F. A. C. S.™
FIELD-APPLIED COMPOSITE SYSTEMS

Analysis of Aquawrap® for use in Repairing Damaged Pipelines

Environmental Exposure Conditions
Property Testing Procedures
Field Testing Evaluations

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INTRODUCTION

The repair of corroded or damaged pipelines using composite repair systems is growing, especially in the oil and gas industries. Composites have proved themselves as a strong and durable material, capable of providing the qualities required when performing critical repairs. Numerous field trials, in-house testing, and third party testing have demonstrated that Aquawrap® possesses those performance qualities, and as such, has been successfully used on many pipelines for repairing external corrosion and mechanical damage.

Aquawrap® is comprised of a proprietary polyurethane formula and custom-woven biaxial glass fiber. As a biaxial fabric, it provides strength in two directions, hoop and transverse. For piping, hoop strength is critical, but handling the transverse load is also important. Strength in two directions can be equally important to many other types of reinforcement that Aquawrap® is designed to handle. For these reasons, biaxial fabric was a sound choice.

The material installation requires use of a base primer material to provide a proper bond to the surface being repaired. Aquawrap® is then installed, utilizing water as the activator. The material can be installed circumferentially around the object, or spiraled at an angle to provide uniform coverage over long distances. After installation, a unique method is used to compress and consolidate the composite.

The purpose of this analysis is to provide a single document, which summarizes the entire properties test results and field testing results. The following is an analysis of tests and trials completed that relate to repairing pipelines, as well as other cylindrical objects of metal or concrete. The results will reveal that these tests prove Aquawrap® is a practical and economical repair for damage to these structures, and in many cases, can increase the strength and durability of the virgin component.

F.A.C.S.™ GROUP QUALITY OVERVIEW

Objective

To produce a high quality product having outstanding performance characteristics with consistent handling and mechanical properties coupled with excellent longevity. The program, from product design through field performance monitoring, is outlined below.

Design

The design activity entails not only that of the product but of the facility and equipment required to produce it.

Product Design: The product design activity required several years of resin development and testing coupled with evaluation of fabric weaves and construction alternates. The design activity has produced a number of product variants to suit specific customer applications.

Facility and Equipment: Due to the water cure nature of the product, consideration must be given to the facility design and construction. The facility must be designed to maintain a low ambient humidity and temperature control in spite of the effects of material and personnel entry and egress. The equipment required to produce the product entails measuring and mixing of the various resin formulations, drying the fabric, impregnation of the fabric, and product packaging. Air Logistics has completed the design, fabrication, and construction of a well-equipped facility for the manufacture of its Aquawrap® products.

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Development and Qualification Testing

Air Logistics has completed extensive strength and environmental testing as a part of the product development process utilizing our internal test facility. Outside test laboratories have confirmed the results of this internal testing. Having complete test capability is a key asset in the product formulation and the ongoing product improvement process.

Workmanship Practices

The development of, and rigorous adherence to, proper workmanship and processing practices is essential to achieve quality manufacturing of a unique product such as Aquawrap®. Air Logistics has developed a complete set of operational processes and procedures for the manufacture of its products. These processes include, but are not limited to, incoming material inspection, resin mixing, facility environment monitoring, equipment set-up, operational functions, and packaging integrity.

Incoming Material: Supplier certifications are required on all incoming production material used in the manufacturing process. The certifications are maintained as a part of the quality records. Where appropriate, physical measurements of testing are completed and recorded.

Material Traceability: Lot numbers of all materials used in production are recorded. Retains are also kept for future inspection if needed. Resin mixing and daily run MO logs are used to record traceability data for all components used in the production of each lot of Aquawrap® material. In addition, equipment setup settings are also logged.

Packaging: Packaging quality is essential to the production process due to the moisture cure nature of Aquawrap®. If the packaging material is faulty or if the pouch seal is improperly finished, the material will cure before it can be used in the field. Close attention to the sealing machine setup and operation is crucial. Each pouch is inspected as it is labeled for shipment to assure that the pouch and its seal are intact.

Product Testing: As part of our commitment to quality assurance, samples from different lots of product are periodically drawn from production, made into coupons, and tested.

Field Evaluation: Material quality data are collected and monitored as received from users. Should problems develop, they will be investigated to isolate the root cause and corrective actions will be taken as required.

Test Facilities

Air Logistics has a test facility capable of verifying most of the mechanical and life characteristics of our Aquawrap® products. Each test complies with the appropriate ASTM standard and procedure. When a required test is beyond the scope of our facility, the material is sent to a reputable third-party test lab. The ability to test and verify new and existing products is an invaluable asset in the development process, as well as ongoing quality assessments.

TEST DESCRIPTIONS

This section details the various property tests Air Logistics Corporation has completed on its Aquawrap® material. Results of the test are provided. As mentioned, testing has been conducted in a multitude of venues. Each test indicates the location of the test facility. All of the testing, as well as the results, have been reviewed and approved by Air Logistics' quality control department.

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Those tests that were done by an independent group have been referenced here. The results indicated by those tests have been reviewed by Air Logistics Corporation, and found to be consistent with its own private and third party tests.

2.0 Individual Tests Performed

Tests 2.1 through 2.7, 2.9, 2.12, 2.16, 2.24 and 2.25 were performed on the current Aquawrap® product. The balance of the tests have been conducted over the past two years and used a number of different fabric weaves and weights which produced lower and sometimes higher tensile and other properties. Unless otherwise noted, the resin system in all of the tests is the same and, as such, the comparative results remain valid.

2.1 Tension -
The tensile properties of the material are determined in accordance with ASTM D-3039. The data includes not only the tensile characteristics of the material but modulus and strength per ply data as well.

2.2 Flexural Strength -
The flexural properties of the product were determined by testing in accordance with ASTM D-790. The data includes both the flexural strength and modulus.

2.3 Compressive Strength -
The compressive properties of the product were determined by testing in accordance with ASTM D-695.

2.4 Interlaminar Shear -
The interlaminar shear strength of the product was determined by the short beam shear method in accordance with ASTM D-2344.

2.5 Glass-Transition Temperature (Tg) -
The Tg of the material was determined in accordance with ASTM E-831.

2.6 Flammability -
The flammability of the product was determined by testing in accordance with ASTM E-84.

2.7 Burst Strength -
The burst strength of the product was determined by testing cured NOL rings on a burst fixture. The results were converted into strength per ply and compared to tensile strength determined in paragraph 2.1 above.

2.8 Tension Properties of Aquawrap® Cured Under Water -
This test was done in order to determine if the tensile properties are affected when Aquawrap® is cured under water. This test duplicates any situation where the material is applied under water such as on a pier piling or pipeline. The test consists of preparing and curing a panel under water and then tension testing it in accordance with ASTM D-3039. In this case the important parameter is the strength per ply, as the compression of the lay-up completed under water is not as good as a normally prepared laboratory sample.

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2.9 Adhesion (Lap Shear) to Steel, Stainless Steel and Aluminum -
Although a specific ASTM test does not exist, ASTM D-3165 was used as a guide. The test consisted of bonding three one-inch wide pieces of the product to one-inch wide A36 steel, 304 stainless steel, and 6061 aluminum strips with various surface preparations and Base Primer No.1 adhesive. The cured samples were then tension tested to determine the shear force required to break the bond between the three layers of cured product and the stainless steel or aluminum.

2.10 Adhesion (Lap Shear) to Steel While Submerged in Water -
In this test, ASTM D-3165 type coupons were assembled under water using Bio-Dur® 563 epoxy adhesive. The steel strips were submerged in a container of water, the adhesive was then applied to the steel, and then the composite strips were applied to the adhesive coated steel. This arrangement was secured and allowed to cure. The cured samples were tension tested to determine the shear force required to break the bond between the steel and the cured composite.

2.11 Adhesion (Lap Shear) to Steel Subjected to 1,000 Hour Water Soak -
This test is a part of the ASME <u>PCC-2 Repair Standard – Non-Metallic Composite Systems for Pipelines and Pipework: High Risk Applications</u>. Two sets of ASTM D-3165 lap shear coupons are prepared using Base Primer No. 1 adhesive. The samples are uncoated. One set is subjected to a 1,000 hour water soak at a minimum temperature of 104°F. The other is a baseline.

2.12 Thermal Cycling of Aluminum Bonded Joints -
This test is on joints similar to those in paragraph 2.9 which have been subjected to thermal cycling. Samples of the product bonded to aluminum as in paragraph 2.9 above and subjected to a total of thirty freeze thaw cycles from 0°F to 70°F. After each cycle the coupons were removed from the freezer and placed in water at 70°F and placed back in the freezer wet. The coupons were allowed to stabilize for a period of at least one-hour. At the end of the test the bond strength of the samples were determined and compared to unexposed samples.

2.13 Alkali Soak -
Panels of the cured product are coated with Base Primer No. 4 Primer/Adhesive (which is also used as a coating) and placed in a closed tank filled with a buffered solution at pH 10 for a period of 10,000 hours. At the completion of the soak the panels are removed, dried off, weighed, cut into coupons, and tension tested in accordance with ASTM D-3039. The results are then compared to coupons made from the same material.

2.14 Salt Water Soak -
This test is identical to the alkali soak test above except that the panels are soaked in seawater rather than an alkali solution. The duration of this test is 10,000 hours.

2.15 Tensile Properties at Elevated Temperatures -
See sections 2.24 and 3.24 for details of the testing and the results. These sections provide data on creep testing, which is then related to tensile strength.

2.16 Chemical Resistance -
The chemical resistance of the product to various liquids was determined in accordance with ASTM D-543(A).

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2.17 NSF Approval -

NSF International tested and approved Aquawrap® under its guidelines for NSF Standard 61.

2.18 Cure Time -

This test is intended to determine the cure time of thick lay-ups of the product. Several panels of the product were prepared and cured. They were then cut into coupons for interlaminar shear testing over a 24-hour period. The coupons were tested in accordance with ASTM D-2344 immediately after they were cut. The data was then analyzed to determine the cure time of the resin in these thick samples.

2.19 Impact Resistance -

Impact resistance of cured material was determined by testing in accordance with ASTM D-5420-98a. The panels were fabricated using three layers of woven roving (G-05) and one layer of tape (G-03).

2.20 Cathodic Disbondment -

The cathodic disbonding properties of the product were determined in accordance with ASTM G-8.

2.21 UV Resistance -

A cured panel of colored UV resistant material was placed in a chamber simulating the conditions of ASTM D-2565 for a period of five weeks. After the exposure the panel was visually examined and cut into coupons. The coupons were then tension tested in accordance with ASTM D-3039 and the results compared to unexposed coupons.

2.22 Long Term Exposure to Dry Heat -

Two panels of slightly different construction were placed in dry heat at 140°F for periods of 1,000 and 3,000 hours. At the end of each exposure the panels were visually examined, weighed, cut into coupons, and tension tested in accordance with ASTM D-3039. The results were then compared to unexposed coupons.

2.23 Diesel Soak -

This test is identical to the Alkali Soak test above except that the panels are soaked in diesel rather than an alkali solution. The duration of this test is 2,000 hours.

2.24 Creep Rupture Tests -

Coupons were loaded in tension on a specially designed load frame, which maintains a constant tensile force on the coupons. The basis for this test is ASTM's D-2990 and D-2992. The intent of the test is to determine the long-term tensile performance of the composite material by establishing a load profile and extrapolating it on a semi-logarithmic scale. These tests were conducted at the University of Wyoming.

2.25 Cyclic Loading -

ASTM D-3039 type coupons were subjected to repetitive loads (sine wave) in a conventional load frame. Coupons were tested over a range of peak loads until they failed. The load vs. cycles to failure was then recorded and plotted on a semi-logarithmic scale.

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3.0 Summary of Test Results

3.1 Tension: The tension test results are summarized in the following table:

3.1 TENSION PROPERTIES	THICKNESS (inches)	AREA SQUARE (inches)	ULTIMATE LOAD (pounds)	TENSILE STRENGTH (psi)	TENSILE MODULUS (e^6 psi)	STRENGTH PER INCH PER PLY (pounds)
AVERAGE RESULTS	0.056	0.057	3,921	68,983	3.74	769

Test number 1691. The standard deviation of the tensile strength of the samples is 3,140 PSI, or about 4.6% of the average tensile and is an indication of a good test. Location L1.

3.2 Flexural Strength: The results of the testing are as follows:

3.2 FLEXURAL STRENGTH PROPERTIES	WIDTH (inches)	THICKNESS (inches)	SPAN (inches)	ULTIMATE LOAD (pounds)	FLEXURAL STRENGTH (psi)	FLEXURAL MODULUS (e^6 psi)
AVERAGE RESULTS	1.033	0.107	2.00	167	42,368	2.968

Test number 1773. Location L1.

3.3 Compressive Strength: The results of the testing are as follows:

3.3 COMPRESSIVE STRENGTH PROPERTIES	THICKNESS (inches)	WIDTH (inches)	ULTIMATE LOAD (pounds)	COMPRESSIVE STRENGTH (psi)	COMPRESSIVE MODULUS (e^6 psi)	COMPRESSIVE STRENGTH PER INCH PER PLY (pounds)
AVERAGE RESULTS	0.3293	0.5114	4,715	28,066	4.00	369

Test numbers are 1775 and 1776. The results of these tests are averaged. Location L1.

3.4 Interlaminar Shear: The results of the tests are as follows:

3.4 INTERLAMINAR SHEAR	WIDTH (inches)	THICKNESS (inches)	SPAN (inches)	ULTIMATE LOAD (pounds)	INTERLAMINAR STRENGTH (psi)
AVERAGE RESULTS	1.021	.247	1.00	1,134	3,372

Test number 3485. Location L1.

3.5 Tg: Test number T-36462-131794. The Tg of the sample was 142°C (288°F). Location L3.

3.6 Flammability: Test number 162244. The flame spread was 110 and the smoke density was 385. This certifies the material to NFPA Class C or UBC Class III. Location L5.

3.7 Burst Strength: The results of the burst strength testing are as follows:

3.7 BURST STRENGTH			
SAMPLE	PRESSURE (psi)	PLIES	STRENGTH PER PLY PER INCH OF WIDTH (pounds)
BASELINE			800
1	1,434	17	844
2	1,390	17	818
3	1,372	17	807
4	1,425	17	838
AVERAGE	1,405	17	823

In all cases the samples failed at loads above the baseline. This is partially due to the fact that the test duration is a bit shorter than ASTM D-3039 coupon test. Excellent results are still observed. See section 4.0 for detailed information on full scale burst testing.
Location L2.

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3.8 Tension Properties Aquawrap® Cured Under Water: This test was performed on a 24 oz. unidirectional material. The average tensile properties of material cured under water and cured per the field lay-up procedure are as follows:

3.8 TENSION PROPERTIES	THICKNESS (inches)	AREA SQUARE (inches)	ULTIMATE LOAD (pounds)	TENSILE STRENGTH (psi)	TENSILE MODULUS (e^6 psi)	STRENGTH PER INCH PER PLY (pounds)
FIELD PROCEDURE CONTROL	0.0772	0.0771	4,583	59,580	3.58	2,294
FIELD SAMPLE	----	0.0801	4,582	57,180	---	2,287
UNDER WATER LAY-UP	0.0849	0.0868	4,511	52,136	3.36	2,207
ADJUSTED UNDER WATER LAY-UP	0.0770	0.0790	4,511	57,553	3.71	2,207
VACUUM LAY-UP	0.0568	0.0565	4,686	83,160	5.08	2,354

Test numbers are 833, 578, 1661 and 226. The key data in this test is the strength per ply, which are comparable within the expected deviation between the two tests. The compression of the sample cured under water was not as respectable as the control panel, resulting in a thicker panel. If the thickness of the test panel is adjusted to be the same as the control panel, the tensile strength and modulus are comparable to those of the control panel. The Shore D hardness of the panel cured under water was 85, which is typical of a normal vacuum lay-up. Location L1.

3.9 Adhesion to Steel, Stainless Steel, and Aluminum: The test was performed on steel and aluminum with four configurations using Base Primer No. 1 adhesive. The results of the tests are as follows:

3.9 SUBSTRATE	NO ADHESIVE NO ABRASION (psi)	ABRASION NO ADHESIVE (psi)	ADHESIVE NO ABRASION (psi)	ADHESIVE ABRASION (psi)
STEEL	NO TEST	NO TEST	NO TEST	1,360
STAINLESS STEEL	602	717	1,008	1,128
ALUMINUM	557	604	557	1,009

Test numbers are 79-83, 1130, 1132, 1133, 1135, and 1824. The area of the bond in each test was one square inch and the units of the pull off strength are both pounds and PSI. Location L1.

3.10 Adhesion (Lap Shear) to Steel while submerged in water: The results of the tests are as follows:

3.10 ADHESION TO STEEL UNDER WATER	AVERAGE PULLOFF FORCE (pounds)
PROCESSED COUPONS	719

The test numbers are 74-78. The area of the bond in each test was one square inch. The ASME PCC-2 standard requires a minimum bond strength of 580 psi. Location L1.

3.11 Adhesion (Lap Shear) to steel subjected to 1,000 hour water soak: The results of the tests are as follows:

3.11 ADHESION TO STEEL WITH 104° F 1000 HOUR WATER SOAK	AVERAGE PULLOFF FORCE (pounds)
BASELINE COUPONS	1,360
PROCESSES COUPONS	628

The test numbers are 79-89. The bond strength of the processed coupons was 46.2% of the baseline. The minimum requirement per the ASME PCC-2 standard is that the processed coupons be greater than 30% of the baseline. Location L1.

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3.12 Thermal Cycling of Aluminum Bonded Joints: The results of the tests are as follows:

3.12 BONDING TO ALUMINUM	AVERAGE PULL OFF STRESS (psi)
BASELINE	870
CYCLED - NO ALODINE	537
CYCLED - WITH ALODINE	965

Test numbers are 2957 and 3008. The bond does not appear to be affected by the freeze thaw cycling, in fact the strength increased during the cycling. The use of Alodine is important as the bond strength increased dramatically by its use. This is true in pull off tests without freeze thaw cycling as well. Location L1.

3.13 Alkali Soak: The tensile strength of the processed panels and reference panels are as follows:

3.13 TENSION	THICKNESS (inches)	AREA SQUARE (inches)	ULTIMATE LOAD (pounds)	TENSILE STRENGTH (psi)	STRENGTH PER INCH PER PLY (pounds)
BASELINE RESULTS	0.048	0.048	2,659	55,713	669
AVERAGE RESULTS	0.048	0.048	2,430	50,904	610

Test numbers 51, 59-67. The change in strength was approximately 9%. Location L1.

3.14 Salt Water Soak: The tensile strength of the processed panels after 10,000 hours and reference panels are as follows.

3.14 TENSION	THICKNESS (inches)	AREA SQUARE (inches)	ULTIMATE LOAD (pounds)	TENSILE STRENGTH (psi)	STRENGTH PER INCH PER PLY (pounds)
BASELINE	0..048	0.048	2,659	55,716	669
PROCESSED PANEL 10,000 HOURS	0..048	0.048	2,635	55,202	662

Test numbers 63-73. There was negligible loss of strength as the result of the 10,000 hour soak. Location L1.

3.15 Tensile Properties at elevated temperatures: See paragraph 3.21 for creep-rupture test details. The slope of the load vs. cycles to failure for the room and elevated temperature (160°F) tests were the same and the offset between the plots is 9%. This indicates that the creep-rupture performance at the material at the elevated temperature is 9% lower than at room temperature.

3.16 Chemical Resistance: The results of the test are:

CHEMICAL	REACTION
Acetone	No Reaction
Diesel Fuel	No Reaction
Ethyl Alcohol	No Reaction
Gasoline	No Reaction
HCL (30%)	Slight Softening
MEK	No Reaction
Toluene	No Reaction

3.17 NSF Approval: Aquawrap® was tested by NSF International and was determined to comply with ANSI/NSF 61. As such, we are authorized to use the NSF mark on our products specified on the NSF listing. Certificate #37231-01. Location L4.

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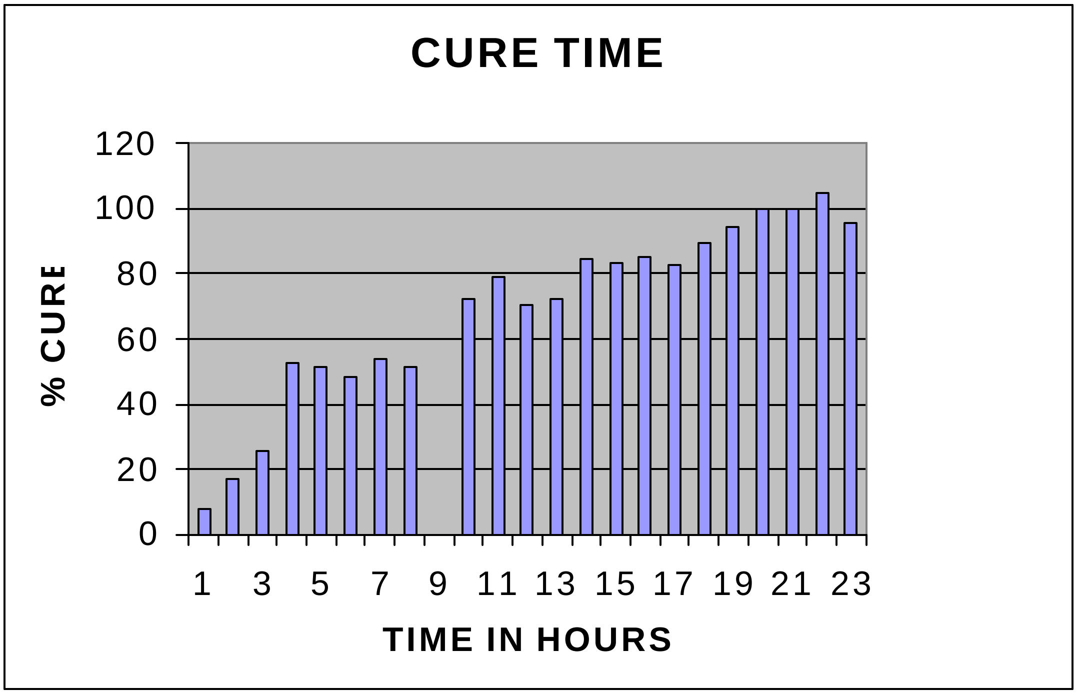
3.18 Cure Time: The results of the cure time were converted into percent of the final interlaminar shear strength. These tests were completed on coupons over 0.25” thick to simulate the cure of a thick lay-up. Due to the coupon thickness, the data needed to be plotted and then analyzed to determine the actual cure times of each sample.



The conclusion is that the material cures to about 60% of its final strength in about 8 hours. Location L1.

3.19 Impact Resistance: Test number 162527. The coupons had a Mean-Energy of 80 in.-lbf. Location L5.

3.20 Cathodic Disbondment: Test number 28184. The preliminary results of the test are 0.6 inches. Subsequent testing results showed no evidence of cathodic disbondment. Location L4.

3.21 UV Resistance: Two panels were prepared using our UV resistant resin formulation. The tensile strength of the processed panels and reference panels are as follows:

3.21 TENSION	THICKNESS (inches)	AREA SQUARE (inches)	ULTIMATE LOAD (pounds)	TENSILE STRENGTH (psi)	TENSILE MODULUS (e^6 psi)	STRENGTH PER INCH PER PLY (pounds)
BASELINE RESULTS	0.060	0.060	2,644	43,870	3.07	524
AVERAGE RESULTS	0.055	0.055	2,520	45,460	2.86	504

Test numbers are 800 and 801. The strength data between the two samples is less than normal to test variance. The conclusion is that the exposure had no effect on the coupons. Location L1.

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3.22 Long Term Exposure to Dry Heat: The tensile strength of the baseline and processed panels are as follows:

3.22 TENSION	TENSILE STRENGTH (psi)	TENSILE MODULUS (e^6 psi)
BASELINE (5011)	49,200	2.9
AVERAGE RESULTS - 1000 HOURS	50,200	3.2
AVERAGE RESULTS - 3000 HOURS	49,500	3.2
BASELINE (5050)	41,611	2.8
AVERAGE RESULTS - 1000 HOURS	44,400	2.8
AVERAGE RESULTS - 3000 HOURS	42,400	2.9

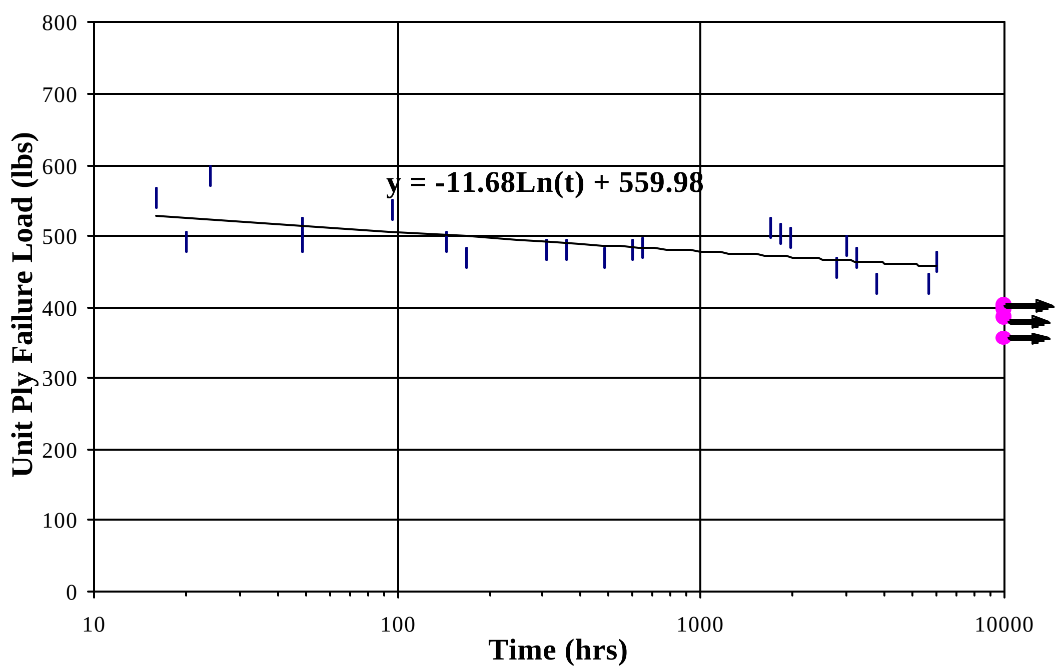
Test number 939799. The tensile and modulus data between the processed and baseline panels are essentially identical. Location L7.

3.23 Diesel Soak: The tensile strength of the processed panels and reference panels are as follows:

3.23 TENSION	THICKNESS (inches)	AREA SQUARE (inches)	ULTIMATE LOAD (pounds)	TENSILE STRENGTH (psi)	TENSILE MODULUS (e^6 psi)	STRENGTH PER INCH PER PLY (pounds)
BASELINE RESULTS	0.042	0.043	2,730	63,627	3.2	667
AVERAGE RESULTS	0.042	0.042	2,704	65,832	3.1	673

Test numbers are 1727 and 1726. The weight of the processed panel increased slightly during the processing from 65.6 grams to 67.1 grams. There does not appear to be any difference in the appearance of the panels and the Shore D Hardness of both panels was 90. The conclusion of the test is that there was no difference between the processed and baseline panel. Location L1.

3.24 Creep Rupture: Test number 907198. The results of the room temperature 10,000-hour test are shown in the following graphs:



The baseline strength of this 11 oz. tape material is 801 pounds per ply. The 25-year projection of 416 pounds per inch represents a long-term load capability of 52% of its initial tensile strength.

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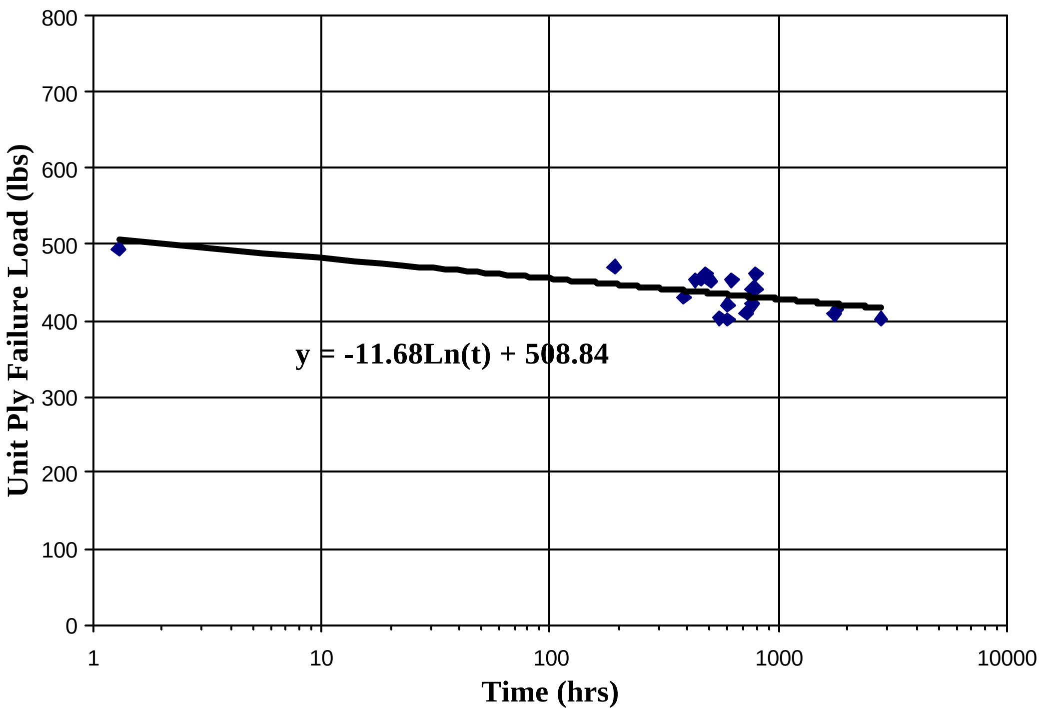
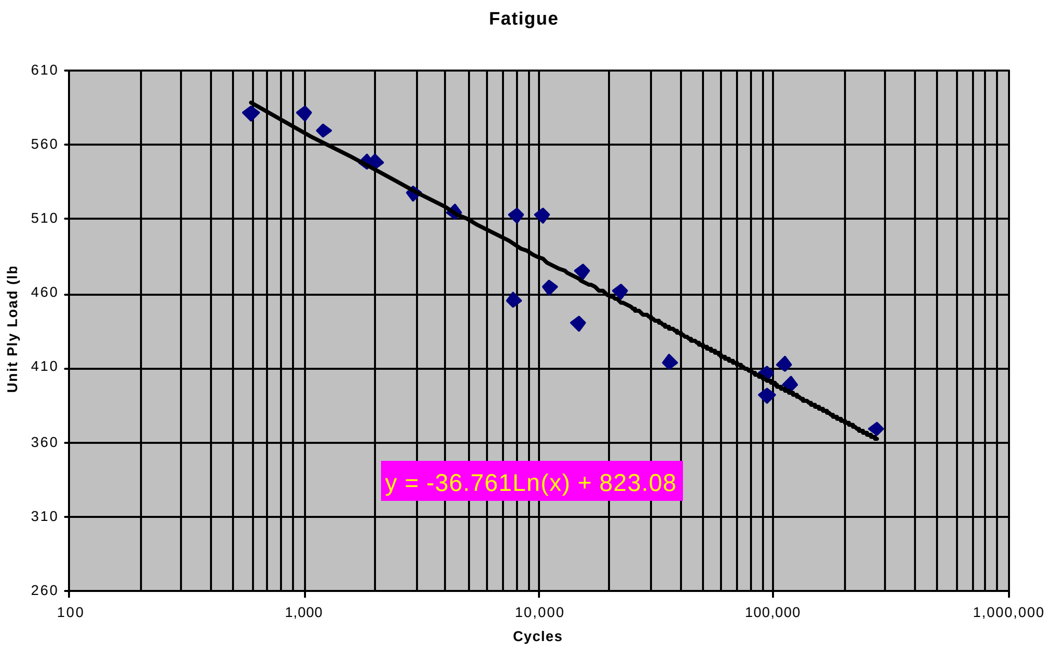
The results of the testing at 160° F are shown in the following graph.



First the slope of the room and elevated temperature plots is identical and the offset between them is 9%. This indicates that the long term load handling capability at elevated temperatures had a difference of only 9%. This is an excellent result. Location L7.

3.25 Cyclic Loading: Test number 907198A. The results of the testing to date are shown in the following graph. The baseline load per ply of this material is 801 pounds per ply. Location L7.



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4.0 Full Scale Testing

4.1 Pipe Burst Test

Although multiple burst tests have been performed under a variety of conditions, the validation of the material should be based on its ability to contain the Maximum Allowable Operating Pressure of any given system. The following chart outlines results from a few of these tests.

Discussion of the Chart

- The first column outlines the pipe detail such as the outside diameter of the pipe, the original wall thickness of the pristine pipe, the grade of the pipe, the specified minimum yield strength (SMYS) of the pipe, and the ultimate tensile strength (UTS) of the pipe.
- The second column is the calculated yield pressure of the particular specimen. This is derived using Barlow's Equation (P=2ST/D).
- The third column is the calculated burst pressure of the particular specimen. This is also derived using Barlow's Equation.
- The fourth column represents the calculated maximum allowable operating pressure (MAOP) of the pristine pipe. This number uses 72% of the calculated yield pressure of the pristine pipe.
- The fifth column is a summary of the defect that was created in the pipe. It lists the length and width of the defect, as well as the depth. All defects were machined and measurements confirmed. Depth of the defect and the remaining pipe wall thickness were verified using calibrated ultrasonic testing equipment.
- The sixth column is the calculated burst pressure of the pipe specimen when the defect is entered into the equation.
- The seventh column indicates the number of layers of Aquawrap® G-03 Fabric that was applied and the approximate thickness of the lay-up.
- The final column lists the failure mode of the test.

Pipe Preparation

- All pipe specimens were verified for proper diameter and wall thickness.
- The pipe was cleaned to a near-white metal finish and then wiped with a solvent cleaner such as acetone.
- The filler material, or load transfer compound, was then applied in the defect area. Enough material was applied to restore the profile of the pipe. This was allowed to cure prior to subsequent steps.
- Proper primer was applied and the required number of layers of Aquawrap® G-03 Fabric were installed.
- Stricture Banding™ was used to compress and consolidate the final installation.
- The lay-up was allowed to completely cure prior to any pressure application.

Burst Testing

- A section of pipe was capped on both ends with welded end-caps. On opposite ends of the pipe specimen, ¾" threaded half couplings were welded on. One was to accept the pressurization hose and the other was used to bleed air during the filling process.
- Pipe was filled with ambient temperature water and all air was purged.
- Pressure was applied steadily throughout the test. On some instances, the pressure was held at particular stages for 5-10 minutes.
- Test was completed upon failure of the pipe specimen or the wrap itself.

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Burst Test Results

PIPE DETAILS	PIPE YIELD PRESSURE	PIPE BURST PRESSURE	MAOP[1]	DEFECT DETAILS	CALCULATED BURST PRESSURE WITH DEFECT	CALCULATED BURST PRESSURE WITH REPAIRED DEFECT	LAYERS	RESULT
8.644" OD [2] 0.322" wall A53 Gr.B 44,000 SMYS 71,000 UTS (Serial #967296)	3,278 psi	5,290 psi	2,360 psi	External 8" long 4" wide 0.192" deep (59.6% wall loss)	2,136 psi	5,271 psi	38 layers (0.418")	Leakage under wrap at 5,100 psi
8.644" OD [2] 0.322" wall API 5L 44,000 SMYS 71,000 UTS (Serial #947996)	3,278 psi	5,290 psi	2,360 psi	External 8" long 4" wide 0.192" deep (59.6% wall loss)	2,136 psi	5,897 psi	44 layers (0.484")	Burst under wrap at 5,159 psi
12.75" OD [2] 0.250" wall ERW 54,000 SMYS 72,000 UTS (Serial #958497)	2,118 psi	2,824 psi	1,525 psi	External 6" long 1.47" wide 0.125" deep (50% wall loss)	1,412 psi	4,311 psi	62 layers (0.6875")	Pipe burst outside of wrap at 2,740 psi
16" OD [3] 0.250" wall ERW 50,000 SMYS 70,000 UTS (Serial #938098)	1,563 psi	2,188 psi	1,125 psi	External 8.50" long 4" wide 0.125" deep (50% wall loss)	1,460 psi [4]	1,513 psi	13 layers (0.143")	Wrap failure at 2,045 psi
20" OD [3] 0.562" wall API 5L X60 60,000 SMYS 87,747 UTS (Serial #899697)	3,374 psi	4,934 psi	2,428 psi	External 19.69" long 3.74" wide 0.370" deep (66% wall loss)	1,536 psi	3,204 psi	89 layers (0.984")	Held at 3,374 psi for a 4 hour test

1. Using a 0.72 design factor
2. Pipe specimens were prepared and wrapped at Air Logistics, Azusa, CA facility. Tests completed by a third party at their testing facility. Location L2.
3. Tests were conducted at the request of a third party. Installations and testing were done at their site, with their material and test equipment.
4. The calculated burst pressure with the defect was 1,094 using Barlow's formula and 1,213 using RSTRENG. Pressure indicated was derived from a ruptured test sample using similar corrosion depth, width, and length dimensions.

Figure 4.1
8.644" OD pipe with ruptured Aquawrap® at defect location.

Figure 4.2
12.75" OD pipe with ruptured section adjacent to wrap.

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4.2 Burst Test Evaluation

The following provides a simple background of each of the tests that were performed.

1. 8.644” OD Pipe (Serial #967296) -
   This test involved a pipe section with a machined defect measuring 8” long x 4” wide x .192” deep (59.6% wall loss). The pipe section was 60” long and closed at both ends with welded end-caps. Actual failure occurred within 3.5% of the calculated failure. This test provided very desirable results. Location L2.

2. 8.644” OD Pipe (Serial #967296) -
   This test was similar to the previous test done on 8” pipe, yet the test duration was longer. During the first pressure stage, the test piece was taken from 0 psi to 2,771 psi (over 400 psi beyond the MAOP of the pipe) in 90 seconds. It was then held at that pressure for 3 minutes. No drop in pressure or material damage was observed. The second stage increased the pressure from 2,771 psi to 3,265 psi, which is just under the yield point of the steel. Elapsed time to reach this pressure was 2 minutes, and it was held at that point for 3 minutes. The final stage was a slow increase in pressure until failure occurred. The duration of this stage was 10 minutes. This type of test was useful in qualifying previous tests done on the creep-rupture properties of Aquawrap®. This test resulted in a very successful outcome. Location L2.

3. 12.75” OD Pipe (Serial #958497) -
   This section of pipe had a machined defect measuring 6” long x 1.47” wide x .125” deep (50% wall loss). The pipe section was 60” long and closed at both ends with welded end caps. The wrap installation was fairly conservative, as the goal was to burst the pipe outside the wrap section. Using our current Aquawrap® Composite Wrap Reinforcement Calculator, the 62 layers that were applied equates to inputs of 400 pounds per ply for the material, using a 0.67 design factor for the composite, and a safety factor of 1.25. Location L2.

4. 16” OD Pipe (Serial #938098) -
   This test specimen was provided by a third party for testing at their facility. This test was designed to take the pipe over the yield pressure, as the normal operating pressure would never be expected to reach that point. The defect was 8.5” long x .125” deep (50% wall loss). The pipe section was 20 feet long and closed at both ends with welded end caps. A static burst test of a similar piece of pipe ruptured in the defect area at 1,406 psi. This pressure was used as the base to determine how much load the composite wrap was to hold.

5. 20” OD Pipe (Serial #899697) -
   The pipe specimen used in this test had a machined defect measuring 19.69” long x 3.74” wide x .370” deep (66% wall loss). The purpose of this test was to verify the capability of the composite to repair external defects. This test was comprised of three pressure cycles. The first cycle took the specimen to 90 percent of the design pressure of the piping (2,428 psi). After this, the pressure was relieved and the repair inspected for visual defects. The second pressure cycle took the specimen to the SMYS of the pipe (3,374 psi). It was held at this pressure for four hours and then the pressure was once again relieved. The last pressure cycle was composed of ten cycles that went from 0-2,428 psi. The repair passed all three test cycles for external repair of the defect. Location L9.

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4.3 Dent/Gouge Repair

This test was performed to analyze Aquawrap® G-05 (woven roving) for use in repairing dents in piping. A section of 12.75” OD pipe was dented and a simulated gouge was ground within the dented area. The pipe was pre-pressurized to 900 psi, which was the calculated MAOP of the pipe when factoring in the wall loss from the gouge. The pipe was then wrapped with Aquawrap® G-05 and subjected to a series of three pressure cycling tests. Each test had a duration of 5,000 cycles. The maximum pressure of each of the tests were as follows: first phase to 1,525 psi (MAOP), second phase to 1,800 psi (85% of SMYS), third phase to 2,118 psi (100% SMYS). This test was considered successful as there were no leaks present during any of the test cycles and there was no evidence of damage to the pipe or the composite repair material.

<u>Pipe and Defect Details</u>

Test End Date: April 19, 2005 Test Location: L2
Serial # 967594

Pipe Details - 12.75” OD
0.250 wall
ASTM A53 Grade B Pipe
54,000 SMYS (2,118 psi)
72,000 Ultimate (UTS) (2,824 psi)
MAOP 1,525 psi

Defect Details - Dent - 11” long (axial length) x 5” wide (circumferentially)
Deepest point of dent – 0.91” (7.2% of pipe OD)
Created with blunt force object and an abrasive tool
Dent ground smooth before repair application
Gouge - 0.1875” wide x 4” long
0.0875” deep (35% of pipe wall thickness)


Fig. 1 – Top view of impact dent with gouge.


Fig. 2 – Angled view of dent with gouge.


Fig. 3 – Dent ground smooth prior to repair.

Wrap Details - 34 Layers of Aquawrap® G-05, 24” of linear coverage

Fabric Weight	24 oz.	Nominal Thickness	27 mils
Tensile Strength	47,500 psi	Tensile Modulus	3.2 e6 psi
Tensile Load/Ply	1,280 psi	Compressive Strength	25,000 psi
Interlaminar Shear	2,750.00 psi		

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Repair Process

Prior to the repair, the pipe specimen was taken to Authorized Testing and pre-conditioned. The pipe was hydrostatically pressurized and taken from 0 psi to 900 psi within 7 minutes, and then was held at that pressure for another 7 minutes. The pressure was then relieved and the pipe drained of water. Very little re-rounding of the dent was observed. Refer to Fig. 4 for before and after measurements. The pressure of 900 psi was calculated by figuring what the MAOP would be, given the depth of the wall loss within the dented area.

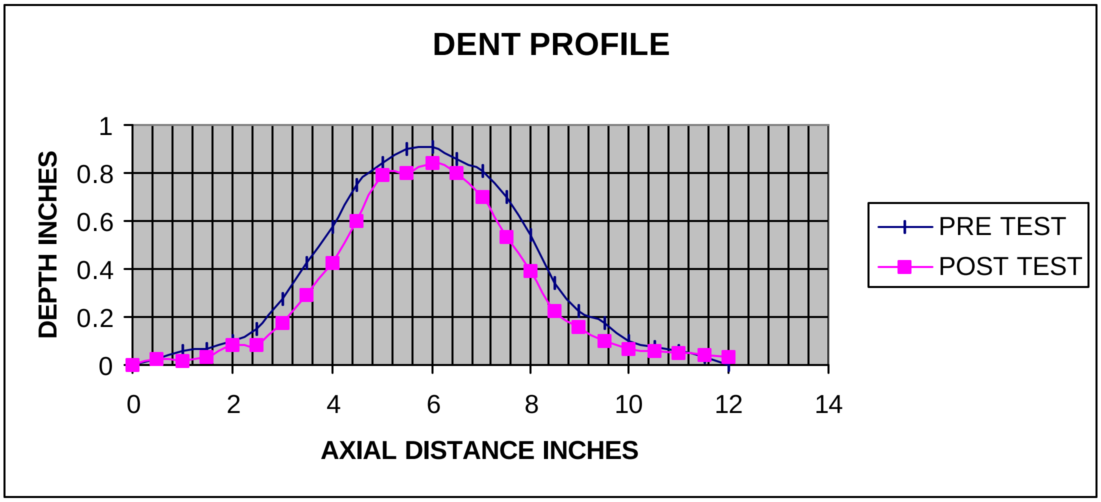

Fig. 4

The pipe was prepared by sandblasting to a NACE II finish and wiped clean with acetone. The dent was filled using TFT Bio-Fix 911 repair epoxy (Fig.5). This high strength filler material will act as the load transfer compound between the composite and the steel. The material was allowed to cure, and then contoured to match the profile of the pipe. Again, the pipe was wiped clean with acetone to remove any loose debris that may have accumulated from the contouring process. BP-1 Primer was applied and allowed to become slightly tacky (Fig. 6). Next, the first lift (courses one and two with a total of 18 layers) of Aquawrap® G-05 was installed circumferentially around the pipe, with the dent centered within the repair area. Stricture Banding™ was applied, and the lay-up was then allowed to cure. The duration from the application of the BP-1 to the end of this initial installation was sixty minutes. After two hours of cure time, BP-2 Interlaminar Adhesive was applied, along with the second and final lift (courses one and two with a total of 16 layers) of G-05 fabric. This lift was again installed circumferentially. The final application of Stricture Banding™ was installed and the lay-up was allowed to completely cure (Fig. 7). The total number of layers of G-05 material applied to the pipe was thirty-four. Refer to the Lay-up Diagram for clarification.

Fig. 5

Fig. 6

Fig. 7

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Cycle Test Procedure

The maximum allowable operation pressure (MAOP) of the undamaged 12” pipe is 1,525 psi, using a 72% design factor, per ASME B31.4. The SMYS pressure for this same pipe is 2,118 psi. We have chosen to design this repair so that the repair system can handle at least 100% of the SMYS pressure. The wrap design was based upon no allowance for the steel in the dent area, using the long term (creep-rupture) strength of the wrap, and a 67% design factor for the composite (in accordance with the pending ASME PCC-2 Post Construction Repair Standard for Non-Metallic Composite Repair Systems).

The initial cycle-test phase consisted of pressurizing the repaired specimen from 200 psi to 1,525 psi (MAOP of pristine pipe) for a minimum of 5,000 cycles. When this was complete, the next phase took the specimen from 200 psi to 1,800 psi (85% of the SMYS) for a minimum of 5,000 cycles. The final phase took the specimen to 2,118.00 psi (100% of the SMYS) for a minimum of 5,000 cycles.

The test was performed using ambient temperature water in a warehouse environment. The minimum dwell time in each of the pressure ranges between 90 and 100 percent of the target pressure was not less than 1.2 seconds.

Cycle Test Results

The specimen was inspected after the first phase of cyclical testing, with no visual damage to the pipe or the repair material. The specimen was checked again after the second phase, and again, no visual damage was found on either the pipe or the repair material. After the final test phase, the specimen was removed from the test apparatus and inspected in greater detail. The specimen survived all three 5,000-cycle tests without any signs of leakage or other failure mechanism. This test was deemed a success.

Another similar, but more detailed, test was performed at Stress Engineering Services in Houston, Texas. For detailed information, please refer to SES Report PN114315CRA – Evaluation of the Aquawrap® System in Repairing Mechanically Damaged Pipes.

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4.4 NOL Ring Test Data Summary

The NOL (Naval Ordinance Laboratory) ring test is done on a 0.20 inch thick, 1" inch wide ring of composite material, 20" in diameter. The ring is placed in a special test machine mounted outside of a bladder. The bladder is then pressurized with liquid, thus causing hoop stress to be applied to the entire ring simultaneously. The pressure is increased until the ring fails. The stress in the ring at failure is then compared to that of ASTM D-3039 coupon results. The reason this test was devised is that test results done on composite structures, such as rocket motor casings and infrastructure column reinforcements, did not always match those calculated using coupon test data. The reason for this is inadequate interlaminar shear strength of the composite. If the interlaminar shear properties of the composite are not good enough, the composite delaminates rather than fails in a normal tension mode. The NOL ring test was devised to measure the composite system under true hoop stress loading. Air Logistics has completed NOL ring tests on four of its materials; Glass Tape (G-03 Fabric), Glass Woven Roving (G-05 Fabric), UD Glass (G-06 Fabric), and UD Carbon (C-14 Fabric). Although this paper focuses on the G-03 Fabric, the other materials are included for reference. The NOL ring testing was performed at Alliant TechSystems Inc. (Location L8).

Chart Layout

- The first column is the coupon test number.
- The second column is the pressure at which the ring failed.
- The third column is the force on the ring at failure.
- The next four columns list the number of layers and the per layer strength of materials used to fabricate the ring.
- The next column is the total calculated force of the ring.
- The last column lists the difference between the actual test results and the calculated force.

Discussion of Test Results

In all cases the actual force the material withstood during the test was greater than that calculated based on the ASTM D-3039 coupon test data. It should be noted that the pressurization rate of the rings generally resulted in failure in about 30 seconds. This rate is determined by the test machine and cannot be easily changed. The specified time to failure of coupons in the ASTM test is between one and ten minutes. The pull rate of the data taken on the coupons of the materials listed generally resulted in failure between two and four minutes. The creep rupture characteristics of these materials could explain the better results of the rings with respect to coupons.

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NOL Ring Test Results

TEST NUMBER	PRESSURE AT FAILURE (psi)	FORCE (pounds)	PLIES G-03	PLIES OTHER	STRENGTH PER PLY G-03 FABRIC (pounds)	STRENGTH PER PLY OTHER FABRIC (pounds)	TOTAL CALCULATED FORCE (pounds)	DELTA FORCE (pounds)
G-03 FABRIC								
Ring 1	1,434	14,340	17		750		12,750	1,590
Ring 2	1,390	13,900	17		750		12,750	1,150
Ring 3	1,372	13,720	17		750		12,750	970
Ring 4	1,425	14,250	17		750		12,750	1,500
Average	1,405	14,053			750		12,750	1,303
G-05 FABRIC								
WR 7-101	1,132	11,320		7		1,200	8,400	2,920
WR 7-201	1,024	10,240		7		1,200	8,400	1,840
WR 7-301	968	9,680		7		1,200	8,400	1,280
Average	1,041	10,413				1,200	8,400	2,013
G-06 UD FABRIC								
SIR00101	2,189	21,890	1	8 (G-06)	750	2,400	19,950	1,940
SIR00102	2,357	23,570	1	8 (G-06)	750	2,400	19,950	3,620
Average	2,273	22,730			750	2,400	19,950	2,780
C-14 UD FABRIC								
SIR00103	3,003	30,030	2	8 (C-14)	750	3,400	28,700	1,330
SIR00104	2,680	26,800	2	8 (C-14)	750	3,400	28,700	-1,900
SIR00105	2,868	28,680	1	8 (C-14)	750	3,400	27,950	730
SIR00106	2,890	28,900	1	8 (C-14)	750	3,400	27,950	950
Average	2,860	28,603			750	3,400	28,325	278

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5.0 Test Locations

Location L1 Air Logistics Corporation 3600 East Foothill Boulevard Pasadena, CA 91107 Phone 626-795-9971	Location L2 Authorized Testing Inc. 2522 Kansas Avenue Riverside, CA 92507 Phone 909-682-4110
Location L3 Delsen Test Laboratories, Inc. 1024 Grand Central Avenue Glendale, CA 91201-3011 Phone 818-247-4106	Location L4 National Testing Laboratories 877 Rose Place Anaheim, CA 92805 Phone 714-991-5520
Location L5 SGS U.S. Testing Company, Inc. 5555 Telegraph Road Los Angeles, CA 90040 Phone 323-838-1600	Location L6 University of Utah Civil & Environmental Engineering College of Engineering 122 South Central Campus Drive - Rm. 104 Salt Lake City, UT 84112-0561 Report No. CVEEN-03/01
Location L7 University of Wyoming Composite Materials Research Group PO Box 3295 Laramie, WY 82071 Phone 307-766-4266 Fax 307 766-2695	Location L8 Alliant Techsystems Inc. Freeport Center PO Box 160433 Clearfield, UT 84016-0433 Phone 801-775-1729 Fax 801-775-1207
Location L9 Petrobras Research Center (CENPES) Luiz C.M. Meniconi Catholic University of Rio de Janeiro Jose L.F. Freire Ronaldo D. Vieira Jorge L.C. Diniz Reference ASME Document IPC02-27372	

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6.0 References

Standard or Specification	Title	Revision Date
ASTM D-3039	Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials	2000
ASTM D-790	Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Insulating Materials	2000
ASTM D-695	Standard Test Method for Compressive Properties of Rigid Plastics	1996
ASTM D-2344	Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates	2000
ASTM E-831	Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis	2000
ASTM E-84	Standard Test Method for Surface Burning Characteristics of Building Materials	2000
ASTM G-8	Standard Test Method for Cathodic Disbonding of Pipeline Coatings	1996
ASTM D543	Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents	1995
ASTM D-5420	Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact)	1998a
ASTM D-2990	Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep Rupture of Plastics	1995
ASTM D-2992	Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings	1996e1
ASTM D-3165	Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies	2000
ASTM D-2565	Standard Practice for Xenon Arc Exposure of Plastics Intended for Outdoor Applications	1999

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7.0 Conclusion

Through laboratory testing and field testing, Aquawrap® has proven itself to be an easy to use, reliable, and efficient means of repairing piping that has been subjected to damage caused by external corrosion or by other mechanical means. The product has undergone extensive development to arrive at the final stage you see today. By testing many different resin formulations, fabric weaves and types, and the combination of both, Air Logistics was able to distinguish itself from other products in the same market. Aquawrap® is an engineered composite product, designed specifically for structural reinforcement.

By performing burst tests, we are able to see the actual performance of material in a real life situation. Most pipelines may never see their maximum allowable operation pressure, but testing to that threshold proves the viability of the product. The ability of Aquawrap® to be applied in layers provides the end user with the option of installing more strength to the system if they so choose. A minimum of four layers is recommended on any installation, regardless of strength calculation results. Air Logistics provides a simple calculation program that one can use to determine the number of layers required for a given repair.

Aquawrap® is an environmentally safe product which uses no hazardous chemicals. No measuring or mixing of resins is required and clean-up is safe and quick. Primer systems are prepackaged to ensure the right ratios, and are designed to be mixed in their own containers. This eliminates the need for extra mixing buckets, and extra waste.

Air Logistics will continue its commitment to provide high strength composites to the pipeline market. These products will help prevent system shut-downs, costly repairs, and damage to the environment.

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