SEAMAN CORPORATION

Improved Polyurethane Storage Tank Performance

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14. ABSTRACT
o allow for maximum mobility and flexibility in the field, the US Armed Services rely extensively on the use of Collapsible Fuel Tanks (CFT) for refueling. The Services have experienced a large number of failures of these CFTs in the field. These failures have created a concern that polyurethane collapsible fuel tanks will not be able to meet the service life requirement of 3 years as specified in MIL-PRF-32233. To proactively address these problems, a congressionally mandated research project was undertaken to study polyurethane coated fabric systems and fabrication processes that are or may be used, in the production of CFTs.

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Acronyms

CFT – Collapsible Fuel Tank
DLA – Defense Logistics Agency Energy
DOE – Design of Experiments
F/B – face/back – referring to face and back side polyurethane coatings
FEA – Finite Element Analysis
HAW – hot air welding
HBW – hot bar welding
HTF – high temperature fuel
RF – Radio Frequency welding
SwRI – Southwest Research Institute
2 MP – two minute peak

Units

ft/min – feet per minute
lbs_f/in – pounds force per inch
psf – pounds per square foot
psi – pounds per square inch
°F – degrees Fahrenheit

Executive Summary

Problem Statement

To allow for maximum mobility and flexibility in the field, the US Armed Services rely extensively on the use of Collapsible Fuel Tanks (CFT) for refueling. Tank requirements are specified in MIL-PRF-32233, Performance Specification – Tanks, Collapsible, 3,000, 10,000, 20,000, 50,000 & 210,000 U.S. gallon capacity, collapsible fuel tank storage assemblies. The Services have experienced a large number of failures of these CFTs in the field. While some failures have been material-related, the majority are due to either seam separations/tears or seam leaks in the tanks. These failures have created a concern that polyurethane collapsible fuel tanks will not be able to meet the service life requirement of 3 years, when operated in an environment from -25^{o} to +120^{o}F, as specified in MIL-PRF-32233. To proactively address these problems, a congressionally mandated research project was undertaken to study polyurethane coated fabric systems and fabrication processes that are or may be used, in the production of CFTs.

Technical Approach

This study includes review of seam design and seam fabrication techniques that are commonly used for CFTs, suggested manufacturing process control, and quality control requirements, with tank seam performance being the focus. The major seam related characteristics investigated were: catastrophic seam failure, seam integrity and seam longevity.

Both empirical testing and computer-based structural modeling were conducted through ILC Dover. ILC Dover was the first manufacturer of CFTs and has multi-discipline expertise in the design, evaluation and fabrication of soft goods made with flexible membranes. Testing was performed on nylon based, polyurethane coating compounds, polyurethane coated fabric, and fabric seams. The testing provided information that was used to determine the longevity of fabric seams and to provide inputs for Finite Element Analysis (FEA) that was more representative of actual fabric and seams. FEA was used to provide an understanding of stresses in seams at peak service loads. ILC Dover experimentally established a material performance baseline (load vs. elongation) for both Seaman Style 1940 coated fabric and typical welds (lap and double strap butt seams). A performance comparison between the coated fabric and welded joints of coated fabric was also completed.

Seam design, the weld technique employed, and variables inherent in the manufacturing process all contribute to fuel storage tank reliability. These factors were studied with respect to their application in the seams. Seam welding techniques include hot air, hot bar, impulse, and dielectric (RF or HF). Specific manufacturing process variables for each of the welding methods were investigated. This included, where applicable, energy input (in terms of heat or power), welding pressure, process steps, and process speed or cycle time.

Seams were prepared and laboratory testing was conducted at Seaman Corporation to establish performance of seams manufactured by different methods and across a range of process variables. A dead-load test chamber was designed to handle up to 120 seam samples, simultaneously, for an extended period of time. All samples were immersed in high temperature fuel (HTF) under dead-load. A Design of Experiments (DOE) was conducted to define and determine the significance of contributing manufacturing process variables.

All of the dead-load samples were visually inspected to determine the mechanism by which failure occurred. The failures were classified based on type, in an effort to determine most probable root cause.

Based on this study, recommendations were made for manufacturing process quality control, including appropriate test methods and documentation for end product qualification, to ensure improved tank reliability and performance. This included identifying and establishing statistical process control for each critical fabrication process parameter.

Two 3,000 gallon model tanks were fabricated utilizing a Fiab RF welder. One tank was designed with narrower 34” panels (1/2 width) to increase the number of seams for evaluation. The second tank was fabricated with 68” panels, for comparison. The tanks height, warp and fill peak stretch were measured for various fill volumes and compared to the biaxial stress-strain curves for the fabric. This was done to determine if controlled overfill of a small tank could be used to approximate the stresses typically seen in large tanks.

Findings and Conclusions

The work completed by ILC Dover contributed greatly to the understanding of the properties of the polyurethane coated, nylon woven fabric, as well as the seam welded material. Previously published work assumed a linear material response for the coated material, creating a source of potential model error. The initial material testing provided critical load versus elongation data that allowed for the development of a more representative, non-linear finite element model. Three material configurations were tested: 1) un-seamed Seaman Style 1940 coated fabric, 2) lap seams, and 3) double strap butt seams. The strain results after load cycling were documented for comparisons with the analytical model. Stiffness measurements made over the top of the bonded areas of both the lap and butt seams were approximately two times stiffer than the parent Style 1940 coated fabric.

The FEA hyper-elastic material model was used to predict the tensile behavior of two Fuel Tank seam configurations. From this model it was possible to develop force / extension curves for both the lap seam and butt seam configurations. These curves predicted a significantly stiffer result for the butt seam.

Experimental work was performed on the four welding methods (impulse, hot air, hot bar and RF) to identify critical welding control parameters. Based on these parameters, samples were fabricated and evaluated for performance in hot temperature fuel (JP8) under dead-load, per the MIL-PRF-32233 requirements. A DOE was constructed to minimize the number of samples necessary for test while still identifying the variables that contribute to sample failure. The dead-load test chamber was constructed for repeatable control of these test variables. In summary, it was found that any of the four different types of welding equipment could be used to manufacture a successful seam, able to withstand the HTF dead-load test. Regardless of the welding process, the ability to get the polyurethane coated fabric to a high enough melt temperature was the key to a successful weld.

Failure analysis of exposed samples resulted in two primary types, those where the weld was inadequate, or those where damage occurred to the underlying fabric layer. In the case of the inadequate weld, under or overheating the weld area probably led to the separation in the weld area. In some cases, overheating or too much power probably was delivered to the weld area, possibly damaging the yarns. This effort verified that the fundamental physical and material interaction during the weld process needs to be further understood and would be the basis for future study. This also emphasizes the critical need for appropriate process control.

The model tanks were fabricated from the Seaman Style 1940 coated fabric. The biaxial stretch characteristics (warp and fill stretch % as a function of the applied load) of the fabric were determined. The load applied was up to 75lbs_f/inch, creating in-plane stress representative of maximums encountered in large fuel tanks. After fabrication, the tanks were filled with water and the warp and fill peak stretch measured as a function of tank height and water volume. The model tank results suggest that a 3,000 gallon tank with a controlled fuel overfill should undergo the same stresses as seen in a 50,000 gallon tank. This will allow us to further study the different welding techniques and tank designs in the field, using a smaller scale tank.

No matter what the welding process was, the ability to get the urethane coated fabric to a high enough melt temperature was the key to a successful weld. It was demonstrated that any of the four different types of welding equipment could be used to manufacture a successful seam, as defined as being able to withstand the high temperature fuel dead-load test.

For defining manufacturing repeatability and control, a number of critical performance parameters were identified. It was determined through testing that the initial weld adhesion and weld adhesion after high temperature fuel (HTF) immersion have a linear relationship. Unfortunately, the relationship between HTF weld adhesion and HTF dead-load performance is not as predictive. From 30 to approximately 45 lbs_f/inch, the data shows a steep increase in dead-load performance with associated increase in seam adhesion. Beyond the 45 lbs_f/in., the dead-load performance is relatively flat, with no relative increase in dead-load performance as weld adhesion increases. The data indicates that a 29 day dead-load value (equivalent to a 3 year service life) can be obtained at a minimum HTF seam adhesion of 39 lbs_f/in. A 45 lbs_f/inch HTF seam adhesion (~15% above the minimum), translates into a 55 lbs_f/in. initial seam adhesion, which is considered the target for the seam specification. A process control plan was developed for each of the welding methods utilized in the experimental evaluation: Impulse, RF, Hot Air and Hot Bar.

Recommendations

Based on the dead-load test results it was noted that samples exposed to high temperature fuel that did not fail by 4 days would typically last until 29 days. Hence, the current specification of 70 hours might not be an adequate predictor of success in the field (MIL-PRF-32233, section 4.5.2.8). A limit of 96 hours with a constant dead load tension force equivalent to a 2.5 safety factor in JP-8 at 160 °F should increase the probability of success in the field.

Additional study should be considered before a fabricator selects a welding technology. An examination of other variables, such as throughput speed and cost of each welding process, in production, should be performed. Testing that focuses on the repeatability of producing fuel tight seams with any of the welding systems, should also be investigated.

Studying model tanks is the best way to determine the ability of a welding method to minimize or eliminate seam leaks. This work will be continued under actual environmental field conditions, in the FY2009 Improved Polyurethane Fuel Tank study.

1.0 Introduction

The Services have experienced a large number of failures of collapsible fuel tanks in the field. While there have been some failures that are material related, the majority have been the result of either seam separations/tears or leaks in the tanks, primarily at the seams. These failures have created a concern in the services that urethane collapsible fuel tanks will not be able to provide the 3 year service life that is required by MIL-PRF-32233.

In 2003, a study was done and a report was prepared by Southwest Research Institute (SwRI) project 03-06149, March 2003, on "Failure Analysis and Alternative Solutions for Collapsible Fabric Tanks" (Appendix F). The goal of the study was to collect and analyze data from a variety of sources for the purpose of identifying and describing common failure mechanisms for collapsible tanks and to make recommendations that would lead to the improvement of tank quality and design. A portion of the analysis related to the structural integrity of seams, which is the focus of this study. A Finite Element Analysis (FEA) was performed on a 50,000 gallon fuel tank, configured per specification ATPD-2266, in order to understand the peak stress regions of the tank wall. The analysis yielded a visualization of the shape of the collapsible fuel tank at its full fill height and a contour plot of the in-plane stresses that were present. The maximum in-plane stress data is useful since it provides the largest stress values that occur in the plane of the fabric and allow an evaluation of the breaking strength requirements of the membrane. The results of the study showed a maximum in-plane stress of 14610 psf. Adjusting this number for the thickness of the fabric, the load in the fabric is approximately 50 lbs_f/in. This load was used as the baseline load for the seam studies that follow.

The purpose of the work performed by Seaman Corporation, under the contract with DLA, is to study the fabrication of collapsible fuel tanks made with polyurethane coated fabrics. This work focused on seaming methods that are or may be used in the fabrication of tanks, to provide insight into the following:

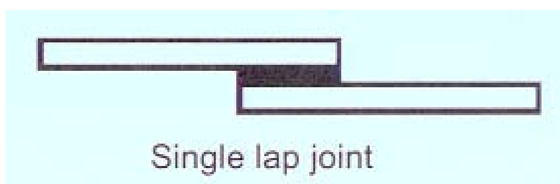
1) Seam design options and an FEA analysis of seams
2) Review of welding methods including an evaluation of performance and ease of manufacturing
3) Quality and Process control requirements for welding of fabric seams
4) Model Tank Investigation to determine if small scale tanks can be used to simulate the performance of larger tanks.

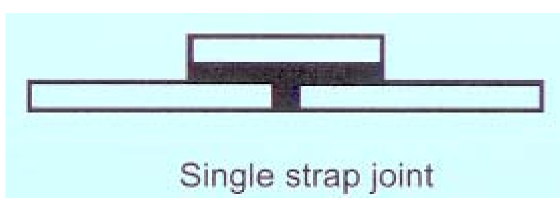
2.0 Seam Review

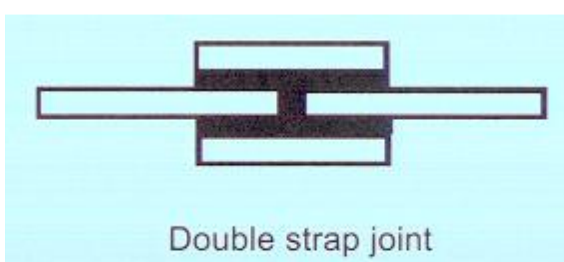
Coated fabrics are multilayer composites. In the case of collapsible fuel tanks under investigation in this study, the composite is made with a high strength woven fabric that is coated with a polyurethane resin. The fabric is designed to carry the loads that the tank is subjected to with a safety factor greater than the 2.5 designated in MIL-PRF-32233. The urethane coating is linked to and forms a matrix surrounding the fiber of the coated fabric. The matrix material, a thermoplastic polyurethane, is where heat-bonded seams are made to construct the fuel tanks and the urethane is the medium by which seams can transfer loads across the joints in the fabric.

Heat bonded seams are made by a variety of methods. There are a number of different seam designs that can be used for homogenous materials. However, seam designs for coated fabrics, where the seams need to be liquid tight and the seam shear strength needs to be as great as the strength of the fabric, are limited to lap designs. These will be discussed in more detail in the section on seaming methods. For lap seams, the seam shear strength is directly proportional to the seam width, up to a limit. By adjustment of the seam width, these seams can be made to be stronger than the coated fabric; seam efficiency equals 100%.

There are three common types of joints possible for fabricating collapsible fuel tanks: the single lap joint or modified lap joints - the single strap (-butt) joint, or the double strap (-butt) joint.







Others include end, corner and fitting seams. These seams are not as standard as the panel - warp seams and vary from fabricator to fabricator as well as from one tank design to the next. In some instances, the fabricator may consider these seams proprietary. In addition, the FEA analysis, both in the SwRI and the ILC Dover reports, indicated that the area of highest stress occurs at the top of the tank, at the panel - warp weld seams. Since these seams should then see the "worst case stress concentration", they are the focal point of this investigation. Further investigation into end closure, fitting and corner seams will be undertaken in the future.

The single lap joint is the most commonly used joint for seaming thermoplastic membranes because it is simple to fabricate and, under load, it stresses the bond area in shear. Shear stress is caused by forces applied parallel or tangential to the bond, such as in a dead-load test. There is a slight misalignment of load when the single lap seam is loaded in shear which can result in some cleavage stress at the ends of the joint. This seam is used by a number of fabricators of collapsible fuel tanks.

The single strap joint is generally used only when the single lap joint is impractical. It is subject to cleavage stress under bending forces. It is not currently being used by any fabricator for collapsible fuel tanks.

The double strap joint has lower cleavage stress under bending forces than either of the other seams. In addition, for the same overlap width, it has twice the weld area, and consequently, will handle a higher (theoretically double) shear load. This weld joint is currently being used to fabricate collapsible fuel tanks.

3.0 FEA Analysis

As a prelude to FEA analysis on seams that might be used in normal tank construction, ILC Dover was asked to perform testing on Seaman's fuel tank fabric to help define linear elastic Hooke's Law constitutive constants to be used for finite element modeling. The report for the work is shown in Appendix A1. The testing on the 1940 fabric showed very good agreement with the fill yarn properties used by SwRI in their analysis. It did not show the best agreement with the warp direction properties used by SwRI. The 1940 warp stiffness data was higher than the warp stiffness assumed by SwRI. However, the differences seen in the warp direction stiffness were not so great that it would significantly affect the tank geometry. Consequently, the maximum in-plane stress data from the report was used as the basis for the balance of the testing at Seaman Corporation.

With the SwRI report validated, the focus shifted to modeling stresses in seams. In order to better understand the value of the two seams that are currently being used to fabricate fuel tanks, a FEA was performed for each. The entire finite element analysis is shown in Appendix A. The analysis is reviewed below:

3.1 Seam Analysis FEA

1) The nylon base cloth and the urethane coating compound used on the 1940 PTFF were subjected to engineering tests to determine their structural properties. These were used to develop hyperelastic models to use in the finite element analysis. A two parameter Mooney-Rivlin model was used for the urethane and two - five parameter Mooney-Rivlin models were used for the nylon.

2) Models of the coated fabric were prepared using the material models. The model assumed a 0.020 in. thick fabric layer sandwiched between two 0.015 in. thick coating compound layers. Stress strain results from the model were compared with actual test results for the fabric with reasonable agreement. The fill direction model showed good agreement with the test data. The warp direction model predicted lower stress at a given strain than was seen in actual testing of the fabric. No attempt was made to refine the warp model to reconcile this difference, since the maximum in-plane stress on the tank occurs in areas where the fabric heads into the seams in the fill direction.

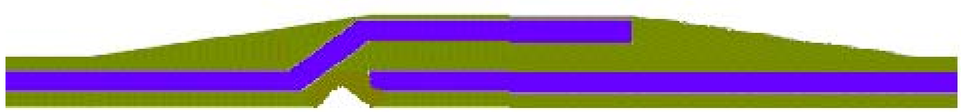
3) Models were developed for the overlap and double strap butt seam based on samples provided by Seaman Corporation. The geometry of the seam samples were approximated using high magnification images of the seam. These were the basis for establishing the geometry of the seam types.

4) Models were prepared and minor adjustment made to geometry to improve the models. These results were compared to the actual test results. The overlap model appeared to be in good agreement with load extension data generated on samples. The double strap butt seam model did not show as good agreement with the actual test results. It over predicts the stiffness by about 30%.

5) The models were used to examine the x direction normal stress (loads in the fabric layer), the y direction normal stress (peel loads of the polyurethane coating at the fabric interface), and the xy shear stress loads (shear in the coating layer). This was done for both the lap seam and the double strap butt seam at the maximum in-plane stress that was developed in the SwRI study. Contour plots of these stresses are shown in the report.

3.2 Lap Seam FEA

An approximation of the geometry used by the lap seam model is shown below. It should be noted that the lap seam used for this evaluation was made on a hot bar welder, and other welding methods may give slightly different geometries. The fabric makes a step on one side of the seam leaving a small groove in the coating compound and the fabric goes directly into the seam on the other side of the seam. There is some flow of compound into areas where there is a step.



Because the geometry is different at each end of the seam, the stress contours are different for each end of the seam.

3.2.1 Right Hand Side of Seam

The stress in the fabric layer is at the maximum in-plane stress value as it approaches the seam area – 2400 to 2700 psi. This stress comes from a load of approximately 50 lbs_f/in. As the urethane thickness increases, the stress in the fabric decreases. It decreases further once it reaches the overlapping fabric layer. It ultimately goes to 0 at the cut edge.

The peel stress resulting from the normal force in the coating compound shows a maximum of 27 to 36 psi between the fabric layers right at the cut edge of the upper layer of fabric. The area of concentration is very small and the resultant peel force is very low compared to the peel adhesion of the fabric.

The shear contours in the coating show nothing of interest as the impact is negligible.

3.2.2 Left Hand Side of Seam

The stress in the fabric layer is at the maximum in-plane stress value as it approaches the bend in the fabric– 2400 to 2800 psi. This stress corresponds to a load of approximately 50 lbs_f/in. As the fabric transitions through the bend in the fabric, the stress on one side of the fabric drops while the stress on the other side of the fabric increases. The same thing occurs at the next bend as it approaches the overlap, but to a lesser extent. The increase in stress is from a range of 2400 to 2800 psi to a range of 3200 to 3600 psi. The magnitude of the increase on average is about 30% or an increase in the load in the fabric just outside the seam area to 65 lbs/in. At 65 lbs/in, the stress in the fabric is $< 20\%$ of the ultimate tensile strength of the fabric at 158°F and represents no threat to performance. The stress in the fabric decreases once it reaches the overlapping fabric layer at the seam. It ultimately goes to 0 at the cut edge.

The normal force or peel stress in the coating compound shows a maximum of 220 to 270 psi between the fabric layers right at the cut edge of the upper layer of fabric. The area of concentration is very small. If the area of concentration is overestimated and is taken as 0.020 in., the thickness of the fabric, the resultant peel force is only 5.4 lbs_f/in. This is much lower than the peel adhesion of the fabric.

The shear contours in the coating show some stress concentration at the cut edge of the fabric on the bottom of the seam. The stress concentrations are low (shear stress ≤ 90 psi), the associated area small and the impact of the local geometry on the weld is not significant.

3.3 Double Strap Butt Seam FEA

An approximation of the geometry used by the double strap butt seam model is shown below. The fabric makes a step on the left hand side of the seam and the fabric goes directly into the seam on the right hand side of the seam. There is some flow of compound into areas where there is a step.

Because the geometry is different at each end of the seam and in the middle of the seam, the stress contours are different for each.

3.3.1 Right Hand Side of Seam

The stress in the center fabric layer is at the maximum in-plane stress value as it approaches the seam area, 2400 to 2700 psi. This stress corresponds to the load of approximately 50 lbs_f/in. As the urethane thickness increases, the stress in the fabric decreases. It decreases further once it reaches the overlapping fabric layer. The stress in both the strapping fabrics starts at 0 at the cut edge and increases as it moves into the seam.

The peel stress resulting from the normal force in the coating compound shows a maximum of 150 to 180 psi between the fabric layers in the fillet areas between the fabric layers. The normal or peel force at the fabric compound interface is a maximum of 60 to 90 psi. The area of concentration is small. If we assume an area equal to the thickness of the fabric, the maximum peel force would be 1.8 lbs_f/in which is much lower than the peel adhesion of the fabric.

The shear contours in the coating show some stress increase at the cut edge of the strap fabric on the bottom of the seam and some compression at the cut edge of the strap fabric on the top of the seam. The area and the stress concentration are low at the fabric compound interface where peel would occur and the resultant impact would be minimal.

3.3.2 Middle of Seam

The stress in the center fabric layer declines as the fabric moves to the center of the double strap butt seam, ultimately reaching zero at the cut edge. The stress in the strapping fabrics increases steadily as it moves along the fabric toward the center of the seam. The stress in the strapping fabric at the center of the seam is, as expected, about half of the maximum in-plane stress.

The peel stress in the coating compound shows a maximum of 56 to 72 psi at the cut edges of the center fabric. There is no peel force at the fabric compound interface where peel would occur.

The shear contours in the coating compound show some stress increase at the cut edges of the center fabric. The area and stress concentrations are minimal.

3.3.3 Left Hand Side of Seam

The stress in the fabric layer is the at the maximum in-plane stress value as it approaches the bend in the fabric. It is 2400 psi corresponding to a load of approximately 50 lbs_f/in. As the fabric transitions through the bend in the fabric layer, the stress on one side of the fabric drops and the stress on the other side of the fabric increases. The same thing occurs at the next bend as it approaches the overlap, but to a lesser extent. The increase in stress is from a range of 2400 to 2800 psi to a range of 3200 to 3600 psi. The magnitude of the increase on average is about 30% or an increase in the load in the fabric just outside the seam area to 65 lbs/in. At 65 lbs/in, the stress in the fabric is <20% of the ultimate tensile strength of the fabric at 158 °F and represents no threat to performance. The stress in the fabric decreases once it reaches the overlapping fabric layer at the seam. It ultimately goes to 0 at the cut edge.

The peel stress resulting from the normal force in the coating compound shows a maximum of 360 to 480 psi between the fabric layers right at the cut edge of the lower layer of strapping. This is not an area that would be subject to peel failure. The peel stress in the area between the upper strapping tape and the center fabric and the lower strapping tape and the center fabric in the bend areas are 0 to 120 psi. Assuming the width of the areas to be equal to the overall thickness of the fabric, the resulting peel force at the fabric compound interfaces would be 6 lbs_f/in. This is lower than the peel adhesion of the fabric.

The shear contours in the coating show some stress increase at the cut edge of the strap fabric on the bottom of the seam. The area and the stress concentration are low and the resultant impact would be minimal.

3.4 FEA Summary

1) In general, the stress in the tank fabric falls as it enters the seam area decaying to 0 at the cut edge. In the double strap butt seam, the stress in the strapping fabric increases from 0 at the edge of the seam to about half of the maximum in-plane stress at the center of the seam (i.e., 1200 – 1350 psi).

2) There appears to be some stress concentration in the fabric where there is a bend in the fabric plane as a result of the welding process. The stress concentration would be eliminated if the fabric does not step down at the edge of the weld. The magnitude of the stress concentration was much greater in the double strap butt seam than in the overlap seam. In either case, the stress concentration did not result in a stress in the fabric that was greater than 33% of the ultimate tensile strength at elevated temperature, or a safety factor of 3.0.

3) Peel forces were highest at the cut edges of the fabric or the strapping tape in the seam areas where there was a bend in the fabric. The peel forces were in all cases much lower than the peel adhesion of the fabric.

4) The stress contours of the coating compounds were all within the required specification for the coated fabric. Both seams were made with a hot bar welder, which may result in geometries that are not seen in all welding methods. Neither of the seam models had an edge tape included. Edge tape is needed to prevent liquid from pressure transferring through the base fabric. If fuel is able to make it to the scrim by a breach in the coating compound on the interior of the tank or because of an exposed edge, it can flow under the head pressure in the tank, through the scrim and out a breach in the coating on the exterior of the tank or to an exposed edge.

4.0 Welding Equipment/Methods

Heat sealing equipment applies a measured amount of heat and pressure to fabric seams to fuse them together. There is commercially available heat sealing equipment that seams the fabric in a discrete type process where a length of seam is held under pressure while heat is applied or while the seam is cooling. This type of equipment would include hot bar, impulse and dielectric welders. Other welders make seams in a continuous process where the fabric pieces to be seamed move through the weld area, generally pulled along by some type of drive wheel. This type of equipment would include rotary hot air and hot wedge welding. All of these types of equipment have been used over the years to produce collapsible fuel tanks.

In order to understand the strengths and weaknesses of each welding method, the following experimental work was performed:

1) A single lot of Seaman 19401600A68, 1940 PTFF MS337 68 inch (in.) fabric was dedicated for seam sample fabrication using the various weld methods. The lot number was 83264. The lot was characterized and tested within the lot to assure consistency. A single lot was chosen for the work to minimize the impact that fabric variability might have on weld method performance evaluation. The test data on the initial lot is shown in Appendix B1.

2) A test plan was established and a standard sample was designed that would be used for all of the weld method evaluations. All seams were made with the fill yarn running perpendicular to the weld. This is the fiber orientation that is present in the peak stress areas of the tank. The sample was designed to allow collection of test specimens along the length of the seam to quantify position variability. It was also designed and match marked to provide for alignment of fill yarns and to minimize misalignment issues during welding. The sample design is shown in Appendix C. Testing to be performed included the following:

Test	Timing	Test Method	Units
Adhesion of coating to fabric, F/B	Initial	ASTM D751	lbs_f/in.
Adhesion of coating to fabric, F/B	After high temp fuel immersion	ASTM D751	lbs_f/in.
Weld adhesion, 3 samples	Initial	ASTM D751	lbs_f/in.
Weld adhesion, 3 samples	After high temp fuel immersion	ASTM D751	lbs_f/in.
Dead-load, 3 samples	After high temp fuel immersion	MIL-PRF-32233	days

*(lbs_f/in. – pound-force per inch)

High temperature dead-load testing of seam samples, while immersed in Jet Petroleum 8 (JP8) was performed. For the dead-load testing, the MIL-PRF-32233 procedure was used where the fuel temperature and load were controlled. A special test chamber was constructed to perform the dead-load testing. The chamber and the specifics of the dead-load testing are discussed in more detail in Appendix D. The days to failure, either by separation or by tear, was chosen as the continuous indicator in dead-load shear resistance.

3) Thermo Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) analysis was performed on the 1940 fabric by ILC Dover to understand the degradation characteristics and the melt profile for the coatings. The degradation onset for the coating was determined to be 290^o Celsius (C) (554^o Fahrenheit (F)). The DSC analysis was performed from room temperature to 275^o C (527^o F). The DSC analysis showed three melt transitions; at about 70^o C (158^o F), melting of minor crystallinity in the soft segment, at about 140^o C (284^o F), less organized crystalline melting point, and at 172^o C (342^o F), amorphous phase melting. The data is presented in Appendices E and E1.

4) For each welding method, experimental work was performed, in advance of the welding for long term testing in order to identify critical welding control parameters, to determine heat or energy values that gave target bond-line temperatures (where possible) and to establish ranges for control parameters that provided welds with acceptable initial properties. These ranges would be used to set the upper and lower limits of the experimental design space. Initial properties monitored included weld adhesion and the appearance of the weld during testing. The seam needed to pull to the base fabric across the full width of the seam during adhesion testing. The critical control parameters that were used were based on ones commonly used by the fabricators for welding of urethane tanks.

5) Once the preliminary work was completed, the Design of Experiments (DOE) was laid out, levels of the weld control parameters were selected, and seam samples were generated for long term testing. The specific DOE that was used depended on the number of control parameters to be studied and the ability to choose ranges for parameters that were broad enough to allow study. All processes were to be run through several warm-up cycles so as to be at steady state operation before samples were produced for the DOE study. The seam area for all of the samples was wiped with a cleaning solvent prior to the weld work to insure the surface was free from contamination. The expectation of the long term dead-load testing was that all specimens would fail at some point during a 60 day test period so that a response surface, showing the most robust processing conditions, could be established.

The work performed on each of the welding methods is discussed in detail in the following section.

4.1 Impulse Welding

Impulse welding is a form of hot bar welding in which both the heating and the cooling regimes are controlled while the seam is held under pressure. In impulse welding, the coated fabrics to be seamed are placed between two bars, one of which contains a nickel chromium wire strip or analogous material for generating the energy for welding. This element would be specific to the impulse welder's equipment design. The strip is covered on both sides with a non stick layer, such as Teflon coated fiberglass, to keep molten materials from sticking to it and to separate it from the bar. The bars are pressurized together to hold the seam area in place and a pulse of electrical energy is passed through the wire, causing the temperature to increase rapidly and transfer heat to the fabric. The coating compounds melt at the interfaces and co-solidify during the cooling cycle to form a weld. Pressure is applied throughout the process to insure the molten surfaces are in intimate contact during both the heating and cooling phases. For this study, controlled impulse welding was used, where the heating was set to a precise set temperature, the pressure was controlled to ensure that a constant welding force was applied to the fabric, and there was controlled cooling under pressure.

The impulse welding work done for this study was performed at ILC Dover. ILC Dover was one of the first companies to manufacture collapsible fuel tanks made with urethane coated fabrics using impulse welding. Based on the ILC Dover experience, the following parameters were identified as the critical control parameters for the welding trials:

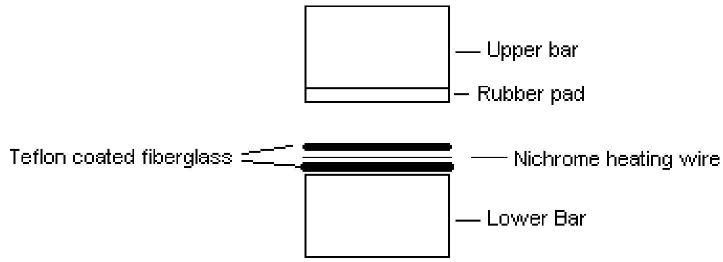
1) Pressure

2) Peak temperature between the upper and lower bar at 2 minutes (2MP temperature)

3) Dwell time

4) Cooling temperature

The following is a general schematic of the bars that were used on the welder:



Warm water was circulated through the bars to keep the heat loss from the bars at a constant level. A thermocouple was located in the bottom bar, near the upper surface of the bar and was used as the set-point for temperature control. The unit used at ILC Dover was their TP15 machine. A drawing of the unit is shown in Appendix G.

In preparing for the DOE samples, ILC Dover made a number of measurements on the equipment in order to determine the relationship between the temperature reading in the thermocouple located in the lower bar and the 2 MP temperatures, the bond-line temperature on heating, and the bond-line temperature on cooling. These were determined by placing thermocouples imbedded in capsan between the upper and lower bars and by inserting the thermocouples in the seam area during the seaming process. The data generated for these trials is presented in Appendix I. The data indicated that bond-line temperatures for a DOE would range from 300^o F to 370^o F using 2MP temperatures ranging from 365^o F to 405^o F with dwell times ranging from 2 to 5 minutes. Based on the preliminary data on the coated fabric characterization, it was determined that this would provide an acceptable temperature range for sealing. The preliminary range for pressure on the cylinders pushing the bars together was set at 30 to 60 psi, based on experience, providing a pressure on the seam of 22.5 to 45 psi. It was decided to hold the temperature of the bond-line on cooling to a constant for the experiments to keep the number of variables to 3. The target bond-line temperature was targeted to be 135^o F, below the lowest melting transition and it experimentally determined that this occurred when the thermocouple in the lower bar reached 110^o F. This allowed for a 3 factor, 3 level, full factorial experiments as outlined below:

Factor 1 – Pressure setting – 30, 45, 60 psi
Factor 2 – Dwell Time after reaching the desired bar thermocouple temperature
(which correlates with the 2 MP temperature) - 2, 3.5, 5 minutes
Factor 3 – 2 MP temperature (which correlated with the bar thermocouple setting) –
365^o, 385^o, 405^o F

The 3 factor, 3 level full factorial designs requires 27 experiments. In addition, 5 replicate experiments were run to provide an estimate of error. Three welds were to be tested for each experiment. The total number of specimens for the dead-load testing was 96.

The experimental design data and the data collected while generating the samples is shown in Appendix J. Review of the data shows the time for the bar to reach the desired temperature varied by less than 30 seconds, the dwell times were controlled to the target times, and the cooling times varied from 3.5 to 7 minutes depending on the target temperature and dwell time. Welding of the DOE samples at ILC Dover took two days to complete. Several warm up and test seams were made at the start of each day and any time the machine sat idle for a period of time to insure the welding equipment was at steady state, prior to preparing the DOE samples. A visual review of the samples showed some minor discoloration of the samples run at the 405^o F 2MP temperature and significant thinning of the coating compound at the 405^o F 2MP temperature.

Samples were returned to Seaman Corporation for testing. Initial properties of the welds were tested and samples cut for long term fuel immersion testing. The initial load for the long term dead with fuel immersion was set at 120 lbs. This was chosen based on the FEA analysis which showed a maximum in-plane stress of about 50 lbs_f/in and the MIL-PRF-32233 requirement of a 2.5 safety factor.

Dead-load testing proceeded as planned. However, after a week, only 3 specimens of 96 had failed. After some discussion, regarding increasing temperature or increasing load to further accelerate the failure rate, the load was increase to 135 lbs on day 9 of the test. Only 1 specimen failed over the next 9 days and the load was further increased. Additional increases in load and 1 increase in temperature were made over the course of the test (62 days) in an attempt to force the dead-load specimens to fail. At the completion of the test, the load was at 250 lbs_f/in and the temperature at 180^o F. A little over half of the specimens failed during testing. A value of 99 days was arbitrarily chosen for samples that did not fail during the test period.   A number of the specimens failed due to tear rather than seam separation at the higher loadings. The load and temperature schedule used during the test and the outcome of the dead-load testing, and a table of all of the other test results are provided in Appendix K. A 99 value in the table indicates that no test result could be obtained. In the case of peel adhesion, it means that the film could not be peeled from the substrate without breaking. In the case of the dead-load, it means that the sample did not fail during the duration of the test.

4.1.1 Data Analysis

The purpose of the response surface design is to generate formulae that accurately describe the response of interest (seam duration under dead-load) as functions of the weld method variables that are under investigation. The output of the DOE would be a model described by best fit quadratic equations. These formulae can then be used to map variable space in order to find optimum process conditions and to evaluate how robust the dead-load outcome is to variations in welding variables. A secondary goal is to determine the natural variation in the dead-load response.

A number of specimens did not fail during the duration of the test. As the DOE analysis requires a numerical value for the time to failure, an arbitrary value of 99 days was assigned to all non-failed test specimens. In addition to complications arising from the inability to fail specimens, the need to change the load and temperature conditions during the test period made it difficult to make projections about the time to failure for the fuel tank seams. Normalization factors needed to be developed to bring the times that specimens were exposed to differing conditions back to a baseline value. It is reasonable to expect that if a sample lasted one day at 250 lbsf/in and 180°F it would last longer at 120 lbsf/in and 160 °F.

ILC Dover was engaged to help develop normalization factors and to perform the DOE analysis. Two different methods were used to try to produce normalization factors; one involved investigation of creep factors, an approach that ILC Dover had used successfully in predicting the performance of fabrics in inflatable structures, the other utilized time-temperature and stress temperature superposition. DOE analysis was performed using several different scenarios to determine the best fit. This work is discussed in Appendix L in detail, along with academic discussion of the techniques, and is summarized below:

1) Creep Rate Normalization

Short term tensile tests give the load at which an item will creep rupture instantaneously, 100% of the ultimate tensile strength (UTS). However, if the same item is held at a lower percent of the UTS, it would take much longer for creep rupture to occur. This is because polymers, like nylon and polyurethane, are viscoelastic materials which show elastic responses when subjected to rapid loading as is typical in a tensile test, but viscous responses when subjected to long term static loads. These types of creep tests in real time could take years for failure to occur. This question is discussed in detail within the study. It was not possible to get samples to fail by the creep method. A combined time - temperature-load superposition method was used and found that some samples would not fail during a lifetime. In this case, an attempt was made to develop normalization factors based on the creep rate of the fabric at different temperatures. Assumptions were made that there would be a failure at a consistent amount of total creep and that the time-temperature superposition principle (TTSP) could be used to accelerate the test and to predict the time, at a reference temperature, where failure would occur. This approach is based on the Bailey-Norton Creep model. However, this approach yielded much, much lower factors than had been generated in prior work for similar materials. It is expected that the reason for the poor results arises from the fact that ILC Dover was unable to get any of the creep samples to fail during the accelerated creep testing. Additionally, at the temperatures used for the tests and with the extended duration to try to fail the samples, it appeared that the modulus of the material was shifting, similar to strain hardening. This could be the result of a change in the polymer structure such as a shift in crystallinity.

Because of this, the technique was abandoned and a time-temperature–stress superposition methods was investigated.

2) Time-Temperature-stress superposition (TTSSP)

This technique creates a master curve of a wide time scale at a reference temperature (71^o C, 158^o F) and reference stress level (~ 119 lbs_f/in) via a temperature stress shift factor allowing the construction of a long term creep compliance curves. These curves provide a basis for adjusting the exposure time for a temperature and a stress that is different from the reference temperature and stress. The normalization factors that were developed are presented in the table below:

temp	load	99	200	Creep Method	Scarborogh Method
160	120	1	1	1.0000	1
160	135	1	1	1.1518	6
160	150	1	1	1.3070	27
160	175	1	1	1.5726	309
160	200	1	1	1.8459	3507
180	200	1	1	2.3804	66820
180	225	1	1	2.7418	758525
180	250	1	1	3.1114	8610590
> 62 Days =		99	200	113.7654	66145340

The normalized cumulative days are shown below:

Day	99	200	Creep method	Scarborough method
1	1	1	1	1
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4
5	5	5	5	5
6	6	6	6	6
7	7	7	7	7
8	8	8	8	8
9	9	9	9.1518	14
10	10	10	10.3036	20
11	11	11	11.4554	26
12	12	12	12.6073	32
13	13	13	13.7591	38
14	14	14	14.9109	44
15	15	15	16.0627	50
16	16	16	17.2145	56
17	17	17	18.3663	62
18	18	18	19.5182	68
19	19	19	20.6700	74
20	20	20	21.9770	101
21	21	21	23.2841	128
22	22	22	24.5911	155
23	23	23	25.8982	182
24	24	24	27.2052	209
25	25	25	28.5123	236
26	26	26	29.8193	263
27	27	27	31.3920	572
28	28	28	32.9646	881
29	29	29	34.5372	1190
30	30	30	36.1099	1499
31	31	31	37.6825	1808
32	32	32	39.2551	2117

Day	99	200	Creep method	Scarborough method
33	33	33	40.8278	2426
34	34	34	42.6737	5933
35	35	35	44.5197	9440
36	36	36	46.3656	12947
37	37	37	48.2115	16454
38	38	38	50.0575	19961
39	39	39	51.9034	23468
40	40	40	53.7494	26975
41	41	41	56.1298	93795
42	42	42	58.5103	160615
43	43	43	60.8907	227435
44	44	44	63.2712	294255
45	45	45	65.6516	361075
46	46	46	68.0321	427895
47	47	47	70.4125	494715
48	48	48	72.7930	561535
49	49	49	75.5348	1320060
50	50	50	78.2767	2078585
51	51	51	81.0185	2837110
52	52	52	83.7603	3595635
53	53	53	86.5022	4354160
54	54	54	89.2440	5112685
55	55	55	91.9859	5871210
56	56	56	95.0972	14481800
57	57	57	98.2086	23092390
58	58	58	101.3199	31702980
59	59	59	104.4313	40313570
60	60	60	107.5427	48924160
61	61	61	110.6540	57534750
62	62	62	113.7654	66145340
>62	99	200	113.7654	66145340

The normalization data indicates that samples that survived 29 days using the test protocol used in this study for the dead-load testing, would have met the 3 year service requirement at a load that is 2.5x the maximum in-plane stress that occurs in a full 50,000 gallon collapsible fuel tank at a service temperature of 158^{o} F. The data in the table under the Scarborough Method is the result of the time-temperature-stress superposition study that was performed. This study is presented in detail in appendix L. The table gives the number of days at the reference temperature and load that result from the increase temperature and load that were used in the study.

The table shows that 29 days using the study dead load test protocol is equivalent to 1190 days (3.26 years) at a service temperature of 158°F and 2.5X the maximum in plane stress.

3) DOE analysis

DOE analysis was performed using a number of different scenarios in order to determine which approach provided the best fit. The following approaches were examined:

a) Using the lowest of the three times to failure for a given trial as the outcome of the trial and using the arbitrary 99 day value for specimens that did not fail during the duration of the test.

b) Using the average of the three times to failure for a given trial as the outcome of the trial and using the arbitrary 99 day value for specimens that did not fail during the duration of the test.

c) Using all three times to failure for a given trial as replicates and using the arbitrary 99 day value for specimens that did not fail during the duration of the test.

d) Using all three times to failure for a given trial as replicates and using an arbitrary 200 day value for specimens that did not fail during the duration of the test.

e) Using all creep rate normalized values for all three times to failure for a given trial as replicates with a normalized 99 day value for specimens that did not fail during the duration of the test.

f) Using all Scarborough normalized values for all three times to failure for a given trial as replicates with a normalized 99 day value for specimens that did not fail during the duration of the test.

g) Using Scarborough normalized values for the average of the three times to failure for a given trial as the outcome for the trial and using the 99 day value for specimens that did not fail during the duration of the test.

Copies of several of the DOE analysis are shown in Appendix L. The results of all are summarized in the table below:

					>5% OK >10% Good	Want to match			
		Higher is better			Higher is better	Higher	Higher	Higher is better	
Analysis Method	Model	Box-Cox Recommended Transform	Model F-Value	Significant Factors (Descending Effect)	Probability that Lack of Fit is due to Noise	Adj R^2	Pred R^2	Adequate Precision	Model's Optimized Settings
99 Minimums only	Quadratic	None	7.89	Temp	0.3135	0.4001	0.2724	8.673	HI Temp, LO Dwell, LO Pressure
99 Averages of 3	Quadratic	None	7.16	Temp, Temp^2	0.6217	0.6414	0.473	8.488	HI Temp, LO Dwell, LO Pressure
99 Individuals	Quadratic	None	6.64	Temp, Temp^2, Temp x Junk	0.4965	0.5025	0.3793	10.24	HI Temp, LO Dwell, HI Pressure
200 Individuals	Quadratic	Square Root	5.01	Temp, Temp^2, Temp x Junk	0.7096	0.4176	0.2876	8.933	HI Temp, LO Dwell, All Pressures
Creep Rate Individuals	Quadratic	Power (Deadload^2.1)	12.94	Temp, Temp^2, Temp x Junk, Dwell^2, Dwell x Junk	0.0005	0.6811	0.5816	14.049	HI Temp, Medium Dwell, All Pressures
Scarborough Individuals	Quadratic	Square Root	10.26	Temp, Temp^2, Temp x Junk, Pressure, Dwell x Junk, Dwell, Dwell^2	0.0036	0.6237	0.5175	13.04	HI Temp, Medium Dwell, All Pressures
Scarborough Averages of 3	Quadratic	Square Root	18.04	Temp, Temp^2	0.0027	0.8319	0.7066	11.522	HI Temp, Medium Dwell, LO or HI Pressures

Note: "Junk" was a categorical factor added so that all three test specimens from each sample could be treated individually. This factor should not have exhibited any significance.

The analysis that used the average of the results for the three specimens as the outcome of the trial provided the best statistical model for the welding process with a low probability that lack of fit is due to noise, reasonable R^2 value and agreement, and adequate precision. The model developed by the DOE can be used to explore design space, in terms of actual factors, as follows:

Dead-load Time (Test days duration not normalized) =
-6644.98807
-4.95395 x Pressure
+69.33882 x Dwell Time
+33.91351 x 2MP Temp
+ .005436396 x Pressure^2
-1.03385 x Dwell Time^2
-.042482 x 2MP Temp^2
+.12593 x Pressure x Dwell Time
+.010093 x Pressure x 2 MP Temp
-018333 x Dwell Time x 2 MP Temp

The model provides an optimum setting of 398.4^o F for the 2 MP temperature, a 2 minute dwell time, and a 30 psi pressure. The average dead-load time predicted for these conditions is 96.2355 days.

However, in the results of all 7 analyses, it is very clear that welding temperature is the overwhelming contributor to dead-load durability, with slight variation in durability resulting from the other factors. At a 2 MP temperature of about 400^o F, durable seams, with dead-load test times greater than 75 days, would be produced using any combination of sealing pressures and dwell times. It is interesting that the 400° F 2 MP temperature experiments would have resulted in bond-line temperatures at or above the amorphous phase melt transition for the dwell times used for the trials. Based on the model derived from the DOE looking at averages, seams with dead-load times greater than 29 days (more than 3 years projected life based on the normalization data), could be produced over a broader range of process conditions.

There are two items of interest that should be noted:

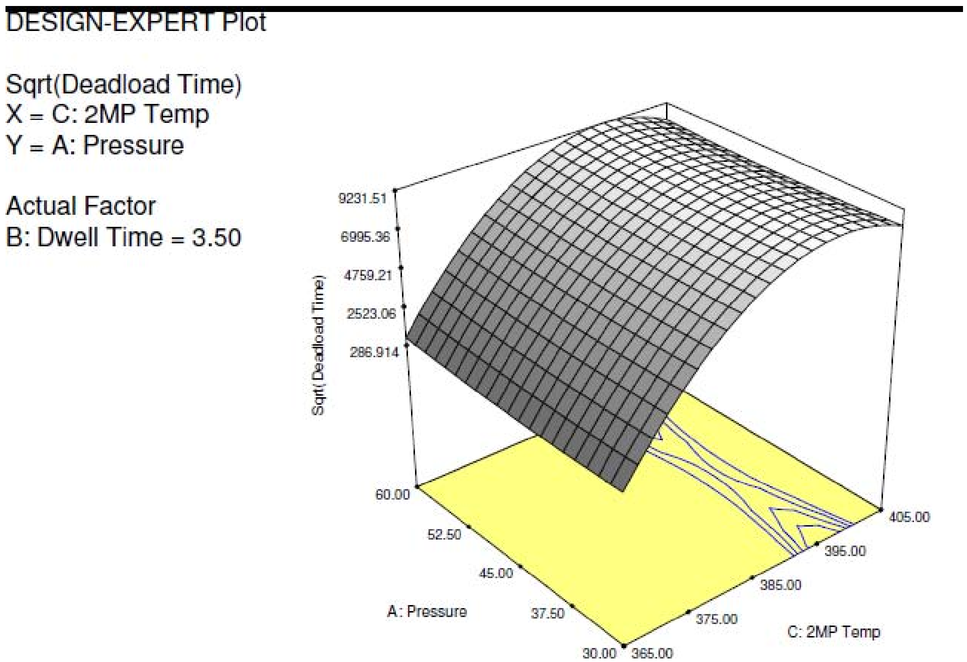
1) The predominant mode of failure for samples run at high temperature is tear of the fabric, rather than separation of the seam. All of the samples that failed using the 405 ^{o}F 2 MP temperature failed by tear. At 405°F there is some damage to the base cloth that results in fabric failure.

2) The model that used the Scarborough transformation of the average of the three times to failure for a given trial as the outcome for the trial provided a good model except for its lack of fit. The significant lack of fit was the result of one outlying data point, at a low temperature, that provided good dead-load results. When this data point was excluded, the fit was very good. The DOE is shown in Appendix L1.

The results are summarized below:

					>5% OK >10% Good	Want to match			
			Higher is better		Higher is better	Higher	Higher	Higher is better	
Analysis Method	**Model**	**Box-Cox Recommended Transform**	**Model F-Value**	**Significant Factors (Descending Effect)**	**Probability that Lack of Fit is due to Noise**	**Adj R^2**	**Pred R^2**	**Adequate Precision**	**Model's Optimized Settings**
Scarborough Averages of 3 (ignore std # 4)	**Quadratic**	**Square Root**	**336.95**	**Temp, $Temp^2$**	**0.7136**	**0.9902**	**0.9851**	**42.151**	**HI Temp, Medium Dwell, LO or HI Pressures**

The model, with the outlier excluded, makes predictions for optimum conditions that are in line with the model chosen above, with temperature the overwhelming contributor to dead-load durability in normalized time. A surface plot of the response curve is shown below:



4.2 Radio Frequency Welding

High Frequency or Radio Frequency (RF) welding is a form of bar welding that uses high frequency electromagnetic energy to generate heat in polar materials resulting in melting and welding after cooling.

The RF welding press has two platens, a moveable one and a fixed one that is also called a bed. The upper platen is generally connected to an RF generator and the lower platen to electrical earth. Tooling, for this study was an aluminum welding bar, attached to the upper platen. The coated fabric to be seamed is overlapped and placed between the platens and the press is lowered so that a preset amount of pressure is applied to the joint area. Once the fabric joint is held in place, the RF energy is applied in a controlled manner and the joint area is heated. This can be applied for a specific time, in which case it is referred to as the welding or heating time. Once the controlled heat cycle is complete, the platens continue to hold the joint in place for a preset time allowing the weld to cool, and the urethane to solidify. This is generally referred to as the cooling time. Once the cooling time is complete, the press opens. The platens, or sometimes the tool itself, are generally cooled or temperature regulated.

The RF welding work done for this study was performed at Seaman Corporation. Seaman Corporation has a long history of using RF welding for the fabrication of architectural structures including inflatable and tension structures. The equipment used for the study was a Fiab 922 High Frequency Welder. The control system for the welder allowed for producing seams under two different modes, an anode control mode (AC mode) or an energy control mode (EC mode). In the AC mode, the operator selects all of the process control factors; welding time, anode current, and pressure. When a weld is initiated in the AC mode, the platens close and apply the preset pressure to the seam, there is a specified preseal delay and then the anode current is applied and increases up to its set value. Once the anode current reaches the set value, the welding time starts and the power is automatically regulated to keep the anode current at the target level. When the heating time is complete, the power is turned off and the seam is allowed to cool under pressure. When the cooling time is reached, the pressure is released and the platens open. In the EC mode, a program calculates the energy required for a specific tool area. Based on the calculation, it chooses welding time, anode current and pressure. There is an opportunity using this program to apply factors to the energy and the pressure to vary these to obtain the desired welding characteristics. The overall cycle for welding in the EC mode is the same as in the AC mode, except that the energy applied to the weld is controlled rather than manually setting the anode current and welding time. As noted above, the preseal time, the time that a seam is held together before any energy input, and the cooling time, the amount of time that the seam is held together after the energy is shut off giving the seam an opportunity to cool are manually selected for both welding modes. A schematic and the spec for the welder are shown in Appendix M.

Based on Seaman's experience and with the assistance of Fiab's manufacturer's representative, the following parameters were identified as the critical control parameters for welding trials:

AC Mode
1) Pressure
2) Anode current
3) Welding time
4) Cooling time

EC Mode
1) Pressure factor
2) Energy factor
3) Cooling time

In preparing for the DOE work, a number of trials were run on the welder in order to select the correct tool size and configuration for the work, to minimize the number of control factors, and to develop ranges for the factors.

A variety of bar lengths and widths were investigated, including a bar with grooves in the surface to allow for flow of molten polyurethane compound. A 2 in. x 33 in. flat bar gave the best results with seam adhesion values in the target range and seams that pulled to the base fabric cleanly along the entire length and width of the bar. This aluminum bar was chosen as the tool for the work.

It was decided to hold the cooling time constant for the experiments to reduce the number of variables to 3 for the AC mode study. The same cooling time was used for the EC mode study. Selection of the ranges for the remaining factors was by trial and error. Factor ranges were chosen that did not appear to damage the fabric, provided good initial adhesion values and gave clean weld adhesion pulls along the entire tool area. Since radio frequency energy is used to heat the weld area for dielectric welding, it was not possible to insert a thermocouple into the weld area to determine bond-line temperatures that were obtained during heating and cooling. Unsuccessful attempts were made to determine the peak temperature using a color change temperature indicator tape and using an Infrared (IR) pyrometer. Based on the flow of compound during welding, it is expected that most welding conditions gave peak temperatures in excess of the amorphous phase transition.

For the AC mode study a 3 factor, 3 level, full factorial design was run as outlined below:

Factor 1: Anode current (amperage): 1.5, 1.8, 2.1 amps
Factor 2: Seal Time: 5, 6, 7 seconds
Factor 3: Pressure: 4.5, 5.2, 5.9 bar

As noted previously, this design requires 27 experiments. In addition, 3 replicates were run to provide information regarding error. The total number of dead-load specimens for testing was 90.

For the EC mode study, a 2 factor, 3 level, full factorial design was run as outlined below:

Factor 1: Energy Factor: 0.8, 1.0, 1.2
Factor 2: Pressure factor: 0.9, 1.0, 1.1 (corresponding to a 4.8, 5.3, 5.8 bar)

This design requires 9 experiments. One replicate was run. The total number of dead-load specimens for testing was 30.

Welding of the DOE samples took 3 days to complete. Several warm-up and test welds were made at the start of each day and any time the machine sat idle for a period of time to insure that the welding equipment was at steady state prior to preparing the DOE samples. The experimental design and the data collected while generating the samples is shown in Appendices N and N1. Samples that were prepared for the DOE were tested for initial properties and for high temperature fuel immersion testing using the exact same protocol (the same load, temperature, time schedule) as was used for the impulse welding samples. For the AC mode DOE, about half of the samples failed during the duration of the test. For the EC mode DOE, about two-thirds of the sample failed during the duration of the test.

4.2.1 Data Analysis

As was done with the impulse welding study, a value of 99 days was assigned to all specimens that did not fail during the duration of the test. DOE analysis was performed using the method that provided the best correlation for the impulse welding study which used the average of the three times to failure for a given trial as the outcome of the trial. The DOE analysis is provided in Appendices O and O1.

For the AC mode DOE, the model F value was 3.29 which implied that the model is significant. The lack of fit F value of 2.14 indicates the lack of fit is not significant relative to pure error. There was not the best agreement between the actual and predicted R^2 values which may indicate that there is a large block effect due to the run order or more likely, that the model should be reduced. The signal to noise ratio of 6.95 indicates adequate signal. Based on these results, the model can be used to explore design space. In terms of actual factors the model would predict the following:

Dead-load Time (Test days duration not normalized) =

-800.24734
+630.76465 x Amperage
+269.82990 x Seal Time
-168.42268 x Pressure
-139.77002 x $Amperage^2$
-15.52374 x Seal $Time^2$
+8.56832 x $Pressure^2$
-56.20370 x Amperage x Seal Time
+36.11111 x Amperage x Seal Time
+2.10317 x Seal Time x Pressure

The model provides an optimum setting of 1.62846 amps, 6.01632 second seal time and 4.5 bar pressure. The average dead-load time predicted for these conditions is 98.2664 test days. This has not been normalized for predicted life but is well beyond the 3 year requirement.

At a 4.5 bar pressure, the operating range that will produce a durable seam, with dead-load time greater than 75 days, is very large, as can be seen in the response surface for this experiment. This is provided in Appendix O. Based on the model derived from the DOE looking at averages, seams with dead-load times greater than 29 days (more than 3 years of projected life), would be produced over the majority of the entire design space.

One item of interest is that at the 7 second seal time and at the maximum anode current, there appears to be a number of short term failures in the fabric, due to fabric tear, rather than a separation of the weld. The seal times were restricted to less than 7 seconds to guard against this issue.

For the EC Mode DOE, the model F value was 14.07 which implied that the model is significant. The lack of fit F value of 0.12 indicates the lack of fit is not significant relative to pure error. There was good agreement between the actual and predicted R^2 value. The signal to noise ratio of 8.832 indicates adequate signal. Based on these results, the model can be used to explore design space. In terms of actual factors the model would predict the following:

Dead-load Time (Test days duration not normalized) =

+303.31889
-203.61111 x Energy
-51.11111 x Pressure

The model provides an optimum setting of 0.83 for the energy factor and a 0.92 for the pressure factor. This would correspond roughly to a 1.66 amp anode setting and a 4.8 bar pressure with seal time varying to achieve the energy target. Seal times varied from 8.5 to 12 seconds for these trials. Aside from the seal times, these conditions are in good agreement with the optimum setting provided by the AC mode DOE. The average dead-load time predicted for these conditions is 87.5714 test days. This has not been normalized for predicted life but is well beyond the 3 year requirement.

The operating range for the EC mode is very restricted as compared to the design space for the AC mode, with a narrow window of conditions that produce durable seams, with dead-load times greater than 75 days. Based on the model derived from the DOE looking at averages, seams with dead-load times greater than 29 days (more than 3 years projected life based on the normalization data) the operating range is much broader.

At the high energy factor levels, there appears to be a number of immediate or short term failures in the fabric, due to fabric tear, rather than a separation of the weld. The fabric failure at the loads used in the study is due to base fabric damage during the welding process. The energy factor would need to be restricted to 1.1 or less to prevent this being an issue in achieving expected life requirements. The high seal times chosen by the EC program mode definitely contributed to the issue.

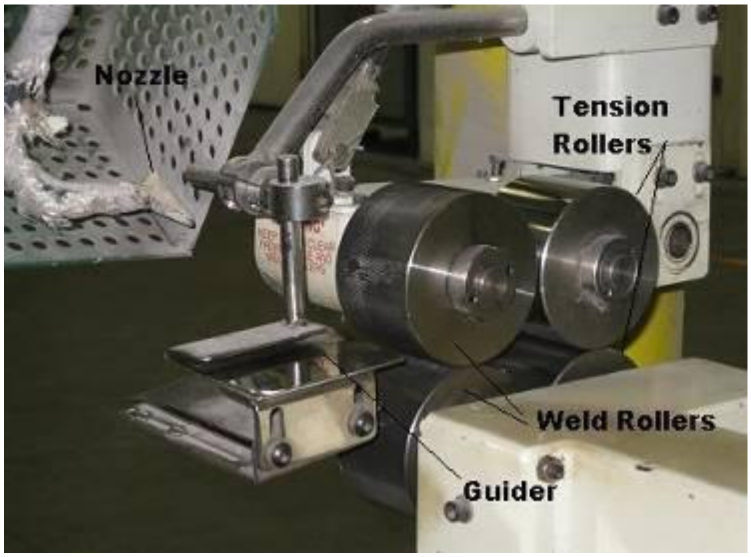
Based on the study, the best approach for using the RF welder for fuel tank seams is to use the AC mode of operation.

4.3 Hot Air Welding

Hot air welding, sometimes called rotary welding, is a continuous welding process where the pieces to be seamed continuously move through the weld area, generally pulled along by a pair of drive wheels. Hot air is blown into the weld area through a nozzle that approximates the width of the seam, with the heated air impinging on both of the surfaces to be welded as the fabric is pulled through driven wheels where a controlled welding pressure is applied. The air flow rate is fixed and the temperature of the air is controlled. A second set of driven wheels are located behind the pressure wheels and are used to control the tension in the fabric. These also apply some pressure to the seam area as the weld cools. However, the cooling is not controlled in any way.

It was the initial plan for the study to work with fuel tank fabricators to generate samples for evaluation in the study. However, contract activity at the fabricators prevented using this approach. Consequently, the work done on hot air welding was performed jointly by Seaman Corporation personnel and engineering personnel from a local hot air equipment manufacturer whose welder is most commonly used by fuel tank fabricators. Both Seaman and the hot air equipment manufacturer have experience in using Hot Air Welding equipment on a variety of coated fabrics.

All of the work performed for the study used a T-500 welder. The T-500 welder is used by several current fuel tank manufacturers. Information on the T-500 welder is provided in Appendix S. A picture of the weld area is shown below:



When a weld is to be run using the T-500, the edge of one fabric panel is positioned in the upper part of the guider and the edge of the mating panel is positioned in the lower part of the guider to help maintain overlap width. The welding wheels are opened and the fabric is pushed into the nip and then the wheels are closed to a preset pressure. The upper and lower panels come together in a V at the welding wheel nip. The weld is then initiated. The nozzle swings into a preset position between the fabric panels and into the fabric V and begins blowing hot air at a controlled temperature. There is an opportunity to set a delay so that the fabric preheats slightly before the welding wheels begin to pull the fabric into the nip at the preset speed. When the weld is complete, the nozzle swings out of position and the nip rollers are opened.

Based on the experience of the hot air equipment manufacturer, four variables were identified as critical control parameters for making a good hot air weld. These were as follows:

1) Hot Air Temperature
2) Speed of welding
3) Type of weld rollers (this relates to the actual pressure and time in the nip area)
4) The location of the air nozzle in relation to the nip of the welding wheels

After some discussion with the hot air equipment manufacturer, it was determined that most companies that use the T-500 to fabricate collapsible fuel tanks would set up their machine with the welding nozzle placed as close to the nip as possible, adjusting the location of the nozzle based on a "whistling" sound when welding. Based on this, it was decided to "fix" the location of the nozzle so that it was one-half inch back from the nip. This allowed the focus to shift to the other three variables and the selection of ranges for variables for a 3 factor, 3 level DOE.

Preliminary welding work was performed at both Seaman Corporation and at the hot air equipment manufacturer to identify ranges for the control variables. The welder was set up for a 2 in. weld width with 2 in. wide wheels and a 1.875 in. wide fan shaped nozzle. The target temperature range was selected as 800^o to 1000^o F, which is the range of temperature that is used by current fabricators. Somewhat unexpectedly, the preliminary work indicated that the welding speed required for obtaining a good seam varied dramatically with changes in temperature. The variation was so large that it was impossible to find a range of speeds that could be used across the temperature range of interest. Consequently, a 3 factor, 3 level design was not possible and it was decided to run three 2 factor, 3 level experiments, each at a fixed temperature and vary speed and wheel hardness in order to examine the area of interest. A second set of experiments was outlined where the wheel hardness was fixed, the nozzle distance was increased to three-fourth inch and the speed was varied at fixed temperatures. The ranges for the factors were determined by trial and error. Conditions were chosen that provided seams that pulled to the base fabric across the full width and along the full length.

The experiments and ranges are shown in the table below:

Samples	Factor 1	Levels	Factor 2	Levels	Air Temp,° F
4101- 4110	Wheel Durometer (Shore A)	55, 85, 100	Speed, ft/min	4.01, 4.76, 5.01	850
4201- 4210	Wheel Durometer (Shore A)	55,85,100	Speed, ft/min	5.93, 6.5, 6.99	900
4301 - 4310	Wheel Durometer (Shore A)	55,85,100	Speed, ft/min	2.77, 3.76, 4.76	800
4401 - 4403	Wheel Durometer (Shore A)	55	Speed, ft/min	1.98, 3.31, 4.53	850
4501 - 4503	Wheel Durometer (Shore A)	55	Speed, ft/min	3.04, 4.29, 5.45	950
4601 – 4604	Wheel Durometer (Shore A)	55	Speed, ft/min	4.03, 4.80, 5.33, 6.00	1050

The experimental design data and the data collected while generating the samples is shown in Appendices T, T1 and T2, along with additional notes from the preliminary study. The experimental work provided for the three 2 factor, 3 level designs, each with one replicate along with some general data about the effect of temperature changes on required welding speed.

Welding of the samples took two days to complete. Several warm-up and test welds were made at the start of each day and any time the machine sat idle for a period of time to insure that the welding equipment was at a steady state. Samples that were prepared were tested for initial properties and for high temperature fuel immersion testing using the exact same protocol (load, temperature, time) as was used for all of the other samples. Most of the initial dead-load test samples failed during the normal duration of the test. There were a few samples that survived the 62 day test protocol that had some scrim exposure or had a lifted tab in the fabric in the overlap. A much broader range of temperatures was investigated with the Hot Air Welding compared to the other methods. This is due to the fact that the initial ranges selected for the study by Seaman Corporation, based on those used by current tank fabricators were far too broad. Subsequent samples that were obtained directly from tank fabricators were tested and performed consistently when compared to the other weld methods. It may not be the method that gave the most robust manufacturing range, but the method did prove to be capable of providing seams that meet the 3 year service requirement of the specification. A more detailed description of the Hot Air Weld sample fabrication issue is located in Section 5.6, Item 3).

4.3.1 Data Analysis

A value of 99 days was assigned to specimens that did not fail during the duration of the test. Samples that had not separated during the duration of the test, but had a failure designated in MIL-PRF-32233 (seam slip, scrim exposure or lift of weld) were assigned a value of 62 days. DOE analysis was performed using the average of the three times to failure for a given trial as the outcome for that trial. The DOE analysis is provided in Appendices U, U1 and U2.

The results are shown in the table below:

Air Temp (°F)	Model F-value	Significant Factors		Adj R^2	Pred R^2	Adequate Precision	Optimum settings
800	14.46	Speed		.7495	.5790	8.657	Low Speed
850	7.24	Speed		.5809	.4119	6.838	Low Speed
900	8.8	Speed		.6341	.4868	7.428	Low Speed

All of the models were significant. The lack of fit for the models was not significant relative to pure error. There was good agreement between the actual and the predicted R^2 values for all of the models. The signal to noise ratio for all models was acceptable indicating adequate signal. Based on these results, the models can be used to explore design space. In terms of actual factors, the models would predict the following:

800 ^{o} F model Dead-load Time: (Test days duration not normalized) =

+90.67047
+.054106 x Wheel Durometer
-14.48333 x Speed

850^o F model Dead-load Time: (Test days duration not normalized) =

+83.47889
+.10074 x Wheel Durometer
-12.60000 x Speed

900^o F model Dead-load Time: (Test days duration not normalized) =

+142.27874
-.088245 x Wheel Durometer
-18.00000 x Speed

The models provide for the following optimum settings:

Air Temp (°F)	Predicted Dead-load	Welding speed		Wheel Durometer
800	56.5224	2.75 ft/min		105.00
850	43.4872	4.00 ft/min		103.49
900	28.9840	6.00 ft/min		60.00

None of these models predict dead-load times that are as long as the models from the other studies. Using the optimum settings, all models predict dead-load times close to or greater than 29 days (more than 3 years projected life based on the normalization data).

The following general conclusions can be reached from the work:

1) The best dead-load results are obtained when running at the slowest speeds that can be used regardless of the air temperature.

2) Even running at the lowest speeds, the seaming is not adequate with cold weld and split weld failures as the common failure modes. Cold and split welds are the result of improper heating of the weld area.

3) Welding speed is the dominant control variable. The dead-load result increases with decreasing weld speed. Wheel Durometer had no significant effect on the dead-load results.

4) As the gap between the nozzle and the nip is increased, the welding speed must be decreased to obtain similar seam performance. The significance of the nozzle location became obvious as the later experiments were conducted.

5) Additional studies were conducted with additional hot air welding samples produced by the hot air equipment manufacturer and by current fuel tank fabricators. The results highlight the importance of maintaining tight process and quality control, especially when compared to the much broader operational parameters initially used. Results from all sample testing are presented in Sections 5.5 and 5.6.

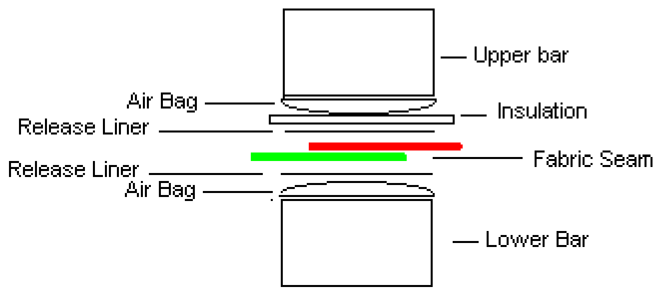
4.4 Hot Bar Welding

Hot bar welding is based on the principle that if two thermoplastic items are pressed against a heated metal bar, they will soften and a seam can be made between them. The equipment is generally comprised of one or two metal bars, one or both of which is heated. The heating can be electrical, by steam, or by circulating a heat transfer fluid through them. One of the bars is generally moveable, to allow placement and removal of the items to be welded. The weld pressure can be applied using a variety of methods: mechanically, pneumatically or via the use of a bladder. A release coating or release membrane is often located between the heated bar and the items to be seamed to prevent molten material from sticking to the bar. With conventional hot bar welding, the heated bar is removed while the weld is still hot or molten. The joint is not cooled under pressure during the cooling phase. Heated tool/cooled tool welding has been developed where the weld is held under pressure while the tool is cooled.

The Hot Bar welding work for this study was performed by an experienced fabricator that has been using hot bar welding to manufacture collapsible fuel tanks using rubber coated fabrics. They had limited experience in the fabrication of fuel tanks with polyurethane coated fabrics. Consequently, the selection of process variables and the preliminary work to develop ranges for these variables was done jointly with Seaman Corporation. Since the welder is a hot bar welder, the potential control parameters fall in line with other bar welders, those being:

1) Pressure
2) Temperature
3) Dwell Timing
4) Cooling Temperature

The hot bar welder used was a scaled down version of the bar welder used in their normal manufacturing process. The welder was about 6 foot long. The following is a general schematic of the welding head:



Hot oil is circulated through the lower bar to heat the bar and there is a thermocouple in the lower bar to measure the temperature. The upper bar is also fixed and is not heated. Air bags or bladders are located between both the upper and lower bars. The fabrics to be seamed are positioned between the upper and lower bars. When the seam area is being heated, the lower bag is deflated and the upper bag is pressurized with air to hold the seam together under pressure during heating and welding. The seam is heated to the desired temperature, held for a set amount of time, and then the upper bag is deflated and, the seamed panel is removed. The release liner on both sides of the welded material is a fabric or film, such as Teflon coated fiberglass that releases from the urethane easily, allowing for the material to separate cleanly from the upper and lower bar assemblies. If cooling is planned, at the end of the heating time, the lower bag is pressurized with chilled air pushing the fabric away from the heated platen, to maintain pressure on the seam while it is cooled. Once cooling is complete, the lower bag is deflated and the weld is complete.

In order to provide for the best control during the testing, the welder was equipped with some additional thermocouples to allow monitoring of the seam temperature at all external seam surfaces and in all bond-lines. Bond-line temperature was the basis for the control of the heating portion of the welding process.

The fabricator has generally used double strap butt seams for the production of thermoset collapsible fuel tanks and generally run using a constant bladder pressure during the heating period and remove the weld while hot rather than using a cooling period where the weld is held under pressure during cooling. For the DOE study, 2 in. overlap and a 6 in. double strap butt seams were prepared for testing, holding the bladder pressure constant, the bond-line temperature constant, varying the dwell time and the cooling temperature.

For the study, the bag pressure was held at 30 psi, and the bond-line temperature set at 340° F (amorphous phase transition temperature) using a 350° F bar temperature. This provided for two 2 factor, 3 level experiments as outlined below:

Factor 1: Dwell Time at 340° F: 1, 4, 7 minutes
Factor 2: Cooling bond-line temperature: 250°, 300°, 340° F

Each design required 9 experiments. One replicate was run. The total number of dead-load specimens for each experiment was 30. Some additional experimental work was performed to investigate varying the bond-line temperature at a fixed dwell time without cooling. Twenty additional experiments were run to look at varying bond-line temperature.

Welding of the DOE samples took 10 days to complete, in part, due to some equipment issues. Because of the lengthy time required for each weld cycle, warm-up and test welds were not produced at the start of each day. The experimental design and the data collected while generating the samples is shown in Appendix V. Samples that were prepared for the DOE were tested for initial properties and for high temperature fuel immersion testing using the exact same protocol (the same load, temp, time schedule) as was used on all previous studies. For each experiment, less than half of the specimens failed during the duration of the test. There were a number of specimens that survived the 62 day test protocol that had some scrim exposure or had a lifted tab in the fabric in the overlap area. It is not known why or when the tab lift and scrim exposure occurred.

The equipment issues were upper air bag or bladder failures; it is not believed the warm up and test welds were a factor. The cycle time for this type of weld is long and the bond line temperature was monitored to assure that the temperature was reached. There is no explanation for the tab lifts; the assumption is that adequate welding did not occur. For the case of the scrim exposures, it might have been related to the long cycle times. Seams that lasted the entire test protocol would not have failed by seam separation during the normal service life of the tank. Seams that had a weld lift would not have resulted in any tank performance issues. However, since samples were checked daily for seam failure but not for scrim exposure, there is uncertainty as to when the scrim exposure occurred. Scrim exposure can result in a tank leak.

4.4.1 Data Analysis

As was done with previous studies, a value of 99 days was assigned to all specimens that did not fail during the duration of the test. Samples that had not separated during the duration of the test, but had a failure designated in MIL-PRF-32333 (seam slip, scrim exposure, or left of weld) were assigned values of 62 days. DOE analysis was performed using the average of the three times to failure for a given trial as the outcome of the trial.
Neither DOE produced an acceptable model – there were no significant model factors. In both cases, the predicted R^2 was negative, indicating that the overall mean of the experiment is a better predictor of the response than a model would be. For the 6 in.

double strap butt seam, the average dead-load was 77.33 days. For the 2 in. overlap seam, the average dead-load was 79.51 days. All of the actual dead-load results obtained for the DOE samples were greater than 29 days (more than 3 years projected life based on normalization data).

The additional experimental work performed with varying bond-line temperature showed that there was a tendency for samples to show more weld lift issues at bond-line temperatures below 340° F and more tear and strip failures at temperatures above 340° F. The 6 in. double strap butt samples seemed to be more prone to strip types of failures than the 2 in. overlap seams, possibly due to a longer overall cycle time required to reach the desired temperatures. In general, those samples that had longer overall cycle times, greater than 30 minutes, were more prone to failures that were related to separation at the seam; scrim exposure, tear, stripping of yarn from the weld.

The following general conclusions can be reached from the experimental work:

1) Operating the bar welder using a 30 psi bag pressure and a 340° F bond-line temperature results in durable seams irrespective of the dwell time or the cooling temperature.

2) Additional work is warranted to more thoroughly understand the effect of bond-line temperature on dead-load performance with special focus on scrim exposure and weld lift failures. The effect of bond line temperature on the weld integrity was investigated during the study. Welds with good integrity were produced over a broad temperature range. However, weld lifts and scrim exposures were not checked on a daily basis as the testing was being performed. Weld lifts do not represent a performance issue, but scrim exposure does. Since the samples are immersed continuously in the high temperature fuel, in a sealed assembly, it was not possible to physically see the sample without disassembling the fixture. Weld lifts and scrim exposures were not observed until the samples were removed from the dead load chamber. This became the justification for de-rating the samples to 62 days, since it is not known if the weld lifts or scrim exposures would lead to eventual failure.

3) Both the 2 in. overlap and the 6 in. double strap butt seam, when properly prepared, should provide for service lives that exceed the requirements of MIL-PRF-32233. It is somewhat surprising that the overall dead-load times for both seams are similar given that the 6 in. double strap butt seam has significantly more overlap area to hold the seam together. However, a longer duration test possibly could show some difference.

5.0 Manufacturing Variability

5.1 Impulse Welding

For the impulse welding work, the pressure was a machine setting and the dwell time was a machine setting. The cooling temperature, which was not selected as a process variable, was also a machine setting. The 2 MP temperature was a result of setting the temperature for the thermocouple in the lower bar. There was some adjustment required of the thermocouple set point to achieve the correct 2 MP temperature. The adjustment procedure was straightforward and new setting held over the course of a day within about 2 degrees F. Some slight adjustment was required when the machine was restarted the next day. Once process variables were selected for the machine, the operator was responsible for a number of tasks to complete a weld. In sequence this included, 1) inputting the process parameters into the control panel, 2) positioning the first fabric panel so that it was aligned correctly with the welding bar (accomplished by alignment marks on the lower bar) and, 3) positioning the edge of the second fabric panel to ensure that the overlap width was correct (accomplished by marking the first panel with a line showing where the edge of the second panel needed to be positioned). After this was completed, the operator pressed a button and the welding process ran to the settings that were input.

Overall, the welding cycle time was very reproducible. A review of the heating time to reach the 2 MP temperature shows it varied by less than a minute. The weld cycle time was controlled. The cooling time increased with an increase in the 2 MP temperature. At a given 2 MP temperature, it varied by a maximum of 2.5 minutes. Over the entire 2 MP temperature range studied, it varied by 3.7 minutes.

Seam adhesion values varied with the 2 MP temperature. Lower 2 MP temperatures provided lower average adhesion values and lower dead-load durability. In general, seam appearance and quality was good when pulled in peel, pulling clean to the base fabric over the entire length and width of the seam. This was true for the entire experimental range.

5.2 RF Welding

For the RF welding work, all of the process variables were machine settings. Once process variables were selected for the machine, the operator was responsible for a number of tasks to complete a weld. In sequence this included, 1) inputting the process parameters into the control panel, 2) positioning the first fabric panel so that it was aligned correctly with the welding bar (accomplished by alignment marks on the lower bar), and, 3) positioning the edge of the second fabric panel to ensure that the overlap width was correct (accomplished by marking the first panel with a line showing where the edge of the second panel needed to be located). After this was completed, the operator pressed a button and the welding process ran to the settings that were input.

For the AC mode, all of the welding cycle times were very reproducible. The preseal, seal, and cool times are machine settings. The only variation is in the time to reach the amperage setting. This time varied by several seconds at most. For AC mode, seam adhesion values varied with seal amperage. The higher seam adhesion did not necessarily translate into better dead-load durability. In general, seam appearance and quality was good when pulled in peel, pulling clean to the base fabric over the entire length and width of the seam. This was true for the entire experimental range. For the EC mode, all conditions provided high seam adhesion and good seam appearance. Weld adhesion did not vary directly with either process variable. Weld adhesion did not correlate well with dead load durability with a number of samples failing by tear outside the weld area due to base fabric damage. Seam Shear testing should be incorporated into the quality assurance and process control plans to assure this is not an issue. In general, seam appearance and quality was good when pulled in peel, pulling clean to the base fabric over the length and width of the seam. There were a number of split welds noted, but these pulled clean to the side where they split.

5.3 Hot Bar Welding

For the hot bar welding work, the pressure was a machine setting and the dwell time was a machine setting. The bond-line temperature and the cooling temperature were not machine settings. For this experiment, thermocouples were placed in the bond-line in order to control using these parameters. While this can be measured on an experimental basis, it is not practical on a production basis. However, there did appear to be a good relationship between the temperature between the fabric and lower platen and the bond-line temperature on both heating and cooling. On heating, the bond-line temperature lagged the lower platen temperature by 8° F for the overlap seam and by 10° F for the double strap butt seam. On cooling, the bond-line temperature lagged the lower platen temperature by 7° F for the overlap seam and by 10° F for the double strap butt tape. These could be used as control parameters.

Once process variables were selected for the equipment, the operator responsibility was to set the process, place the fabric seam so that it was aligned correctly with the upper and lower bars. Note, the seam samples were prepped prior to introducing into the welding process by tacking the seam together. This was to enable us to incorporate the thermocouples into the seam to stay in-place as well as alignment of the yarns in the seam area. The seam was sandwiched between the bags and insulation and introduced into the welder. When the seam interface reached the desired temperature, the dwell time was started according to the experimental design. The dwell time was completed, the cooling started until the desired temperature was reached on cooled samples. Once the seam reached the target cooling temperature, the pressure was dropped and the seam removed from the welder.

Overall, the welding cycle time was not the most reproducible. The time to reach a 340^{o} F bond-line temperature during heat up varied by 5 minutes. The weld cycle time was controlled. The cooling time increased as the bond-line temperature on cooling decreased. For a given cooling temperature, the time varied by as much as 8 minutes.

For hot bar welding, all conditions provided high seam adhesion. Seam appearance and quality was good with welds, pulled in peel, pulling clean to the base fabric over the entire length and width of the weld for the entire experimental range.

5.4 Hot Air Welding

For the hot air welding work, air temperature and speed are machine settings. The pressure on the welding wheels and the delay on welding, neither of which was selected as a process variable, were also machine settings. The welding wheels are selected when the machine is set up. The nozzle position and the distance from the nip, height relative to the nip, and angle relative to the nip are operator adjusted items. In this case, the distance was adjusted using a ruler and the height and angle adjusted by eye. The nozzle location and orientation is verified with a test weld and adjusted as needed to obtain a uniform test weld. Once process variables are established for the machine, the operator responsibility was to verify the appropriate process parameters have been entered, install the correct welding wheels, and adjust the nozzle position. This being completed the fabric panels are pulled into the weld roller nip, the relative positions of the lower and upper panel edges are set using a manual guider along with manual alignment possible by marking the lower panel with a line showing where the edge of the upper panel needed to be positioned. After this is completed, the operator presses a foot switch, the welder nozzle is pushed into the nip area and, after a brief delay, the welding wheels turn to pull the fabric through the welding area at the preset speed. During the welding process, the operator manually adjusts the fabric into the guider to maintain seam width. When the welding is complete, the operator releases the foot switch and the hot air nozzle swings out of the weld area.

Overall, the welding cycle time for hot air welding is very reproducible depending directly on the speed setting.

For hot air welding, all conditions provided reasonable weld adhesion. It was, on average, lower than the weld adhesion that was obtained with the other welding methods. Weld appearance was good. Weld quality, however, was variable, with a number of seams splitting or separating at the compound interface over a portion of the weld width, rather than separating at the base fabric.

5.5 Seam Failure Review

An extensive study of all 576 dead load samples tested was conducted to understand the typical root cause of failures associated with the various methods of seam welding. The dead load samples reviewed were all exposed to the high temperature fuel (HTF) under increasing temperature and load conditions in the Dead Load Chamber. A failure classification convention was created which defines the results observed across all of the sample seams.

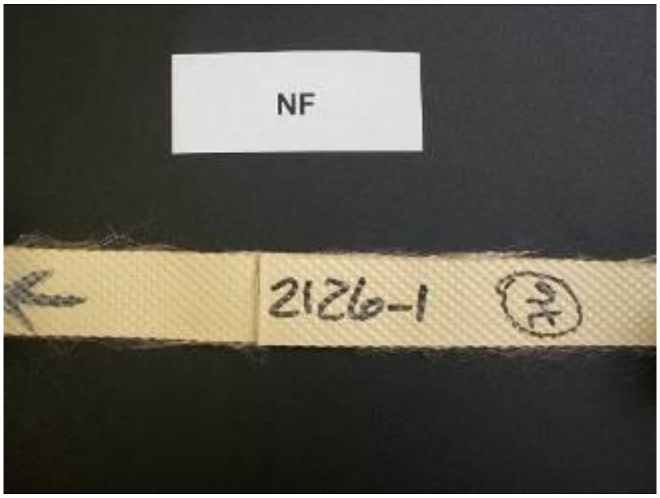
Seam failures were grouped in to 3 major classifications - 1) Seam Opened-Up, 2) Designated, and 3) Other Failures. These classifications were formed based on the common underlying root cause or the anticipated outcome of such a failure. The failure convention is defined generally in the following few paragraphs with specific details and photograph examples of each failure further on in this section. This is followed by a detailed discussion of the summarized data.

As the name suggests, the Seam Opened-Up category contained observed failures where separation between the two panels occurred. These included the Interply Separation Failure (IUS), Pull to Base (PTB), Split Weld (SW), Tore Inside Weld (TIW) and Yarns Bunched-Up (YBU) failure conditions. The Designated failure group was defined to cover those samples which made it to the end of the exposure period, but might lead to eventual catastrophic (e.g., seam rupture) or non-catastrophic (e.g., weeping, seeping or blistering) failures. Scrim Exposure (SE) and End Tab Lifts (ETL) were identified as the two Designated failure conditions. Other Failures included Tore Adjacent to Weld (TA), Tore Outside of Weld (TOW) and Yarns Stripped-Out of Seam (YSOS). TOW was included because it was an observed test outcome however it is not certain as to whether it is a condition that would occur in a collapsible fuel tank (CFT) or rather an artifact of the test method.

5.5.1 Failure Defintions

5.5.1.1 Non-Failure (NF)

NF - Non Failure – The test sample lasted to the end of the dead load exposure period, without a notable failure.

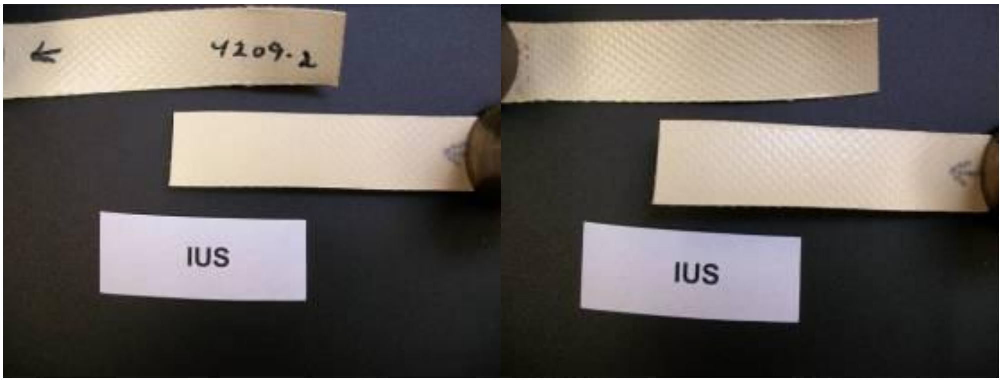


5.5.1.2 Seam Opened-Up Failures

This class of failures occurs when there is separation between the two inner urethane layers of the weld seam, either cleanly (IUS) or with associated material damage (PTB, SW, TIW or YBU).

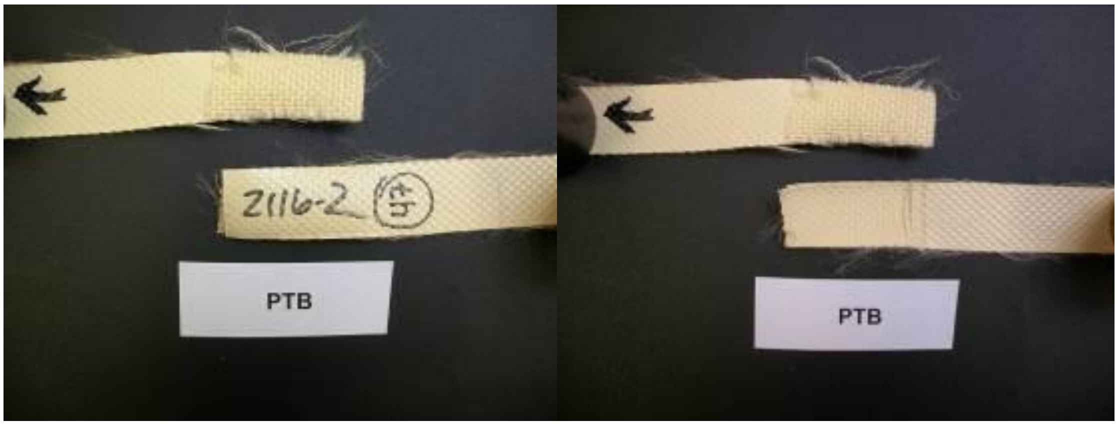
5.5.1.2.1 IUS – Interply Urethane Separation

IUS – Interply Urethane Separation – the separation occurred between the two inner urethane layers between the weld seam. In some cases, an inadequate "cold weld" possibly occurred.



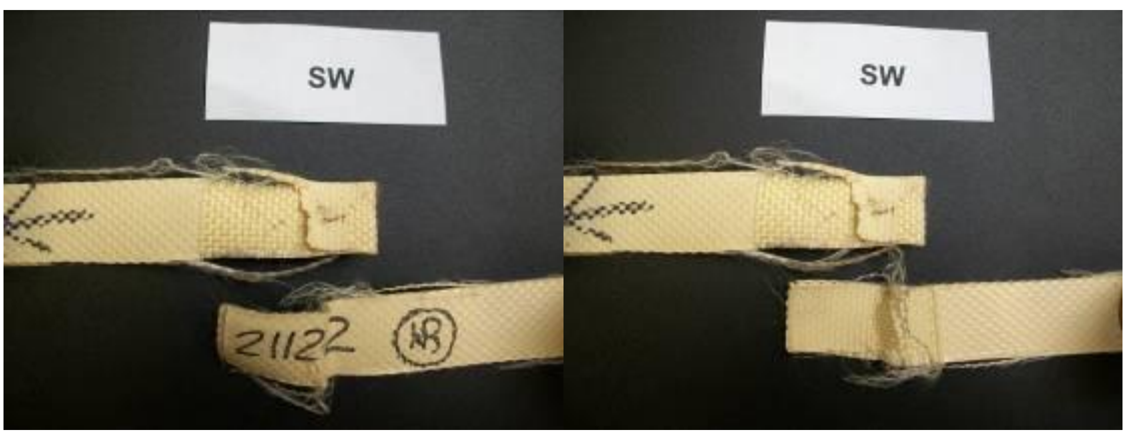
5.5.1.2.2 PTB – Pull to Base

PTB – Pull to Base – The urethane from one side of the weld was pulled away from the base fabric on the adjoining material.



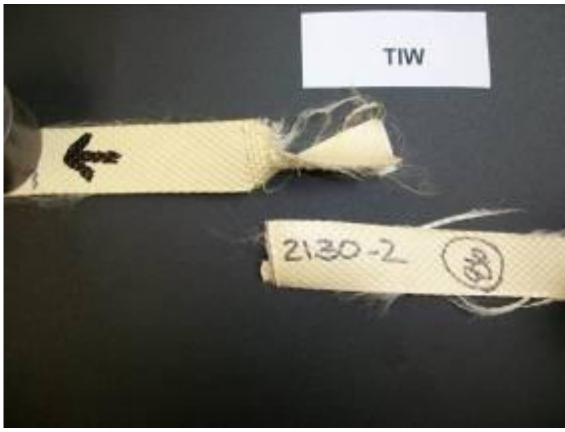
5.5.1.2.3 SW – Split Weld

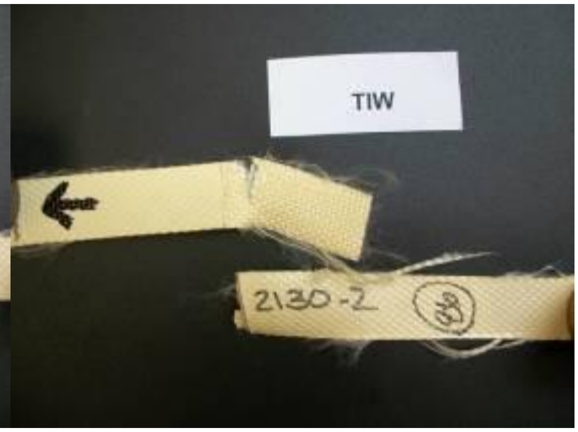
SW – Split Weld – a PTB occurs on both sides of the weld, with urethane weld "splitting" and being removed and adhering on both sides, in different areas.



5.5.1.2.4 TIW – Tore Inside Weld

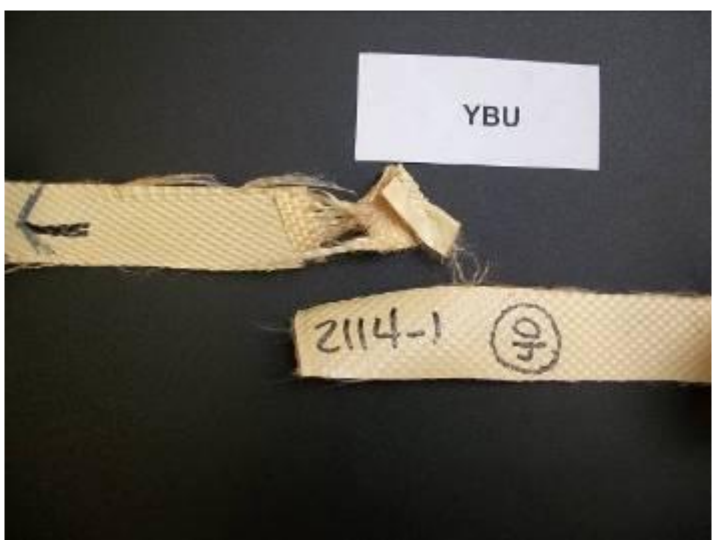
TIW – Tore Inside Weld – a tear occurred inside the weld area, typically parallel to the warp seam direction.





5.5.1.2.5 YBU – Yarns Bunched-Up

YBU – Yarns Bunched-Up – the urethane layer separates from one side of the weld, exposing the yarns. The load is then concentrated on the remaining attached area. The yarns will elongate causing bunching in the attached area and thinning of the yarns in the exposed area.



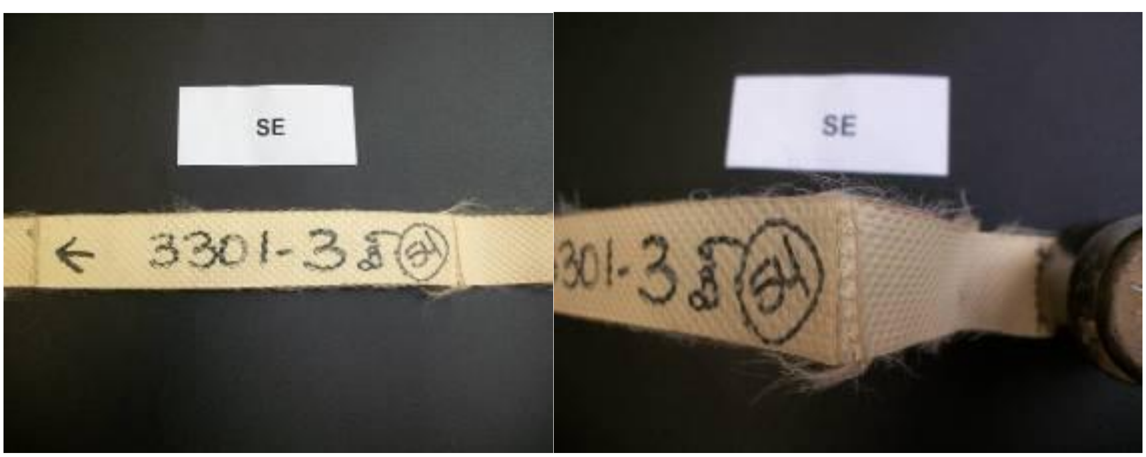
5.5.1.3 Designated Failures

5.5.1.3.1 ETL – End Tab Lift

ETL – End Tab Lift – the edge of the weld on one or both pieces, separates from the seam area from the edge, inward.

5.5.1.3.2 SE – Scrim Exposure

SE – Scrim Exposure – The scrim is exposed on the coated fabric adjacent to the weld not in the yarn area associated with the edge of the seam itself. This can create a potential leak path.



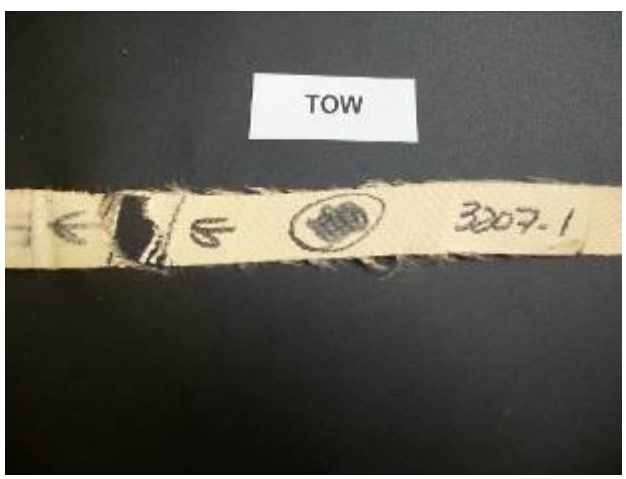
5.5.1.4 Other Failures

5.5.1.4.1 TA – Tore Adjacent to Weld

TA – Tore Adjecent to Weld – the material on one piece tears parallel to the edge of the welded seam. A complete TA is shown below.

5.5.1.4.2 TOW – Tore Outside Weld

TOW – Tore Outside Weld – the material on one piece tears, either partially or completely away from the weld area. It is directly related to testing and preparation.



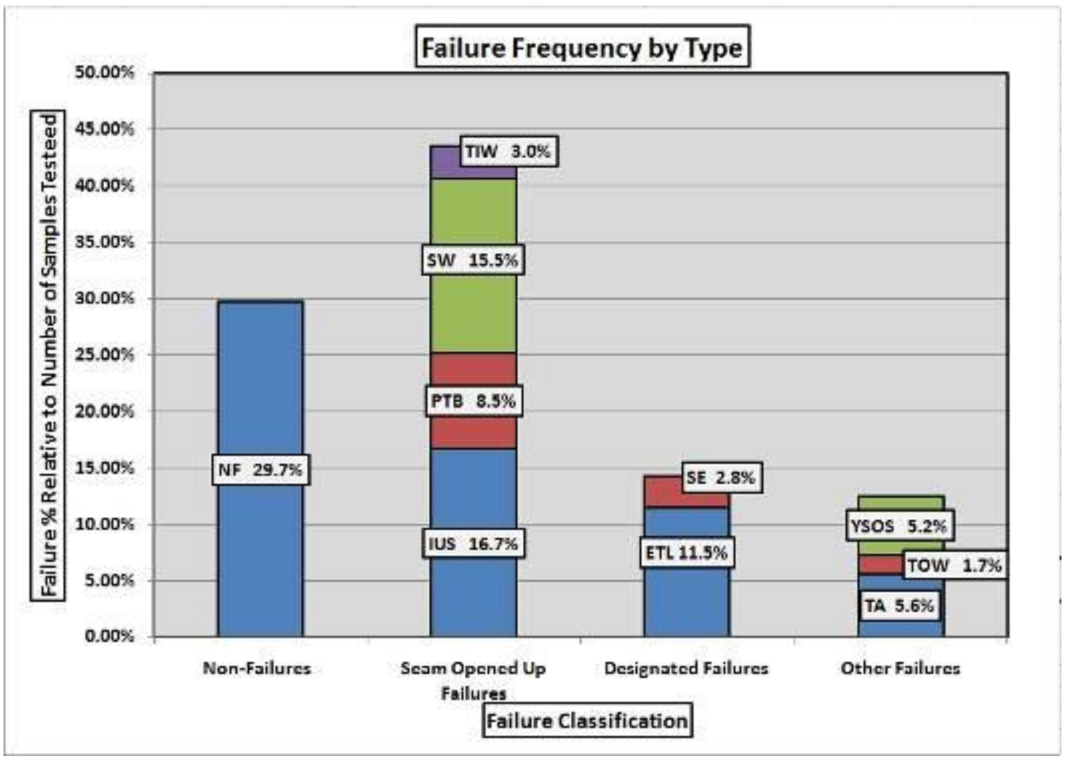
5.5.1.4.3 YSOS – Yarns Stripped-Out of Seam

YSOS – Yarns Stripped-Out of Seam – some or all of the yarns are completely or partially pulled out of the weld area.

5.5.2 Failure Data Summary Review

5.5.2.1 Failure Frequency

In analyzing the results, the three major failure classes were further qualified by their frequency of occurrence. This is illustrated in the graph below. It was possible for more than one failure mode to occur on a single sample. However the major failure mode was determined for each sample and utilized in the evaluation. For example, for trial # 2105-002, an RF welded sample, there was a significant Pull to Base (PTB) area (>90%), a tear designated by a Tore Inside the Weld (TIW) and also Yarns Stripped-Out of the Seam (YSOS). It was determined that the PTB was the predominant cause of the failure and possibly contributed to the other failures occurring. The total number of samples evaluated across the five welding methods tested was 576. The graph below illustrates the percentage of the failures, by each failure class (e.g., Seam Opened-Up) and failure type (e.g., PTB), out of the total number of samples tested (576).



It is evident from this graph that the Seam Opened-Up classification occurred most often (~ 45% of the total samples). The theory as to why this was so frequent is discussed in the next section. The seam opened up typically when separation occured between the two inner urethane layers of the weld. In the case of the IUS this happened cleanly with no visual damage to the urethane layers or yarns.

This is different from the other four types where material damage occurred. In the case of the Pull to Base (PTB), the welded urethane layer was pulled away from the yarns on one side of the weld. For a Split Weld (SW) it split and pulled to the base on each split or it split and partially pulled to the base with partial inter-ply urethane separation.

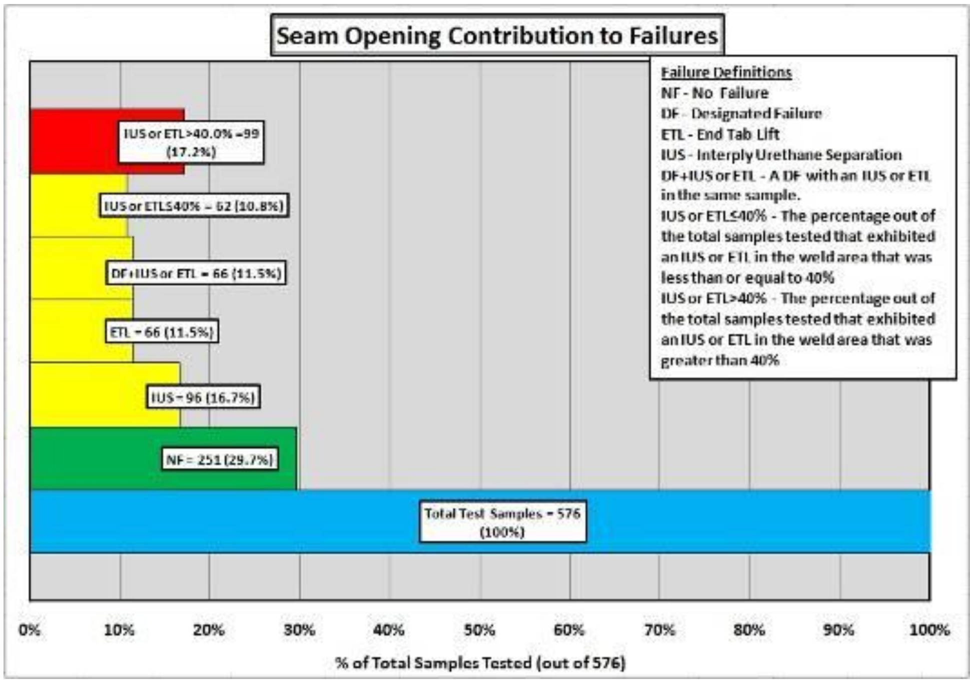
Sometimes when the seam separated, a tear in the weld area (TIW) occurred or the Yarns Bunch-Up (YBU) as the urethane covering those yarns was pulled away by the other side of the weld (see above). Note in this graph, the YBU failure doe not occur as the primary failure cause and therefore is not shown in the Seam Opened Up category. For all five types, the failure in a CFT would be considered catastrophic.

The Designated Failure classification (~14% of the total samples) covers two cases that typically completed exposure without failing the dead load test. These samples were reduced from a complete pass (99 days) to a designated failure condition (62 days) to reflect the potential that they could cause a leak, or eventually lead to a catastrophic failure. This rating was assigned to show that they were not the same as samples that survived the test with absolutely no issues. Since the dead load specimen did not completely separate, it was impossible to recognize these failures until they were removed from the dead load test chamber at the end of exposure.

The Other Failure classification (~12.5% of the total samples) covered the remaining three failure types. Although there is no direct evidence as to the root cause of these failures, it is believed that potential damage to the yarns during the welding process was a contributing factor. The three failure types, TA, TOW and YSOS, occurred more often in welding methods where Seam Opened Up failures are not as predominant.

5.5.2.3 Seam Opened-Up Failures

The Seam Opened-Up failures occurred more often than the other two failure classifications. It is believed that the underlying cause for this failure could be inconsistent welding or adhesion in the weld area. The impact of this partial weld can be seen in the Seam Opening Contribution to Failures graph below.



This graph focuses on failures which occur when no material damage is present. In the case of an IUS, the two pieces separate with no visible damage to the urethane coating on either side. For an ETL, the end tab has started to lift away from the weld area, again with no visual damage to the urethane on either piece. In the dead load test, the sample is cut from two panels that have been welded together. The sample is typically 1 inch in width, with the weld surface area covering 2 inches of panel overlap. Therefore, for a quality weld there should be urethane inter-ply adherence over the entire 2 inch square area.

When a load is applied to this sample, the stress seen in the weld is inversely proportional to the surface area, for a fixed load:

$$\sigma = F/A$$

where:

σ = stress
F = force or applied load
A = area of weld

If the area welded is less than that recommended or required, due to inadequate weld conditions or process control, the stress in the remaining weld area will increase accordingly. For example, if the actual surface area welded is approximately ½ the recommended area or 1 sq inch, the stress for a fixed load will double. If this area is approximately ⅛, the stress will be 8 times for the same fixed load.

This is clearly seen in the graph above. For a percentage of the cases, DF + IUS or ETL (~12%), a test sample successfully passed the dead load test even though the weld was not over the complete recommended weld area (i.e., 2 sq inches). In addition, the number of samples which had an IUS or ETL ≤40% which was ~11% of all of the samples tested. The majority of these samples successfully completed the exposure period. They were assigned a Designated Failure condition due to the occurrence of the inter-ply separation. In the field, this could lead to a tank with a potential weld seam issue. The mechanism through which this separation occurs is not currently known. One possibility is that the weld partially consists of only soft segment entanglement that is solvated when the material swells with fuel, thereby creating the separation phenomena. This is an area for potential future study.

In general, the weld area threshold necessary for reaching the end of the dead load exposure appeared to be approximately 60% or greater. There were very few samples (1 or 2 out of 576) that had an IUS or ETL >40% that completed the dead load exposure period. The majority of the IUS or ETL ≤40%, on the other hand, did reach the end of the exposure period, and were labeled Designated Failures.

This increased stress within the weld area is also believed to create the other, more material destructive (PTB, SW, TIW and YBU) failures, as a function of actual weld area and geometry. An inadequate weld can take many forms, not only having less weld area but also covering non-uniform areas within the weld, leading to areas of greater stress concentration based on voids within the weld area. Further study would be needed to understand the fundamental mechanism behind these individual failures.

It bears repeating that the loads used in the dead load testing are significantly higher than the loads that a tank would be exposed to, as defined by the FEA. Collapsible Fuel Tanks are typically designed with a 2.5 safety factor over the peak stress. An inconsistent weld created by voids during fabrication or separation that occurs in use, could possibly still achieve the required life specification for a CFT.

5.5.3 Failure Trends Observed in Different Fabrication Methods

5.5.3.1 Inside-Out Heating – Hot Air and Hot Wedge

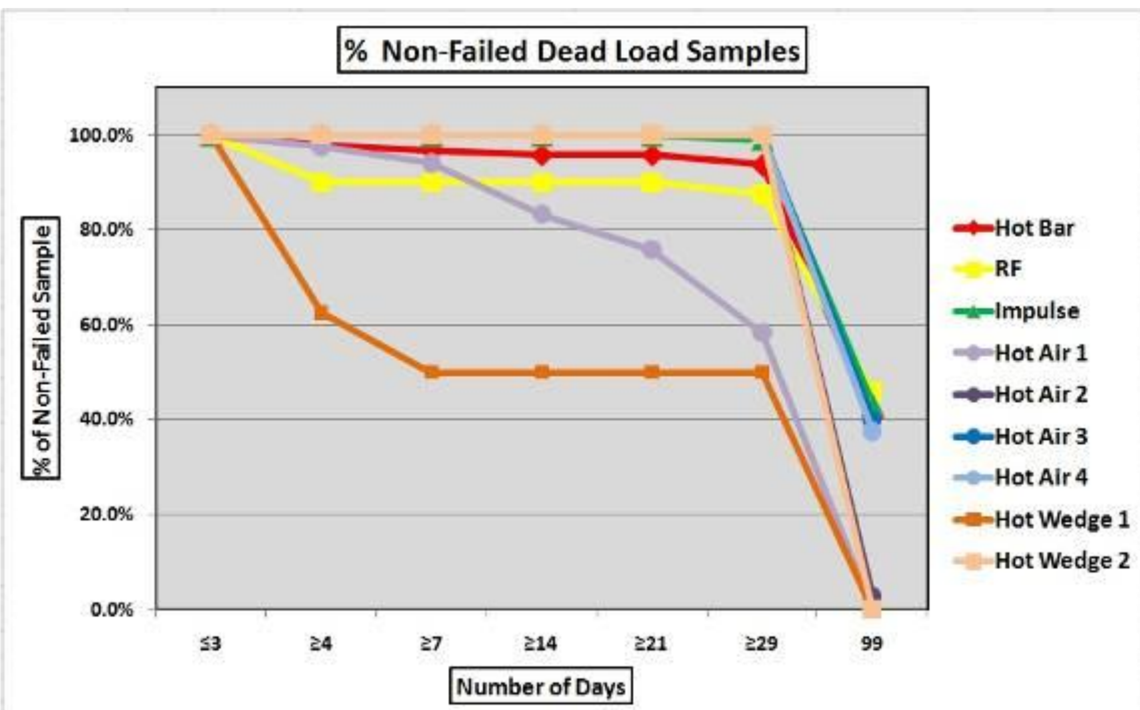
For samples fabricated with Hot Air and Hot Wedge methods, the Seam Opened-Up class of failures predominated. This included IUS, PTB, TIW, SW and also ETL failures. These methods count on supplying an internal heat source, i.e., a hot air nozzle or hot wedge, between the two plies of material to be welded. If for any reason the heat source is inadequate or non-uniform, voids and separation between urethane layers can occur. The tighter the process control parameters, the greater the probability of delivering a successful weld.

5.5.3.2 Outside-In Heating – Impulse and RF, Hot Bar

These methods rely on energy transfer from an external source to the internal urethane to urethane interface to create a weld. For Impulse and RF, Seam Opened-Up failures were noticeably minimal when compared to the Hot Air and Hot Wedge methods. The more frequent failures with this method were TA, TOW, SE and YSOS, failures which occurred around the periphery or outside of the weld area. This might suggest, in some instances that the weld area might actually be more prone to over-heating, leading to localized urethane thinning, increased urethane weld flow and possible yarn damage.

5.5.4 Failure Predictability

A plot of the % Non-Failed Dead Load Samples as a function of number of days of exposure is shown below. It illustrates, with a couple of exceptions, that the majority of the samples that passed at 4 days typically made it to 29 days. Samples that survived 29 days, referencing the test protocol used in this study, would have met the 3 year service requirement (i.e., Load = 2.5x maximum in-plane stress for a full 50,000 gallon CFT at a service temperature of 158° F). The exceptions mentioned included a Hot Air and a Hot Wedge run where the fabrication process was not yet optimized. The RF samples had some initial failures attributed to over welding of the sample. Once the process control parameters were optimized, the Hot Air and Hot Wedge runs became quite repeatable, as is evident in the data.



5.6 Summary

The following is a summary of the results of the seam method experiments:

1) For the discrete welding methods, notably for impulse and hot bar welding, operating at bond-line temperatures of 340° F provides seams with excellent dead-load durability. This corresponds to the melting transition for amorphous phase of the coating compound. This was demonstrated in both the hot bar and the impulse welding experiments. It was not possible to obtain bond-line temperature readings for the RF sealing work. However, for the RF welding work, the seam durability varied with the power applied (AC mode), which should relate to the temperature that the compound reaches.

   At lower bond-line temperatures, the seams show more weld lift, cold weld separations and split weld failures.

   At long dwell times at 340° F or at higher bond-line temperatures, seams show more failures that are related to damage of the fabric or coating compound (tears, weld strips, and scrim exposures on static loading).

2) For the continuous welding method studied, rotary hot air welding, measurement of the bond-line temperatures to determine if the same correlation applied was not possible. In general, lowering the speed of the welding, at any temperature reviewed in this study, provided the best dead-load durability. It is expected that lowering the speed, increases the fabric surface temperature.

3) For the design spaces analyzed for this study, the discrete welding methods provided durable welds over good portions of the design space investigated giving broad ranges of acceptable processing conditions. For hot air welding, the peak dead-load durability of welds was less than those achieved by the discrete methods. Hot air welding provided the maximum dead-load durability over narrow ranges of each design space investigated and showed considerable interdependence of process variables. For example, a change in a hot air temperature or nozzle location required readjustment of the welding speed to obtain reasonable weld results. The samples initially fabricated for Seaman Corporation (HAW 1 and 2), based on welding parameters from tank fabricators, had far too broad a range. Tests of samples provided directly by fabricators (HAW 3 and 4), using hot air welding were obtained and tested. These samples do not provide a range of process variables, but are representative of current process settings and control. The results of these tests are presented in Sections 5.5 and 5.6.

4) The discrete processes, hot bar, RF and impulse welding, showed less operator dependence and required less adjustment on set up to obtain acceptable welds than did the hot air welding. For hot air welding, nozzle position, and nozzle alignment had a significant influence on whether the weld pulled clean to the base fabric on initial testing or whether it split or pulled cold on one edge or another. All of the methods are capable of producing welds that will meet the service life requirements of the contract. None of the welding methods investigated have limits that preclude their use. There is no reason why discrete welders with tools that are shorter than the entire seam can't be used to make the required length seam by overlapping. Other seam methods may be required for other areas of the tank design (e.g., closing seams, might not lend themselves to the same type of seaming methods that are used for the main panel seams because of limited access, fabric bulk, etc.), irrespective of the method used for the bulk of the tank.

5) The analysis of the sample failures, exposed to HTF under increasing temperature and load, clearly illustrated the critical importance of tight process control and quality assurance in the fabrication of the CFTs. Incomplete and excessive welding conditions were contributing factors to welds which proved to be inadequate. Incomplete welding predominated in Inside-Out processes, such as Hot Air and Hot Wedge, as was witnessed by the large number of Seam Opened-up type failures. Excessive welding occurred with greater frequency with Outside-In processes such as Impluse and RF, with failures occuring more often in the yarns or around the periphery of the weld.

   The three main classes of failures observed were 1) Seam Opened-Up, 2) Designated , and 3) Other Failures. ETL, although a Designated failure, should also be considered a type of IUS, most probably in its initial stage. Urethane separation based failures all typically occurred within the weld area. The only exception appeared to be Scrim Exposure (SE), which typically occurred adjacent to the weld area. The failures which occurred typically outside of the weld area, e.g, the Other Catatrophic class, appeared to be a yarn, testing discrepancy or combination yarn and urethane. This was exhibited by the tendency for these failures to be tears (TA or TOW) or breakage of yarn (YSOS), usually initiating near the edge of a welded seam. It is critical that seam shear be run due to TA and YSOS because of excessive heating causes damage to the weld area.

   The fact that some of the samples, where IUS or ETL was present up to 40%, without failure, is of some concern. Therefore, it is considered critical that both seam peel adhesion be run on samples to verify appropriate process control.

In all cases, the CFT fabricator should consider all of the contributing factors that would effect fabrication (e.g., cost, quality, reproducibility, equipment, available space, staff training) before deciding on which method best meets their operational needs and the military's requirments. Based on the data summarized here, all of the methods require process control procedures to insure seam performance. The critical factor appears to be the ability to maintain tight process control and the to fine tune all of the factors associated with optimizing the process.

6) A summary table of the welding methods and the associated failure modes recorded during this testing is shown below. When reviewing the information in this table it is important to remember the following critical points:

a) For some methods (e.g., RF), the equipment utilized was new and there were not recommeded settings available for the material. A lot of time was spent in "dialing in" the equipment to find the best operational range and settings. This could be further optimized if transferring to a production environment.

b) For other methods (e.g., Hot Wedge), initial welding parameters were based on the fabricators experience with similar materials. This lead to many early failures. Once these parameters were optimized for the Seaman 1940 PTFF MS-337 polyurethane, the weld samples were much more robust.

c) The primary modes of failure were due to either polyurethne separation caused by inadequate welding (e.g., IUS) or weld tearing and exposure of the yarns created by excessive energy in the weld (e.g., TA).

Welding Method	Application	Weld Energy	% Non-Failures	Failure Type			Failure Trends	Comments
				Seam Opened Up	Designated	Other		
Hot Bar	Discrete	Outside In (OI)	41.7%	50.0%	2.1%	6.3%	Seam Opened Up (separation failures) ~ 50/50 split between IUS and tear related failures (PTB, SW, TIW)	· Hot bar fabricator had not previously worked with polyurethane material · Preliminary work done jointly with Seaman Corporation to develop process variable ranges
Radio Frequency	Discrete	OI	45.0%	25.0%	0.0%	30.0%	Separation Failures and weld periphery failures (TA) occurred ~25 and 30% each	· Seaman "learning curve" on use of RF welder - AC mode of operation preferred · Separation failures suggest inadequate welding dwell time · TA failures suggest damage around periphery of weld in underlying yarn
Impulse	Discrete	OI	46.7%	7.5%	20.8%	25.0%	Separation Failures minimal, SE greater than 50% of Designated Failures, YSOS major Other Failure noted	· Predominance of both YSOS and SE failures suggest damage around periphery of weld in underlying yarn · Samples that were fabricated at 405 °F 2 MP temperature most probably failed by tear
Hot Air 1	Continuous	Inside Out (IO)	0.0%	96.7%	3.3%	0.0%	Majority of Designated Failure were ETL - separation based	· Broad initial process parameter range lead to multiple early failures · Inadequate temperature control (under or overheating) suspected cause
Hot Air 2	Continuous	IO	2.8%	58.3%	38.9%	0.0%	Majority of Designated Failure were ETL - separation based	· Inadequate temperature control (under or overheating) suspected cause
Hot Air 3	Continuous	IO	40.0%	6.7%	53.3%	0.0%	Majority of Designated Failure were ETLs - completed exposure period for dead load but were derated due to presence of ETL at post exposure inspection - separation based	Majority of samples (93%) completed dead load exposure period, successfully
Hot Air 4	Continuous	IO	33.3%	4.2%	62.5%	0.0%	Majority of Designated Failure were ETLs - completed exposure period for dead load but were derated due to presence of ETL at post exposure inspection - separation based	Majority of samples (96%) completed dead load exposure period, successfully
Hot Wedge 1	Continuous	IO	0.0%	100.0%	0.0%	0.0%	None of the initial samples completed dead load exposure (longest 59 days). Indication that weld parameters were not correctly optimized for material	· Initial weld parameters based on fabricators experience with different material
Hot Wedge 2	Continuous	IO	0.0%	0.0%	100.0%	0.0%	All of Designated Failure were ETLs - completed exposure period for dead load but were derated due to presence of ETL at post exposure inspection - separation based	· Consistent performance occurred when weld parameters were optimized for material

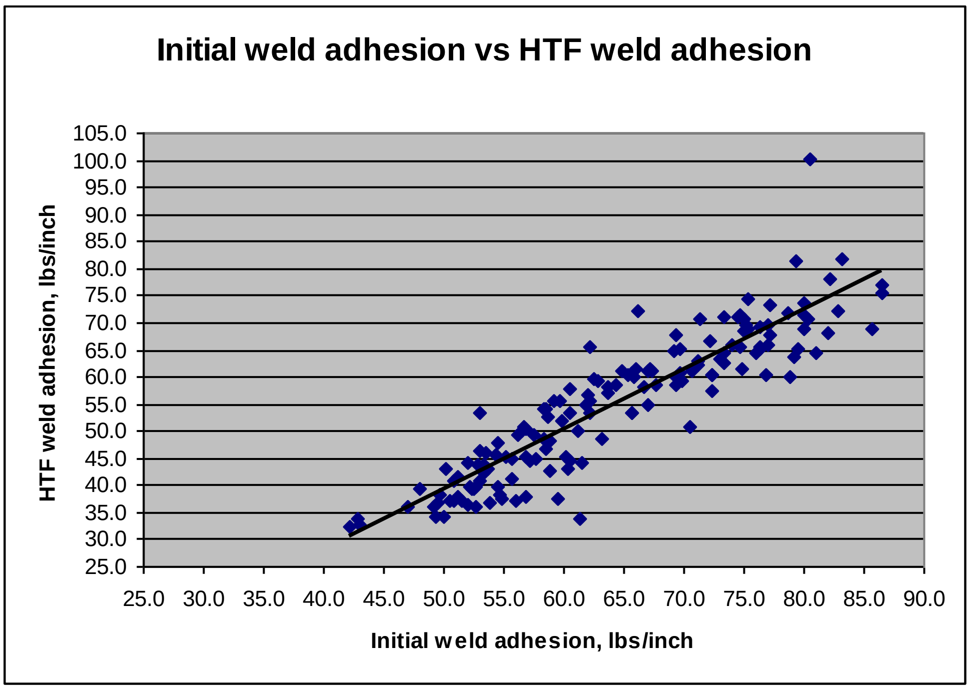
6.0 Process Control

There are a number of items that are common to all welding processes that need to be part of the process control plan. These items are:

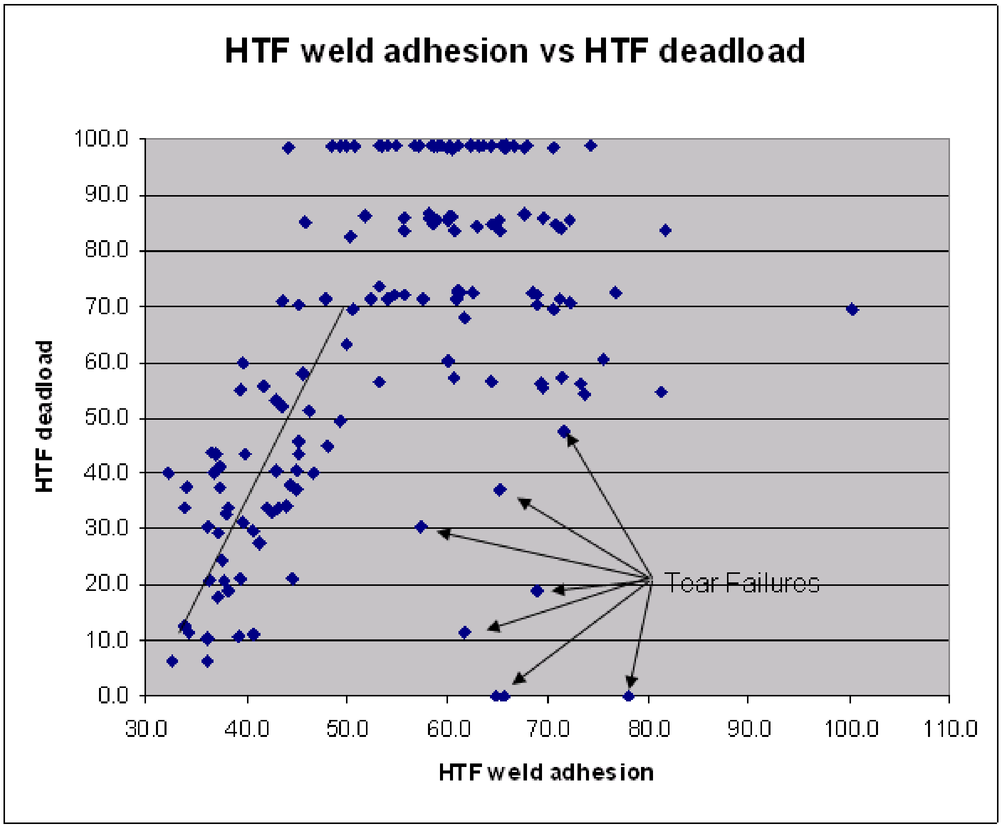
1) The weld adhesion should reach a minimum value that has proven to give acceptable results.

   A review of the initial weld adhesion data, the HTF weld immersion and the HTF dead-load results across all of the studies shows the following:

   Initial weld adhesion and weld adhesion after HTF immersion have a linear relationship.



The relationship between HTF weld adhesion and HTF dead-load performance is shown below.



While not as clean as the relationship between HTF adhesion and initial adhesion, the data shows a steep increase in dead-load performance with an increase in seam adhesion as it goes from 30 to approximately 45 lbs_f/in. Beyond the 45 lbs_f/in. levels, the dead-load performance is relatively flat, except for a few points where poor dead-load performance was seen with high seam adhesion. For these points, the failure mode is generally tear rather than seam separation, indicating the fabric had been damaged during the welding process.

As noted in previous discussions, a 29 day dead-load duration corresponds to a 3 year service life. A linear fit of the HTF adhesion data and the HTF dead-load data between 30 and 50 lbs_f/in. shows that a 29 day dead-load value can be obtained at a HTF seam adhesion of 39 lbs_f/in. However, a much safer seam adhesion value would be at about 45 lbs_f/in.

A 45 lbs_f/in. HTF seam adhesion translates into a 55 lbs_f/in. initial seam adhesion. Based on these results, a 55 lbs_f/in. initial seam adhesion should be considered as the target.

2) The seam when pulled in shear should break in the base fabric at a force that is no less than 90% of the base fabric strength as an indication that the base fabric has not been damaged.

3) The seam, when pulled in peel, should separate at the base fabric. This should have the lowest bond strength. If a seam does not pull to the base cloth across the entire width of the seam area and along the entire length of the seam, it indicates that the seam is not uniform and there is an issue with the set up of the equipment. In this study, split seams, especially those that pulled to the compound interface, showed to perform poorer than welds that pulled uniformly to the base cloth.

4) At a minimum, the process parameters used in the DOE studies should be monitored and controlled to within ranges that provide acceptable dead-load durability.

5) Cycle times for the various portions of the welding process should be monitored for changes that would be indicative of a change in equipment performance. This might translate into results that are different than were obtained in the studies.

6) Set up, start-up, operating and process control procedures should be developed for each of the welding processes. Process control procedures need to detail the control parameters, the tolerances for the parameters, the measurement system that will be used, testing and sampling that will be performed, sampling frequency, control methods, and reaction plans.

The process control plans that would be developed for a manufacturing operation will be dependent on the equipment that the manufacturer is using. All impulse welders, hot bar welders, hot air welders, and RF sealers are not the same. However, as a guide, typical process control plans are provided on the following pages for the equipment and configurations that we used for the study.

6.1 Process Control Plan

Process	Process step	Machine, device, tool	*Characteristics* Product	Process	*Methods* Product or Process spec/tolerance	Evaluation method	Sample size	Sample frequency	Control method	Reaction Plan
Panel	Panel Weld	Impulse		Dwell time, minutes	2 +2.25/ - 0	Machine display	1	1 x/ shift	Control Sheet	Manual adjustment
				Platen Temp F - Heat	394	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Platen Temp F - Cool	120	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				2 MP Temp, F	398 +/- 3	Trial	1	1x/day	X bar - R chart	Adjust platen temp /retest
				Pressure, psi	30 +15, -0	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Coolant Temp	120 F	Machine display	1	2 x/shift	Control Sheet	Manual adjustment
				Heat up time, minutes	1.0 +/- 0.5 minutes	Machine log	1	2 x/shift	X bar - R chart	Adjust PID platen
				Cooling time, minutes	3.0 - to 7.0 minutes	Machine log	1	2 x/shift	X bar - R chart	Maintenance
				Bondline temp, F	340 +0/- 5	Trial	1	weekly	X bar - R chart	Reset 2 MP target/retest
			Weld Width		2" min	Ruler	1	each panel	X bar - R chart	Check/correct markings
			Weld Adhesion		55 lbs/inch min	ASTM D751	test weld	2 x/ shift	X bar - R chart	Run Hold - notify QC
			Weld consistency		clean to base	Visual	test weld	2 x/ shift	Visual to std	Run Hold. Check platen alignment, check tool , run test weld
			Weld Aesthetics		no defect	Visual	1	each panel	Visual to std	Check contact surfaces for damage, Maintenance

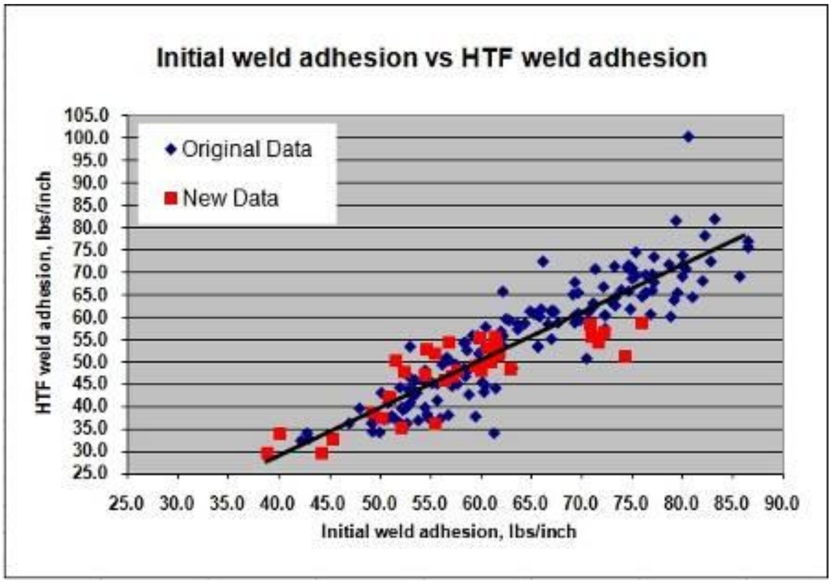
Process	Process step	Machine, device, tool	Characteristics		Methods					Reaction Plan
			Product	Process	Product or Process spec/tolerance	Evaluation method	Sample size	Sample frequency	Control method	
Panel	Panel Weld	RF, 2 x 33		Seal time, seconds	6, +1/-0.5	Machine display	1	1 x/ shift	Control Sheet	Manual adjustment
				Pressure, bar	4.5	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Amps	1.63 to 1.95	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Preseal time, seconds	3	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Cooling time, seconds	15	Trial	1	1 x/shift	X bar - R chart	Manual adjustment
				Air Coolant temp, F	80 F	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Overall cycle time, seconds	24 to 28	Machine log	1	1 x/shift	X bar - R chart	Maintenance
			Weld Width		2" min	Ruler	1	each panel	X bar - R chart	Check/correct markings
			Weld Adhesion		55 lbs/inch min	ASTM D751	test weld	2 x/ shift	X bar - R chart	Run Hold - notify QC
			Weld consistency		clean to base	Visual	test weld	2 x/ shift	Visual to std	Run Hold. Check platen alignment, check tool , run test weld
			Weld Aesthetics		no defect	Visual	1	each panel	Visual to std	Check contact surfaces for damage, Maintenance

Process	Process step	Machine, device, tool	Characteristics		Methods					Reaction Plan
			Product	Process	Product or Process spec/tolerance	Evaluation method	Sample size	Sample frequency	Control method	
Panel	Panel Weld	T 500		Speed, ft/min	4 to 4.5	Machine display	1	1 x/ shift	Control Sheet	Manual adjustment
		2" 100A wheel		Pressure, psi	80	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
		1 7/8" tip		Air Temp, F	850	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
		2" Guider		Nozzle position, inches	0.5	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Delay	3	Trial	1	1 x/shift	Control Sheet	Manual adjustment
			Weld Width		2" min	Ruler	1	each panel	X bar - R chart	Check/correct markings
			Weld Adhesion		55 lbs/inch min	ASTM D751	test weld	2 x/ shift	X bar - R chart	Run Hold - notify QC
			Weld consistency		clean to base	Visual	test weld	2 x/ shift	Visual to std	Run Hold. Check tip position, check weld wheels for damage of buildup, run test weld
			Weld Aesthetics		no defect	Visual	1	each panel	Visual to std	Check weld wheels for damage, Maintenance

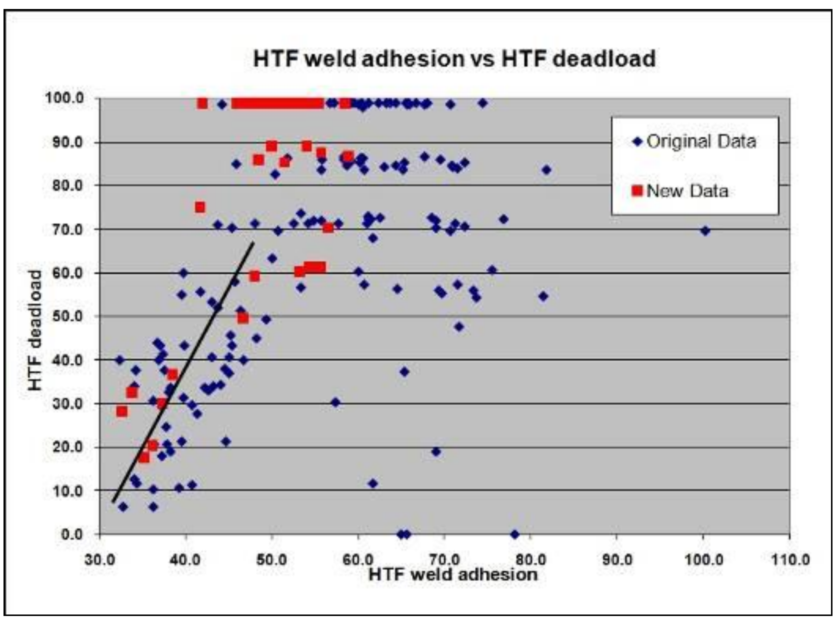
Process	Process step	Machine, device, tool	Characteristics: Product	Characteristics: Process	Methods: Product or Process spec/tolerance	Methods: Evaluation method	Methods: Sample size	Methods: Sample frequency	Methods: Control method	Reaction Plan
Panel	Panel Weld	Hot bar		Dwell time, minutes	1	Machine display	1	1 x/ shift	Control Sheet	Manual adjustment
				Bar temp, F	350	Machine display				
				Platen fabric interface temp F – Heat	348	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Platen fabric interface temp F – Cool	340	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Pressure, psi	30	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
				Coolant Air Temp	NA	Machine display	1	2 x/shift	Control Sheet	Manual adjustment
				Heat up time, minutes	17.5 +/- 2.5 minutes	Machine log	1	2 x/shift	X bar - R chart	Adjust PID platen
				Cooling time, minutes	0	Machine log	1	2 x/shift	X bar - R chart	Maintenance
				Bondline temp, F	340 +0/- 5	Trial	1	weekly	X bar - R chart	Reset 2 MP target/retest
			Weld Width		2" min	Ruler	1	each panel	X bar - R chart	Check/correct markings
			Weld Adhesion		55 lbs/inch min	ASTM D751	test weld	2 x/ shift	X bar - R chart	Run Hold - notify QC
			Weld consistency		clean to base	Visual	test weld	2 x/ shift	Visual to std	Run Hold. Check pressure, check contact surfaces for damage, run test weld
			Weld Aesthetics		no defect	Visual	1	each panel	Visual to std	

6.2 Additional Testing - Process Control

With the addition of the data from the Run 5 testing, there was little change in the process control relationships. The initial weld adhesion and weld adhesion after HTF immersion relationship remained linear and the additional test points fell within the scatter of the original plot. The resultant recommended initial seam adhesion of 55 lbs_f/in. still corresponds well through the linear curve fit to a HTF weld adhesion of 45 lbs_f/in.



In the relationship between the HTF weld adhesion and the deadload, there was a slight increase in the dead-load performance with an associated increase in seam adhesion, as it went from 30 to 45 lbs_f/in. Beyond the 45 lbs_f/in. levels, the dead-load performance was once again relatively flat, which was consistent with the earlier results.



7.0 Quality Control

7.1 Raw Materials

The coated fabric to be used for the tank must have been certified by the fabric manufacturer to meet the fabric requirements of the fuel tank specification and any fabricator specific quality requirements.

Prior to using the fabric to produce a fuel tank, the coated fabric should be pre-qualified by the fabricator. The material should not be stored outside. It is recommended that the material be stored inside, out of direct sunlight, at ambient temperatures (70ºF), at a humidity below 65%. High humidity and UV exposure may affect the weldability of the material, especially if the environmental conditions exceed the recommended limits (verify material suitability through standard such as ASTM D638). To qualify the material, take a sample from the lot of material to be fabricated and prepare welds on the tank welding equipment. The weld conditions should duplicate the conditions that will be used in fabricating the tank. In the event the welding equipment, personnel, environmental conditions, equipment operation, etc. changes, requalification must be performed.

Wiping of the seam area with a cleaning solvent to remove any contaminants, such as oil, dirt, and grease just prior to the welding process is recommended. This ensures that there are no contaminants present to inhibit the molecular bonding of the coating compound. One must allow adequate time for the solvent to flash off the seam area prior to manufacture to avoid having the solvent cause issues during the welding process. The solvent(s) used should only be those recommended by the material supplier. In addition, the material supplier should also provide the appropriate procedures and conditions for use of the solvents (e.g., contact time, environmental condition restrictions, required drying time, etc).

7.2 General Testing

Historically, fuel tank seam have been evaluated by weld adhesion and some form of dead-load testing. The tests to evaluate the seam performance for this report, and for production set-up and operation, were based on the requirements as outlined in MIL-PRF-32233. Adhesion of coating to fabric, known as peel adhesion, was added to the test parameters to determine if there is a correlation to the weld adhesion. The use of ASTM International Standard ASTM D751 Standard Test Methods for Coated Fabrics was deemed appropriate for use in determining the strength of the seam and peel adhesion. The adhesion was performed along the length of the seam. The peel adhesion was pulled in the warp direction. Fuel immersions on the seams were performed to ASTM D471

Standard Test Methods for Rubber Property-Effect of Liquids. One specimen each (peel and seam adhesion) was attached separately to the deadload test fixture. The use of glass beads for separation was not applicable. The apparatus used for exposure is given in detail in Appendix D. JP-8 conforming to Mil-T-83133F was used as the testing medium. These standards are recognized test methods in the coated fabric industry. Upon review of the data, test specimens, and manufacturing processes, these methods were found to be adequate in the evaluation of the samples.

Care must be taken in preparation of the dead-load seam specimens. The load bearing characteristics are dependent on the yarns in the seam area. The seamed areas on the tanks are viewed as a continuation of the coated fabric. Load calculations are based on the tenacity of an inch of yarn. Since dead-load specimens are taken perpendicular to the seam, it is important to follow the yarns across the seam to give certainty that a full one inch of yarn is attained. The inability to test one inch of yarn can cause the load bearing characteristics to be lower by concentrating the load over a smaller area of reinforcement.

7.3 Set Up

Set up should include the following:

The welding should be set using process parameters required for the specific process.
Several warm-up and test welds are to be made prior to starting into production. This would include at the start of each day and any time the machine sits idle for a period of time, to insure that the welding equipment is at steady state.

Seam adhesion and seam appearance are used to validate the set up. To properly evaluate the adhesion of the seam, the seam area must be cooled thoroughly. This is done by allowing the seam area to cool in air to room temperature. Once cooled, it must be pulled at a constant rate of extension on a tensile strength tester the entire length of the seam. It was noted that the seam would pull down to the base cloth at the start of the adhesion then in some cases go into an inter-ply separation further into the seam. The adhesion is to pull down to the base cloth the entire length and width of the seam. Failure to do so is an indication of a poorly welded seam. The seam shall represent the width and length of the material being welded. It is not recommended to evaluate the adhesion pulling perpendicular to the seam as the entire seam integrity will not be evaluated.

Note: To further verify the seam's integrity, a seam shear test should be performed (ATPD-2266). The seam shear test will indicate any damage that has occurred to the reinforcement due to the welding process. Excessive heating and/or pressure on the seam area potentially might damage the reinforcement causing premature breakage adjacent to the seam. The seam shear strength should coincide with the tensile strength of the material. The seam shear test would catch any excessive damage or degradation to the fiber. This is assuming correct sample preparation and the variability associated with the test method (~90%).

7.4 Manufacturing

The process control plan should be used to guide the manufacturing of the tanks (previous section).

All data and documentation shall be maintained on the testing performed on the samples. Sample identification, date, time, operator, equipment identification, operating parameters to name a few, should be documented with the test data. The results shall be maintained to cover the length of exposure of the tank according to contractual and/or specification language. This will enable the manufacturer to evaluate the results in the event of a field failure.

8.0 Model Tank

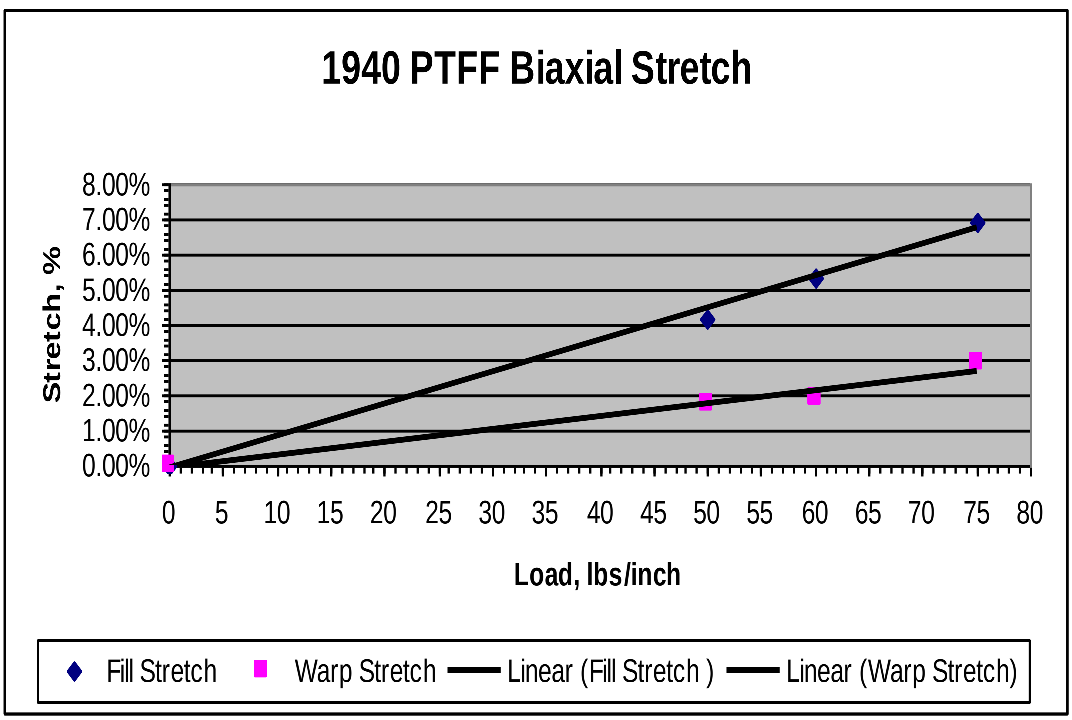
A model tank was manufactured by Seaman Corporation. The tank was approximately the same size as a 3,000 gallon fuel tank. The tank was filled in a stepwise fashion with water to various fill levels to determine if it was possible to duplicate the stresses seen in larger tanks. The work performed is detailed below.

8.1 Preparation

The fabric used for the tank was Seaman Corporations 1940 PTFF from the lot that had been set aside for the study. The biaxial stretch characteristics of the fabric were determined per the biaxial stretch test outlined in Appendix Z with the exception that the load was run from 50 to 75 lbs_f/inch, the load range that would be seen at the maximum in-plane stress for large fuel tanks, and the duration of the test at each load was increased from 2 to 48 hours minimum to be sure the fabric reached equilibrium. The data is presented in the table below:

Load, lbs_f/inch	Warp Stretch, %	Fill Stretch, %
0	0	0
50	1.73	4.16
60	1.90	5.37
75	2.94	6.93

The data is presented graphically below:



8.2 Tank Manufacturing

The tank was designed to use half widths of the standard 68 in. fabric in order to have a tank with more seams than would normally be seen in a 3000 gallon tank. The panels used for the tank were cut and marked on a Computer Aided Design driven cutting table. In addition to markings for seam overlap and fitting locations, the panels were marked with grids that could be used to measure the stretch once the tank was filled. Twenty 10 in. x 10 in. squares, in various locations on the tank, were selected for stretch measurement and one 3 in. x 6 in. rectangle. Additional stretch measurements were taken at all of the squares along one side of the tank (A to D).

The tank was manufactured in the following manner:

1) Eleven tank panels were cut and marked. The panels were welded together using a 2 in. overlap seam on the Fiab RF welder. The panels were shingled. Other methods can be used for model tank fabrication. RF was readily available to Seaman Corporation for this scale model tank. There are current commercial fuel tank manufacturers that are producing large scale fuel tanks that are using RF welding for multiple seams on each tank. The RF is being used to produce both overlap and butt seams.

2) The edges of the seams were capped with a 1 in. wide, 30 mil urethane tape on all exposed edges using a hot air welder with tape dispenser.

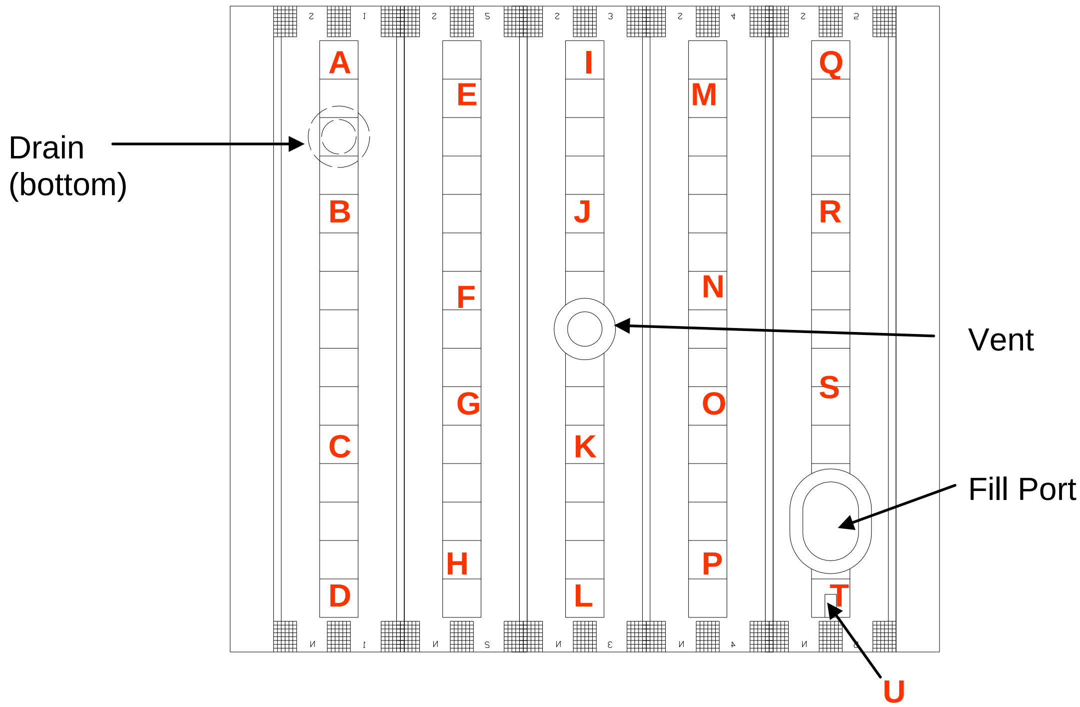
3) The ends of the panel were welded together to make a large tube.

4) Overlap seams were made to close the tube on both ends into a pillow. The end seams were not cap stripped with tape.

5) Diagonal seams were run across each corner by welding the inside surfaces of the tank together. The corner seams were mechanically clamped.

6) The fittings were attached.

A sketch of the tank is shown below showing the fill, drain, and vent ports along with the location of the squares for stretch measurement:



After the tank was manufactured it was air tested and leaks were fixed. The tank was inflated with compressed air. The seams and fixtures were checked using a soapy water solution. Air leaks were present on two of the four corners. It is believed that these corner leaks were caused by a thinning of the polyurethane during welding. The leaks were repaired with 1940 polyurethane patches and seam tape applied with a hot air gun. A berm area was prepared for the fill test to be performed. Skids were placed on the floor of the berm and covered with a ground cloth to elevate the tank above the floor level so that a drain line could be run out of the bottom of the tank. In addition to the drain line, the tank was equipped with a fill line, water meter, and a vent line.

A photograph of this is shown below:

The tank was initially filled with water to 2500 gallons. Water was chosen instead of JP-8 since the intention of this test was to check the effect of over-filling the tank. The tank was inspected for leaks and silicone was applied on the filler-discharge bulk head assembly at three bolt-hole locations. The tank was then filled with water at 300 gallon increments, stopping after each fill to, 1) check for leaks, 2) allow the tank to equilibrate to the surrounding environment for two days, and, 3) measure stretch in the panels. At 3000 gallons, additional leaks were noted at the filler-discharge bolts. They were re-tightened and Loctite Superflex Red High Temp RTV (59630) was applied and successfully sealed the leaks. A minor end closing seam leak (weep) was also detected and repaired with a polyurethane adhesive, "Gorilla Glue". For each 300 gallon fill, stretch measurements were taken at all 21 locations and the height of the tank was measured. The incremental fills continued until the volume of water added reached 4500 gallons. All of the data generated on the model tank is presented in Appendix Z1 and Appendix Z2.

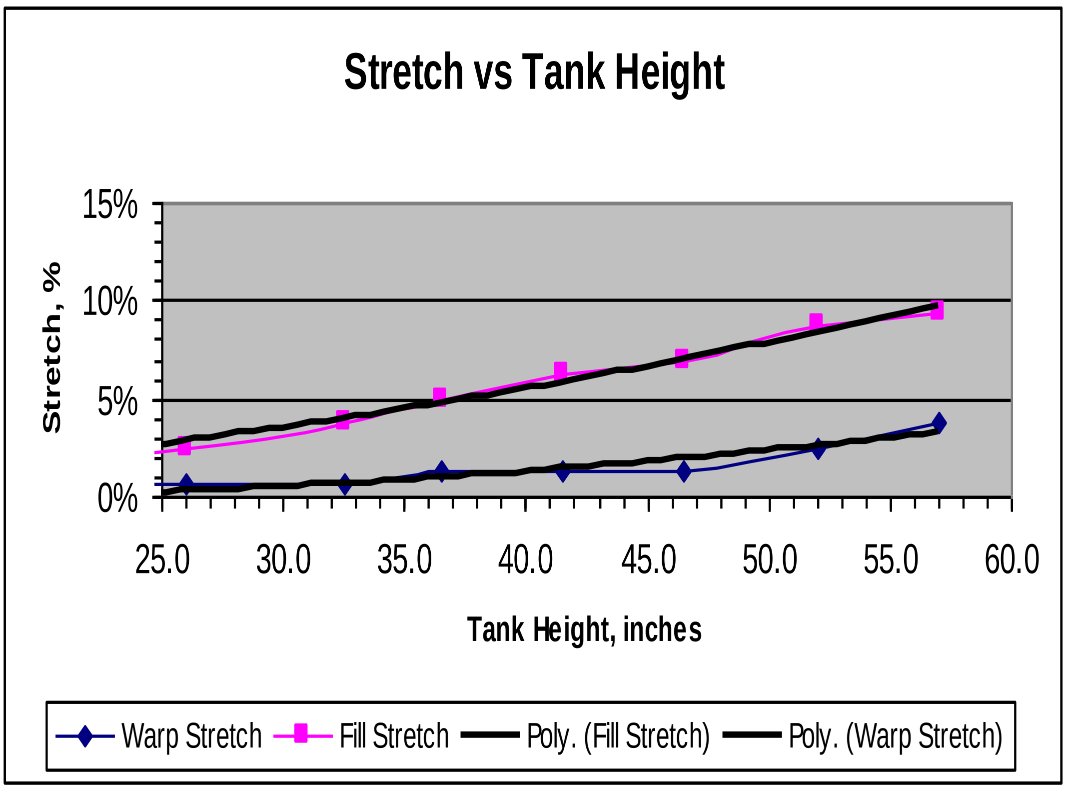
8.3 Tank 1 Analysis

As mentioned previously, the tank was constructed using ½ width panels in order to have more seams in the tank. The largest stretch readings always occurred near the top center of the tank. This was expected based on the stress concentration diagrams provided in the SwRI report on a 50,000 gallon fuel tank.

The table provides data on the tank height and peak stretch for the water fill level:

Volume, gallons	Height, inches	Peak warp stretch, %	Peak fill stretch, %
2500	26.0	0.63	2.50
3000	32.5	0.63	3.75
3300	36.5	1.25	5.00
3600	41.5	1.25	6.25
3900	46.5	1.25	6.88
4200	52.0	2.50	8.75
4500	57.0	3.75	9.38

The data is presented graphically below, along with a polynomial fit:



Photographs of the tank at various stages are below:

TANK 1 AT 3300, 3900, 4200, 4500 GALLON FILLS (Clockwise from upper left)

Looking at the biaxial stretch and the fill stretch data, one would expect that a 50 lb_f/inch load is achieved at a warp stretch of 1.73% and a fill stretch of 4.16% using the least squares fit of the data (the polynomial fit at a 50 lb_f /inch load was 1.93% for the warp and 4.40% for the fill).

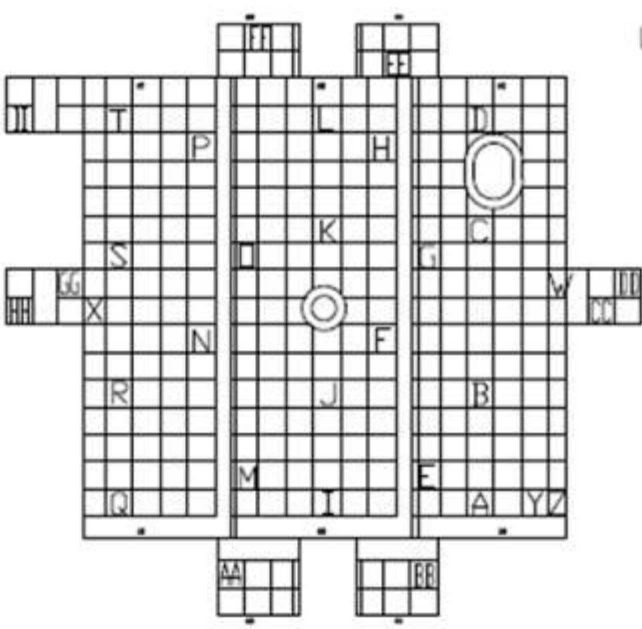
A review of the data on tank height vs. stretch shows that the 50 lb_f /inch load is reached in the fill at a height of 33.3 inches. It is interesting that the stretch in the warp direction that corresponds to the same load is not reached until a tank height of 49.8 inches is obtained. After review of the peak stretch data, it was thought that the warp stretch data from the tank was biased by the fact that there are 2 in. overlap seams at 34 in. on center that act as reinforcing webbing, constraining the warp stretch. This was checked subsequently with a 68 in. panel width tank, to look at the effect of seam webbing on warp stretch. The results of this comparison are located in the next section). The fill height of 33.3 inches corresponds roughly to a fill volume of about 3200 gallons. Considering the specific gravity difference between JP-8 and water, this roughly results in an over-fill, on a weight basis of 32%, assuming a JP-8 specific gravity of 0.81.

8.4 Tank 1 – Tank 2 Comparison

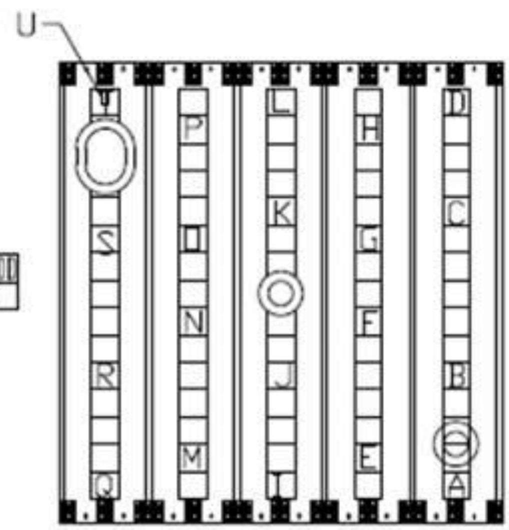
8.4.1 Tank 2 Design and Test

The original tank (Tank 1) was made with 34 inch panels, to maximize the warp seam length and increase the probability of introducing a failure. After the data from the Tank 1 testing was reviewed, it was decided to run a second test consisting of a tank made with 68 inch panels (Tank 2). This was done to verify that there would be no appreciable difference in the maximum stresses seen in the tank when over-filled.

In an effort to allow for a direct comparison between the two tanks, 10 inch stretch measurement squares were inscribed on Tank 2 analogous to what was originally measured on Tank 1 (see below, lettered A – T). The vent fitting was used as a central reference common between both tanks. A few key differences in the two tanks should also be noted. The fill and drain fittings were located on opposite corners in Tank 2. Also, since Tank 2 was fabricated with 68 inch panels, many of the 10 inch stretch measurement squares were adjacent to warp seams, rather than in the middle of the panel (e.g., P and F).



Tank 2



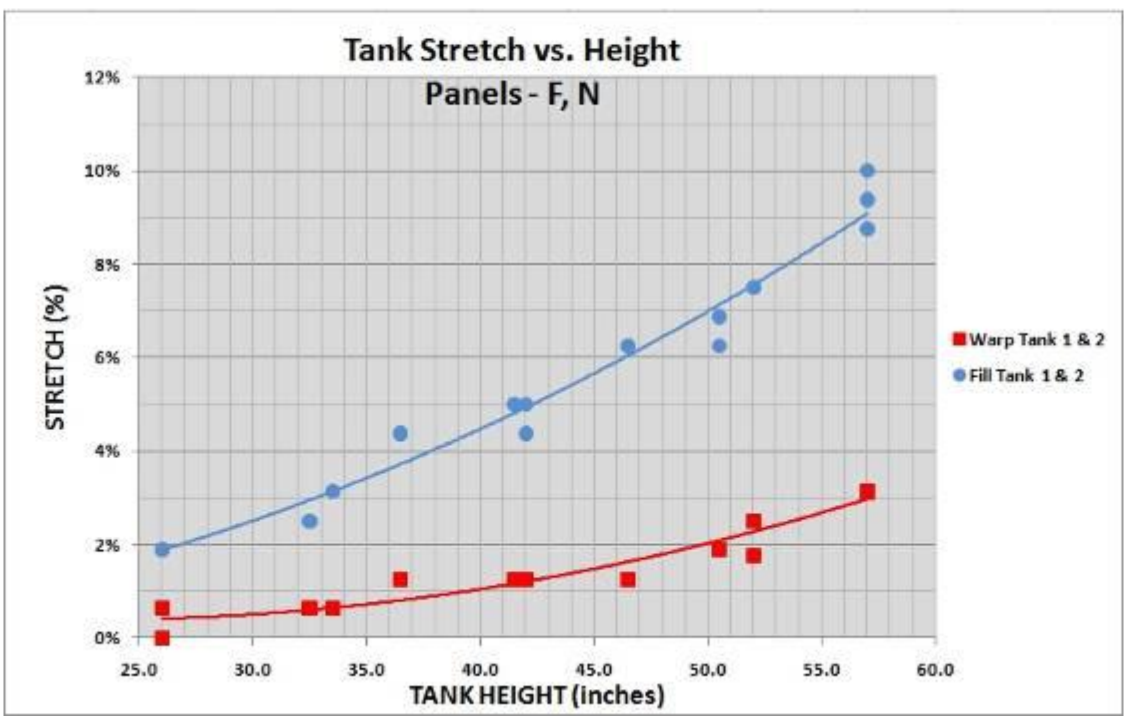
Tank 1

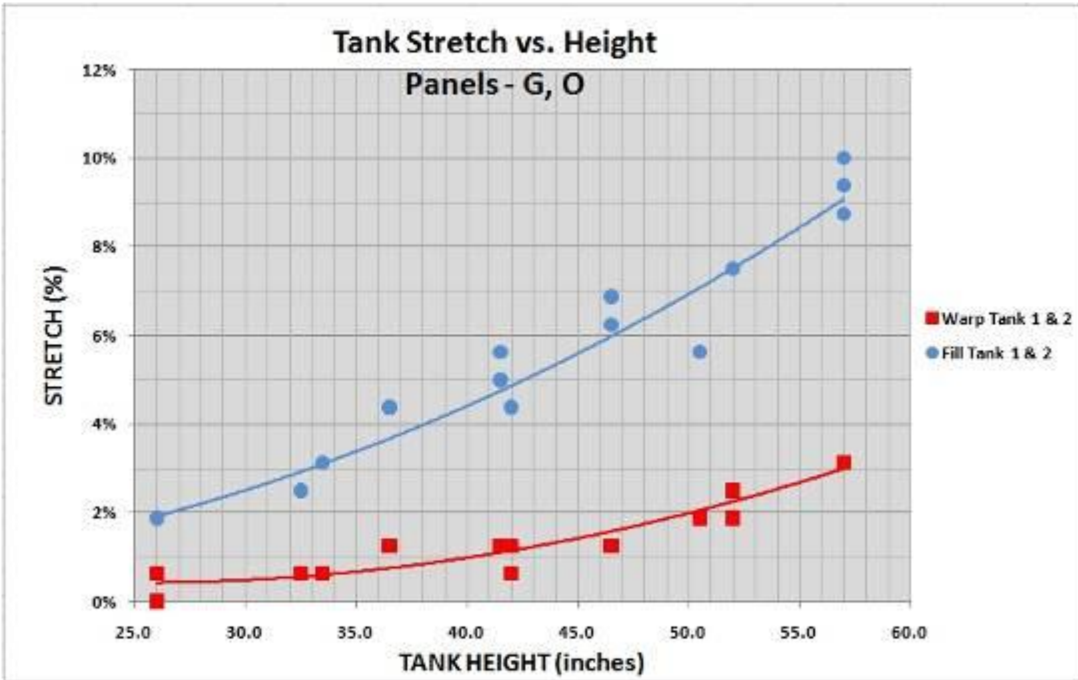
8.4.2 Test Results

The data for tank 2 is provided in Appendix Z2. A review of the data from the two tanks showed the following:

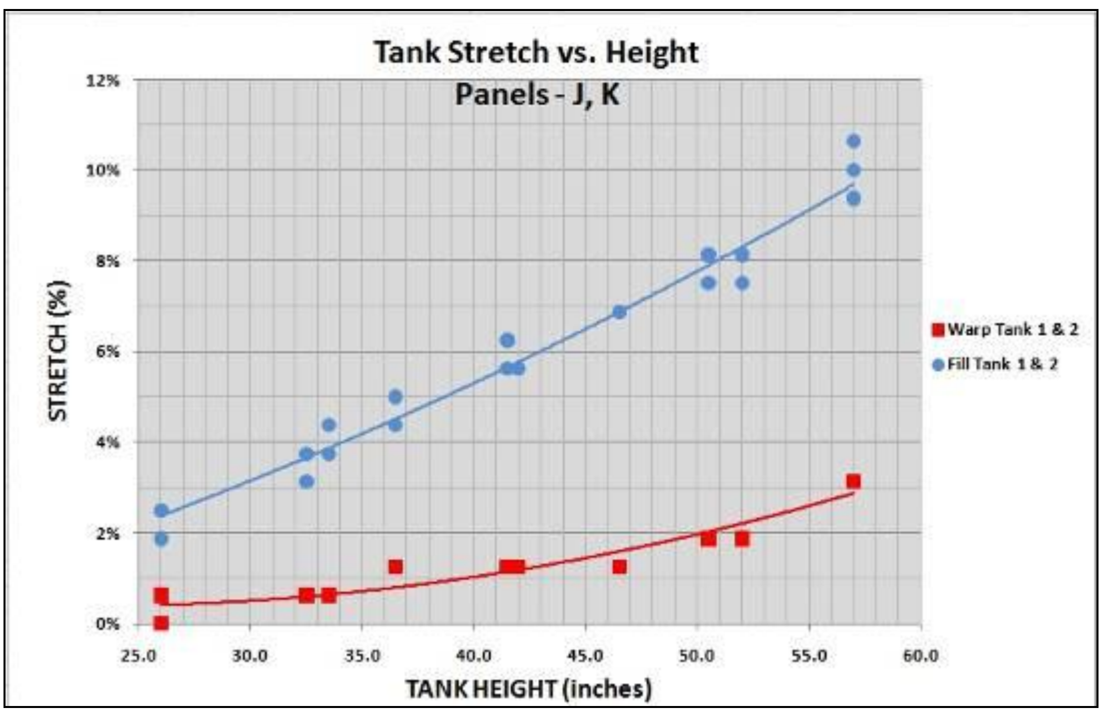
1) The stretch observed as a function of tank height, does not differ significantly between Tank 1 and Tank 2, even when over-filling to 4500 gallons. This is especially true in the top, central area of the tank, where the FEA indicates maximum stresses would be expected. Four 10 inch measurement squares were compared, F and N, and G and O, because of their close proximity to the top, center of the tank as well as their location along the diagonal axes. A location on the diagonal axes was chosen since theoretically the stress in both the warp and fill directions should be similar. Two additional squares, J and K, were chosen since they were in the direct center of both tanks, in the center warp panel.

After graphing the data, a second order polynomial curve fit was done to check the repeatability of the data between the various locations. As can be seen, in both the warp and the fill direction, the stretch measured is practically a mirror image when comparing the graphs of the four diagonal axis based squares (i.e., F, N, G, and O).





When compared to the central warp seam panel containing J and K to the diagonal squares, a slight increase in the fill stretch was noted (i.e., within 0.5%) at both the top and bottom of the curve. This is expected since the location of J and K is on the overall central warp axis of the tank and therefore should be nearest the location of peak stretch.



When comparing the peak stress location between Tank 1 and Tank 2, the % fill stretch is typically within 0.5%. There was minimal variance in warp stretch between the two tanks.

2) The warp stretch does not appear to concentrate in any great degree along the top of the tank. The warp stretch at the top of the tank in most cases is the same irrespective of position. The only place where this is not the case is along the edges of the tank where the fill stretch is very low and crimp interchange is playing a role in the stretch values. The loads in the warp direction are carried by the warp yarn, not by a homogeneous shell and contrary to the FEA model, appear to be distributed evenly in the warp direction.

The fill stretch does seem to concentrate. The fill yarn is not continuous in fill direction. At each seam, there is a break in the yarn and an opportunity for stresses to build. This is indeed what is seen in the data. The stretch in the fill varies by position in a way that is consistent with the FEA.

3) The stress in the fill direction does appear to concentrate and represents the maximum stresses that will be present in the tank. The stretch in the fill direction should be used as the basis for comparison of loads.

8.5 Conclusion

The stresses that are seen in large tanks can be approximated by controlled overfilling of smaller tanks. The comparison between Tank 1 and Tank 2 successfully demonstrated that there was little difference in the measured stretch as a function of tank height. This is further illustrated by the close correlation between fill volume and tank height for both tanks. Hence, the previous conclusion that the stresses seen in large tanks can be approximated by controlled overfilling of smaller tanks still appears to be valid.

9.0 Testing Program Summary

9.1 FEA Analysis

A review of the FEA analysis on the fuel tank confirmed loads that are seen on the 50,000 gallon fuel tanks and provided information to set-up the dead-load testing program. Industry experts that have done work on both 50K and 210K tanks indicated that the stresses seen in the 50K tank are consistent with those seen in the 210K tank.

The FEA on the two different seam types showed a reduction of stresses in the tank fabric as it enters the seam area. There is a slight effect at the edge of the seams, causing a small peel force; however, this force was extremely small when compared to the peel adhesion strength of the material.

9.2 Welding Equipment Evaluation

Seams prepared by various welding methods were tested for survival time under static load at elevated temperatures while immersed in fuel. A time-temperature-stress superposition technique was used to establish a relationship between the number of days a seam survived under test conditions vs. the expected actual service days at use conditions. The testing showed that seams that lasted 29 days under test conditions would last 3 years at actual service conditions.

It was demonstrated that any of the four different types of welding equipment could be used to manufacture a successful seam, as defined as being able to withstand the high temperature fuel dead-load test for the time corresponding to a three year service life. No matter what the welding process was, the ability to get the urethane coated fabric to a high enough temperature was the key to a successful weld. Production considerations such as the speed of fabrication and the associated cost of each method are not included in this report. Also, the results did not take into consideration the ability to make a fuel tight seam with any of the welding systems; the focus was on seam integrity as defined by HTF dead-loads.

One finding of note is that is that dead load samples exposed to high temperature fuel that did not fail by 4 days, typically lasted until 29 days. This applies to those samples that were fabricated with known, controlled process parameters. The current specification of 70 hours might not be an adequate predictor of success in the field (MIL-PRF-32233, section 4.5.2.8). A limit of 96 hours with a constant dead load tension force equivalent to a 2.5 safety factor in JP-8 at 160 °F should increase the probability of success in the field.

9.3 Model Tank

It was demonstrated that two model tanks could be constructed and over-filled with water such that the material/seams were exposed to the peak stresses seen on a 50,000 gallon tank. This allows us to further study the different welding techniques and tank designs using a small scale model tank. Studying model tanks is the best way to determine the ability of a welding method to minimize or eliminate seam leaks. This work will be continued in the FY2009 Improved Polyurethane Fuel Tank study.