	50%	$77,548,196	47%	$3,478,072	2%
2006	0	0%	0	0%	2	100%	0	0%	$62,150,187	$19,855,728	31%	$38,032,187	61%	$4,262,271	6%
2007	2	50%	2	50%	9	90%	1	10%	$50,594,673	$18,982,971	37%	$28,072,501	55%	$3,539,201	7%
Totals	7	63%	4	36%	28	80%	7	20%	$491,721,182	$187,642,449	38%	$288,528,955	58%	$15,549,777	3%

National Gas Transmission: Consequences Summary Statistics: 2003-2007

Year	Public Fatalities		Industry Fatalities		Public Injuries		Industry Injuries		Total Property Damage (B) (C)	Damage to Public Property (D) (B)		Damage to Industry Property (E) (B)		Value of Product Lost (B)	
2003	0	0%	1	100%	3	37%	5	62%	$56,232,363	$11,407,440	20%	$27,054,585	48%	$17,770,337	31%
2004	0	0%	0	0%	0	0%	2	100%	$38,262,823	$174,417	0%	$28,571,481	74%	$9,516,923	24%
2005	0	0%	0	0%	2	40%	3	60%	$237,212,368	$92,511,087	39%	$120,315,593	50%	$24,385,687	10%
2006	1	33%	2	66%	1	25%	3	75%	$38,827,402	$2,706,730	7%	$28,860,670	74%	$7,260,002	18%
2007	1	50%	1	50%	1	14%	6	85%	$53,907,130	$793,500	1%	$35,294,884	65%	$17,818,746	33%
Totals	2	33%	4	66%	7	26%	19	73%	$424,442,088	$107,593,176	25%	$240,097,214	56%	$76,751,697	18%

National Gas Gathering: Consequences Summary Statistics: 2003-2007

Year	Public Fatalities		Industry Fatalities		Public Injuries		Industry Injuries		Total Property Damage [B] [C]	Damage to Public Property [D] [B]		Damage to Industry Property [E] [B]		Value of Product Lost [B]	
2003	0	0%	0	0%	0	0%	0	0%	$2,004,378	$1,571,384	78%	$152,888	7%	$280,104	14%
2004	0	0%	0	0%	0	0%	1	100%	$35,512,213	$10,935	0%	$34,249,286	96%	$1,251,992	3%
2005	0	0%	0	0%	0	0%	2	100%	$154,202,256	$113,403	0%	$152,378,741	98%	$1,710,111	1%
2006	0	0%	0	0%	0	0%	1	100%	$11,304,786	$0	0%	$10,606,866	93%	$697,920	6%
2007	0	0%	0	0%	0	0%	0	0%	$5,512,694	$0	0%	$5,087,126	92%	$425,568	7%
Totals	0	***%	0	***%	0	0%	4	100%	$208,536,329	$1,695,723	0%	$202,474,909	97%	$4,365,696	2%

National Gas Distribution: Consequences Summary Statistics: 2003-2007

Year	Public Fatalities		Industry Fatalities		Public Injuries		Industry Injuries		Total Property Damage [B] [C]	Damage to Public Property [D] [B]		Damage to Industry Property [E] [B]		Value of Product Lost [B]	
2004	13	100%	0	0%	22	66%	11	33%	$32,407,600	$24,222,505	74%	$6,983,318	21%	$1,201,776	3%
2005	11	78%	3	21%	31	79%	8	20%	$536,955,458	$27,200,095	5%	$504,283,125	93%	$5,472,238	1%
2006	10	62%	6	37%	11	42%	13	50%	$19,862,069	$17,656,433	88%	$1,891,623	9%	$314,012	1%
2007	7	77%	2	22%	23	63%	13	36%	$23,434,503	$20,043,622	85%	$3,114,135	13%	$276,746	1%
Totals	41	78%	11	21%	87	64%	45	33%	$612,659,631	$89,122,656	14%	$516,272,202	84%	$7,264,773	1%

Design Guidelines: Minimum Requirements for Composite Pipe Repair

The following list compiled reflects the minimum requirements that any composite repair should meet.

1. The composite material used in the repair system should possess sufficient tensile strength. The combination of the remaining pipe wall and composite material should possess a long term failure strength that is at least equal to the specified minimum yield strength (SMYS) of the pipe material. Although a strength equal to 100 percent SMYS is sufficient, one option is to recommend that a safety factor be placed on the maximum operating pressure (MOP) and determine the required number of wraps based on this pressure. If MOP is assumed to be 72 percent, a safety factor of two corresponds to a stress level of 144 percent SMYS. While this may be an overly-conservative safety factor, the unknowns relating to the long-term performance of composites in aggressive soil environments require that a conservative position be taken.

2. The material should demonstrate that it can perform adequately in repairing corroded pipelines. This involves strength in burst mode, but also involves ensuring that the repair does not degrade with time or cyclic pressure service. Experimental testing must be conducted to address this issue. In addressing the effects of cyclic operating pressures, the service conditions in actual operating lines should be considered. A typical liquid pipeline may experience approximately 1,800 cycles per year (at a 200 psi pressure differential), while gas transmission lines see 10 times fewer, or 60 cycles, for the same pressure level.

3. Testing should be conducted to address long term behavior of the material under dead weight loading. Idealistically, a battery of tests should be conducted using weights as a percentage of the lower bound failure load for the given material. The testing should be conducted so that failures occur over loading time periods up to 1,000 hours at a minimum (longer if possible).

4. Lap shear testing should be conducted to ensure that an adequate bond exists between the pipe and wrap. For composite repair methods that are not monolithic (monolithic meaning that all layers combine to form a homogenous unit), these tests should also include composite-composite test samples as well as the composite-steel test coupons. The composite-composite sample is used to assess the bond strength between the layers, while the composite-steel samples are used to determine the lap shear strength at the interface between the pipe material and composite.

5. Testing should be conducted to address cathodic disbondment and the system should meet the requirements as set forth in ASTM G8 (Standard Test Methods of Cathodic Disbonding for Pipeline Coatings).

6. Repair materials should resist mild acid and alkaline environments, including a range of 4 to 11 pH. Alkaline soils may have a pH of 11 or higher, which will attack fiberglass and polyester resin. In general, epoxies can handle mild acids and strong alkalines.

7. Testing should be conducted to address water penetration into the system using test method ASTM G9 (Standard Test Method for Water Penetration and Pipeline Coatings).

8. The composite material should be able to withstand temperatures of the operating line on which it is to be installed. The operator should consider the effects of temperature in selecting regions of application (e.g. compressor station may see temperatures of 200F).

9. Product must be environmentally-safe and possess low toxicity for the applicator.

10. To minimize the possibility for improper installation, the system must be user-friendly and have instructions that are easily understood. For two-part systems, the greatest problem associated with improper application involves incorrect mixing of the adhesive. Installation should only be conducted by a certified applicator.

11. The product must have clearly stated on it the expiration date (if applicable) of any component within the system. The system must demonstrate that it possesses adequate strength over a long period of time (2 to 3 year testing period). This should involve testing of the composite itself as well as adhesive bonds under load. Samples should be exposed to harsh environments (such as saturation in water) where composite properties are known to degrade with time.

12. A field monitoring program should be conducted to assess performance of the wrap over several years. This involves inspection of the buried line at least one year after installation. The repair should be inspected for soundness and any possible signs of degradation. If possible, strain gages should be installed beneath the wrap to determine any changes in the pipe strain that occur with time.

13. The adhesive system must demonstrate that it can be used in a variety of temperature environments and permit installation in a range of ambient temperature conditions (e.g. between 0F and 120F). Ultimate responsibility is on the operator to ensure that the system can adequately cure and is not damaged at elevated ambient conditions.

14. For cold weather applications, the system should have sufficient toughness to ensure that the material does not become brittle and lose its ability to properly reinforce the pipeline.

15. When a repair method is used for restoring corroded pipes, calculations relating to its strength should incorporate severity of the corrosion using methods such as those used in ANSI/ASME B31G. This is especially important considering that most of the wet lay-up system permit the number of wraps to be varied depending on the severity of corrosion level.

Material Systems Data

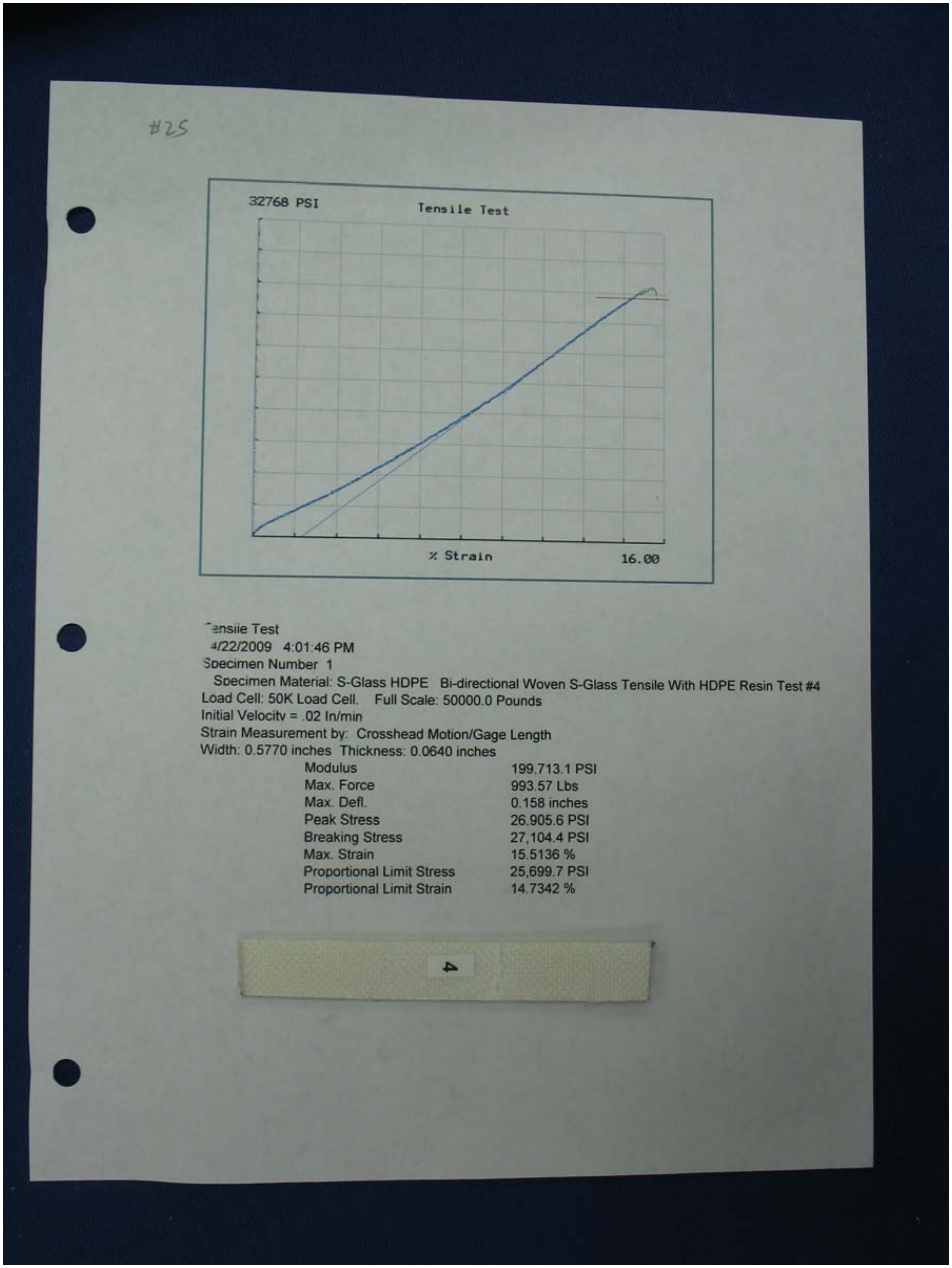
The following material system data was taken from TenCate Advanced Composites USA, Inc. The results are taken at room temperature (72 F) at 50% humidity. The reason for taking all the data from one manufacturer was for consistency when comparing different material systems side-by-side.

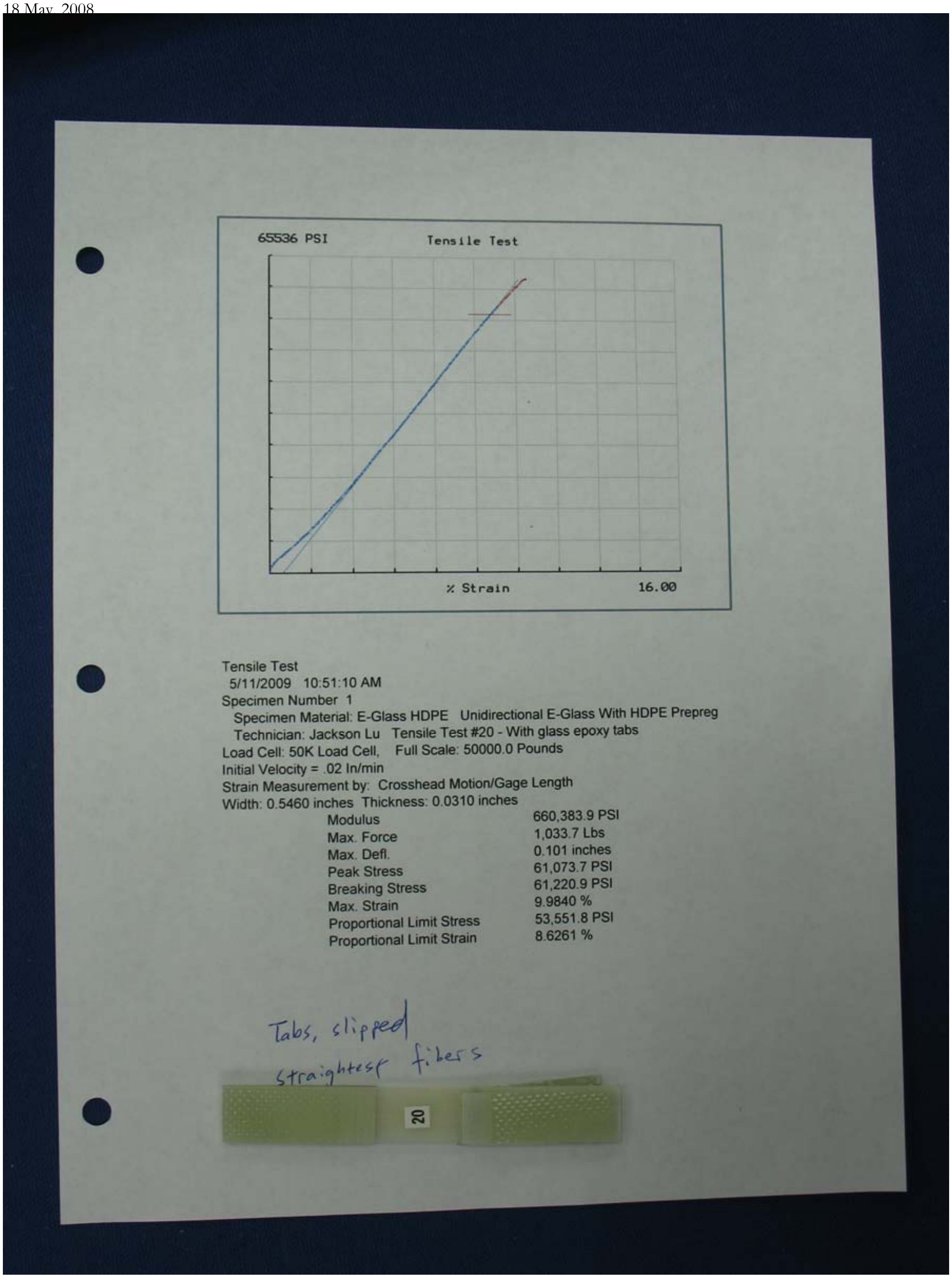
Material Systems Properties (CFR)

	CETEX PPS	**CETEX PPS**	**CETEX PEI**	**CETEX PEI**
Tensile Strength (psi)	109800	49300	95100	70200
Tensile Modulus (psi)	8100000	3100000	8100000	3800000
Flexural Strength (psi)	148900	74200	126200	97000
Flexural Modulus (psi)	8700000	3300000	7300000	4100000
Percent Elongation	3	3	7	7
Compression Strength (psi)	93300	61600	108000	105400
Compression Modulus (psi)	7500000	3700000	7500000	4200000
Poisson's Ratio – Hoop	0.36	0.36	0.36	0.36
Coefficient of Thermal Expansion	52.2 um/m-C	52.2 um/m-C	55.8 um/m-C	55.8 um/m-C
Glass Transition Temperature	194 F	194 F	419 F	419 F
Process Temperature	212 F	212 F	392 F	392 F
Fiber Type	*Carbon Fabric (50%)*	*E-Glass (47.5%)*	*Carbon (50%)*	*E-Glass (50%)*
Resin Type	Polyphylene	Polyphylene	Polytherimide	Polytherimide
Architecture	Unidirectional	Unidirectional	Unidirectional	Unidirectional
Thickness	0.0122"	0.0098"	0.0122"	0.0094"
Resin Material System	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic

	Thermo-Lite 4245E	Thermo-Lite 4060R	Thermo-Lite 4268I	Thermo-Lite 4268P
Tensile Strength (psi)	65000	108000	175000	162000
Tensile Modulus (psi)	2500000	4100000	6500000	6300000
Flexural Strength (psi)		85000	185000	174000
Flexural Modulus (psi)		3800000	6400000	6200000
Compression Strength (psi)			170000	161000
Compression Modulus (psi)			6400000	6000000
Poisson's Ratio - Hoop				
Coefficient of Thermal Expansion				
Glass Transition Temperature				
Process Temperature	350 F	400 F	725 F	625 F
Fiber Type	E-Glass (45%)	E-Glass (60%)	E-Glass (68%)	E-Glass (68%)
Resin Type	*Polyethylene*	*Polypropylene*	*PEEK*	*PPS*
Architecture	Unidirectional	Unidirectional	0-90 bidirectional	0-45-90 Directional
Thickness	0.02"	0.01"	0.0093"	0.0076"
Resin Material System	Thermoplastic	Thermoplastic	Thermoplastic	Thermoplastic

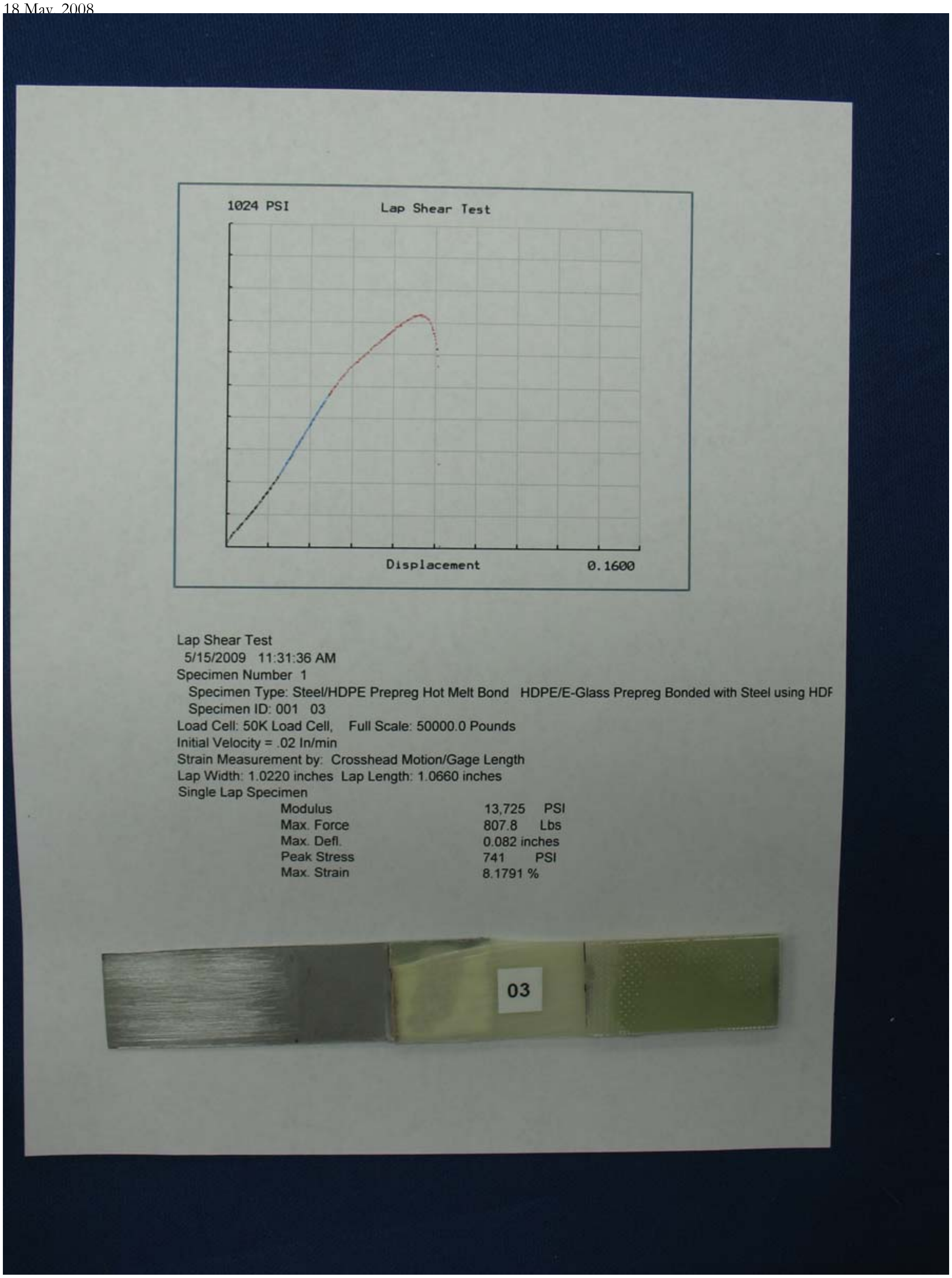
APPENDIX B – IN-HOUSE TENSILE TESTING DATA





Tensile Test
5/11/2009 10:51:10 AM
Specimen Number 1
Specimen Material: E-Glass HDPE Unidirectional E-Glass With HDPE Prepreg
Technician: Jackson Lu Tensile Test #20 - With glass epoxy tabs
Load Cell: 50K Load Cell, Full Scale: 50000.0 Pounds
Initial Velocity = .02 In/min
Strain Measurement by: Crosshead Motion/Gage Length
Width: 0.5460 inches Thickness: 0.0310 inches

Modulus	660,383.9 PSI
Max. Force	1,033.7 Lbs
Max. Defl.	0.101 inches
Peak Stress	61,073.7 PSI
Breaking Stress	61,220.9 PSI
Max. Strain	9.9840 %
Proportional Limit Stress	53,551.8 PSI
Proportional Limit Strain	8.6261 %


1024 PSI
Lap Shear Test
Displacement
0.1600
Lap Shear Test
5/15/2009 11:31:36 AM
Specimen Number 1
Specimen Type: Steel/HDPE Prepreg Hot Melt Bond HDPE/E-Glass Prepreg Bonded with Steel using HDF
Specimen ID: 001 03
Load Cell: 50K Load Cell, Full Scale: 50000.0 Pounds
Initial Velocity = .02 In/min
Strain Measurement by: Crosshead Motion/Gage Length
Lap Width: 1.0220 inches Lap Length: 1.0660 inches
Single Lap Specimen
Modulus 13,725 PSI
Max. Force 807.8 Lbs
Max. Defl. 0.082 inches
Peak Stress 741 PSI
Max. Strain 8.1791 %
03

APPENDIX C – PROVIDED DATA

Celstran CFT® HDPE-GF70

Ticona

-Preliminary Values -

Celstran CFT HDPE-GF70 is a 70% by weigth endless fibre reinforced UD-tape.

	PROPERTY	VALUE	UNIT	TEST METHOD
Material	Polymer	HDPE		
	Reinforcement	E-Glass		
	Density	1,69	g/cm³	ISO 1183
	Content of reinforcing fibres	70	% by wt.	
		46	% by vol.	
	Tape thickness	0,254	mm	
	Area weight	430	g/m²	
	MECHANICAL PROPERTIES, measured under standard conditions, ISO 291-23/50			
Mechanical	Tensile strength	831	MPa	D 638
	Elongation at break	2,1	%	D 638)
	Tensile modulus	37200	MPa	D 638
	Flexural strength	270	MPa	D 790
	Flexural modulus	25600	MPa	D 790
	Multi-Axial Impact-Test (MAI), 0/90 Layup			D 3763
	Total Energy		ft-lbf	D 3763
	Energy to max. Load		ft-lbf	D 3763
	Propogation Energy			D 3763
	Max Load		lbf	D 3763
	THERMAL PROPERTIES			
Thermal	Melting Temperature	128	°C	
	Glass Transition Temperature	-90	°C	
	Heat deflection temperature HDT/A (1.8 MPa)		°C	ISO 75, part 1/2
	Heat deflection temperature HDT/C (8.0 MPa)		°C	ISO 75, part 1/2
	Coefficient of linear thermal expansion between -50 and 90° C		1/°C	ISO 11359, part 1/2
	Coefficient of linear thermal expansion between 90 and 250° C		1/°C	ISO 11359, part 1/2

APPENDIX D – ANALYSIS CALCULATIONS

The following values below (in bolded lettering) were calculated on a Microsoft Excel spreadsheet which is copied here for viewing. The actual Excel spreadsheet file is available upon request.

Use of the design method for non-leaking pipes

Symbol	***Description***	***Value***	***Misc***
D	external pipe diameter	6.625	in
S	Specified Minimum Yield Strength (SMYS) of pipe	24000	psi
Es	Tensile modulus for steel (or pipe material)	30000000	psi
Ec	Tensile modulus of composite laminate (circumferential)	5395402	psi
Ps	MAWP for the pipe determined from API 579, ASME B31G, or equivalent	150	psi
F	Sum axial tensile loads due to pressure, bending, and axial thrust	35740.66209	lb
ts	Minimum remaining wall thickness of the pipe	0.27	in
Fdes	Design factor determined in accordance with CFR 192.111	0.72	
Elong	Longitudinal joint factor determined in accordance with CFR 192.113	0.8	
fT	Temperature derating factor (table 3) or CFR 192.115	1	
ec0	allowable circumferential strain (table 4)	0.0025	
deltaT	temperature difference between operation and installation	93.333333	C
as	thermal expansion coefficient of the substrate or original pipe	1.08E-05	1/C
ac	thermal expansion coefficient of the repair laminate in the circumferential direction by determined test (Table 1)	8.60E-06	1/C
P	***Internal design pressure***	***1126.786415***	***psi***
ec	***Allowable circumferential strain (from equation)***	***0.002294667***	
tmin	***Minimum repair laminate thickness for hoop stresses due to internal pressure for piping systems***	***0.749620927***	***in***

tmin	***Minimum repair laminate thickness for axial stresses due to internal pressure, bending, and axial thrust for piping systems***	***0.282728831***	***in***

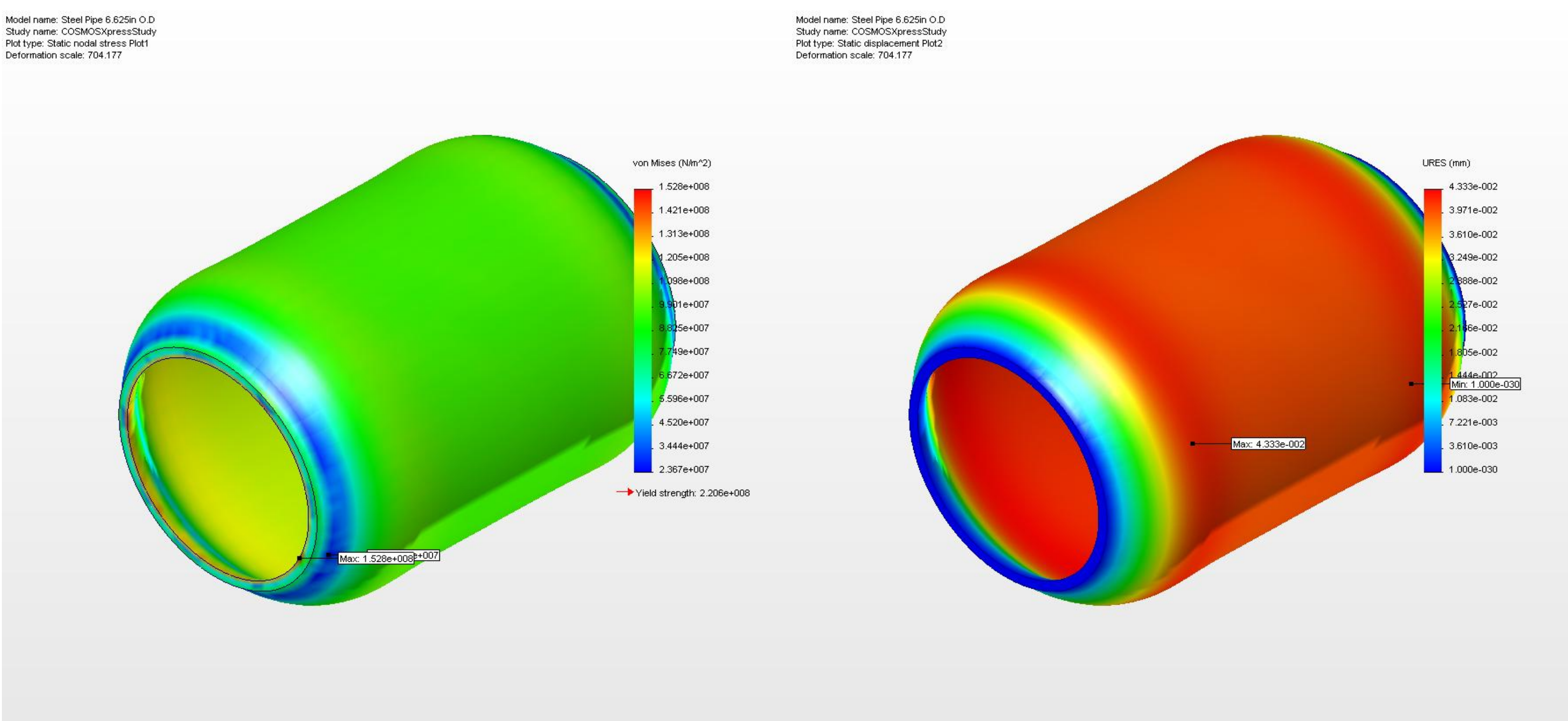
E-hoop	***Maximum hoop stress***	***17688.80724***	***psi***

Use of the design method for leaking pipes

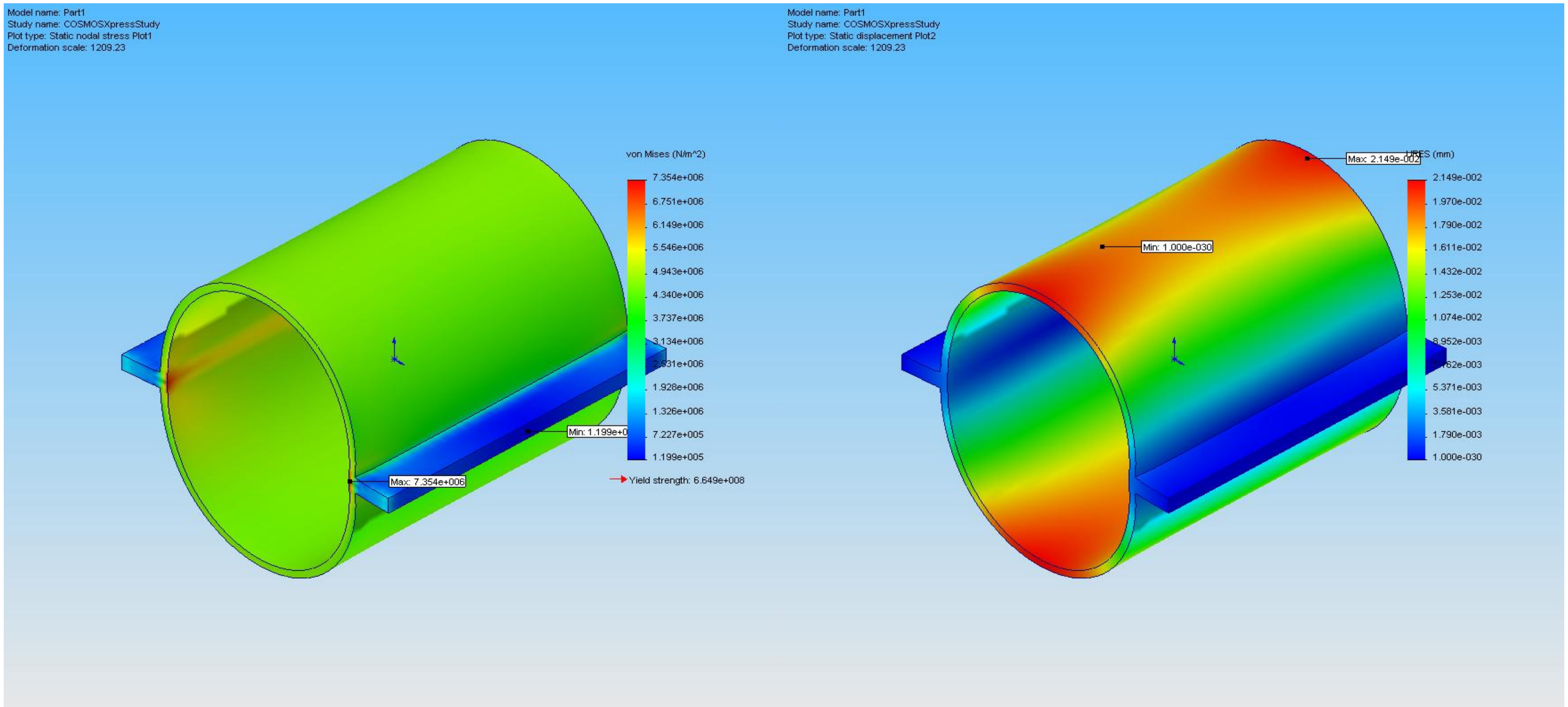
Symbol	***Description***	***Value***	***Misc***
Ec	Tensile Modulus of composite laminate (circumferential)	5395402	psi
Ea	Tensile Modulus of composite laminate (axial)	5395402	psi
D	External Pipe Diameter	6.625	in
F	Sum axial tensile loads due to pressure, bending and axial thrust	35740.66209	lb
Vca	Poisson's ratio for the composite laminate in the cicumferential direction	0.36	
S	Specified Minimum Yield Strength of the pipe	24000	psi
th	Nominal wall thickness of pipe	0.27	in
Fdes	Design factor determined in accordance with 192.111	0.72	
Elong	Longitudinal joint factor determined in accordance with 192.113	0.8	
fT	Temperature derating factor (table 3)	1	
ec0	allowable circumferential strain (table 4)	0.0025	
ea0	allowable axial strain obtained (table 4)	0.001	
deltaT	temperature difference between operation and installation	93.333333	C
as	thermal expansion coefficient of the substrate or original pipe	1.08E-05	1/C
ac	thermal expansion coefficient of the repair laminate in the circumferential direction by determined test (Table 1)	8.60E-06	1/C
aa	thermal expansion coefficient of the repair laminate in the axial direction by determined test (Table 1)	4.80E-06	1/C
P	***Internal Pipe Design Pressure***	***1126.786415***	***psi***
ec	***Allowable circumferential strain (from equation)***	***0.002294667***	
ea	***Allowable axial strain (from equation)***	***0.00044***	
tmin	***Minimum repair laminate thickness for hoop stresses due to internal pressure***	***0.251544122***	in
tmin	***Minimum repair laminate thickness for axial stresses due to internal pressure, bending and axial thrust***	***0.15734389***	In

APPENDIX E – ADDITIONAL FEA ANALYSIS

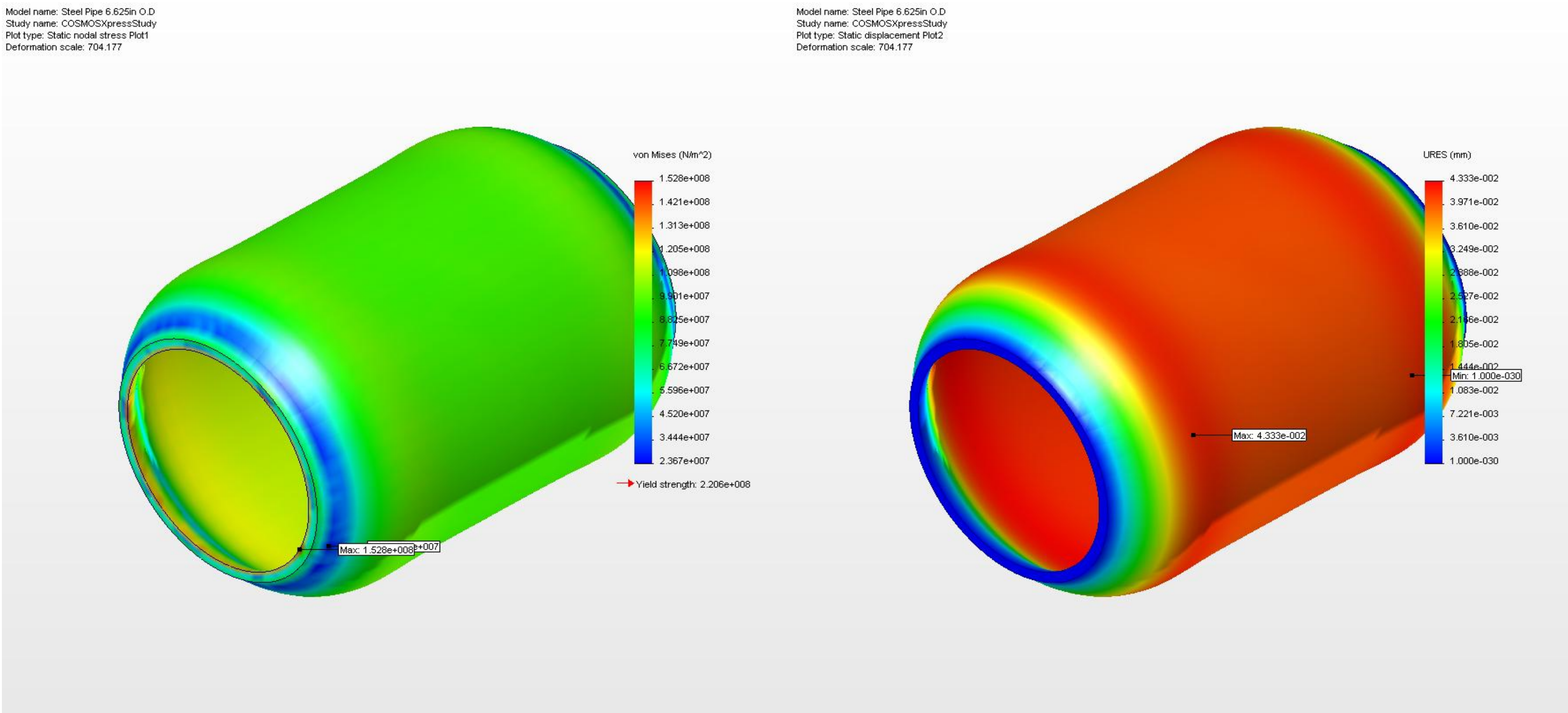
The results listed here are additional FEA analysis done at 1000 and 1500 psi. The left shows stress concentrations and the right shows deformation.



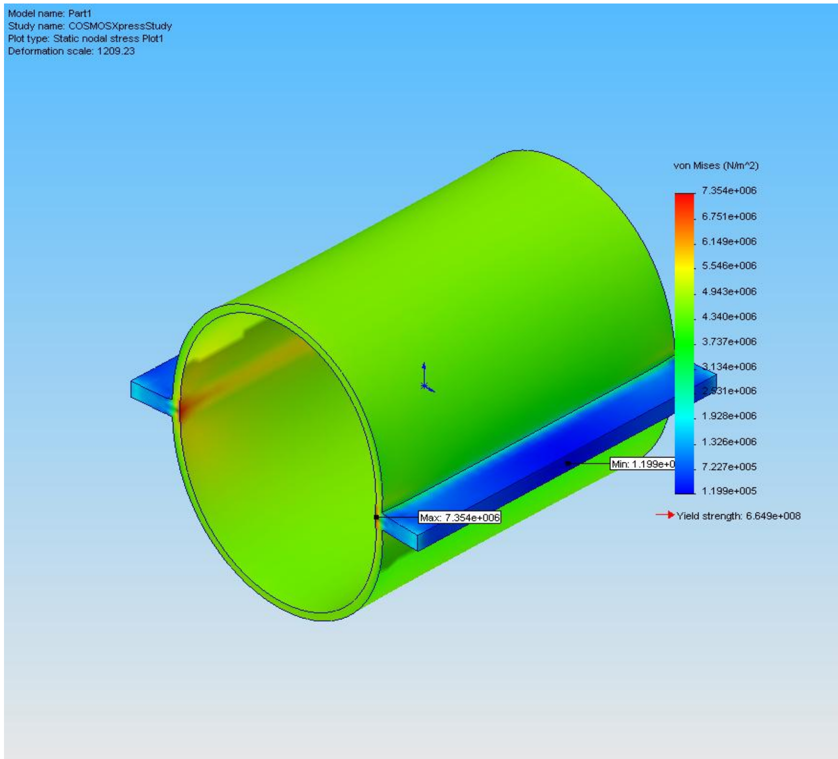
Steel Pipe 1000 psi

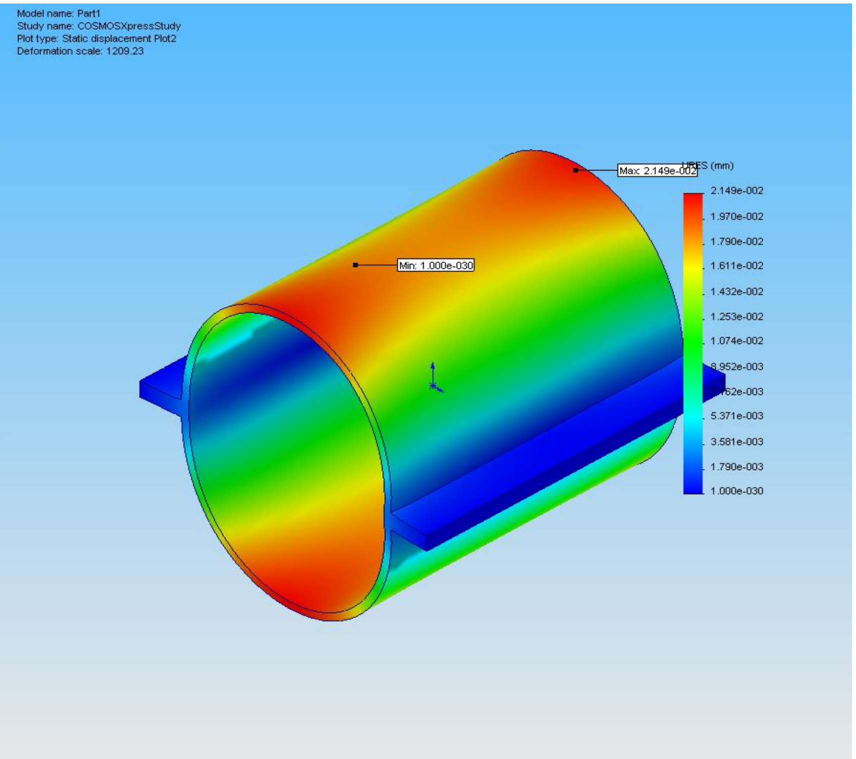


Composite 1000 psi



Steel Pipe 1500 psi





Composite 1500 psi

APPENDIX F – LETTERS OF INTEREST

STRESS ENGINEERING SERVICES INC.
an employee-owned company

13800 Westfair East Drive, Houston, Texas 77041-1101
Phone: (281) 955-2900 Fax: (281) 955-2638 Website: www.stress.com
HOUSTON • CINCINNATI • NEW ORLEANS

May 18, 2009

Odyssian Technology
Attn: Mr. Barton Bennett, President
511 East Colfax Avenue
South Bend, IN 46617

Subject: Stress Engineering Services, Inc. Interest in Odyssian Technology's Phase II SBIR to Develop New In-field Composite Repair Techniques for Transmission or Distribution Pipelines

Dear Mr. Bennett:

The purpose of this letter is to express our support for your proposed SBIR project to develop a novel thermoplastic composite based system for in-field repair of transmission and distribution pipelines. As a business involved in the testing and analysis of composite repair systems, Stress Engineering recognizes the possibilities for reducing cost and time of repair for our nation's pipelines using your technology. The integrated sensor concept for leak detection and strain measurement looks interesting and is one of the missing elements in current pipe repair systems.

As we have discussed, Stress Engineering Services is interested in participating in Phase II of your US DOT SBIR program as a paid consulting service provider. As outlined in our most recent discussion, we anticipate supporting your Phase II SBIR Program on the order of $80,000 to perform analysis and testing of your composite repair system. Once the program has been executed, specific details on the proposed test program can be determined.

Based on the discussions that you and I have had, it appears that your new repair technology may offer significant benefits for improving pipeline repair. We look forward to working with you on this effort.

Regards,

Chris Alexander

Chris Alexander, Ph.D.
chris.alexander@stress.com
Direct phone: 281-897-6504

DESIGN • TESTING • ANALYSIS