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FINAL REPORT

Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery

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Executive Summary

The "Development of High Pressure Hydrogen Storage Tanks for Storage and Gaseous Truck Delivery" project [DE-FG36-08GO18062] was initiated on 01 July 2008. Hexagon Lincoln (then Lincoln Composites) received grant funding from the U.S. Department of Energy to support the design and development of an improved bulk hauling and storage solution for hydrogen in terms of cost, safety, weight and volumetric efficiency. The development of this capability required parallel development and qualification of large all-composites pressure vessels, a custom ISO container to transport and store said tanks, and performance of trade studies to identify optimal operating pressure for the system.

Qualification of the 250 bar TITAN® module was completed in 2009 with supervision from the American Bureau of Shipping [ABS], and the equipment has been used internationally for bulk transportation of fuel gases since 2010. Phase 1 of the project was successfully completed in 2012 with the issuance of USDOT SP 14951, the special permit authorizing the manufacture, marking, sale and use of TITAN® Mobile Pipeline® equipment in the United States.

The introduction of tube trailers with light weight composite tankage has meant that 2 to 3 times as much gaseous fuel can be transported with each trip. This increased hauling efficiency offers dramatically reduced operating costs and has enabled a profitable business model for over-the-road compressed natural gas delivery. The economic drivers of this business opportunity vary from country to country and region to region, but in many places gas distribution companies have realized profitable operations.

Additional testing was performed in 2015 to characterize hydrogen-specific operating protocols for use of TITAN® systems in CHG service at 250 bar. This program demonstrated that existing compression and decompression methodologies can efficiently and safely fill and unload lightweight bulk hauling systems.

Hexagon Lincoln and U.S. DOE agreed to continue into Phase 2 of the project without pursuing the development of higher pressure capabilities as originally planned. At 250 bar, development of equipment for hydrogen transport is supported by strong activity in the adjacent natural gas transportation sector. Trade studies performed since 2011 indicate optimization of hauling efficiency and system cost for hydrogen transport at about 350 bar (5076 psi). However, due to reduced efficiency of compression of natural gas above 250 bar, 350 bar operation is not an attractive option for natural gas transportation. The CHG market is not developed at this time, and it is difficult to forecast the arrival of significant revenues.

On the investment side, the cost to fully qualify a large tank module at 350 bar is estimated at $3MM to $5MM. There is insufficient CHG market definition to support a stand-alone business case for this investment without near term revenue in the adjacent CNG transportation market. Therefore development of a 350 bar TITAN® system was deferred and not pursued under this project. Hexagon Lincoln continues to support the development of tankage and equipment for operation at 350 bar and above; with 700 bar vehicle tanks and 950 bar tanks for ground storage applications.

Phase 2 activities were focused on reducing system cost, increasing system capacity, increasing system safety and characterization of polymer material performance specific to hydrogen pressure vessel usage. With the successful launch of TITAN® modules and trailers in natural gas transportation, over 600 units have been produced through the end of 2016, resulting in improved purchasing power for raw materials and manufactured components. This has allowed Hexagon Lincoln to approach the current project goals for system cost. At $590/kg of compressed hydrogen delivered, the system cost of the baseline TITAN® module is below the project's 2015 target of $730/kg H2 delivered, and very close to the project's 2020 target of $575/kg H2 delivered. [Based on product pricing in 1Q2017.]

Emphasis was placed on configuration of larger capacity systems within the vehicle weights and dimensions allowed on federal and state highways in the United States and other countries. These activities resulted in the design and development of integrated tube trailer systems that have increased delivery capacities by 45%. The hydrogen delivery capacity of our largest system is 845 kg, exceeding the project's 2015 target of 700 kg H2 delivered. Emerging technologies offering improvement of the safety systems used on the equipment were investigated, with particular focus on improving the reliability and cost of the emergency venting system for fire protection. Finally, investment in our materials laboratory improved detection and characterization of hydrogen-induced damage in polymer materials, supporting the development of operational protocols to avoid damage to pressure vessel liners and valve components.

Performance versus Goals

Overall Objective

The objective of the project was to design and develop the most effective bulk hauling and storage solution for hydrogen in terms of cost, safety, weight, and volumetric efficiency. This was accomplished by developing and manufacturing a tank and corresponding ISO container to be used for the 250 bar storage of hydrogen in stationary and transportation applications.

The most significant commercial objective of the project was accomplished in 2012 with the issuance of USDOT SP 14951, the special permit authorizing the manufacture, marking, sale and use of TITAN® Mobile Pipeline® equipment in the United States. The introduction of tube trailers with light weight composite tankage has meant that 2 to 3 times as much gaseous fuel can be transported with each trip. This increased hauling efficiency offers dramatically reduced operating costs and has enabled a profitable business model for over-the-road compressed natural gas delivery. With the successful launch of TITAN® modules and trailers in natural gas transportation, over 600 units have been fielded internationally through the end of 2016, with about half operating in the United States.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery Program Roadmap.

- E. Gaseous Hydrogen Storage and Tube Trailer Delivery Costs
- I. Other Fueling Site/Terminal Operations

Technical Targets

The technical targets of DE-FG36-08GO18062 are listed in Table 1. The first phase of this project has focused primarily on the design and qualification of a 250 bar pressure vessel and ISO frame system to yield a combined storage capacity solution of approximately 34,000 liters of water. As discussed previously, this was completed in 2012 with the issuance of USDOT SP 14951. The original plan for a second phase of this project was to increase working pressure of the baseline large tank system to 350 bar and perhaps higher. However the high costs of prototyping and validation testing of such large vessels cannot be offset by a market case for higher pressure operation in the foreseeable future. This business case for investment in such higher pressure systems is not supported by the adjacent natural gas transportation industry. Natural gas becomes progressively harder to compress at pressures higher than 250 bar, hence there is no demand for CNG equipment operating at 350 bar. Together with DOE, it was agreed that project scope be changed to work towards increasing available volume at the baseline 250 bar working pressure by optimizing packaging and integration of systems.

Table 1. Achievement in Meeting Technical Targets for Hydrogen Storage

Goal	Units	2015 Target	2020 Target	Status	Comments
Storage Costs	$/kg	$730/kg	$575/kg	$590/kg	2016 acquisition cost of TITAN® module Operation at 95% delivery efficiency
Delivery Pressure	bar	400 bar [5801 psi]	520 bar [7542 psi]	250 bar [3626 psi]	Goals deferred because development cost of higher pressure systems is not supported by adjacent CNG business case
Delivery Capacity, Trailer	kg	700 kg	940 kg	845 kg	Current status based on capacity of XL trailer

Approach

Task 1.0 Develop and Qualify a 3600 psi Tank

Develop and manufacture a tank that can be used for the storage of hydrogen in a stationary or hauling application.

Task 2.0 Develop and Qualify an ISO Frame

Based on current knowledge of tube trailer design, carry out preliminary design and qualify an ISO frame mounting 3600 psi tanks, each with 510000 in3 (~8500L) water volume.

Task 3.0 5000 psi Trade Study

Complete trade studies needed to increase vessel capacity by increasing pressure to 5000 psi (ultimately exceeds the DOE's FY10 capacity target by >15%).

Task 4.0 Develop and Qualify a 5000 psi Tank

Complete trade studies needed to increase vessel capacity by increasing pressure to 5000 psi (ultimately exceeds the DOE's FY10 capacity target by >15

Task 5.0 Cost Reduction Studies

Complete the enhancement of the 250 bar system with respect to capacity (> 700 kg/liter) and safety (fire protection).

Task 6.0 Investigate Increased Capacity

Investigate alternative packaging configurations to maximize system capacity in target markets

Results

Task 1.0 Develop and Qualify a 250 bar [3600 psi] Tank

The baseline TITAN® vessel has a 250 bar service pressure, with an outer diameter of 1087 mm [42.8 inches] and a length of 11.67 meter [38.3] feet. The weight of this tank is approximately 2175 kg [4800 lb]. The internal volume is equal to 8500 liters water capacity and will contain 154 kg [340 lb] of compressed hydrogen gas. The contained hydrogen is approximately 7.0% of the tank weight (6.6% of the combined weight). The large size of the TITAN® vessel also offers benefits in system configuration. A limited number of large tanks is easier to package into a container and requires fewer valves and fittings. This results in higher system reliability and lower system cost. The larger diameter also means thicker tank walls, which will make the vessel more robust and damage tolerant.

The design of the 250 bar pressure vessel architecture was completed using Finite Element Analysis to find a composite solution that resolves the internal pressure requirements and expected external loads. This design was translated into a manufacturing process that addresses the feasibility of vessel production. Several development (DVT) units were fabricated and pressurized until burst to validate the proposed manufacturing process and design.

With the completed design and working manufacturing process, several additional vessels were fabricated and tested to address optimizing manufacturing issues and minimize production expenses. One of the units was fabricated with an alternative carbon fiber and tested to ensure that the highest material availability risk could be addressed. By ensuring multiple sources of supplied materials, more leverage is available during procurement and lower production costs can be realized. Another vessel was fabricated to help establish confidence with migrating to a design having a higher margin of safety. Both of these vessels were subjected to a proof cycle and hydraulic burst test. The result of the testing met the expectations predicted by the design.

As seen in Figure 1, the composite pressure vessels developed in the project are much larger in size compared to typical commercial pressure vessels and their usage is much different compared to prior practice. Consequently, there were no published standards to directly qualify the product. Hexagon Composites worked with the American Bureau of Shipping (ABS) from the inception of the TITAN® project. Existing standards for qualification of small pressure vessels of similar construction were reviewed for input to determine the appropriate requirements that would apply to a vessel of this geometry and construction. It was acknowledged that there were several standards for composite pressure vessels but none was fully applicable for this size of composite pressure vessels or for the intended application.

ABS proposed treatment of the TITAN® composite pressure vessel as a special case and subject to the qualification methodology proscribed by the ABS Pub-116 “Guidance Notes on Review and Approval of Novel Concepts” [1] for its approval and certification. Hexagon Composites and ABS then worked closely to develop an applicable standard for the approval of large composite pressure vessels. This new code was formulated by adopting the appropriate and conservative requirements of the following established pressure vessels codes and standards:

- ISO 11439 2000, Gas cylinders – High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles [2]

- ISO 11119-3 2002, Gas cylinders of composite construction – Specification and test methods –Part 3: Fully wrapped fibre reinforced composite gas cylinders with non-load-sharing or non-metallic liners) [3]
- ANSI/CSA NGV2-2007, American National Standards for Natural Gas Vehicle Fuel Containers [4]
- ASME BPVC-X-2010, ASME Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels. [5]

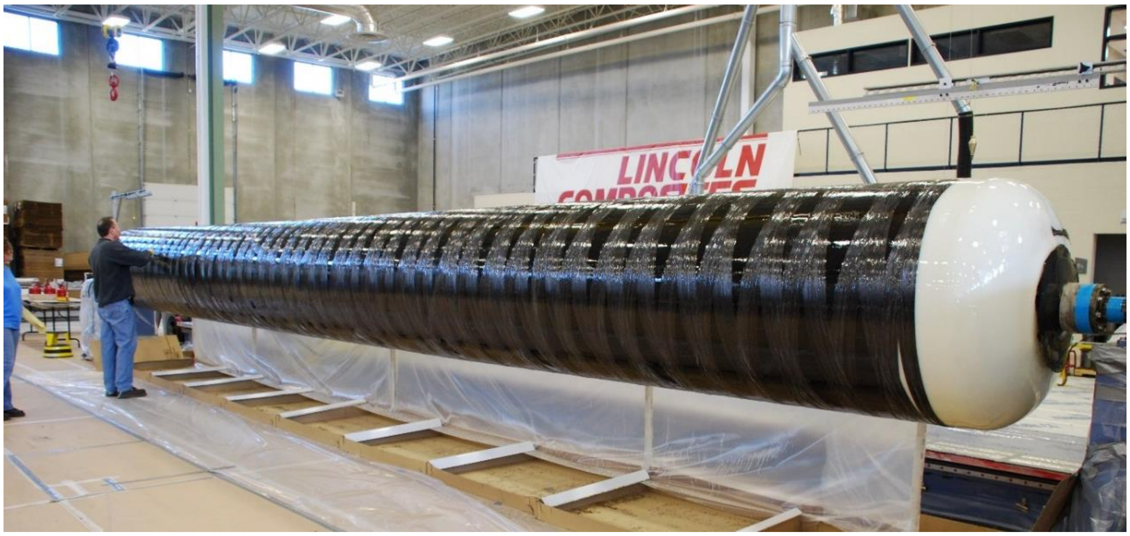

Figure 1 - Filament winding of TITAN™ COPV at the Hexagon Composites facility in Lincoln, Nebraska, USA

A gap analysis was performed comparing the proposed requirements to existing pressure vessel codes and existing marine standards such as classification society rules. Hazard Identification (HAZID) and Failure Mode and Effects Criticality Analysis (FMECA) studies were jointly performed by ABS and Hexagon Composites. A prototype testing plan was then developed to validate design, performance, and to address the risks identified by the risk analyses. This plan is included as Appendix A to this report. Tests performed included:

- Hydrostatic Burst
- Ambient Pressure Cycle Test
- LBB (Leak Before Burst) Test
- Penetration Test
- Environmental Test
- Flaw Tolerance Test
- High Temperature Creep Test
- Accelerated Stress Rupture Test
- Extreme Temperature Cycle Test
- Natural Gas Cycle Test with Blow-down

All agreed upon testing was successfully completed in 2009. A comprehensive qualification test report is included as Appendix B to this report.

Special consideration is given to the size and mass of large vessels. Damage resistance is managed at the system level, with strict requirement that the vessels are mounted in structure that meets the ISO 1496 requirements for tank containers. Fire protection is also managed at the system level, with an emergency venting system evacuating all vessels with fire exposure at any location on the container.

"ABS Requirements for Construction of Refillable Carbon Composite Road and Marine Transport Pressure Vessels – ABSHOU557163, March 2010" is included as Appendix C to this report. This document is the basis for approval and operation of large composite pressure vessel systems in many areas of the world, including Asia, Central America and South America. There are currently more than 2400 total tanks operating in TITAN® 4 modules and TITAN® 5 trailers worldwide under ABS approvals.

The mission of the Pipeline and Hazardous Materials Safety Administration (PHMSA) within the United States Department of Transportation (US-DOT) is to protect people and the environment from the risks inherent in transportation of hazardous materials, by pipeline and other modes of transportation. Authorization for the use of modes of transportation not currently authorized in the US-DOT Hazardous Materials Regulations can be granted by PHMSA through the issuance of a special permit. PHMSA will accept new modes of transportation provided the developer addresses all identified risks through a systematic approach and reduces the risks identified to an acceptable level.

All of the work done by Hexagon Composites and ABS in developing and qualifying the TITAN® large tank product was aligned with the ultimate goal of obtaining a special permit to allow the manufacture, marking, sale and use of TITAN® Mobile Pipeline® equipment in the United States. US-DOT Special Permit 14951 was issued in February of 2012, two years after the release of ABSHOU557163. SP 14951 was written as a variant from ISO 11119-3, but the subsequent requirements were in harmony with ABSHOU557163. This was followed in November of 2012 by the issuance of Equivalency Certificate SU 9806 by the Transport Dangerous Goods Directorate of Transport Canada. There are currently over 250 units of the TITAN® 4 module operating in the United States and Canada. The current revisions of US-DOT Special Permit 14951 and Transport Canada Equivalency Certificate SU 9806 are included as Appendix D and Appendix E to this report.

A program of deep cycle testing of TITAN® pressure vessels with CHG was initiated in 1Q 2015 with completion in 3Q 2015. The goal of this demonstration is to characterize CHG-specific operating protocols for use of TITAN® systems in CHG service at 250 bar. A test protocol was developed which shuttled hydrogen gas between two TITAN® tanks. These test units were subjected to long holds at operating pressure to ensure complete saturation of polymeric tank materials with hydrogen, and long holds at low pressure to allow any decompression issues such as liner blistering or collapse to develop. The testing conducted at Powertech Labs was uneventful, with no hydrogen leakage or unusual behavior observed. The Powertech Labs test report for this activity is included as Appendix F to this report.

Task 2.0 Develop and Qualify an ISO Frame

Installation of the compressed hydrogen vessels into an ISO frame offers the benefit of having one solution for both transportable and stationary storage. This approach decreases research and development costs as well as the amount of infrastructure and equipment needed for both applications. Four TITAN® tanks are mounted in a custom-designed ISO frame, resulting in an assembly with a combined capacity of 616 kg of hydrogen. In addition to the structure, a system for loading, unloading, and pressure relief was designed and implemented.

A complete assembly was constructed including ISO frame, four pressure vessels, and all relevant plumbing including emergency pressure relief systems. The test unit shown in Figure 2 was manufactured in 2009. The following tests per ISO 1496-3 1995(E) [6] and ABSHOU557163 were performed on the entire assembly:

- Stress Analysis
- Dimensional Analysis
- Stacking
- Lifting – Top and Bottom
- Inertia Testing (see Figure 3)
- Impact Testing
- Bonfire Testing

Figure 2 - TITAN® container structural and bonfire test unit.

Final qualification testing of an ISO frame mounting four 250 bar TITAN® pressure vessels was completed in 3Q 2009. A comprehensive qualification test report is included as Appendix B to this report. The American Bureau of Shipping (ABS) approved the entire ISO assembly for production including, pressure vessels, ISO frame and subsequent valves, fittings and emergency pressure relief system. ABSHOU557163 is included as Appendix C to this report.

DOT Special Permit 14951 issued to Hexagon Lincoln on 22 February 2012. SP 14951 authorizes the manufacture, marking, sale and use of TITAN® modules in the United States. This was followed in November of 2012 by the issuance of Equivalency Certificate SU 9806 by the Transport Dangerous Goods Directorate of Transport Canada. The current revisions of US-DOT

Special Permit 14951 and Transport Canada Equivalency Certificate SU 9806 are included as Appendix D and Appendix E to this report.

Figure 3 – ISO 1496 testing of TITAN® container 9longitudinal inertia test).

Task 3.0 5000 psi Trade Study

Trade studies were undertaken to evaluate potential design solutions and operational modes that would increase utilization storage design meet or exceed DOE targets. Hexagon Lincoln's existing TITAN® module was used as the baseline for the studies and a gap audit was conducted.

Design Baseline

- Intermodal ISO 668 1A Frame
- Four (4) Type 4 Pressure Vessels in a square arrangement
- 250 bar Working Pressure
- Carbon Fiber, 2.35 Stress Ratio

Gap Audit

- Increase volumetric capacity from 0.018 kg/liter to 0.035 kg/liter
- Increase delivery capacity from 616 kg to 1100 kg H2 at 15C
- Increase delivery pressure from 250 bar to 700 bar
- Decrease Cost ($ per kg H2) from $500/kg to $300/kg hydrogen

Cylinder size was identified as a potential candidate for increase capacity through the increase of utilization of space. The study compared the baseline four (4) vessel configuration with a single large diameter vessel. Space utilization for the current TITAN® assembly is roughly 60% in volume while replacing it with a single, large tank would increase the utilization to 63%. However, when looking at the sheer size of a single tank, the thickness of a liner to manufacture this tank would not be very efficient and will have its limitations; i.e. pipe extrusion, and injection molding of the domes.

Hexagon Lincoln also looked at different scenarios of packing of pressure vessels within the current ISO frame. The first scenario considered was to add an additional vessel down the center of the existing four (4) vessels. This would increase the utilization of space to 68% from 60%, but the manufacturing of a small diameter tank that would fit in the available space would be difficult to achieve. This is due to the Length/Diameter (L/D) ratio. When this number becomes large, the tanks begin to bend due to the weight and decreased strength of the liner. Straightness is a key factor when trying to place the vessels next to each other within the frame. This also increases the cost of the plumbing of the system.

Second scenario is eight (8) cylinders packed in a 3x2x3 matrix within the existing ISO frame. This arrangement would actually reduce the utilization from 60% to 56%. Lastly, Lincoln Composites performed a study to determine the potential to have many smaller cylinders packed within the frame assembly. Ninety-one (91) smaller cylinders could be packed vertically with the frame. Again, the L/D ratio would increase and thus affect straightness and winding stability. If this were done, utilization would increase from 60% to 68%. However, the cost of plumbing this configuration would increase as well as the complexity of servicing the cylinders.

A third factor that was investigated through the study was to look at raising working pressure to increase compressed hydrogen density. Figure 4 shows the relationship of working pressure to project goals. By raising working pressure from 250 bar to 350 bar we could potentially see an increase of 33% in capacity at 15C. Higher gas densities would be achieved at higher pressures, however cost increases need to be considered. As can be seen in Figure 5 below, acquisition cost increases rapidly as delivery pressure is increased above 350 bar. At higher pressures system costs rise rapidly, as the volumetric performance of the storage systems is negatively impacted as the allowed dimensions of the equipment are reached and pressure vessel diameters cannot be further increased. Increasing wall thickness requires reduced liner diameters and exacerbates thick-wall effects, resulting in reduced strength translation.

This study does not consider that compression equipment and operating costs also increase at higher pressures. These costs are driven by several factors; i.e. increased costs of high pressure plumbing hardware, increased energy and equipment cost for gas chilling, and increased acquisition, energy and maintenance costs of hydrogen compression equipment.

Storage temperature was also investigated as a means to increase hydrogen density. As can be seen in Figure 6 below, with a decrease in storage temperature to -40° C, the current 250 bar tank could potentially see an increase of 33% in hydrogen density. With respect to a 350 bar tank, reducing the storage to the same temperature, -40° C, has the potential to increase hydrogen density by 61%. However, operation at -40° C presents many challenges that would need to be addressed before taking advantage of this increased storage density.

Lincoln Composites also looked at full module costs as well as costs to manufacture pressure vessels for the TITAN® product line. The breakdown of costs associated with a full bulk hauling module and individual pressure vessels are as follows:

Module

- Pressure vessels make up approximately 70% of the total cost
- Frame and Hardware make up approximately 30% of the total cost

Pressure vessel

- End bosses make up approximately 3% of the total cost
- HDPE Liner makes up approximately 11% of the total cost
- Composite material makes up approximately 86% of the total cost

As part of the cost factor associated with this study, Lincoln Composites evaluated scenarios to reduce costs in both the liners and the composite materials. Liner costs are associated with HDPE tubes/domes and the steel end bosses. Current construction and design of the liner shows that we are presently at minimum Thickness/Diameter ratio and any changes would result in difficulties in liner fabrication and filament winding of the vessel. The end bosses are constrained by the current mounting scheme and cost savings would be minimal if changes were made. As for the composite costs, the carbon fiber that is currently being used in the design contributes the lowest stress ratio of allowable fibers at 2.35. Current fiber possesses the greatest strength per unit cost. There are higher strength carbon fibers in existence but would have a 2-4 times increase in cost for a 15-40% increase in strength.

The last factor evaluated was that of reduction of stress ratio. By reducing the stress ratio, one could in turn lower the amount of carbon needed in the assembly of the pressure vessels and thus lower the cost of fiber used.

Stress Ratio

- Current TITAN® stress ratio is 2.40 based on DOT PHMSA mandate.
- ASME H2 allows for a 2.25 stress ratio
- 2.00 stress ratio is considered safe

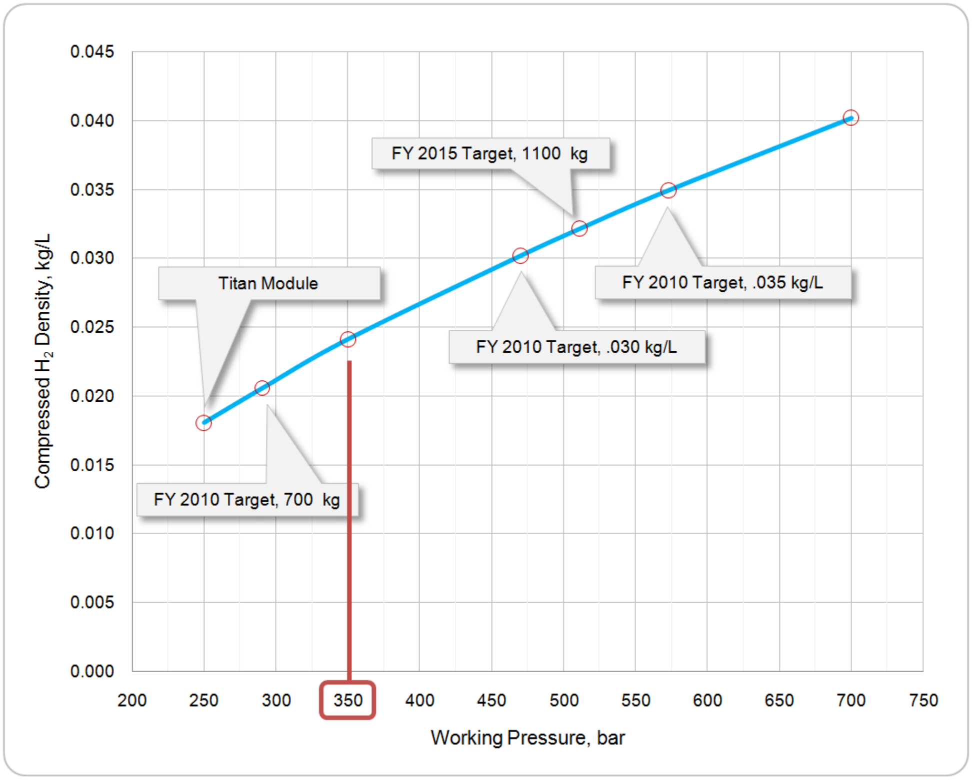

Figure 4 – Working pressure vs. Compressed Hydrogen Density

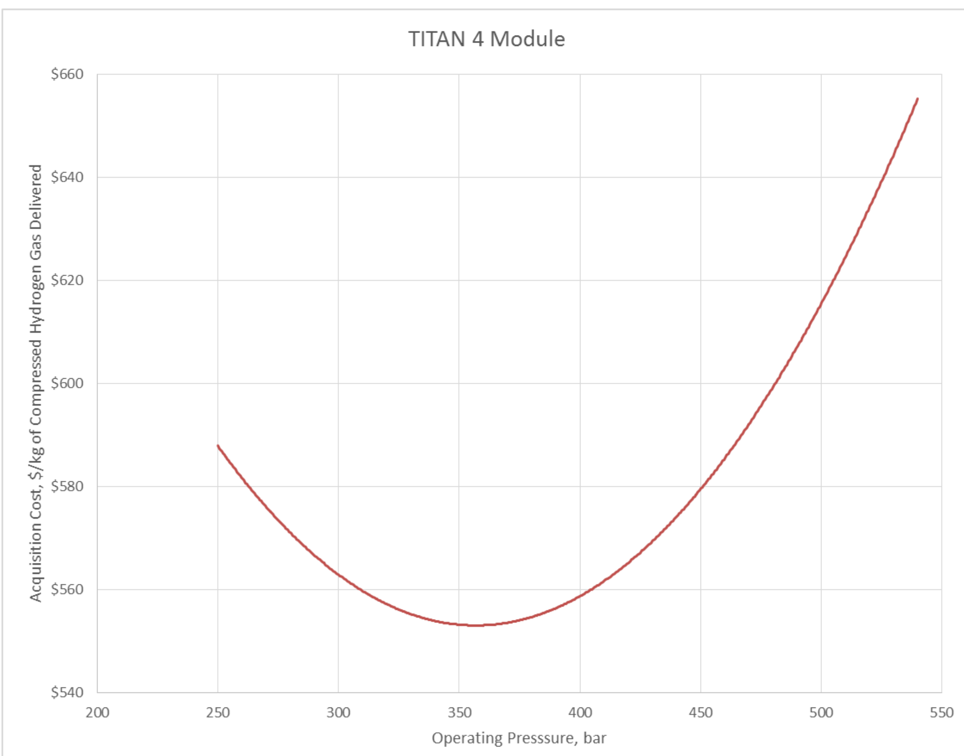

Figure 5 – TITAN 4 Module Acquisition Cost vs Working pressure

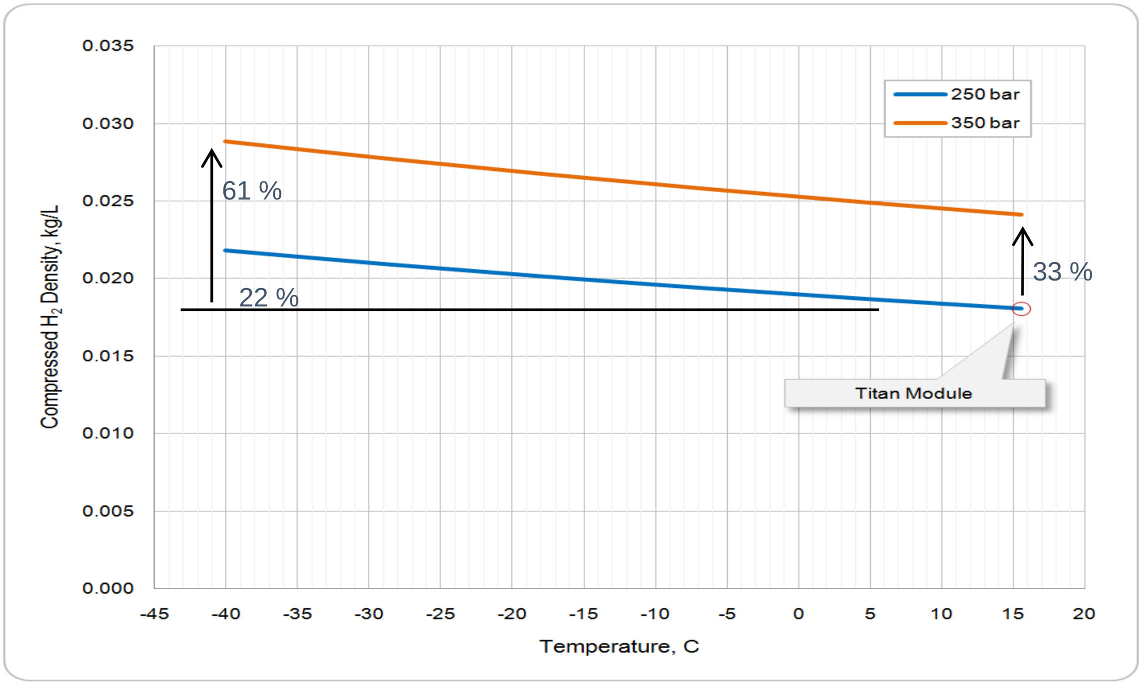

Figure 6 – Compressed Hydrogen Density vs Temperature

Task 4.0 Develop and Qualify a 350 bar [5000 psi] Tank

Hexagon Lincoln worked directly with DOE in determining that qualification of a TITAN® module at 350 bar is not economically feasible at this time. The high cost to complete this qualification and current lack of market demand for fuel gas transport at 350 bar does not support a business case for this investment. Hexagon Lincoln therefore agreed to focus continuing efforts on further optimization and improvement development of our current large tank technology at 250 bar.

Phase 2 of the program was originally scoped to evaluate using the same approximate sized vessel(s) and ISO frame at elevated pressures. Trade studies performed repeatedly since 2011 indicate optimization of hauling efficiency and system cost for CHG at 350 bar. Due to differences in the compressibility of CHG and CNG, 350 bar operation is not an attractive option for CNG. The CHG market is not developed at this time. It is therefore difficult to forecast sales potential. On the investment side, the cost to fully qualify a large tank module at 350 bar is estimated at $3MM to $5MM. Based on insufficient CHG market definition to support a stand-alone business case for CHG, development of a 350 bar TITAN® system has been placed on hold and will not be pursued under this project. Hexagon Lincoln continues to support the development of tankage and equipment for operation at 350 bar and above; with 700 bar vehicle tanks and 950 bar tanks for ground storage applications.

As described in the descriptions of Task 5.0 and Task 6.0 that follow, Hexagon Lincoln continues to work with our current 250 bar product to increase the volume per load as well as improvements in safety. Increased volume has been achieved with the development of the TITAN® V trailers, integrated semitrailer systems with additional tankage. Other system improvements supported by the project include the evaluation, testing and qualification of an improved emergency venting systems as well as development and installation of laboratory capabilities to evaluate the effects of hydrogen on liner materials.

Task 5.0 Cost Reduction Studies

Lincoln Composites has continued the design and evaluation of a more robust emergency venting system utilizing memory metal wire as a trigger mechanism for de-pressurizing the tank in the case of a fire. This patented technology greatly reduces the cost of the system in both components and labor for assembly. The reduction of components in the system affects the potential number of failure modes that could occur and thus making for a more reliable product.

The performance of polymeric liner materials is critical for Type 4 pressure vessels in hydrogen service. Therefore it is important to have the ability to screen candidate materials rapidly in a cost-effective manner. Towards this end, Hexagon Lincoln has developed and purchased laboratory equipment to evaluate the effects of exposure to 100% hydrogen at extreme temperatures and pressures. This capability is used to fully investigate new materials with the potential for them to be integrated into liners. Specifically, the permeation rates of alternate materials will be characterized in addition to evaluation of durability.

Typical material testing is described below. In this case, the response of three different liner materials to repeated saturation/decompression cycles is compared. The materials tested were injection molded HDPE (5.3 mm thick), rotationally molded HDPE (5.2 mm thick) and blow molded nylon alloy (4.21 mm thick). The pressure cycling sequence is shown in Table 1. This sequence was developed to test prolonged hydrogen soaking and rapid depressurization. Diffusion of hydrogen through these materials follows an Arrhenius equation; therefore, elevated temperature was used during part of the hydrogen soaking time to increase the amount of hydrogen diffused into the materials. The temperature was then lowered for a minimum of 14 hours before depressurization was performed. Two stainless steel reactors (pressure vessels) with a combined volume of 2,075 ml were used to isostatically expose the samples to hydrogen. These reactors were heated to a maximum of 60 °C externally and cooled before depressurization.

Microscopic optical comparison of the liner materials as a function of pressure cycles was performed. Optical samples were prepared for each material and pressure cycle exposure. In addition, a set of samples for each material was tested without exposure to hydrogen cycling as a baseline reference. The optical samples were sectioned from the bulk material then the edges were melted against a hot plate to seal cut surfaces. Thin cross-sections were created with a microtome and taken from the center of the optical samples. These optical samples were inspected using a stereo microscope at up to 66x magnification and with the aid of polarized light. When the thin specimens are viewed under polarized light, any small fractures or tears in the material induced by the dissolution of absorbed hydrogen are visible.

Figure 7 shows a magnified view of a specimen of injection molded HDPE which has not been exposed to hydrogen saturation and decompression. There are no visible fractures or tears in the material.

Table 1 - Pressure cycling sequence for saturation/decompression test

Step	Pressure [MPa]	Time [hrs]	Temperature [°C]	Cycle	Description
1	64.8	70	60		Initial soak at elevated temperature to saturate material
2	64.8	48	16		Cool to ambient temperature
3	0	0.2	16	Cycle 1	Depressurize ~ 12 minutes
4	64.8	10	60		Soak
5	64.8	14	16		Cool
6	0	0.2	16	Cycle 2	Depressurize ~ 12 minutes
7	64.8	10	60		Soak
8	64.8	14	16		Cool
9	0	0.2	16	Cycle 3	Depressurize ~ 12 minutes
10	64.8	10	60		Soak
11	64.8	14	16		Cool
12	0	0.5	21	Cycle 4	Depressurize ~ 12 minutes

Figure 8 shows a magnified view of a specimen of injection molded HDPE which has been exposed to a single cycle of hydrogen saturation and decompression. Internal fractures are beginning to develop as indicated by the red arrow. With increased magnification, many small flaws can be seen surrounding the larger fracture (Figure 9).

Figure 10 shows a magnified view of a specimen of injection molded HDPE which has been exposed to 2 cycles of hydrogen saturation and decompression. Internal fractures are beginning to connect and form a delamination surface at the specimen mid-thickness. Thicker specimens have shown that formation of delamination surfaces initiates at a specific depth into the material, in this case that depth corresponds to half the thickness. With increased magnification, the interconnection of small fractures to form a delamination surface can be seen (Figure 11).

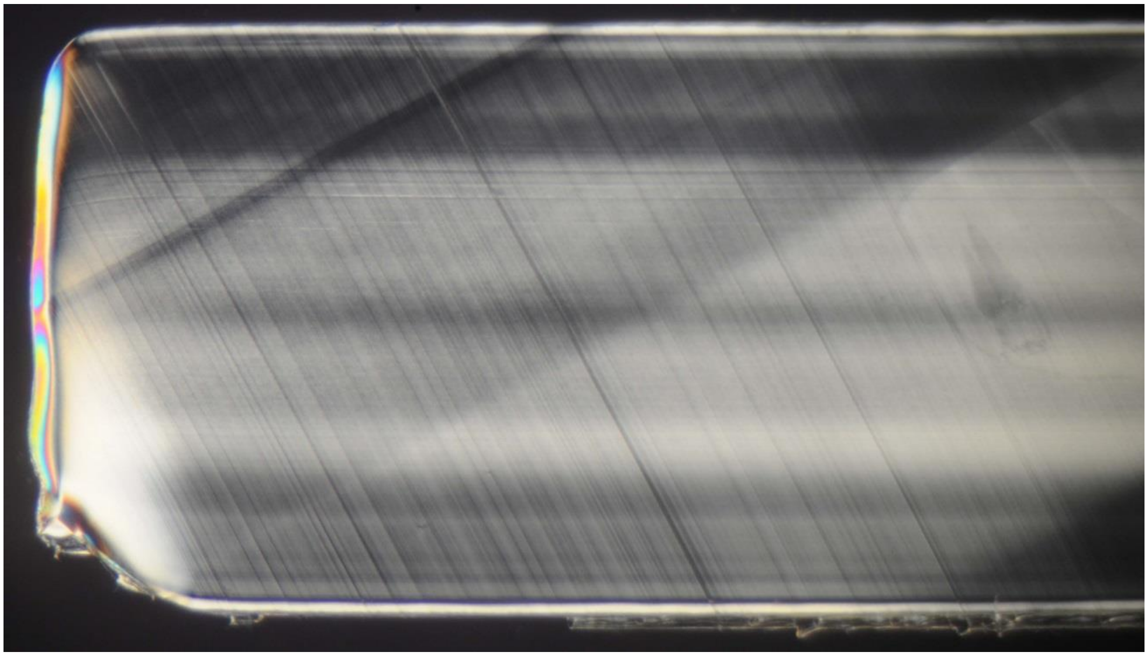

Figure 7 – Injection molded HDPE (5.3 mm) before hydrogen cycling

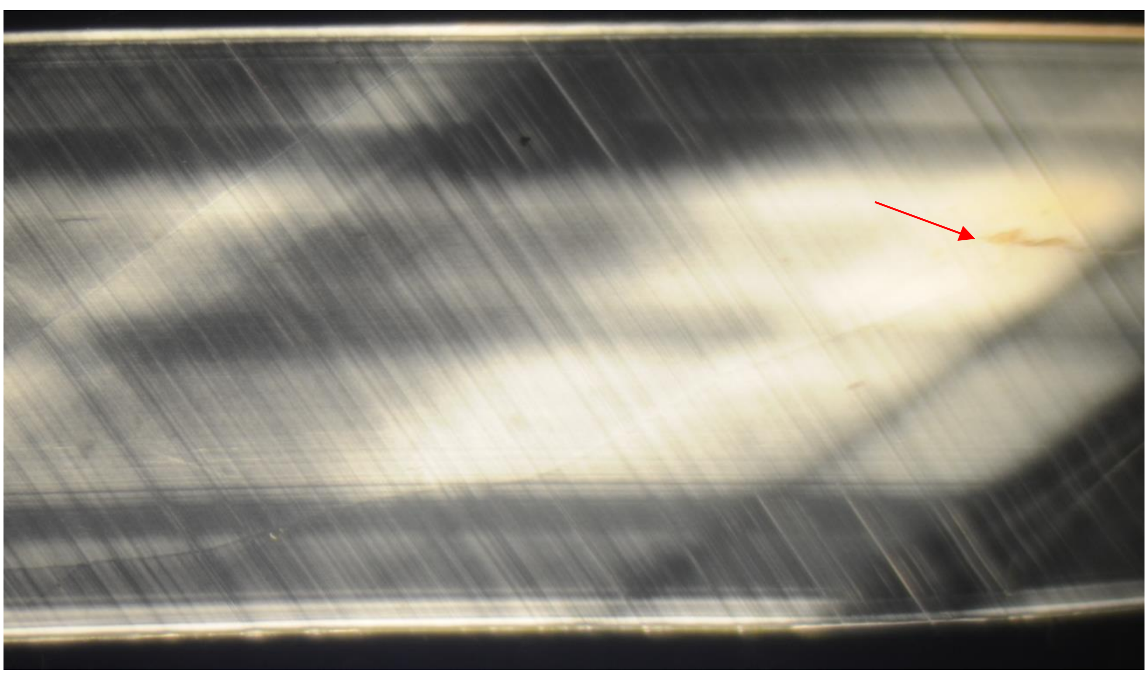

Figure 8 - Injection molded HDPE (5.3 mm) after 1 hydrogen cycle

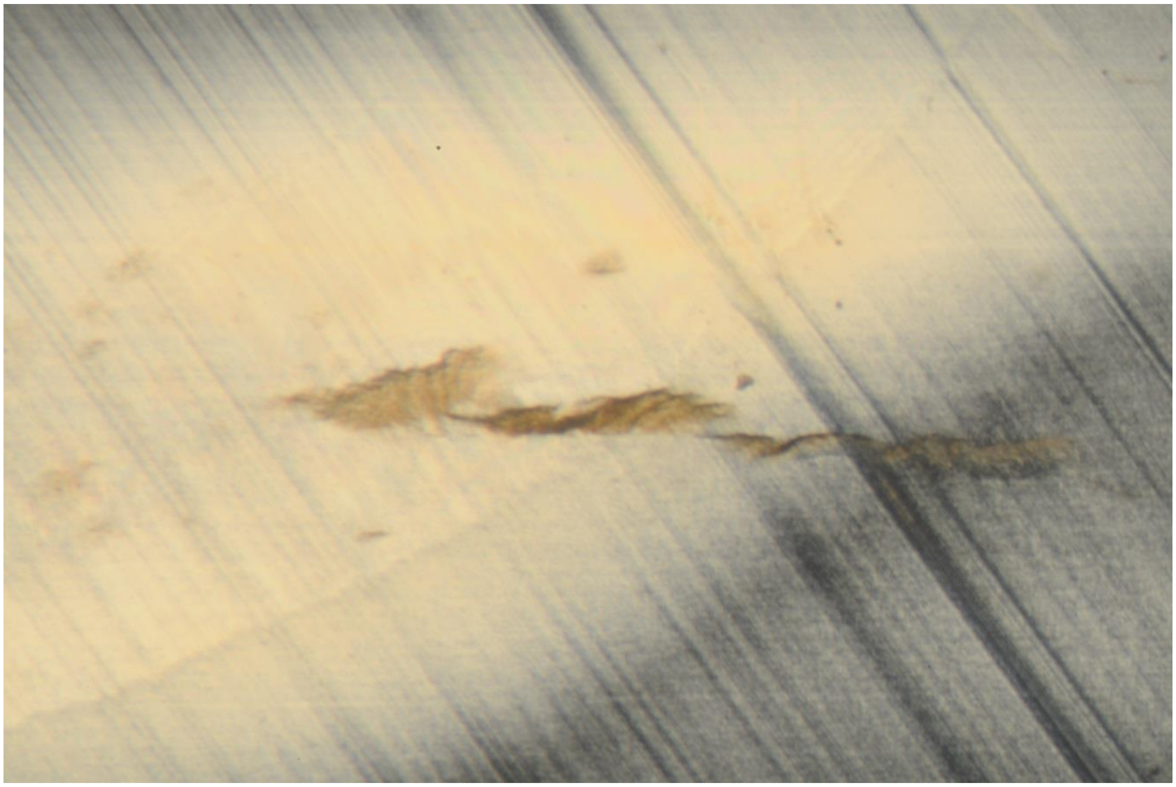

Figure 9 – Close up of injection molded HDPE (5.3 mm) after 1 hydrogen cycle

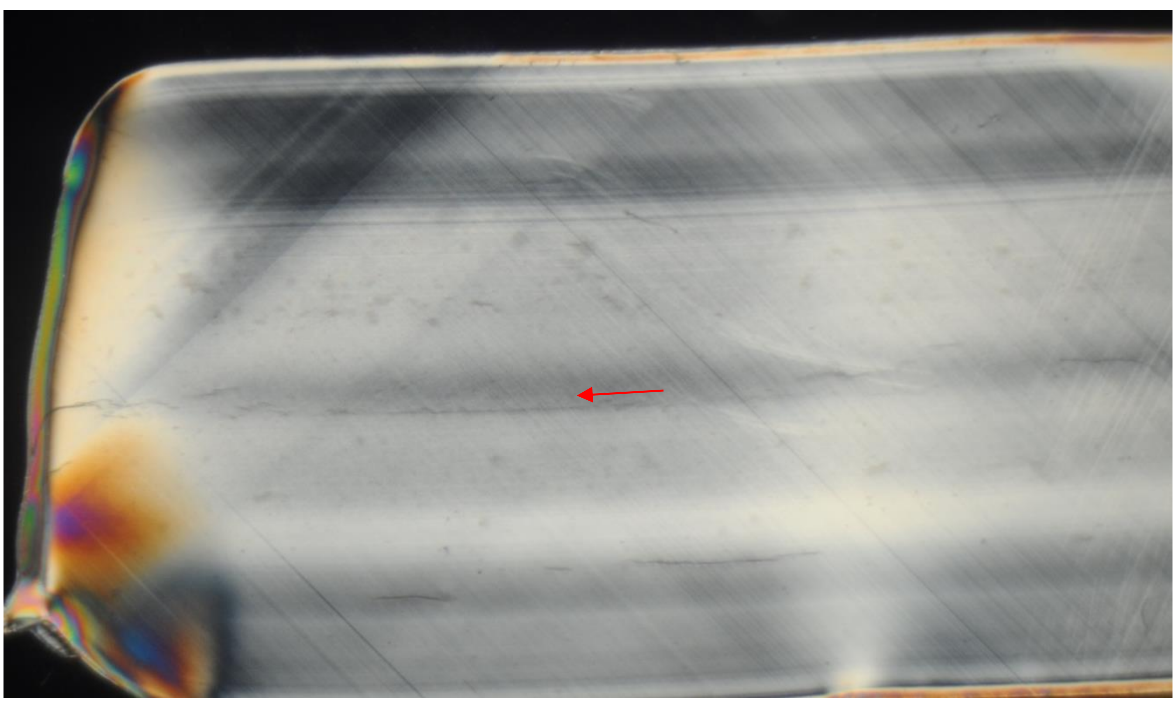

Figure 10 - Injection molded HDPE (5.3 mm) after 2 hydrogen cycles

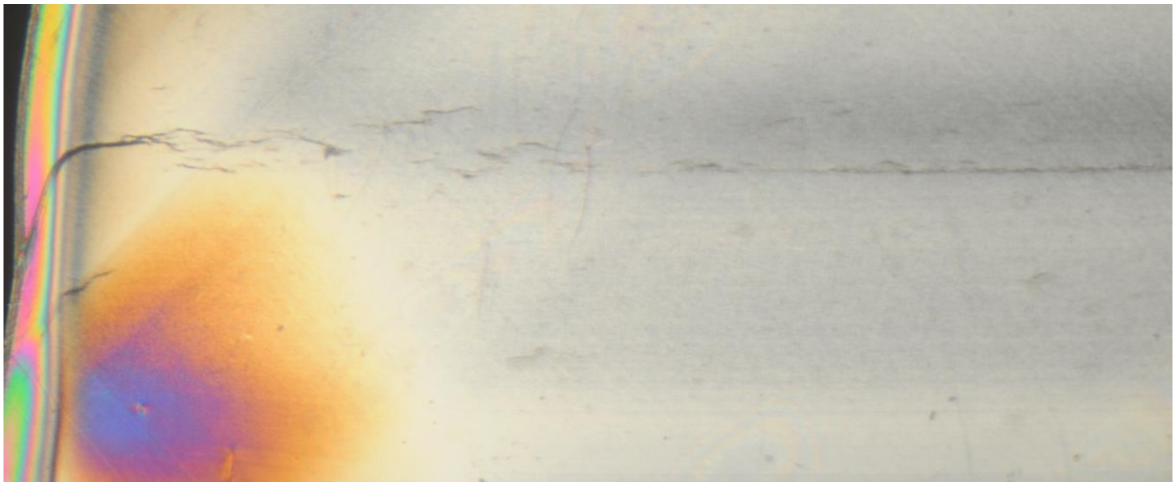

Figure 11 – Close up of injection molded HDPE (5.3 mm) after 2 hydrogen cycles

Figures 12 and 13 show the progression of internal damage in the injection molded HDPE specimens with a third and fourth saturation/decompression cycles, respectively. It is observed that several applications of this exposure the small fractures in the material have grown and connected such that the interior volume of the specimen is compromised. It is also observed that the exterior surfaces of the specimens remain free of fractures to a depth that is characteristic of the material.

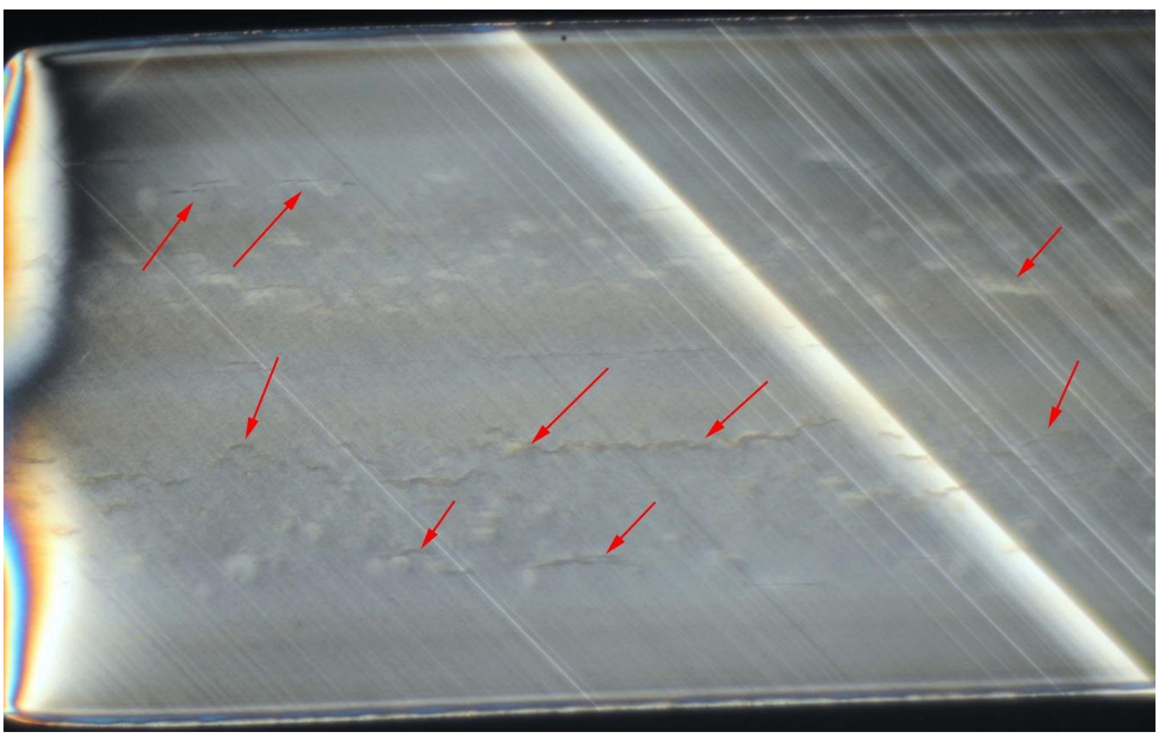

Figure 12 - Injection molded HDPE (5.3 mm) after 3 hydrogen cycles

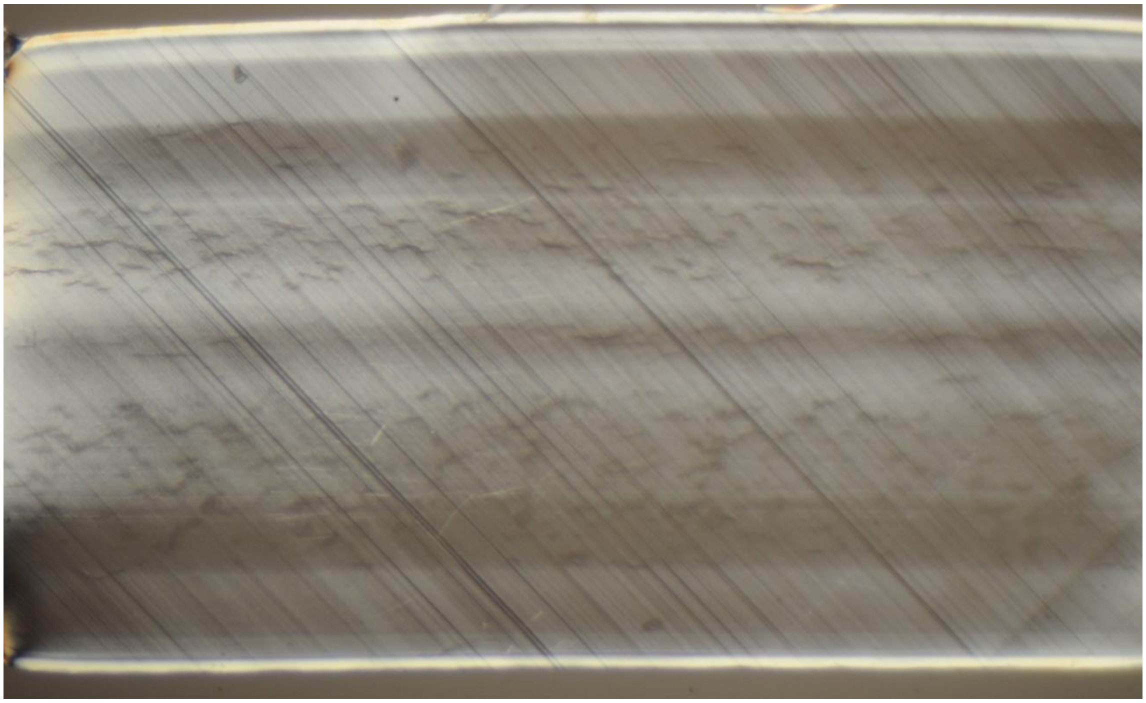

Figure 13 - Injection molded HDPE (5.3 mm) after 4 hydrogen cycles

Figure 14 shows a similar degree of internal damage in a specimen taken from a rotationally molded HDPE liner after 4 saturation/decompression cycles.

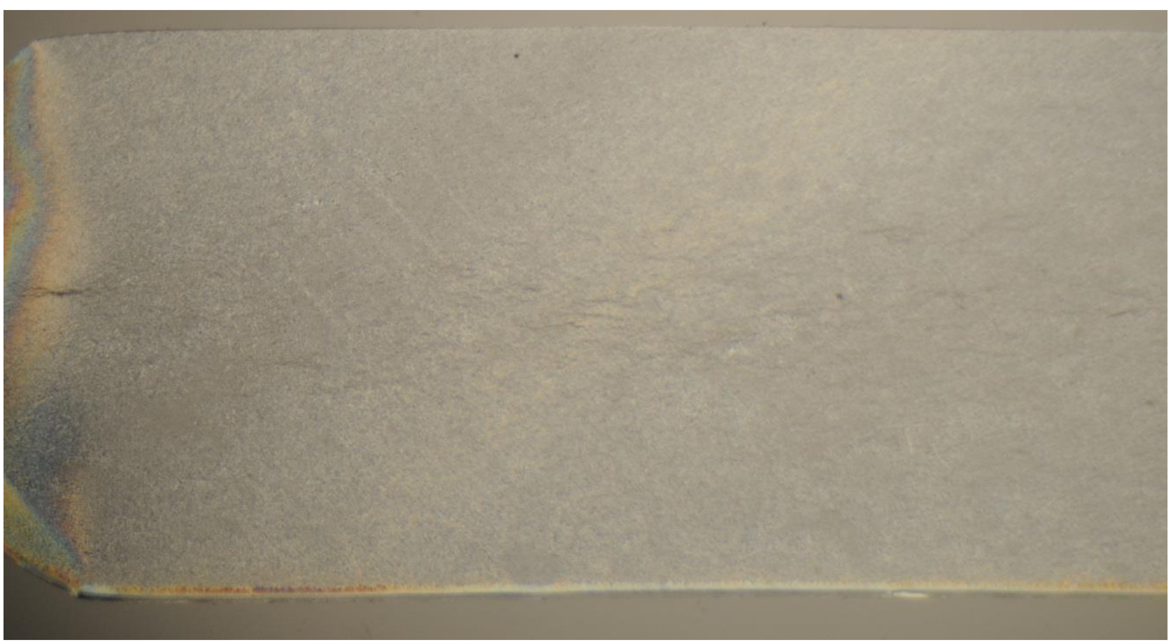

Figure 14 – Rotationally molded HDPE (5.2 mm) after 4 hydrogen cycles

Figure 15 shows the condition before saturation/decompression cycling of a specimen taken form a blow molded nylon alloy liner of 4 mm thickness before saturation/decompression cycling. Figure 16 shows the condition before saturation/decompression cycling of a similar specimen after 4 saturation/ decompression cycles. The microtome shows a general darkening as a result of the exposure, and formation of some discrete small voids or “blisters”. However, the nylon alloy exhibits less tendency to form the large numbers of interconnecting fractures observed in the HDPE samples.

Figure 15 – Nylon Alloy (4 mm) before hydrogen cycling

Sufficient testing with candidate liner materials has been conducted to show that saturation/decompression damage can lead to liner deterioration and leakage in systems operating above 350 bar, and must be managed with operational controls. Saturation/decompression damage has not been identified in systems operating at or below 350 bar.

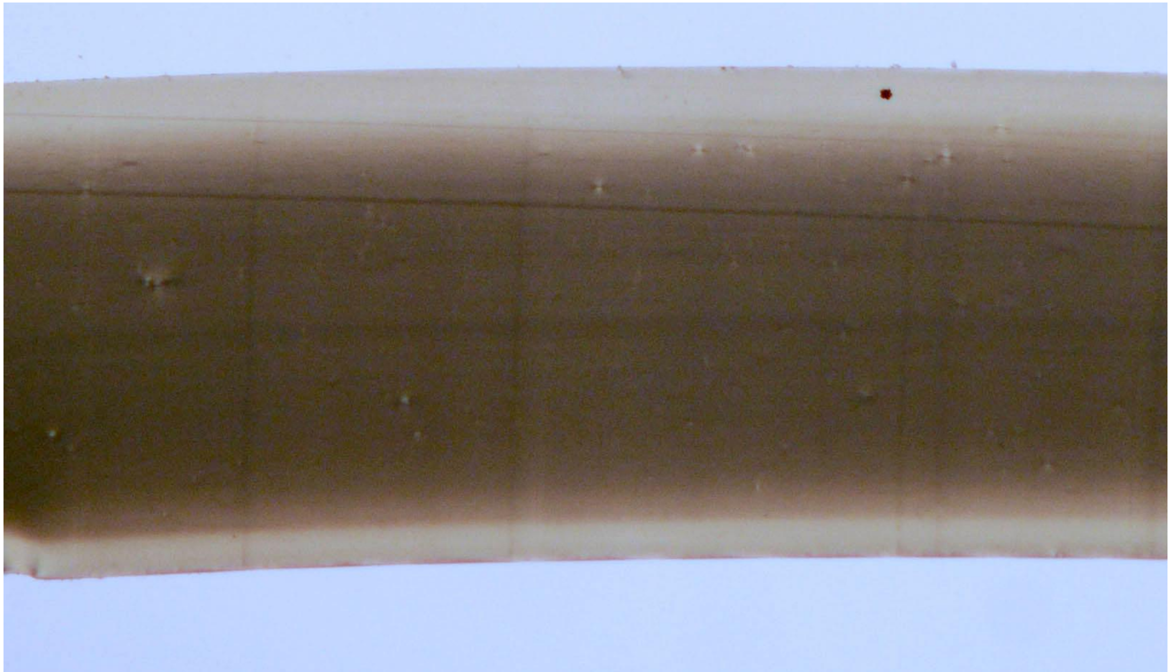

Figure 16 - Nylon alloy (4 mm) after hydrogen cycling. Darker areas are the location of hydrogen influence. Small discrete “blisters” are present. The larger interconnecting cracks as observed in the HDPE are not present.

Task 6.0 Investigate Increased Capacity

In 1Q2012, Lincoln Composites completed a prototype for a TITAN® V semitrailer capable of increasing total payload capacity by 18% as compared with the baseline TITAN® module. This integrated semitrailer system utilized the same four 38.5’ cylinders with the addition of a single 28.5’ tank placed lower in the assembly utilizing space between the frame rails of the chassis. This prototype unit was useful in resolving initial form, fit and function questions for an integrated high-pressure trailer. It was not ultimately fully assembled and tested, primarily due to concerns about roadworthiness due to its high vertical center of gravity.

To further enhance system volume and reduce the vertical center of gravity, the development/design of the TITAN® V Magnum trailer with additional tankage has been completed. First deployed in compressed natural gas (CNG) service in 2013, this design utilizes the TITAN® V prototype as a baseline with the addition of up to nine smaller tanks on either side of the 30’ single tank at the bottom of the module. See Figure 17 for illustration of this design. This configuration has increased capacity by 26% when compared to the standard 4-cylinder TITAN® module. This translates to an overall payload of 775 kg of hydrogen. The TITAN® V Magnum trailer system is currently deployed in CNG service in South and Central America.

To further enhance system volume, the development/design of the TITAN® V trailer systems was extended to the XL40 configuration with larger auxiliary tankage. This design utilizes four 38.5-foot and one 28.5-foot TITAN® tanks with seven 26-inch diameter tanks developed specifically for trailer installation. The new trailer is shown in Figure 2. This configuration has increased capacity by 44% when compared to the standard 4 cylinder TITAN® module. This

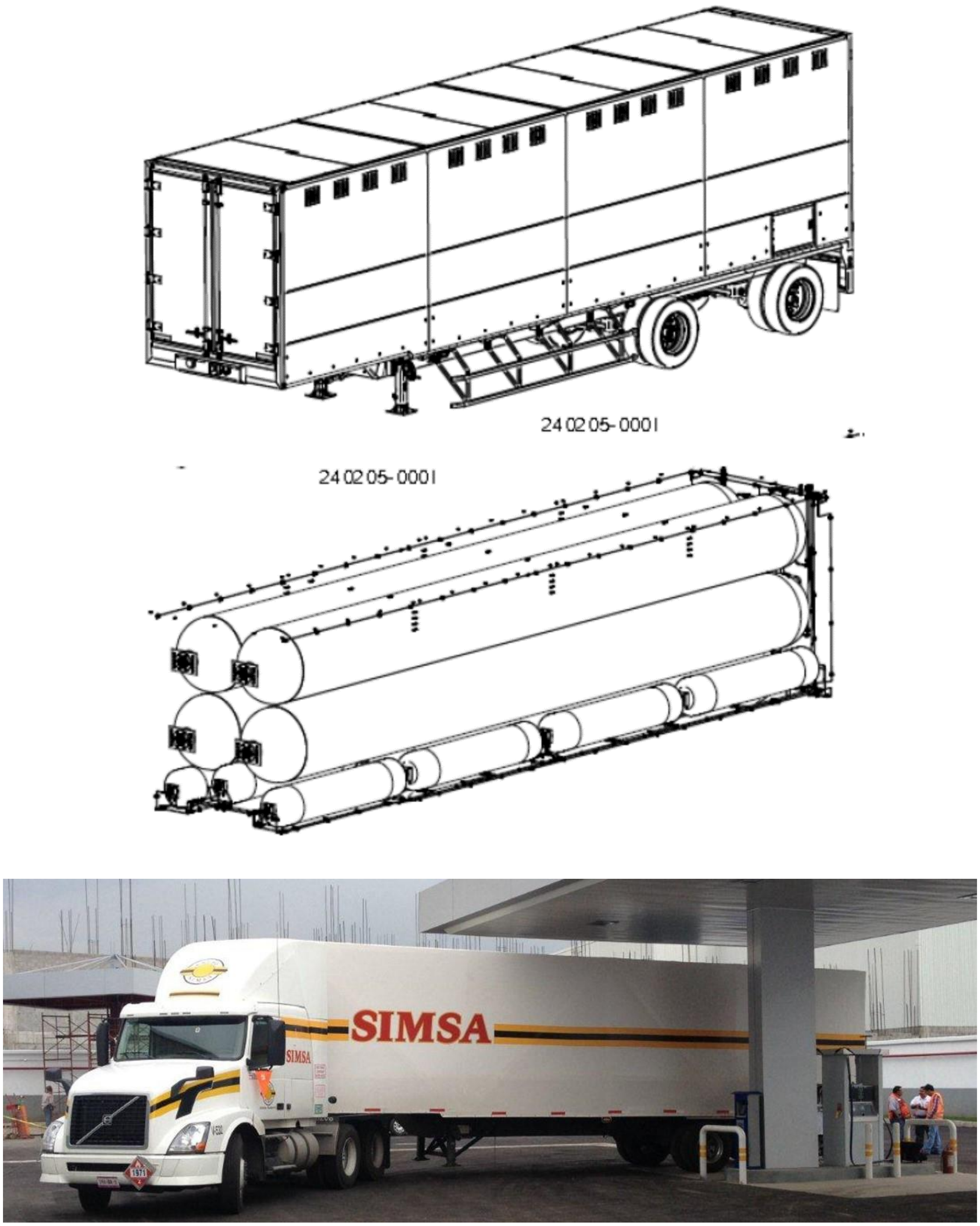

Figure 17 - The Hexagon Composites TITAN® Magnum Trailer System [GVW = 42 500 kg (3 axles)

translates to an overall payload of 890 kg of hydrogen. This increase in capacity was achieved without increasing the loaded mass of the trailer because the trailer structure was designed and configured using high-strength (100 ksi) steels. This new bulk hauling system was first deployed in compressed natural gas (CNG) service in 2015 in Central America. With revision of USDOT SP

14951 to allow semitrailer construction in 2Q2016, the TITAN® V XL40 trailer system is now deployed in CNG service in North America.

Figure 18 - The Hexagon Composites TITAN® XL Trailer System [GVW = 42 500 kg (3 axles)].

Products Developed and Technologies Transferred

Hydrogen gas is recognized as the energy carrier of the future, causing no greenhouse gas emissions when used and making it possible to store energy produced by clean energy producers during periods of reduced demand. Natural gas is an important alternative energy solution now and will become increasingly important as a transition fuel between conventional liquid petroleum fuels and hydrogen. Natural gas is affordable and plentiful now, with well-developed technology and stable pricing. Increasing utilization of compressed natural gas provides an opportunity to soften the societal and economic impacts of conversion to utilization of hydrogen as a gaseous fuel.

Grant funding from DOE was a deciding factor in Hexagon Lincoln's decision to develop the TITAN® large tank technology. Another supporting factor was the favorable economic position of natural gas relative to traditional industrial and heating fuels such as propane and fuel oils. The energy cost savings offered by natural gas use have led to the emergence of a profitable new industry for over-the-road transportation of compressed natural gas. The Hexagon Composites Mobile Pipeline™ products whose development was supported by this project are an enabling technology for this new business sector.

In most regions of the world, access to affordable natural gas has been limited to areas served by natural gas pipelines.

The economics for using over-the-road trucking to transport natural gas were not attractive until the introduction of lightweight composite high-pressure tankage to the industry. In most countries, the national and local regulations for gross vehicle weight (GVW) and the allowable bridge loadings meant that heavy steel tube trailers could only carry enough natural gas payload to make very short distance deliveries profitable. Liquefied natural gas (LNG) trailers could carry enough payload to make profitable deliveries, even with very long trip distances, but limited sources of LNG and high infrastructure and capital equipment costs have discouraged investors.

The recent introduction of Mobile Pipeline™ modules and trailers with light-weight composite tankage has meant that 2 to 3 times as much natural gas can be transported with each trip. This increased hauling efficiency offers dramatically reduced operating costs and a profitable business model for over-the-road compressed natural gas delivery. The Mobile Pipeline™ products produced by Hexagon Composites fill the gap between customers best served by steel tube trailers and those that can justify investment in LNG. The economic drivers of this decision vary from country to country and region to region, but in many places gas distribution companies have created a profitable business opportunity.

Profitable and sustained delivery of gaseous fuel (CNG) to off-pipeline consumers is a reality many regions of the world, in large part due to increased transportation efficiency with lightweight composite tankage. Lessons are being learned every day that are essential to the large-scale transition to a hydrogen economy.

Since the commercial introduction of the TITAN® module in 2010, revenue to Hexagon Lincoln enabled by previous DOE funding has totaled more than $241,000,000 and continues to grow. Export sales constitute $130,000,000 of this total. Over 600 TITAN® systems are in operation globally, with over 300 units operating in the United States and Canada. Hexagon Lincoln's Mobile Pipeline™ production facility in Lincoln, NE maintains 75 employees involved in the design, development and production activities. Since 2008, Hexagon Lincoln has invested an additional $2,700,000 in related technologies and facilities.

Summary and Future Direction

The overall objective of the "Development of High Pressure Hydrogen Storage Tanks for Storage and Gaseous Truck Delivery" project [DE-FG36-08GO18062] was to design and develop the most effective bulk hauling and storage solution for hydrogen in terms of cost, safety, weight, and volumetric efficiency. Hexagon Lincoln agreed to develop and manufacture a tank and corresponding ISO container to be used for the storage of hydrogen in stationary and transportation applications. This overall objective was accomplished in 2012 with the issuance of USDOT SP 14951, the special permit authorizing the manufacture, marking, sale and use of TITAN® Mobile Pipeline® equipment in the United States.

The introduction of tube trailers with light weight composite tankage has meant that 2 to 3 times as much gaseous fuel can be transported with each trip. This increased hauling efficiency offers dramatically reduced operating costs and has enabled a profitable business model for over-the-road compressed natural gas delivery. With the successful launch of TITAN® modules and trailers in natural gas transportation, over 600 units have been fielded internationally through the end of 2016, with about half operating in the United States.

Table 2 summarizes the results achieved during the project, with discussion of future directions that Hexagon Lincoln considers appropriate for each target.

Table 2 – Project results relative to project targets and future direction

DOE Technical Targets	Project Results and Future Direction
Storage Cost Targets **$730/kg** by FY2015 GOAL ACHIEVED → **$575/kg** by FY 2020	Typical acquisition cost of a 250 bar TITAN® 4 module as of 1Q2017 is **$590/kg** of H2 delivered Future Direction Module cost is highly influenced by market cost of carbon fiber, specialty forgings, etc and therefore subject to future variance.
Delivery Pressure Targets **400 bar (5801 psi)** by FY2015, **520 bar (7542 psi)** by FY 2020	Current TITAN® systems operate at **250 bar (3626 psi)** Future Direction Trade studies indicate that optimal storage pressure in terms of acquisition cost for a semitrailer-based bulk hauling system is between 350 bar and 400 bar. Operation at 520 bar disproportionately increases the acquisition cost of tube trailers but may be justified by reduced operating cost for H_2 haulers. Development and qualification of higher pressure TITAN® systems deferred because high development cost of higher pressure systems is not supported by adjacent CNG business case and/or near-term emergence of demand for hydrogen systems. Hexagon Lincoln has developed and continues to develop high pressure tankage for storage and transport of hydrogen at pressures up to 1000 bar (14,500 psi). We

DOE Technical Targets	Project Results and Future Direction
	are currently executing and negotiating several projects that utilize these vessels for stationary and mobile hydrogen applications. Extension of TITAN® large tank systems to 400 bar and 520 bar operation is straightforward in terms of engineering. Costs for qualification testing are very high. Hexagon Lincoln will continue to consider the economic feasibility of continued development in this direction as the hydrogen economy develops and solidifies.
Tube Trailer Delivery Capacity Targets **700 kg** by FY2015 → GOAL ACHIEVED **940 kg** by FY2020	TITAN® module (4-tube ISO container) - contains 616 kg of hydrogen, **585 kg** deliverable at 94% efficiency. XL trailer (5-tube trailer with 7 intermediate tanks) – contains 890 kg of hydrogen, **845 kg** deliverable at 95% efficiency. Future Direction Achieving the FY2020 target requires operation of the XL trailer at 350 bar. Trade studies indicate that a 350 bar system would contain 1176 kg of hydrogen, 1120 kg deliverable at 95% efficiency. The GVW of this truck/semitrailer would be less than 80,000 lb.

REFERENCES

[1] American Bureau of Shipping, ABS Pub-116 *Guidance Notes on Review and Approval of Novel Concepts.*

[2] ISO 11439 2000, *Gas cylinders – High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles.*

[3] ISO 11119-3 2002, *Gas cylinders of composite construction – Specification and test methods –Part 3: Fully wrapped fibre reinforced composite gas cylinders with non-load-sharing or non-metallic liners).*

[4] ANSI/CSA NGV2-2007, *American National Standard for Compressed Natural Gas Vehicle Fuel Containers.*

[5] ASME BPVC-X-2010, *ASME Boiler and Pressure Vessel Code, Section X: Fiber-Reinforced Plastic Pressure Vessels.*

[6] ISO 1496-3 1995(E), *Series 1 freight containers – Specification and testing – Part 3: Tank containers for liquids, gases and pressurized dry bulk*.

APPENDIX A - TITAN® Qualification Plan - TITAN® Tank and ISO Frame Qualification Tests

LINCOLN COMPOSITES
A Member of Hexagon Composites Group

Titan ™ Qualification Plan

Titan™ Tank and ISO Frame Qualification Tests

Lincoln Composites
6801 Cornhusker Highway
Lincoln, NE 68507

Revision E

12 Oct 2009

Verify that printed copies of this document are the correct revision before use.

Approvals	Originator	Program Management	Test Engineer	Design	Quality	Bus. Development
Name	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Date	12 Oct 2009	12 OCT 09	12 Oct 2009	14/Oct/2009	10/14/09	14 OCT 09

Report Change History:

2 Jul 2008 – Initial release

30 Oct 2008 – Changed Para 4.1.18 from 1000 gas cycles to a minimum of 1000 hydro cycles and 5 gas cycles followed by a blow down. Changed the vessel size used in Para 4.1.18 from 120" long to 458.6". D. Morgan

5 Dec 2008 – Moved the bonfire test from the tank testing area to the ISO container test area. The bonfire test will be a test on the system rather than a vessel, see paragraph 4.2.2.

Added allowance to move the pivot point from ground level to 6" maximum off the ground, see paragraph 4.2.3. D. Morgan

18 Jun 2009 - Paragraph 4.1.1.2 reworded to match SPEC 09001
- Changed the leak test in Paragraph 4.1.1 to 15 min hold for leak test.
- Changed the Ambient Cycle test in Paragraph 4.1.5 to 45,000 cycles.
- Added hold time and burst requirement to Paragraph 4.1.8. and increased the cycle test pressure from 125% of working pressure to 130% of working pressure.

18 Aug 2009 – Removed Appendix A, B, C, and D. Items will are covered in SPEC 09001.

12 Oct 2009 – Added reference to Lincoln Composites SPEC 09001.

1.0 Introduction

Lincoln Composites, Inc, (LC), has been a manufacturer of filament wound composite products since its founding as a part of Brunswick Corporation in 1963. Lincoln Composites operated from 1995 under Technical Products Group Inc, and Advanced Technical Products Inc. In June 2002, Advanced Technical Products was purchased by General Dynamics, ATP. Then in January 2006, General Dynamics sold its Commercial Operation to Hexagon Composites group and Lincoln Composites now is a member of this group.

LC first built filament wound rocket motor cases, which developed into a composite pressure vessel product line in 1965. Since that time, LC composite pressure vessels have been used in aerospace, defense, automotive, commercial, and oil & gas applications. LC has produced over 120,000 cylinders, and has many approvals through DOT and other government or certification agencies. Some of these applications are listed in the following table.

Application	Comments
Skylab	first man-rated composite PVs in space
Space Shuttle	23 vessels per orbiter, still in service after 25 years
Life raft	20,000+ units placed in service
Boeing 767	Inflation of escape slide, DOT-E 7769
Sikorsky S-76	490 sphere, FAA approval
CNG tank	13 in x 10 ft hoop wrap, DOT-RSPA special permit
Aircraft systems	Bonded boss, DOT-E 8487
Oil Platform accumulators	ASME Section X approval
Vehicle accumulators	Developed for EPA to improve vehicle fuel efficiency, operating at 500 psi, 5000 psi, and 7000 psi
NGV fuel tanks	In service since 1992. Certified to NGV2. Certified to DOT-NHTSA FMVSS 304. Over 80,000 in service
Hydrogen fuel tanks	In service since 1999.
Snorkler pressure vessel	7.1 x 15.5 in., hydrogen at 10,000 psi, aluminum liner
Hyper-X pressure vessel	7.1 x 31.3 in., hydrogen at 8500 psi, aluminum liner
Tuffshell bulk-hauling tank	Certified to NGV2 and in use in Australia

Recognizing the need for a lightweight transport and storage of bulk gasses, LC has developed the Titan™ Tank, a large, plastic lined, high pressure tank that is 42 inches in diameter and 38 feet long storing approximately 8400 L water volume.

This document outlines the tests that will be used to qualify the Titan™ tank and ISO frame for bulk storage and transportation of gases. LC has designed and built cylinders to be used in applications where they are needed for their lightweight, low cost, high performance, long life, and safe operation. LC currently manufactures the largest high pressure, fully wrapped, composite pressure vessels (Type III or Type IV) available. There are several benefits to increasing the size of the tanks that are available; the biggest advantage is that the user will have the capability to transport a larger volume of gas at a lower weight, decreasing the cost to hauling gas. The large tank size will also reduce the quantity, cost, and complexity of valves and associated plumbing and therefore have higher system reliability. Specific applications include the assembly of these cylinders into an intermodal ISO frame for transportations of hydrogen or natural gas and other specialty gasses such has helium and nitrogen.

The Titan™ Tank is a cylinder with nominal dimensions of 1.07 m (42 inches) in diameter and 11.63 m (458 inches) in length. They will nominally be 8400 liters water capacity for each cylinder. The operating pressure of the tank will be 250 bar (3626 psi) at 15°C (59°F). The tank has a 2.35 burst ratio. The applications would be for individual cylinders and for four cylinders that are installed in a custom designed ISO frame. The ISO frame would be compliant with existing size and interface standards for ISO containers.

The Titan ™ tank will use carbon fiber as the primary reinforcement. The outside of the cylinder will be coated with an elastomeric coating that provides a durable protection against cuts, abrasions, and other similar damage. The cylinders covered under this special permit request use a high density polyethylene (HDPE) liner which is attached to the metal end bosses under an LC patent [1].

None of the current standards specifically apply to this tank due to its large size and volume of gas. However, there are several standards that apply to smaller vessels that are widely accepted. LC has reviewed the existing standards and applied those that best apply to the development of this cylinder. The following standards were reviewed for input to determine the appropriate requirements that would apply to a cylinder of this size.

- Lincoln Composites SPEC 09001 - Gas Cylinders – Refillable, Permanently Mounted Composite Tube for Transportation
- ISO 11439, *Gas cylinders — High Pressure Cylinders for the On-Board Storage of Natural Gas as a Fuel for Automotive Vehicles* [2]
- ISO 11119-3, *Gas Cylinders of Composite Construction (fully wrapped non-metallic liners)*[3]
- ANSI/CSA NGV 2-2007, *American National Standards for Natural Gas Vehicle Fuel Containers*[4]
- ASME Code Case in Work / ASME BPV Project Team on Hydrogen Tanks and Section X

For the ISO frame that will contain the cylinders and plumbing, the design and testing is based on ISO 1496-3, *Tank containers for Liquids, Gases and Pressurized Dry Bulk* [5]. ABS Rules for Certification of Cargo Containers, CSC, The International Convention for Safe Containers, and Section 41 of the UN Recommendation on the Transport of Dangerous Goods, Manual of Test and Criteria (ST/SG/AC.10/11/ Rev.4) were also reviewed to make sure that all the relevant tests were covered.

In addition, LC has employed the services of American Bureau of Shipping (ABS) due to the Titan™ Tanks being mounted in an ISO frame for transportation of CNG and compressed hydrogen via road, rail and ship and is regarded as novel technology based upon the following:

- Large Tank Size compared to existing tanks in use.
- No experience and service history on land or marine
- No regulation and design codes exist for proposed size.

Due to novel technology as determined above, ABS has agreed that this tank would be treated as a special case and follow ABS Novel Technology Guidelines for certification.

The ABS scope of work involves:

1. Engineering Evaluation
2. Risk Evaluation
3. Prototype Test and Evaluation
4. Certification services of the containers to ABS/CSC and ISO and facilitate special approval from IMDG (for marine transportation) and specific approval from the competent authority of the country of use.

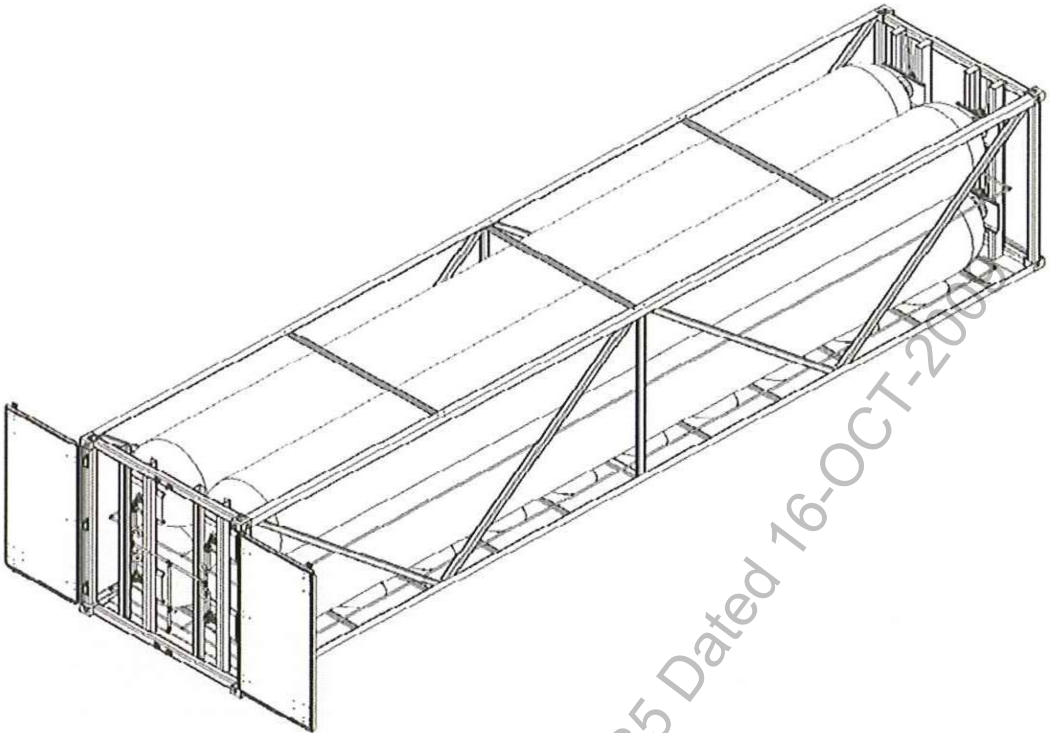

Figure 1, ISO Frame with Four Cylinders

2.0 Written description

Vessel Construction: The ABS plastic-lined composite pressure vessel consists of a durable plastic liner fully wrapped with a high performance carbon fiber reinforced plastic (CFRP) shell. An elastomeric covering is applied over the structural shell to enhance the durability of the vessel.

Plastic Liner: The liner is a non-structural permeation barrier for the containment of gases at high pressure. It is formed from a High-Density Polyethylene (HDPE) copolymer specifically designed for industrial piping. By virtue of its low modulus, the liner transfers all loads to the composite shell.

The liner is an assembly of two injection molded domes and an extruded tube joined together at two places by butt fusion weld. At each end of the liner is a metal boss which provides the structural interface between the system and the vessel. The bosses are integral to the liner, joined to the dome as an insert in the injection molding process. A circumferential keyway in the boss flange fills with plastic in the molding process, which interconnects the dome and boss. The interface is purely mechanical and is designed such that there is no tendency for the plastic to creep under pressure. The interlocking surface of the boss is coated with a thin layer of elastomeric material prior to molding which serves as a low pressure gasket. Contact between the flexible plastic liner and the ridged boss provides a highly effective and reliable seal. The design features of this interface are further described in U.S. Patent 5,429,845 [1].

The primary advantage a flexible plastic liner offers is its general durability and practically infinite cycle life. Due to its low modulus and high elongation, a plastic liner is insensitive to material flaws and loading.

Structural Composite Shell: The structural composite shell is the load-carrying element of the vessel. It is a continuous carbon fiber and epoxy resin composite fabricated by filament winding. Carbon fiber provides high strength-to-weight performance, excellent fatigue properties, insensitivity to environmental degradation, and performance reliability.

The resin system is a proprietary formulation developed by LC specifically for the plastic-lined vessel. This resin provides a suitable glass-transition temperature (T_g) with a cure temperature below the liner softening point. Resin protects the fiber from the environment and maintains fiber placement.

The composite is a multi-layered angle-plied structure constructed by winding resin impregnated fiber (wet) onto the liner using specific patterns to orient the fiber in a manner which yields the most efficient use of material. Composite materials have several advantages over conventional materials. First, polymeric matrix composites can be formulated to be extremely resistant to environmental and chemical exposure. Second, the specific strength of composites (particularly carbon-based) is much higher, thus permitting a lower structure weight. And lastly, the material can be oriented to tailor specific properties for a structure based on the loading condition. In the case of a pressure vessel, the hoop strength and axial strength can be controlled independently by varying fiber orientation and thickness of the reinforcing material respectively. It is because of these qualities that composites are an ideal choice of material for pressure vessels in a variety of applications.

Elastomeric Coating: An elastomeric polyurethane coating is applied to the external surface of the composite to protect against ultra-violet degradation of the epoxy resin and to impede moisture intrusion. This coating will also protect against cuts, abrasions, and other similar damage.

Pressure Relieve Device: A thermally activated sensor will protect the full length of the cylinder or will be located in several discrete locations to protect the full length of the ISO frame. Once the sensors detect a thermal incident it will open a valve on each of the cylinders in the system and vent the cylinders.

ISO Frame: A steel frame will hold four boss mounted cylinders for transport. The frame is a welded assembly that will have a truss-like structure along the sides and a cabinet for protecting the plumbing and associated hardware. The bottom floor is continuous metal with drain holes to reduce the chance of debris hitting the cylinders. The sides and top of the frame can be either left open or optional side panels can be installed.

3.0 Test Summary

Due to the fact that no standard directly covers an all composite cylinder of this size and pressure, several standards were reviewed to determine the best qualification tests.

The following tests will be used to demonstrate the performance of the Titan™ tank and associated ISO frame. Several standards were used to develop the test plan for the Titan™. There are three primary areas the tests can be grouped in to describe the test that will be performed:

1. Subscale tanks – Several tests that will be performed focus on the materials that will be used in the fabrication of the Titan™ tank and not the manufacturing process or the design of the tank. For these tests, subscale tanks will be used to qualify the materials.
2. Full diameter tanks – For tests that are qualifying the manufacturing process or the design of the cylinders, a full diameter tank will be used. For tests that the length does not have a contributing factor on the outcome, 10 foot long tanks will be used as opposed to 38 foot long tanks.
3. ISO frame – The primary outline for the tests on the ISO frame will be from the standard ISO 1496-3 including Amendments 1 and 2.

Table 1 outlines the testing that will be done on the tanks. It includes the tests that will be done on both the subscale and full scale tanks. It provides the passing criteria for the tests as well as the specimen size and the origin of the test. Further explanation for the test and the background for each test will be provided in Section 3.

Table 2 briefly summarizes the tests that will be done on the ISO container and the loads that will be used during the tests. The maximum load rating for a loaded ISO frame (R) is 25401.2 kg (56,000 lbs). This is based on a tare weight of 17690.1 kg (39,000 lbs) and a payload of 7711.1 kg (17,000 lbs).

Table 1, Subscale and Fullscale Tank Testing

Qualification Tests			
Tests	Test Description	Specimens	Standard Reference and exceptions
Hydraulic Proof Pressure Test/Leak Check	This test requires that the hydraulic pressure in the cylinder be increased gradually and regularly to 1.5 x operating pressure (1.5 x 250 bar = 375 bar). The cylinder test pressure shall be held for a sufficiently long period (at least 30 s) to ascertain that there are no leaks and no failure. The cylinder shall be rejected if there are leaks, failure to hold pressure or visible permanent deformation after the cylinder is depressurized.	This will be done on every tank before any other tests.	ASME Code Case in Work / ASME BPV Project Team on Hydrogen Tanks
Hydraulic Volumetric Expansion Test	This test requires that the hydraulic pressure in the cylinder increase gradually and regularly to 1.5 times operating pressure. The cylinder test pressure shall be held for a sufficiently long period (at least 30 s) to ascertain that there are no leaks and that there is no failure. If leakage occurs in the piping or fittings, the cylinders may be re-tested after repair of such leakages. The elastic expansion shall be measured between 10% test pressure and the test pressure and recorded. The cylinder shall be rejected if either: a) it shows an elastic expansion in excess of 110% of the average elastic expansion for the batch at manufacture, or b) there are leaks or failure to hold pressure.	This will be done on every tank before any other tests in parallel with proof/leak test.	ASME Code Case in Work / ASME BPV Project Team on Hydrogen Tanks

Qualification Tests

Tests	Test Description	Specimens	Standard Reference and exceptions
Material test for plastic liners	The tensile yield strength and ultimate elongation shall be determined in accordance with the following: The tensile yield strength and ultimate elongation of plastic liner material shall be determined at -50 °C in accordance with ISO 527-2. The test results shall demonstrate the ductile properties of the plastic liner material at temperatures of -50 °C or lower by meeting the values specified by the manufacturer. The softening temperature shall be determined in accordance with the following: Polymeric materials from finished liners shall be tested in accordance with a method described in ISO 306. The softening temperature shall be at least 100 °C.	As required in ISO 11439	SPEC 09001 paragraph 6.5.2.2 ISO 11439 paragraph 9.5.2.2
Hydrostatic Burst Tests	Cylinders shall be hydrostatically pressurized to failure. The cylinder burst pressures shall exceed 587.5 bar (2.35 x 250 bar), providing a minimum stress ratio of 2.35.	Virgin burst on 16"x71", 42"x120" and 42"x458.6"	SPEC 09001 paragraph 6.5.2.3 ISO 11439 paragraph 9.5.2.3 except two full scale burst units All other subscale tank configurations will also be burst tested for reference.

Qualification Tests			
Tests	Test Description	Specimens	Standard Reference and exceptions
Ambient Cycle Test	Cylinders shall be pressure cycle tested at ambient temperature between 20 bar and 325 bar at a rate not exceeding 10 cycles per minute to a minimum of 45,000 cycles. The cylinders shall not fail before reaching the specified service life (20 yrs) in years multiplied by 750 cycles. Cylinders exceeding 15,000 cycles shall fail by leakage and not by rupture. Cylinders which do not fail within 45,000 cycles shall be deemed to have passed this test. Cylinders exceeding 45,000 cycles are permitted to fail by rupture. The number of cycles to failure and the location of the failure initiation shall be recorded. One full scale test, 750 cycles/year, minimum of 15,000 cycles. The cylinder must not fail by rupture under 45000 but may leak over 15000 cycles. The plan is to test one full scale test unit. Two additional samples will be satisfied by the LBB tests. The LBB is the same test except at a higher pressure. If the LBB tanks do leak before 15000 cycles an additional full scale unit will be tested.	(1) 42"x458.6" + (1 optional) 42"x458.6" if LBB leaks before 15,000 cycles	SPEC 09001 paragraph 6.5.2.4 ISO 11439 paragraph 9.5.2.4, except one full scale cycle test. Service life will be multiplied by 750 cycles per year due to the low cycle requirement for this tank.
LBB	Two cylinders cycled between 20 bar and 375 bar (250 x 1.5) at a rate not to exceed 10 cycles per minute. All cylinders shall either fail by leakage or exceed 45000 pressure cycles.	(2) 42"x120"	SPEC 09001 paragraph 6.5.2.5 ISO 11439 paragraph 9.5.2.5, except two 120" tanks shall be tested.
Penetration Test	A cylinder pressurized to 250 bar with compressed gas shall be penetrated by an armor piercing bullet with a diameter of at least 7.62 mm. The bullet shall completely penetrate at least one side wall of the cylinder. If the initial projectile does not penetrate, additional shots will be fired at the tank until it is penetrated. The projectile shall impact the sidewall at an approximate angle of 45°. The cylinder shall not rupture. Test one 42"x120" tank, shoot with armor piercing bullet	(1) 42"x120"	SPEC 09001 paragraph 6.5.2.7 ISO 11439 paragraph 9.5.2.7.
Environmental Test	Environmental Test per NGV2 Test is for environmental stability of composite, which is independent of the size of the tank.	(1) 16"x71" without outside protective coating	SPEC 09001 paragraph 6.5.2.8 NGV2-2000 paragraph 18.4

Qualification Tests			
Tests	Test Description	Specimens	Standard Reference and exceptions
Flaw Tolerance Test	As a minimum, one flaw shall be 130 mm long and 2.5 mm in depth and another flaw shall be 1000 mm long and 1.5 mm in depth, cut in the longitudinal direction into the cylinder sidewall. The flawed cylinder shall then be pressure cycled between 20 bar and 325 bar at ambient temperature, initially for 3000 cycles, then followed by an additional 12000 cycles. The cylinder shall not leak or rupture within the first 3000 cycles, but may fail by leakage during the further 12000 cycles. All cylinders which complete this test shall be destroyed.	(1) 42"x120" without coating	SPEC 09001 paragraph 6.5.2.9 ISO 11439 paragraph 9.5.2.9 except flaws are larger than specified
High Temp Creep	The cylinder shall be pressurized to 375 (250 x 1.5) bar and held at a temperature of 100° C for not less than 200 h; following the test, the cylinder shall meet the requirements of the volumetric expansion, the leak test, and burst. Test is for thermal stability of composite, which is independent of the size of the tank.	(1) 16"x71"	SPEC 09001 paragraph 6.5.2.10 ISO 11439 paragraph 9.5.2.10, except higher test pressure (ref. ISO 11119-3).
Accelerated Stress Rupture	One cylinder shall be hydrostatically pressurized to 250 x 1.5 bar at 65 °C. The cylinder shall be held at this pressure and temperature for 1000 h. The cylinder shall then be pressured to burst; the burst pressure shall exceed 85 % of the minimum design burst pressure. Test is for thermal stability of composite, which is independent of the size of the tank.	(1) 16"x71"	SPEC 09001 paragraph 6.5.2.11 ISO 11439 paragraph 9.5.2.11, except higher test pressure (ref. ISO 11119-3).
Extreme Temp Pressure Cycling	One cylinder, without protective coating, shall be cycled to 5000 cycles from atmospheric pressure to 250 bar at a temperature between 60 °C and 70 °C and at a relative humidity greater than or equal to 95 % for 48 hours . Then an additional 5000 cycles from atmospheric pressure to 250 bar at a temperature between – 50 °C and – 60 °C by regulating the environmental chamber and the cycling frequency. The cylinder shall then be stabilized to ambient and cycled 30 times from ambient to 375 bar. On completion of these tests, the cylinder shall be burst with a minimum value of 525 bar.	(1) 42"x120"	SPEC 09001 paragraph 6.5.2.12 ISO 11119-3 paragraph 8.5.6

Qualification Tests			
Tests	Test Description	Specimens	Standard Reference and exceptions
Resin Shear Strength	Resin materials shall be tested on a sample coupon representative of the composite overwrap in accordance with ASTM D2344. Following 24 h boiling in water, the composite shall have a minimum shear strength of 13.8 MPa.	Create specimen per ASTM D2344.	SPEC 09001 paragraph 6.5.2.13 ISO 11439 paragraph 9.5.2.13
Drop Test	Due to the large size of these cylinders, the drop test is not a realistic test. Any cylinder dropped from a[illegible]nts described in a typical drop test would be deemed not fit for u[illegible]. These tanks will be installed in the ISO frame for a longitudinal impa[illegible]t will demonstrate the robustness of these tanks.		
Boss Torque test	The body of the cylinder shall be restrained against rotation and a torque of twice the valve or PRD installation torque specified by the manufacturer shall be applied to each end boss of the cylinder. The torque shall be applied first in the direction of tightening a threaded connection, then in the un-tightening direction, and finally again in the tightening direction. The cylinder shall then be subjected to a hydrostatic leak test.	(1) 42"x120"	SPEC 09001 paragraph 6.5.2.15 ISO 11439 paragraph 9.5.2.15
Permeation	One finished cylinder shall be filled with compressed natural gas, H2, or He to working pressure, placed in an enclosed sealed chamber at ambient temperature, and monitored for leakage for 500 h. The permeation rate shall be less than 0.25 ml of natural gas per hour per liter water capacity of the cylinder. The cylinder shall be sectioned and the internal surfaces inspected for any evidence of cracking or deterioration. Liner material is the same on all LC cylinders.	(1) 16"x71"	SPEC 09001 paragraph 6.5.2.16 ISO 11439 paragraph 9.5.2.16
Natural Gas Cycling Test	One cylinder shall be hydraulically cycled for a minimum of 1000 cycles from less than 20 bar to 250 bar (290 psi to 3626 psi) followed by 5 cycles with natural gas from less than 20 bar to 250 -0/+7 bar (290 psi to 3626 psi). The cylinder shall be leak tested. Following the completion of the natural gas cycling the cylinder shall be sectioned and the liner and liner/end boss interface inspected for evidence of any deterioration, such as fatigue cracking or electrostatic discharge.	(1) 42"x458.6"	SPEC 09001 paragraph 6.5.2.17 ISO 11439

Qualification Tests			
Tests	Test Description	Specimens	Standard Reference and exceptions
Blowdown Test	Cylinder is pressurized to 250 bar with natural gas and vented to ambient pressure through an open valve. The cylinder shall be leak tested. Following the completion of the natural gas cycling the cylinder shall be sectioned and the liner and liner/end boss interface inspected for evidence of any deterioration, such as fatigue cracking or electrostatic discharge.	(1) 42"x120"	SPEC 09001 paragraph 6.5.2.17

Table 2, ISO Frame Testing

ISO Frame Qualification Tests		
Tests	Test Description	Standard Reference
Dimensional Check	Dimensions of the frame will be checked to verify they are within specified tolerances	ABS 7.11.1; ISO 668, 5
Stacking	86,400 kg will be applied to each of the corner castings to represent a stacking of 9 containers on top of the ISO frame	ABS 7.11.2; ISO 1493-3, 6.2
Lifting – Top	The container will be lifted from the top four corner fittings when the container is loaded to 2R	ABS 7.11.3; ISO 1493-3, 6.3
Lifting – Bottom	The container will be lifted from the bottom four corner fittings with the container is loaded to 2R	ABS 7.11.4; ISO 1493-3, 6.4
Longitudinal Restraint	While loaded to R, two of the bottom corner fittings will restrained. Then the other two bottom fittings will be loaded horizontally to $2R_g$, first towards the anchor points and then away.	ABS 7.11.9; ISO 1493-3, 6.5
Transverse Racking	With the four bottom corners anchors, a load of 150 kN shall be applied to the top corner fittings in lines parallel to the base and end lines of the container. The force will be applied both towards the container and away from the container.	ABS 7.11.13; ISO 1493-3, 6.8
Longitudinal Racking	With the four bottom corners anchors, a load of 75 kN shall be applied to the top corner fittings in lines parallel to the base and sides of the container. The force will be applied both towards the container and away from the container.	ABS 7.11.14; ISO 1493-3, 6.9
Lateral Inertia	The container shall be loaded to R. The container shall be held with the longitudinal axis held vertical for five minutes.	ABS 9.11.3; ISO 1493-3, 6.6

ISO Frame Qualification Tests		
Tests	Test Description	Standard Reference
Longitudinal Inertia	The container shall be loaded to R. The container shall be held with the transverse axis held vertical for five minutes.	ABS 9.11.2,; ISO 1493-3, 6.7
Dynamic Impact	The container shall be loaded to R. All four bottom corners of the container shall be locked and the container shall be impacted where the corner fittings closest to the impact register an impact that meets or exceeds those shown on Table D.1 in Amendment 1 of ISO 1496-3.	ABS 9 11 X; ISO 1493-3, 6.6 (Amendment 1)
Pressure Test	On the completion of the above tests the tanks will be hydraulically pressure tested to verify the integrity of the tanks and that there is no leakage. The tanks will be taken to operating pressure and held for a minimum of 30 seconds. The tanks may be removed from the frame for this test due to the volume of the water needed to fill the tanks.	ABS 9.11.4; ISO 1493-3, 6.13
Bonfire	One ISO container containing four composite cylinders shall be tested with respect to ISO 11439, A.15.	ISO 11439 paragraph 9.5.2.6

4.0 Test Descriptions

The following paragraphs describe the background for the tests and why they are required for the qualification of the Titan Tanks.

4.1 Tank Testing

4.1.1 Hydraulic Proof Pressure Test/Leak Check

Every tank will be proof pressure tested to 1.56 times operating pressure and checked for water leaks before any additional tests will be done. This is the same as will be done in production. The vessel will be pressurized to 375 bar (5439 psi) then this pressure will be held for 15 minutes. After the pressure is brought down to zero, the tank will then be inspected for water that would indicate a leak.

The purpose of these tests is to check the integrity of the tanks. The proof test indicates that the vessel ready for operation and the leak test checks the integrity of the vessel liner. The vessel must not leak, fail to hold pressure, or have any permanent deformation after the cylinder is depressurized.

4.1.2 Hydraulic Volumetric Expansion

Also during the hydraulic proof test, the volumetric expansion of the vessel will be measured. This test will be done by measuring total axial growth and the total diameter growth in 3 places. The purpose of the test is to check the expansion versus the design and other tanks that have been tested. This is a process check to verify that nothing unusual happened during the manufacture of the tank and that no material was left off of the winding.

The vessel shall not have elastic expansion in excess of 110% of the average elastic expansion for the batch at manufacture or fail to meet the design requirements for elastic expansion or have any leaks or fail to hold pressure.

4.1.3 Material test for plastic liners

The material for the plastic liner will be tested to determine the ductility of the plastic at cold temperatures and the softening temperature at elevated temperatures. These tests will be used to show that the liner can withstand the operating temperatures of the vessel.

ISO 527-2 will be used to check the ultimate elongation, tensile yield strength and show ductile properties of the plastic liner material. ISO 306 will be used to determine the softening temperature.

4.1.4 Hydrostatic Burst

The hydrostatic burst test will be used to show design margin of the structural overwrap. The vessel will be pressurized until failure. There will be a ten second hold at the minimum burst pressure. The results of this test will show adequacy of the design for a 250 bar (3626 psi) tank with a 2.35 burst ratio. The minimum burst pressure will be at least 587.5 bar (8521 psi).

To demonstrate the stress ratio of every size tank that is being tested, every configuration will have at least one burst test.

4.1.5 Ambient Cycle

The ambient cycle test is used to demonstrate the robustness of the tank for the duration of its life. The vessel will be pressurized 45,000 times. The vessel will be cycled from less than 100 psi to 4714 +100/-0 PSI. The vessel must not fail by rupture at less than 45000 cycles; it may leak at over 15000 cycles.

A 42"x458.6" vessel will be tested. Additional cycle performance will be shown on the Leak Before Burst test.

4.1.6 Leak Before Burst (LBB)

The LBB test demonstrates the safety of the tanks, that even under severe conditions the tank will leak and not burst or will have significant safety margin in cyclic fatigue testing. The tank will be cycled from less than 20 bar and 375 bar (290 psi to 5439 psi) for 45,000 cycles unless leakage occurs before 45,000 cycles. This pressure cycle is much more severe than the standard pressure cycle test.

All cylinders shall either fail by leakage or exceed 45,000 pressure cycles.

Two 1.067 m x 3.048 m (42"x120") vessels will be tested. If either of these test leak before 45,000 cycles an additional 120" vessel will by cycled per 4.15.

4.1.7 Penetration Test

The penetration test is to demonstrate the safety of the vessel against rupture, even if it is penetrated by a projectile. A vessel pressurized to operating pressure will be penetrated by an armor piercing bullet with a diameter of at least 0.5 inches. The bullet shall completely penetrate at least one side wall of the cylinder. If the initial projectile does not penetrate, additional shots will be fired at the tank until it is penetrated. The projectile shall impact the sidewall at an approximate angle of 45°.

One 1.067 m x 3.048 m (42"x120") vessel will be tested.

4.1.8 Environmental

The environmental test will be performed per ANSI/CSA NGV2-2000 paragraph 18.4. This will be done without the final coating that will be applied to the vessel. The reason the coating is left off is to show that the composite (fiber and epoxy) is sufficient to withstand the environmental conditions of service. This way if there is a blemish in the coating, the vessel will not be at risk due to environmental conditions. For this test the vessel will be impacted and at the points of impact the vessel will be exposed to

a. Sulfuric acid - 19% solution by volume in water
b. Sodium hydroxide - 25% solution by weight in water
c. Methanol/gasoline – 5/95% concentration of M5 fuel meeting the requirements of ASTM ***04814,*** *Automotive Spark-Ignition Engine Fuel*
d. Ammonium nitrate - 28% by weight in water
e. Windshield washer fluid (50% by volume solution of methyl alcohol and water).

The vessel will then be pressurized 3000 cycles from 10% to 130% of service pressure. At the completion of the cycle test the vessel will be pressurized to 130% of service pressure and held for a minimum of 24 hours and until exposure time for the environmental fluids is 48 hours.

The vessel must not leak or rupture during the test. Upon competition of the pressure hold the vessel is to vented and then burst tested per Paragraph 4.1.4. The minimum burst pressure will be 1.8 time working pressure.

One 0.406 m x 1.08 m (16"x71") tank without outside protective coating shall be used for the test. Since the same resin and fiber will be used on a full scale tank as the subscale tank, size is not a key factor for this test.

4.1.9 Flaw Tolerance

To demonstrate the ability of the tank to withstand damage during service, a flaw tolerance test will be performed. For this test, flaws will be introduced into the vessel. One flaw shall be 130 mm long and 2.5 mm in depth and another flaw shall be 1000 mm long and 1.5 mm in depth, cut in the longitudinal direction into the cylinder sidewall. The flawed cylinder shall then be pressure cycled between 20 bar and 325 bar (290 psi to 4714 psi) at ambient temperature, initially for 3000 cycles, then followed by an additional 12000 cycles.

The cylinder shall not leak or rupture within the first 3000 cycles, but may fail by leakage during the further 12000 cycles.

A 1.067 m x 3.048 m (42"x120") cylinder without coating shall be used for this test.

This test will also be used to determine what type of damage a vessel will be able to have and stay in service.

4.1.10 High Temperature Creep

To test the stability of the composite at high temperatures and pressure, the cylinder shall be pressurized to 375 bar (5439 psi) and held at a temperature of 100°C (212° F) for at least 200 hours. The temperature requirements for this test are more extreme than those found in ISO 11439.

Following the test, the cylinder shall meet the requirements of the volumetric expansion, the leak test, and burst.

A 0.406 m x 1.08 m (16"x71") cylinder without coating shall be used for this test. This test is for thermal stability of the composite, which is independent of the size of the tank.

4.1.11 Accelerated Stress Rupture

Similar to high temperature creep, this test is to also check for the stability of the composite at high temperature and pressure. One cylinder shall be hydrostatically pressurized to 375 bar (5439 psi) at 65°C (149 °F). The cylinder shall be held at this pressure and temperature for 1000 hours. The temperature requirements for this test are more extreme than those found in ISO 11439.

The cylinder shall then be pressured to burst; the burst pressure shall exceed 85% of the minimum design burst pressure.

A 0.406 m x 1.08 m (16"x71") cylinder without coating shall be used for this test. This test is for thermal stability of the composite, which is independent of the size of the tank.

4.1.12 Extreme Temperature Pressure Cycling

To check the robustness of the design at the limits of the temperature range an extreme temperature pressure cycle test will be performed. One cylinder without protective coating, shall be as follows:

a) condition for 48 h at zero to 25 bar pressure, between 60 °C and 70 °C, and 95 % or greater relative humidity;
b) cycle the pressure in the cylinder for 5 000 cycles, between 25 bar and 250 bar, while maintaining a surface temperature between 60 °C and 70 °C by regulating the environmental chamber and cycle rate;
c) release the pressure and stabilize the cylinder at approximately 20 °C;
d) condition for 48 h at zero to 25 bar pressure, between - 50 °C and - 60 °C;
e) cycle the pressure in the cylinder for 5 000 cycles, between 25 bar and 250 bar, while maintaining a surface temperature between - 50 °C and - 60 °C by regulating the environmental chamber and cycle rate;
f) release the pressure and stabilize the cylinder at approximately 20 °C;
g) cycle the pressure in the cylinder for 30 cycles , between 25 bar and 375 bar.

The vessel shall be burst following the cycle test and have a minimum burst value of 525 bar (7614 psi).

A 1.067 m x 3.048 m (42"x120") cylinder without coating shall be used for this test.

4.1.13 Resin Shear Strength

Resin materials shall be tested on a sample coupon representative of the composite overwrap in accordance with ASTM D2344.

Following 24 h boiling in water the composite shall have a minimum shear strength of 2002 psi.

This is a material test that will use coupons for testing.

4.1.14 Drop Test

The only drop test for these tanks will be done in conjunction with the ISO frame drop test.

4.1.15 Boss Torque

To verify that there will be no problems with the hardware is installed on a vessel; the bosses will be torque to twice the value used on the PRD or valves. The boss will have a torque of 546 ft-lb applied a total of two times.

They cylinder shall not leak after the test.

A 1.067 m x 3.048 m (42"x120") or a 1.067 m x 11.65 m (42"x458.6") cylinder shall be used for this test.

4.1.16 Permeation

To determine the amount of gas that permeates through the liner a permeation test will be performed at a pressure of 250 bar.

The permeation rate shall be less than 0.25 ml of natural gas per hour per liter water capacity of the cylinder. The cylinder shall be sectioned and the internal surfaces inspected for any evidence of cracking or deterioration.

Since the same liner material is used on all of Lincoln Composites cylinders, a 0.406 m x 1.08 m (16"x71") vessel will be used for this test.

4.1.17 Natural Gas Cycling

To verify that cycling natural gas does not have a detrimental effect on the liner or boss, the vessel will be cycled for a minimum of 1000 hydro cycles from less than 20 bar to 250 bar (290 psi to 3626 psi) followed by 5 cycles with natural gas from less than 20 bar to 250 -0/+7 bar (290 psi to 3626 psi). Pressure is to be held at 250 -0/+7 bar for 2 hours during each cycle. After the final cycle a blow down test will be conducted using the plumbing that provides the most rapid venting. The tank will be monitored for leaks during the gas cycle and blow down tests.

After the cycling test, the vessel shall pass the leak test. The vessel shall then be inspected and the liner and liner/end boss interface inspected for evidence of any deterioration, such as fatigue cracking or electrostatic discharge.

A 1.067 m x 3.048 m (42"x458.6") cylinder shall be used for this test.

4.1.18 Blowdown

After the completion of the natural gas cycling test, for the final cycle the tank will be vented from 250 bar (3626 psi) to ambient. This will demonstrate the ability of the vessel to withstand the temperatures generated while venting a tank from operating pressure to ambient pressure.

The cylinder shall pass a leak test after this test.

A 1.067 m x 3.048 m (42"x120") cylinder shall be used for this test.

4.2 Frame Testing

As described above, the frame will be tested as outlined in ISO 1496-3 and ABS Rules for Certification of Cargo Containers. Due to this fact, the description of the test will not be described in any greater detail that listed above. The basic frame properties that are used to determine the loading for the frame are summarized below.

4.2.1 ISO Frame Capacities

Table 3 summarizes the capacities of the ISO Container and provides the loading that will be used during the ISO qualification tests.

Table 3, ISO Container Capacities

Maximum Gross Mass:[R]		Tare:[T]		Payload:[P]	
25401	Kg.	15496	Kg.	9905	Kg.
56000	lb	34161	lb	21836	lb
Design Pressure	250	bar		3626	psig

4.2.2 Bonfire

An area of potential concern with a pressure vessel is the presence of a fire under the tank. To mitigate this concern a bonfire test will be performed to demonstrate the ability of the pressure relief device on the tank to prevent the rupture of the cylinder.

The container will be placed horizontally approximately 12 inches above the fire source. A uniform fire source of 48 inches length and 24 inches wide will be used to provide direct flame impingement on the container surface. The flame source will be centered along one lower edge and centered on the containers length. It is to be oriented with it long dimension in the direct of the containers length. Within 5 minutes of ignition, the temperature will be greater than or equal to 1094°F on the control thermocouple. The control thermocouple will be mounted in a 1 inch steel square, .25 inches thick, attached to the bottom of the ISO frame. It will be located such that it is centered in the flame area. The cylinders shall vent through the pressure release device system.

One ISO container that is equipped with the PRD hardware will be tested.

5.0 Acceptance Testing/ Batch Testing

In addition to the qualification testing that will be used to show the adequacy of the design of the tank, every tank that is manufactured will also undergo acceptance testing to demonstrate that it was manufactured correctly. Each cylinder will undergo the following:

- Hydrostatic proof – Each cylinder will be pressured 1.56 times the operating pressure
- Hydrostatic leak – Each tank will be held at proof pressure for 30 seconds minimum. The tank will then be inspected to verify that there was no leakage
- Volumetric expansion – the volumetric expansion of the tank will be measured either direct volume measurement of the water put into the tank or by strain gages mounted on the outside of the tank
- Weight measurement
- Dimensional measurement

Along with the acceptance testing, every batch of tanks will also undergo batch testing. A batch of tanks will be defined as either every 6 months or every 200 tanks manufactured. For the batch testing, a tank of the same configuration will be pressurized to the minimum burst value. Tanks may or may not be ramped to failure if they exceed the minimum burst value. Upon completion of the test the tank will be made inoperable.

6.0 Re-Inspection Methods

The primary re-inspection method to be used is visual examination. LC has 15 years of successful experience using visual examination on NGV fuel containers as the sole or primary inspection method [6]. Periodic hydro-proof testing has not been used. Only one field failure has occurred in this time, in a vehicle fire for which the vehicle OEM determined the root cause was a system problem. These cylinders have been involved in a number of incidents [7], see Section 4.1. No failures resulted from these incidents, which included severe impacts and fires. Burst testing of several returned units showed that, in spite of severe and obvious impact damage, the damaged cylinders that were tested still met the original burst test requirements.

7.0 References

1. Newhouse, Norman L., Ronald B. Veys, and Dale B. Tiller, "Boss for a Filament Wound Pressure Vessel", U.S. Patent 5,429,845, July 4, 1995.

2. ISO 11439, "Gas cylinders — High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles", ISO, Geneva, Switzerland, 2000.

3. ISO 11119-3, "Gas Cylinders of Composite Construction", ISO, Geneva, Switzerland, 2002.

4. ANSI/CSA NGV2, "Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers", CSA International, Cleveland, Ohio, 2000.

5. ISO 1496-3, "Tank containers for Liquids, Gases and Pressurized Dry Bulk", ISO, Geneva, Switzerland, 1995.

6. "Fuel Container Inspection Guidelines, TUFFSHELL® NGV Fuel Containers & Fuel Storage Systems", Lincoln Composites, Inc., Rev.D, 2008.

7. Newhouse, Norman L., William E. Dick, and Michael P. Sheridan, "Safety and Durability of NGV Fuel Storage Systems", NGV2002, The 8th International and 20th National Conference and Exhibition on Natural Gas Vehicles, sponsored by the International Association for Natural Gas Vehicles and the Natural Gas Vehicle Coalition, Washington, DC, October 8-10, 2002

APPENDIX B - Design Qualification Test Report - Titan Compressed Natural Gas Transport Container

FOUNDED 1862 ABS

MMC
Project Number: 2086285
Task Number: 529706

20 NOVEMBER 2009

ABS Engineering Review of
Titan Compressed Natural Gas Transport Container
Design Qualification Test Report [Report No. 08020]

LINCOLN COMPOSITES
6801 CORNHUSKER HWY
LINCOLN, NE 68507

ATTN: MR. DAVE MORGAN, SR. TEST ENGINEER

We have your email dated 16th November 2009 submitting the Design Qualification Test Report [Report No. 08020] and with regard thereto have to advise that the subject document have been reviewed for compliance with the ABS approved Titan TM Qualification Test Plan dated 12 October 2009 Rev. E with satisfactory results. .

Upon your receipt of the ABS Inspection/Testing Reports, same has to be forwarded to this office for our record and file. Stamped copy of the aforementioned test report is attached with this letter. If we may be of further assistance, please feel free to contact the undersigned at (281) 877-6374.

Very truly yours,

Mathew M. Chakala
Managing Principal Engineer
ABS Offshore Engineering Department

cc: Paul L Beattie – Pbeattie@eagle.org
Harish Patel – hpatel@eagle.org

The information in this report is considered "BUSINESS CONFIDENTIAL" by Hexagon Lincoln LLC. Requests to review can be sent to the Director of Product Development, Hexagon Lincoln LLC, for consideration.

APPENDIX C - ABS Document No. ABSHOU557163 - ABS Requirements for Construction of Refillable Carbon Composite Road and Marine Transport Pressure Vessels

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ABS REQUIREMENTS FOR CONSTRUCTION OF REFILLABLE CARBON COMPOSITE ROAD AND MARINE TRANSPORT PRESSURE VESSELS

ABS DOCUMENT NO. ABSHOU557163

MARCH 2010

Revision Status					
Rev.	Date	Descriotion	Revised Bv	Aooroved Bv	Aooroved Bv
0	16 Februarv 2010	Initial Release	PS	MMC	HNP
1	5 March 2010	Editorial Revision	MMC	MMC	HNP

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Contents

Introduction

Cylinders of composite construction from 450 to 10 000 liters of water capacity for the bulk transport of pressurized ladings are desired to be light-weight and at the same time maintaining or improving on the level of safety currently existing for other cylinders.

These requirements are achieved by:

a) ABS Certification (design assessment, inspection and testing)
b) specifying service conditions precisely and comprehensively as a firm basis for both cylinder design and use;
c) using an appropriate method to assess cyclic and static pressure fatigue life;
d) requiring design qualification tests;
e) requiring non-destructive testing and inspection of all production cylinders;
f) requiring destructive tests on cylinders and cylinder material taken from each batch of cylinders produced;
g) requiring manufacturers to have a comprehensive quality system documented and implemented;
h) requiring periodic re-inspection and, if necessary, retesting in accordance with the manufacturer's instructions;
i) requiring manufacturers to specify as part of their design, the safe service life of their cylinders;
j) requiring cylinders to be permanently mounted in a frame during transportation and use.

Cylinder designs that meet the requirements of this Specification:

a) will have a fatigue life which exceeds the specified service life;
b) when pressure cycled to failure, will leak but not rupture or have a demonstrated cycle life three times the design number of filling cycles;
c) when subject to hydrostatic burst tests, will have factors of "stress at burst pressure" over "stress at working pressure" that exceed the values specified for the materials used.

The expiry date shall be marked on each cylinder. It is the responsibility of owners and users to ensure that cylinders are not used after that date and that they are inspected in accordance with the ABS approved inspection procedure.

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Gas Cylinders - Refillable Permanently Mounted Composite Tubes for Transportation

1 Scope

This Specification describes how Gas Cylinders *[Refillable Permanently Mounted Composite Tubes for Transportation]* built under ABS surveillance are inspected and certified in accordance with ABS Rules and ABS recognized industry standards. These instructions are not intended to alter any local regulatory requirements mandated by the country of use and are not intended to preclude the technical judgment that the ABS personnel must use while carrying out the engineering review and survey.

This Specification covers cylinders of filament-wound composite construction, using any design or method of manufacture suitable for the specified service conditions.

Cylinders covered by this Specification are designated as follows[1)]:

Type IV Resin impregnated continuous filament with a non-metallic liner (all composite)

2 Normative References

The following normative documents contain provisions which, through reference in this text, constitute provisions of this Specification. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this Specification are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ABS Rules for Certification of Cargo Containers

ABS Guidance Notes on Review and Approval of Novel Concepts

ABS Guidance Notes on Risk Application for the Marine and Offshore Oil and Gas Industries

ABS Guide for Building and Classing Compressed Natural Gas Carrier

ISO 306:2004, *Plastics — Thermoplastic materials — Determination of Vicat softening temperature (VST)*.

ISO 527-2:1993, *Plastics — Determination of tensile properties — Part 2: Test conditions for moulding and extrusion plastics (incorporating Technical Corrigendum 1:1994)*.

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[1] Type I, II, and III are known to refer to other construction types

ISO 2808:2007. *Paints and varnishes — Determination of film thickness.*

ISO 4624:2002. *Paints and varnishes — Pull-off test for adhesion.*

ISO 7225. *Gas cylinders — Precautionary labels.*

ISO 9227:2006. *Corrosion tests in artificial atmospheres — Salt spray tests.*

ISO 14130:1997. *Fibre-reinforced plastic composites — Determination of apparent interlaminar shear strength by short-beam method.*

ASTM D522-93a(2008). *Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings.*

ASTM D1308-02(2007). *Standard Test Method for Effect of Household Chemicals on Clear and Pigmented Organic Finishes.*

ASTM D2794-93(2004). *Standard Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact).*

ASTM D3170-03(2007). *Standard Test Method for Chipping Resistance of Coatings.*

ASTM D3418-08. *Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry.*

ASTM G154-06. *Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials.*

NACE TM0177-96. *Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H_2S Environments.*

ISO 1496-3. *Series 1 freight containers — Specification and testing — Part 3: Tank containers for liquids, gases and pressurized dry bulk.*

3 Terms and Definitions

For the purposes of this Specification the following terms and definitions apply:

3.1 Batch of Liners

Group of not more than 200 liners (plus liners for destructive testing). or if the number of fabricated liners is less than 200 per year. one year of liners. produced having the same nominal diameter. wall thickness. design. specified material of construction and process of manufacture.

3.2 Batch of Composite Cylinders

Group of not more than 200 cylinders (plus cylinders for destructive testing). or if the number of production cylinders is less than 200 per year. one year of cylinders. produced from qualified liners having the same size. design. specified materials of construction and process of manufacture.

3.3 Burst Pressure

Highest pressure reached in a cylinder during a burst test.

3.4 Composite Cylinder

Cylinder made of resin-impregnated continuous filament wound over a liner.

3.5 Filling Pressure

Pressure to which a cylinder is filled..

3.6 Finished Cylinders

Completed cylinders which are ready for use. typical of normal production. complete with identification marks and external coating including integral insulation specified by the manufacturer. but free from non-integral insulation or protection.

3.7 Gas Temperature

Temperature of gas in a cylinder.

3.8 Liner

Container that is used as a gas-tight. inner shell. on which reinforcing fibres are filament-wound to reach the necessary strength.

NOTE: Non-metallic liners do not carry any part of the load.

3.9 Manufacturer

Person or organization responsible for the design. fabrication and testing of the cylinders.

3.10 Overwrap
Reinforcement system of filament and resin applied over the liner.

3.11 Service Life
life. in years. during which the cylinders may safely be used in accordance with the standard service conditions.

3.12 Settled Pressure
Gas pressure when a given settled temperature is reached.

3.13 Settled Temperature
Uniform gas temperature after the dissipation of any change in temperature caused by filling.

3.14 Test Pressure
Required pressure applied during a pressure test..

3.15 Working Pressure
Settled pressure of 250 bar at a uniform temperature of 15 °C.

3.16 Permanent Gas
A fluid that remains in a gaseous state over the cylinder's rated service pressure and temperature range.

4 Service Conditions

4.1 General

4.1.1 Standard Service Conditions

The standard service conditions specified in this clause are provided as the basis for the design, manufacture, inspection, testing and approval of cylinders that are to be permanently mounted in a frame and used to transport permanent gases at ambient temperatures.

4.1.2 Use of Cylinders

The service conditions specified are also intended to provide information on how cylinders manufactured in accordance with this Specification may safely be used; this information is intended for

a) manufacturers of cylinders;
b) owners of cylinders;
c) designers or contractors responsible for the installation of cylinders;
d) designers or owners of equipment;
e) suppliers of pressurized gases;
f) regulatory authorities who have jurisdiction over cylinder use.

4.1.3 Service Life

The service life for which cylinders are safe shall be specified by the cylinder manufacturer on the basis of use under service conditions specified herein. Service life shall be demonstrated by appropriate design methods, design qualification testing and manufacturing controls. The maximum service life shall be 30 years.

4.2 Maximum Pressures

This Specification is based upon a working pressure of 250 bar settled at 15 °C for a permanent gas with a maximum filling pressure of 325 bar. Other working pressures may be accommodated by adjusting the pressure by the appropriate factor (ratio); e.g., a 200 bar working pressure system will require pressures to be multiplied by 0.80.

Except where pressures have been adjusted in this way, the cylinder shall be designed to be suitable for the following pressure limits:

a) a pressure that would settle to 250 bar at a settled temperature of 15 °C;
b) the maximum shall not exceed 325 bar, regardless of filling conditions or temperature.

4.3 Design Number of Filling Cycles

Cylinders shall be designed to be filled up to a settled pressure of 250 bar at a settled gas temperature of 15 °C for up to 750 times per year of service.

4.4 Temperature Range

4.4.1 Gas Temperature

Cylinders shall be designed to be suitable for the following gas temperature limits:

a) the settled temperature of gas in cylinders, which may vary from a low of - 40 °C to a high of + 65 °C.
b) the developed gas temperature during filling and discharge, which may vary beyond these limits.

4.4.2 Cylinder Temperatures

Cylinders shall be designed to be suitable for the following material temperature limits:

The temperature of the cylinder materials may vary from - 40 °C to + 82 °C.

Temperatures over + 65 °C shall be sufficiently local, or of short duration, that the temperature of gas in the cylinder never exceeds + 65 °C, except under the conditions of 4.4.1 b).

4.5 Gas Composition

Cylinders shall be filled with non-oxidizing, non-lethal gases. Compatibility of the liner shall be demonstrated for the intended lading for all pressure and temperature ranges. If the cylinder is used for toxic or flammable gases, a Failure Modes and Effects Analysis (FMEA) for the cylinder and associated systems shall consider the effects of permeation.

4.6 External Surfaces

It is not necessary for cylinders to be designed for continuous exposure to mechanical or chemical attack, e.g. leakage from adjacent cargo or severe abrasion damage from extreme handling conditions. However, cylinder external surfaces shall be designed to withstand inadvertent exposure to the following, consistent with installation being carried out in accordance with the instructions to be provided with the cylinder:

a) water, either by intermittent immersion or road spray;
b) salt, due to the operation of the vehicle near the ocean or where ice-melting salt is used;
c) ultra-violet radiation from sunlight;
d) impact of gravel;
e) solvents, acids and alkalis, fertilizers;
f) automotive fluids, including petrol, hydraulic fluids, battery acid, glycol and oils;
g) exhaust gases.

5 Approval and Certification

5.1 Inspection and Testing

Evaluation of conformity is required to be performed in accordance with the relevant regulations of the country(ies) where the cylinders are used.

In order to ensure that the cylinders are in compliance with this Specification they shall be subject to design approval in accordance with 5.2. and inspection and testing in accordance with section 6. This shall be carried out by an ABS Surveyor. The Surveyor shall be competent for inspection of cylinders.

Test procedures are detailed in Annex A. An example of acceptable approval and certification procedures is included in Annex B.

5.2 ABS Type Approval Process

5.2.1 General

Type approval consists of the following:

a) design approval. comprising submissions of information by the manufacturer to ABS Engineering. as detailed in 5.2.2.
b) Prototype Testing and Production Surveys and Batch Testing are required to be conducted as per this specification.
c) Prototype testing. comprising testing carried out under the supervision of the attending ABS Surveyor. The cylinder material. design. manufacture and examination shall be proved to be adequate for their intended service by meeting the requirements of the prototype tests specified in 6.5.
d) Inspection and production testing: ABS will monitor the workmanship. materials. procedures. fabrication techniques and testing methods performed by the manufacturer during the layout. material preparation. fabrication. welding. machining. sub-assembly. shop testing of the aforementioned Gas Cylinders
e) In addition to the above. ABS Surveyor will periodically monitor performance of the manufacturer's quality control program to assure implementation and effective control over the following aspects of quality: incoming material. consumables. machinery. traceability of material. forming and welding including inspection procedures. welding and inspection personnel qualification. welding and inspection equipment maintenance and calibration. heat treating. stress relieving and other special treatments. machining. finish surfaces painting.

The test data shall also document the dimensions. wall thicknesses and weights of each of the test cylinders.

5.2.2 Design Approval

Cylinder designs shall be approved by formal ABS Engineering design review. The following information shall be submitted by the manufacturer with a request to ABS Engineering for approval:

a) statement of service. in accordance with 5.2.3:
b) design data. in accordance with 5.2.4:

c) manufacturing data, in accordance with 5.2.5;
d) quality system, in accordance with 5.2.6;
e) specification sheet, in accordance with 5.2.7;
f) additional supporting data, in accordance with 5.2.8.

5.2.3 Statement of Service

The purpose of this statement of service is to guide users and installers of cylinders as well as to inform the ABS Engineer and Surveyor. The statement of service shall include:

a) a statement that the cylinder design is suitable for use in the service conditions defined in clause 4 for the service life of the cylinder;
b) a statement of the service life;
c) a specification for the minimum in-service test and/or inspection requirements;
d) a specification for the pressure relief devices, and insulation if provided;
e) a specification for the support methods, protective coatings and any other items required but not provided;
f) a description of the cylinder design;
g) any other information and instructions necessary to ensure the safe use and inspection of the cylinder.

5.2.4 Design Data

5.2.4.1 Drawings

Drawings shall show at least the following:

a) title, reference number, date of issue, and revision numbers with dates of issue if applicable;
b) reference to this Specification;
c) all dimensions complete with tolerances, including details of end closure shapes with minimum thicknesses and of openings;
d) mass, complete with tolerance, of cylinders;
e) material specifications, complete with minimum mechanical and chemical properties or tolerance ranges;
f) other data such as, minimum test pressure, details of the fire protection system and of any exterior protective coating.

5.2.4.2 Stress Analysis Report

A finite element stress analysis or other stress analysis shall be carried out.

A table summarizing the calculated stresses shall be provided.

5.2.4.3 Material Property Data

A detailed description of the materials and tolerances of the material properties used in the design shall be provided. Test data shall also be presented characterizing the mechanical properties and the suitability of the materials for service under the conditions specified in clause 4.

5.2.4.4 Fire Protection

The arrangement of pressure relief devices, and insulation if provided, that will protect the cylinder from sudden rupture when exposed to the fire conditions in A.9 shall be specified. Test data shall substantiate the effectiveness of the specified fire protection system.

5.2.5 Manufacturing Data

Details of all fabrication processes. non-destructive examinations. production tests and batch tests shall be provided.

The tolerances for all production processes such as resin-mix ratio. filament winding tension. curing times and temperatures shall be specified.

Maximum lot sizes for batch tests shall be specified.

5.2.6 Quality Control Program

The manufacturer shall specify methods and procedures in accordance with a quality assurance system acceptable to the Surveyor and that will comply with any relevant regulations of the country(ies) where the cylinders are to be used.

5.2.7 Specification Sheet

A summary of the documents providing the information required in 5.2.2 shall be listed on a specification sheet for each cylinder design. The title. reference number. revision numbers and dates of original issue and version issues of each document shall be given. All documents shall be signed or initialed by the issuer.

5.2.8 Additional Supporting Data

Additional data which would support the application. such as the service history of material proposed for use. or the use of a particular cylinder design in other service conditions. shall be provided where applicable.

5.3 Inspection and testing

Prior to the attendance. the Surveyor shall coordinate with the ABS engineering office to ensure that a design review letter for the design series to be manufactured has been issued. Previously approved drawings may no longer comply with requested certification as a result of design change or design standard change

5.3.1 Surveillance points

The ABS Surveyor shall coordinate with the manufacturer regarding the required ABS survey points and shall verify that vendor materials. procedures. and workmanship are in accordance with the applicable ABS approved drawings or documents and are in line with the applicable certifications requested. including any additional requirements indicated in the design approval letter.

5.3.2 Scope of Inspection - General

The ABS Surveyor shall ensure that all materials. fabrication methods and materials. nondestructive examination. testing meet the specific ABS requirement. In the case of conflicts with the applicable requirement. clarification and interpretation of the regulations is to be obtained from the ABS technical office that conducted the design review. An ABS plan review letter must be issued prior to commencement of the inspection activities.

5.3.3 Scope of Inspection - Detailed

ABS Surveyor shall determine that each cylinder produced is in conformance with the approved drawings and documents. Except as otherwise specified in the approved documents above. the ABS Surveyor shall perform the following:

1) Inspect all material and reject any not meeting applicable requirements
2) Verify the material of construction meets the requirements of the applicable specification
3) Verify compliance of cylinders with the applicable specification

5.4 Tvpe Approval Certificate

If the results of the design approval according to 5.2 and the prototvpe testing according to 6.5. are satisfactorv. ABS shall issue a test tvpe approval certificate. An example of a tvpe approval certificate is given in the annex B.

6 Requirements for Type IV All-Composite Cylinders

6.1 General

This Specification does not provide design formulae nor list permissible stresses or strains. but requires the adequacy of the design to be established by appropriate calculations and demonstrated by testing to show that cylinders are capable of consistently passing the materials. design qualification. production and batch tests specified in this Specification.

The design shall ensure a "leakage-before-break" failure mode under feasible degradation of pressure parts during normal service. or demonstrate a minimum cycle life of three times the design number of filling cycles.

6.2 Materials

Materials used shall be suitable for the service conditions specified in clause 4. The design shall ensure that incompatible materials are not in contact.

6.2.1 General Requirements

6.2.2 Resins

The material for impregnation may be thermosetting or thermoplastic resins. Examples of suitable matrix materials are epoxy. modified epoxy. polyester and vinylester thermosetting plastics. and polyethylene and polyamide thermoplastic material.

The glass transition temperature of the resin material shall be determined in accordance with ASTM D 3418-99.

6.2.3 Fibres

Structural reinforcing filament material types shall be glass fibre. aramid fibre or carbon fibre. If carbon fibre reinforcement is used the design shall incorporate a means of preventing galvanic corrosion of metallic components of the cylinder.

The manufacturer shall keep on file the published specifications for composite materials. the material manufacturer's recommendations for storage. conditions and shelf life. and the material manufacturer's certification that each shipment conforms to said specification requirements. The fibre manufacturer shall certify that the fibre material properties conform to the manufacturer's specifications for the product.

6.2.4 Plastic Liners

The polymeric material shall be compatible with the service conditions specified in clause 4.

6.2.5 Metal End bosses

The metal end bosses connected to the liner shall be of a material compatible with the service conditions specified in clause 4.

6.3 Design Requirements

6.3.1 Test Pressure

The minimum test pressure used in manufacture shall be 1.5 times working pressure.

6.3.2 Burst Pressure and Fibre Stress Ratios

The minimum actual burst pressure shall be not less than the values given in Table 1. The composite over-wrap shall be designed for high reliability under sustained loading and cyclic loading. This reliability shall be achieved by meeting or exceeding the composite reinforcement stress ratio values given in Table 1. Stress ratio is defined as the stress in the fibre at the specified minimum burst pressure divided by the stress in the fibre at working pressure. The burst ratio is defined as the actual burst pressure of the cylinder divided by the working pressure.

For Type IV designs, the stress ratio is equal to the burst ratio.

Verification of the stress ratios may also be performed using strain gauges. An acceptable method is outlined in annex D.

Table 1 - Minimum actual burst values and stress ratios for Type IV cylinders

Fibre Type	Stress Ratio	Burst Pressure, bar
Glass	3.65	912.5
Aramid	3.10	775.0
Carbon	2.35	587.5
Hybrid	[a]	

[a] Stress ratios and burst pressure shall be calculated in accordance with 6.3.2

6.3.3 Stress Analysis

A stress analysis shall be performed to justify the minimum design wall thicknesses. It shall include the determination of the stresses in the composite fibres.

The pressures used for these calculations shall be working pressure, test pressure and design burst pressure. The calculations shall use suitable analysis techniques to establish stress distribution throughout the cylinder.

6.3.4 Openings

Openings are permitted in the end bosses only. The centre line of openings shall coincide with the longitudinal axis of the cylinder.

6.3.5 Fire Protection

The cylinder design shall be protected with pressure relief devices. The cylinder, its materials, pressure relief devices and any added insulation or protective material shall be designed collectively to ensure adequate safety during fire conditions in the test specified in A.9. A manufacturer may specify alternative PRD locations for specific installations in order to optimize safety considerations.

6.4 Construction and Workmanship

6.4.1 General

The composite cylinder shall be manufactured from a liner over-wrapped with continuous filament windings. Fibre winding operations shall be computer or mechanically controlled. The fibres shall be applied under tension during winding. After winding is complete, thermosetting resins shall be cured by heating, using a predetermined and controlled time-temperature profile.

6.4.2 End Boss Port Threads

Threads shall be clean cut. even. without surface discontinuities. to gauge and comply with International Standards acceptable to the Surveyor.

6.4.3 Overwrap

6.4.3.1 Fibre Winding

The cylinders shall be manufactured by a fibre winding technique. During winding the significant variables shall be monitored within specified tolerances and documented in a winding record. These variables can include but are not limited to:

a) fibre type including sizing:
b) manner of impregnation:
c) winding tension:
d) winding speed:
e) number of rovings:
f) band width:
g) type of resin and composition:
h) temperature of the resin:
i) temperature of the liner:
j) winding angle.

6.4.4 Curing of Thermosetting Resins

The curing temperature for thermosetting resins shall not adversely affect properties of the plastic liner as demonstrated the x and y qualification tests.

6.4.5 Exterior Environmental Protection

The exterior of cylinders shall meet the requirements of the environmental test described in A.8. Exterior protection may be provided by using any of the following:

a) the use of a suitable fibre and matrix material (e.g. carbon fibre in resin): or
b) a protective coating (e.g. organic coating. paint): if exterior coating is part of the design. the requirements of A.3 shall be met: or
c) a covering impervious to the chemicals listed in A.8.

Any coatings applied to cylinders shall be such that the application process does not adversely affect the mechanical properties of the cylinder. The coating shall be designed to facilitate subsequent in-service inspection and the manufacturer shall provide guidance on coating treatment during such inspection to ensure the continued integrity of the cylinder.

6.5 Prototype Testing Procedure

6.5.1 General

Prototype testing shall be conducted on each new design. on finished cylinders which are representative of normal production and complete with identification marks. Prototype testing may be conducted using sub-scale units as noted for each qualification test. The test cylinders or liners shall be selected and the prototype tests detailed in

6.5.2 witnessed by the Surveyor. If more cylinders or liners are subjected to the tests than are required by this Specification, all results shall be documented.

6.5.2 Prototype Tests

6.5.2.1 Tests Required
In the course of the type approval, the Surveyor shall select the necessary cylinders or liners for testing and witness the following tests:

- the tests specified in 6.5.2.2 (material tests) on 1 liner;
- the test specified in 6.5.2.3 (hydrostatic pressure burst test) on 2 cylinders;
- the test specified in 6.5.2.4 (ambient temperature pressure cycling test) on 2 cylinders;
- the test specified in 6.5.2.5 (LBB test) on 2 cylinders;
- the test specified in 6.5.2.6 (bonfire test) on 1 or 2 cylinders as appropriate;
- the test specified in 6.5.2.7 (penetration test) on 1 cylinder;
- the test specified in 6.5.2.8 (environmental test) on 1 cylinder;
- the test specified in 6.5.2.9 (flaw tolerance test) on 1 cylinder;
- the test specified in 6.5.2.10 (high temperature creep test), where appropriate, on 1 cylinder;
- the test specified in 6.5.2.11 (accelerated stress rupture test), on 1 cylinder;
- the test specified in 6.5.2.12 (extreme temperature pressure cycling test) on 1 cylinder;
- the test specified in 6.5.2.13 (resin shear strength) on 1 sample coupon representative of the composite overwrap;
- the test specified in 6.5.2.14 (external loading and impact tests);
- the test specified in 6.5.2.15 (boss torque test) on 1 cylinder;
- the test specified in 6.5.2.16 (permeation test) on 1 cylinder;
- the test specified in 6.5.2.17 (gas cycling and blow down test) on 1 cylinder.

6.5.2.2 Material Tests for Plastic Liners
The tensile yield strength and ultimate elongation shall be determined in accordance with A.15 and shall meet the requirements therein.

The softening temperature shall be determined in accordance with A.16 and shall meet the requirements therein.

The resistance to high temperature creep shall be determined in accordance with A.12 and shall meet the requirements therein.

6.5.2.3 Hydrostatic Pressure Burst Test
Two cylinders shall be hydrostatically pressurized to failure in accordance with A.6. The cylinder burst pressures shall exceed the specified minimum burst pressure established by the stress analysis for the design, in accordance with Table 1, and in no case less than the value necessary to meet the stress ratio requirements of 6.3.2.

6.5.2.4 Ambient Temperature Pressure Cycling Test
Two cylinders shall be pressure cycle tested to failure at ambient temperature in accordance with A.7, or to a minimum of three times the design number of filling cycles. The cylinders shall not fail before reaching the design number of filling cycles defined as the specified service life in years multiplied by 750 cycles. Cylinders exceeding design number of filling cycles shall fail by leakage and not by rupture. Cylinders which do not fail within three times the design number of filling cycles shall be destroyed either by continuing the cycling until failure occurs, or

by hydrostatically pressurizing to burst. Cylinders exceeding three times the design number of filling cycles are permitted to fail by rupture.

Sub-scale units may be used as provided below:

One of the two required tests shall be conducted on a full scale cylinder. Otherwise, design validation may be demonstrated with full scale diameter cylinders of shorter length; however the L/D ratio of sub-scale units must be greater than 2.5. If the full scale cylinder L/D ratio is less than 2.5, a full scale cylinder is required.

6.5.2.5 Leak-Before-Break (LBB) Test

LBB tests shall be conducted in accordance with A.1 and meet the requirements therein.

Sub-scale units may be used as provided below:

Design validation may be demonstrated with full scale diameter cylinders of shorter length; however the L/D ratio of sub-scale units must be greater than 2.5. If the full scale cylinder L/D ratio is less than 2.5, a full scale cylinder is required.

6.5.2.6 Bonfire Test

One or two cylinders as appropriate shall be tested in accordance with A.9 and meet the requirements therein.

6.5.2.7 Penetration Test

One cylinder shall be tested in accordance with A.10 and meet the requirements therein.

Sub-scale units may be used as provided below:

Design validation may be demonstrated with full scale diameter cylinders of shorter length; however the L/D ratio of sub-scale units must be greater than 2.5. If the full scale cylinder L/D ratio is less than 2.5, a full scale cylinder is required.

6.5.2.8 Environmental Test

One cylinder shall be tested in accordance with A.8 and meet the requirements therein.

Sub-scale units may be used as provided below:

Material properties may be demonstrated using a sub-scale unit of a size appropriate to determine the environmental resistance of the laminate and/or protective coating. The stress level of the sub-scale must be the same as the full scale cylinder.

6.5.2.9 Flaw Tolerance Test

One cylinder shall be tested in accordance with A.11 and meet the requirements therein.

Sub-scale units may be used as provided below:

Design validation may be demonstrated with full scale diameter cylinders of shorter length; however the L/D ratio of sub-scale units must be greater than 2.5. If the full scale cylinder L/D ratio is less than 2.5, a full scale cylinder is required.

6.5.2.10 High Temperature Creep Test

In designs where the glass transition temperature of the resin does not exceed 102 °C, one cylinder shall be tested in accordance with A.12 and meet the requirements therein.

Sub-scale units may be used as provided below:

Material properties may be demonstrated using a sub-scale unit of a size appropriate to determine the thermal stability of the laminate. The stress level of the sub-scale must be the same as the full scale cylinder.

6.5.2.11 Accelerated Stress Rupture Test
One cylinder shall be tested in accordance with A.13 and meet the requirements therein.

Sub-scale units may be used as provided below:

Material properties may be demonstrated using a sub-scale unit of a size appropriate to determine the thermal stability of the laminate. The stress level of the sub-scale must be the same as the full scale cylinder.

6.5.2.12 Extreme Temperature Pressure Cycling Test
One cylinder shall be tested in accordance with A.2 and meet the requirements therein.

Sub-scale units may be used as provided below:

Design validation may be demonstrated with full scale diameter cylinders of shorter length: however the L/D ratio of sub-scale units must be greater than 2.5. If the full scale cylinder L/D ratio is less than 2.5. a full scale cylinder is required.

6.5.2.13 Resin Shear Strength
Resin materials shall be tested in accordance with A.19. and meet the requirements therein.

6.5.2.14 External Loads and Impact Tests
Cylinders covered by this Specification are required to be permanently mounted into a transport frame. Requirements pertaining to external loadings arising from transport are specified in standards for transportation containers (i.e. ISO 1496-3 or equivalent). Cylinders and their interface with the transport frame are required to meet all requirements imposed by the applicable transport container standard. Compliance with this requirement shall be demonstrated through container qualification.

As a minimum requirement. subsequent to container loads testing cylinders shall be subjected to a leak test in accordance with A.4. and meet the requirements therein.

6.5.2.15 Boss Torque Test
One cylinder shall be tested in accordance with A.18 and meet the requirements therein.

Sub-scale units may be used as provided below:

Design validation may be demonstrated with full scale diameter cylinders of shorter length: however the L/D ratio of sub-scale units must be greater than 2.5. If the full scale cylinder L/D ratio is less than 2.5. a full scale cylinder is required.

6.5.2.16 Permeation Test
One cylinder shall be tested for permeation in accordance with A.14 and meet the requirements therein.

Sub-scale units may be used as provided below:

Material properties may be demonstrated using a sub-scale unit of a size appropriate to determine the gas permeation rate of the liner.

6.5.2.17 Gas Cycling and Blow Down Test
One cylinder shall be tested in accordance with A.20 and meet the requirements therein.

Sub-scale units mav be used as provided below:

Design validation mav be demonstrated with full scale diameter cvlinders of shorter length: however the L/D ratio of sub-scale units must be greater than 2.5. If the full scale cvlinder L/D ratio is less than 2.5. a full scale cvlinder is reauired.

6.5.3 Change of Design

A design change is anv change in the selection of structural materials or dimensional change not attributable to normal manufacturing tolerances.

Minor design changes shall be permitted to be aualified through a reduced test program. Changes of design specified in Table 2 shall reauire design aualification testing as specified in the table.

Table 2 - Change of Design for Tvpe IV Cvlinders

Design Change	Type of Test											
	Hvdrostatic Burst	Ambient Temperature Pressure Cvcling	Bonfire	Penetration	Environmental	Flaw Tolerance	High Temperature Creep	Stress Rupture	External Loads[d]	Boss Torque	Permeation	Gas Cvcle and Blow Down
	Clause											
	A.6	A.7	A.9	A.10	A.8	A.11	A.12	A.13	—	A.18	A.14	A.20
Fibre Manufacturer	X	X	—	—	—	—	—	—	—	—	—	—
Plastic Liner Material	X	X	—	—	X	—	X	—	—	X	X	X
Fibre Material	X	X	X	X	X	X	X	X	X	X	—	—
Resin Material	—	—	—	X	X	X	X	X	—	—	—	—
Diameter Change ≤ 20 %	X	X	—	—	—	—	—	—	X	—	—	—
Diameter Change > 20 %	X	X	X	X	—	X	—	—	X	—	—	—
Length Change ≤ 50 %	X	—	X[a]	—	—	—	—	—	X[a]	—	—	—
Length Change > 50 %	X	X	X[a]	—	—	—	—	—	X[a]	—	—	—
Working Pressure ≤ 20 % [b]	X	X	—	—	—	—	—	—	—	—	—	—
Dome Shape	X	X	—	—	—	—	—	—	—	X[c]	X	X
Opening Size	X	X	—	—	—	—	—	—	—	—	—	—
Coating Change	—	—	—	—	X	—	—	—	—	—	—	—
End Boss Design	—	—	—	—	—	—	—	—	X[e]	X[c]	X	X
Change in Manufacturing Process	X	X	—	—	—	—	—	—	—	—	—	—
Pressure Relief Device	—	—	X	—	—	—	—	—	—	—	—	—

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[a] Test only required when the length increases.

[b] Only when thickness change proportional to diameter and/or pressure change.

[c] Only when the interface between the end boss and liner, or between the end boss and composite change.

[d] In accordance with 6.5.2.14.

[e] Only when a change will adversely affect performance in the external loads test.

6.6 Material Certification

Material testing shall be conducted on all materials critical to the performance of the cylinder to demonstrate conformance with the design specification. Materials generally considered critical include, but are not limited to, materials of end bosses, plastic liner material, and composite fibres and resin. A material test report or supplier certificate shall be documented for each batch of materials.

6.7 Batch Tests

6.7.1 General Requirements

Batch testing shall be conducted on finished cylinders which are representative of normal production and are complete with identification marks. The cylinder(s) and liner(s) required for testing shall be the first produced from each batch. If more cylinders are subjected to the tests than are required by this Specification, all results shall be documented.

6.7.2 Required Tests

6.7.2.1 At least the following tests shall be carried out on each batch of cylinders:

a) on one cylinder:
   1) one hydrostatic pressure burst test in accordance with A.6.
      — If the burst pressure is less than the minimum calculated burst pressure, the procedures specified in 6.10 shall be followed.

b) on one cylinder, or liner, or witness sample representative of a finished cylinder:
   1) a check of the critical dimensions against the design (see 5.2.4.1);
   2) one tensile test of the plastic liner in accordance with A.15, or a material certificate of conformance from the plastic supplier; the test results shall satisfy the requirements of the design (see 5.2.4.1);
   3) the melt temperature of the plastic liner shall be tested in accordance with A.16, or a material certificate of conformance from the plastic supplier, and meet the requirements of the design;
   4) when a protective coating is a part of the design, a coating batch test in accordance with A.17 to meet the requirements therein. Where the coating fails to meet the requirements of A.17, the batch shall be 100 % inspected to remove similarly defectively coated cylinders. The coating on all defectively coated cylinders may be stripped using a method that does not affect the integrity of the composite wrapping then recoated. The coating batch test shall then be repeated.

All cylinders or liners represented by a batch test which fails to meet the requirements specified shall follow the procedures specified in 6.10.

6.8 Tests on Every Cylinder

Production examinations and tests shall be carried out on all cylinders produced in a batch.

Each cylinder shall be examined during manufacture and after completion, as follows:

a) to verify that the critical dimensions and mass of the completed cylinder are within design tolerances;
b) to verify the markings;
c) by hydraulic test of finished cylinders in accordance with A.5, option 1. The manufacturer shall define the appropriate limit of elastic expansion for the test pressure used, but in no case shall the elastic expansion of any cylinder exceed the expansion of the batch hydrostatic burst test unit by more than 10 %;
d) by leak test in accordance with A.4, and shall meet the requirements therein.

6.9 Batch Acceptance Certificate

If the results of batch testing according to 6.7 and 6.8 are satisfactory, the manufacturer and the Surveyor shall sign an acceptance certificate. An example of an acceptance certificate (referred to as a "Report of Manufacture and Certificate of Conformance") is given in annex C.

6.10 Failure to Meet Test Requirements

In the event of failure to meet test requirements, re-testing shall be carried out as follows:

a) if there is evidence of a fault in carrying out a test, or an error of measurement, a further test shall be performed; if the result of this test is satisfactory, the first test shall be ignored;
b) if the test has been carried out in a satisfactory manner, the cause of test failure shall be identified.
   1) All defective cylinders shall be rejected or repaired by an approved method. Provided that the repaired cylinders pass the test(s) required for the repair, they shall be re-instated as part of the original batch.
   2) The new batch shall be retested. All the relevant prototype or batch tests needed to prove the acceptability of the new batch shall be performed again. If one or more tests prove even partially unsatisfactory, all cylinders of the batch shall be rejected.

7 Marking

On each cylinder the manufacturer shall provide clear permanent markings not less than 6 mm high. Marking shall be made either by labels incorporated into resin coatings and/or labels attached by adhesive. Adhesive labels and their application shall be in accordance with ISO 7225, or an equivalent standard acceptable to the Surveyor in the country(ies) of use. Multiple labels are allowed and should be located such that they are not obscured by mounting brackets.

Each cylinder complying with this Specification shall be marked as follows:

a) if placed in dedicated service, the words "[gas] Only", where [gas] is the gas to be contained;
b) the words "DO NOT USE AFTER XX/XXXX", where XX/XXXX identifies the month and year of expiry.
   1) The period between the dispatch date and the expiry date shall not exceed the specified service life. The expiry date may be applied to the cylinder at the time of dispatch, provided that the cylinders have been stored in a dry location without internal pressure;
c) manufacturers' identification;
d) cylinder identification (a serial number unique for every cylinder);
e) working pressure at temperature;

f) reference to this Specification, along with certification registration number (if applicable);
g) the words "Use only a manufacturer-approved PRD";
h) when labels are used, a unique identification number and the manufacturer's identification placed in an alternate location to permit tracing in the event that the primary label is destroyed;
i) date of manufacture (month and year);
i) any additional markings as required by the Surveyor or the country(ies) of use.

The markings shall be placed in the listed sequence but the specific arrangement may be varied to match the space available. An acceptable example is:

DO NOT USE AFTER 03/2029
Manufacturer/Identification number
250 bar/15 °C
ABS Reg. No AB/XXX/YY-X1
Use only manufacturer-approved PRD
Manufacture date 03/2009

8 Preparation for Dispatch

Prior to dispatch from the manufacturer's shop, every cylinder shall be internally cleaned and dried. Cylinders not immediately closed by the fitting of a valve, and safety devices if applicable, shall have plugs, which prevent entry of moisture and protect threads, fitted to all openings.

The manufacturer's statement of service and all necessary information and instructions to ensure the proper handling, use and in-service inspection of the cylinder shall be supplied to the purchaser. The statement of service shall be in accordance with 5.2.3. Guidance on the content of the instructions is given in annex E.

Annex A
(normative)

Test Methods and Criteria

A.1 Leak-Before-Break (LBB) Test

Two finished cylinders shall be pressure cycled in accordance with the following procedure:

a) fill the cylinder to be tested with a non-corrosive fluid such as oil, inhibited water or glycol;
b) cycle the pressure in the cylinder between 25 bar and 375 bar at a rate not exceeding 10 cycles per minute.

The number of cycles to failure shall be reported, along with the location and description of the failure initiation.

All cylinders shall either fail by leakage or exceed three times the design number of filling cycles.

A.2 Extreme Temperature Pressure Cycling

Finished cylinders, with the composite wrapping free of any protective coating, shall be cycle tested, as follows:

a) condition for 48 h at zero to 25 bar pressure, between 60 °C and 70 °C, and 95 % or greater relative humidity;
b) cycle the pressure in the cylinder for 5 000 cycles, between 25 bar and 250 bar, while maintaining a surface temperature between 60 °C and 70 °C by regulating the environmental chamber and cycle rate;
c) release the pressure and stabilize the cylinder at approximately 20 °C;
d) condition for 48 h at zero to 25 bar pressure, between - 50 °C and - 60 °C;
e) cycle the pressure in the cylinder for 5 000 cycles, between 25 bar and 250 bar, while maintaining a surface temperature between - 50 °C and - 60 °C by regulating the environmental chamber and cycle rate;
f) release the pressure and stabilize the cylinder at approximately 20 °C;
g) cycle the pressure in the cylinder for 30 cycles , between 25 bar and 375 bar.

The fluid shall be selected to ensure that it functions at the temperatures specified in the various cycle tests.

The pressure cycling rate of b) and e) shall not exceed 5 cycles per minute. The pressure cycling rate of g) shall not exceed 10 cycles per minute.

During this pressure cycling, the cylinder shall show no evidence of rupture, leakage or fibre unraveling.

Following the completion of the test the cylinder shall be hydrostatically pressured to failure in accordance with A.6, and achieve a minimum burst pressure of 89.4 % of the minimum design burst pressure.

A.3 Coating Tests

Coatings shall be evaluated using the following test methods:

a) adhesion testing. in accordance with ISO 4624:2002. using method A or B as applicable. The coating shall exhibit an adhesion rating of either 4A or 4B. as applicable:
b) flexibility. in accordance with ASTM D522-93. using test method B with a 12.7 mm (0.5 in) mandrel at the specified thickness at - 20 °C. Samples for the flexibility test shall be prepared in accordance with ASTM D522-93. There shall be no visually apparent cracks:
c) impact resistance. in accordance with ASTM D2794-93. The coating at room temperature shall pass a forward impact test of 18 J (13.3 ft lbs):
d) chemical resistance. in accordance with ASTM D1308-87 except as identified in the following. The tests shall be conducted using the open spot test method and 100 h exposure to a 30 % sulfuric acid solution (battery acid with a specific gravity of 1.219) and 24 h exposure to a polyalkalene glycol (e.g. brake fluid). There shall be no evidence of lifting. blistering or softening of the coating. The adhesion shall meet a rating of 3 when tested in accordance with ISO 4624:2002:
e) minimum 1 000 h exposure. in accordance with ASTM G53-93. There shall be no evidence of blistering. and adhesion shall meet a rating of 3 when tested in accordance with ISO 4624:2002. The maximum gloss loss allowed is 20 %:
f) minimum 500 h exposure in accordance with ISO 9227. Undercutting shall not exceed 2 mm at the scribe mark. there shall be no evidence of blistering and adhesion shall meet a rating of 3 when tested in accordance with ISO 4624:2002:
g) resistance to chipping at room temperature. in accordance with ASTM D3170-87. The coating shall have a rating of 7A or better. and there shall be no exposure of the substrate.

A.4 Leak Test

Finished cylinders shall be leak tested using the following procedure (or an alternative acceptable method):

a) thoroughly dry the cylinders:
b) pressurize the cylinders with water or other suitable fluid to working pressure:
c) with the cylinder having been pressurized for at least 15 minutes. carefully examine for signs of leakage (e.g. a visual indication or decrease in pressure).

Any leakage detected shall be cause for rejection.

A.5 Hydraulic Test

One of the following two options shall be used:

Option 1. Volumetric Expansion Test

a) The cylinder shall be hydrostatically tested to at least 1.5 times working pressure.
b) Pressure shall be maintained for 30 s and sufficiently longer to ensure complete expansion. If the test pressure cannot be maintained due to failure of the test apparatus. it is permissible to repeat the test.
c) Any cylinders not meeting the defined rejection limit shall be rejected and rendered unserviceable.

Option 2. Proof Pressure Test

The hvdrostatic pressure in the cvlinder shall be increased gradually and regularly until the test pressure. at least 1.5 times working pressure. is reached. The cvlinder test pressure shall be maintained for at least 30 seconds to establish that there are no leaks.

A.6 Hvdrostatic Pressure Burst Test

The rate of pressurization shall not exceed 14 bar/s at pressures in excess of 80 % of the design burst pressure. If the rate of pressurization at pressures in excess of 80 % of the design burst pressure exceeds 3.5 bar/s. then either the cvlinder shall be placed schematically between the pressure source and the pressure measurement device. or there shall be a 5 s hold at the minimum design burst pressure.

The minimum required (calculated) burst pressure shall be no less than the value necessary to meet the stress ratio requirements. Actual burst pressure shall be recorded. Rupture mav occur in either the cvlindrical region or the dome region of the cvlinder.

A.7 Ambient Temperature Pressure Cvcling

Pressure cvcling shall be performed in accordance with the following procedure:

a) fill the cvlinder to be tested with a non-corrosive fluid such as oil. inhibited water or glvcol:
b) cvcle the pressure in the cvlinder between 25 bar and 325 bar at a rate not exceeding 10 cvcles per minute.

The number of cvcles to failure shall be reported. along with the location and description of the failure initiation.

A.8 Environment Test

On a finished cvlinder the following test procedure shall be applied:

A.8.1 Container Set-Up and Preparation

One container shall be tested. including coating if applicable.

The upper section of the container is to be divided into five distinct areas and marked for pendulum impact preconditioning and fluid exposure. The areas shall be nominally 4 in (10 cm) in diameter. While convenient for testing. the areas need not be oriented along a single line. but shall not overlap.

Although preconditioning and other fluid exposure is performed on the cvlindrical section of the container. all of the container. including the domed sections. shall be as resistant to the exposure environments as the exposed areas.

A.8.2 Pendulum Impact Preconditioning

The impact bodv shall be of steel and have the shape of a pvramid with equilateral triangle faces and a square base. the summit and the edges being rounded to a radius of 3 mm (0.12 in). The center of percussion of the pendulum shall coincide with the center of gravity of the pvramid: its distance from the axis of rotation of the pendulum shall be 1 m (39.37 in). The total mass of the pendulum referred to its center of percussion shall be 15 kg (33 lbs). The energy of the pendulum at the moment of impact shall be not less than 30 Nm (22.1 ft-lb) and as close to that value as possible.

During pendulum impact, the container shall be held in position by the end bosses or by the intended mounting brackets. Each of the five areas shall be preconditioned by impact of the pendulum body summit at the center of the area. The container shall be unpressurized during preconditioning.

A.8.3 Environmental Fluids for Exposure

Each marked area is to be exposed to one of five solutions. The five solutions are:

a) Sulfuric acid - 19 percent solution by volume in water;
b) Sodium hydroxide - 25 percent solution by weight in water;
c) Methanol/gasoline - 5/95 percent concentration of M5 fuel meeting the requirements *of Standard Specification for Automotive Spark-Ignition Engine Fuel, ASTM D4814*;
d) Ammonium nitrate - 28 percent by weight in water; and
e) Windshield washer fluid (50 percent by volume solution of methyl alcohol and water).

When exposed, the test sample will be oriented with the exposure area uppermost. A pad of glass wool approximately 0.5 mm (1/64 in) thick and between 90 and 100 mm (3.5 and 4.0 in) in diameter is to be placed on the exposure area. Apply an amount of the test fluid to the glass wool sufficient to ensure that the pad is wetted evenly across its surface and through its thickness for the duration of the test, and to ensure that the concentration of the fluid is not changed significantly during the duration of the test.

A.8.4 Pressure Cycle and Pressure Hold

Containers shall be hydraulically pressure cycled between less than or equal to 10 percent of working pressure and 130 percent of working pressure for a total of 3000 cycles. The maximum pressurization rate shall be 27.5 bar (400 psi) per second. After pressure cycling, containers shall be pressurized to 130 percent of working pressure, and held at that pressure a minimum of 24 hours and until the elapsed exposure time (pressure cycling and pressure hold) to the environmental fluids equals 48 hours.

A.8.5 Acceptable Results

Following the above test sequence, the residual burst strength of the container shall be no less than 1.8 times the working pressure when tested in accordance with A.6.

A.9 Bonfire Test

A.9.1 General

The bonfire test is designed to demonstrate that finished cylinders, complete with the fire protection system (cylinder valve, pressure relief devices and/or integral thermal insulation) specified in the design, will prevent the rupture of the cylinder when tested under the specified fire conditions.

Precautions shall be taken during fire testing in the event that cylinder rupture occurs.

A.9.2 Cylinder set-up

The cylinder shall be placed horizontally with the cylinder bottom approximately 100 mm above the fire source.

Metallic shielding shall be used to prevent direct flame impingement on cylinder valves, fittings, and/or pressure relief devices. The metallic shielding shall not be in direct contact with the specified fire protection system (pressure relief devices or cylinder valve).

Any failure during the test of a valve, fitting or tubing that is not part of the intended protection system for the design shall invalidate the result.

A.9.3 Fire source

A uniform fire source of 1.65 m length shall provide direct flame impingement on the cylinder surface across its entire diameter.

Any fuel may be used for the fire source provided it supplies uniform heat sufficient to maintain the specified test temperatures until the cylinder is vented. The selection of a fuel should take into consideration air pollution concerns. The arrangement of the fire shall be recorded in sufficient detail to ensure that the rate of heat input to the cylinder is reproducible.

Any failure or inconsistency of the fire source during a test shall invalidate the result.

A.9.4 Temperature and pressure measurements

Surface temperatures shall be monitored by at least three thermocouples located along the bottom of the cylinder and spaced not more than 0.75 m apart.

Thermocouple temperatures and the cylinder pressure shall be recorded at intervals of every 30 s or less during the test.

A.9.5 General test requirements

The cylinder shall be pressurized to working pressure with the intended lading or compressed nitrogen and tested in the horizontal position at working pressure and at 25 % of working pressure if a thermally activated PRD is not used.

Immediately following ignition, the fire shall produce flame impingement on the surface of the cylinder along the 1.65 m length of the fire source and across the cylinder diameter.

Within 5 min of ignition the temperature at least one thermocouple shall indicate a temperature ≥ 590 °C. This minimum temperature shall be maintained for the remainder of the test.

For cylinders of length 1.65 m or less, the centre of the cylinder shall be positioned over the centre of the fire source.

For cylinders of length greater than 1.65 m, the cylinder shall be positioned as follows:

a) if the cylinder is fitted with a pressure relief device at one end, the fire source shall commence at the opposite end of the cylinder;
b) if the cylinder is fitted with pressure relief devices at both ends, or at more than one location along the length of the cylinder, the centre of the fire source shall be centred midway between the pressure relief devices that are separated by the greatest horizontal distance;
c) if the cylinder is additionally protected using thermal insulation, then two fire tests at service pressure shall be performed, one with the fire centred midway along the cylinder length, and the other with the fire commencing at one of the ends of a second cylinder.

A.9.6 Acceptable results

The cylinder shall vent through a pressure relief device, and without rupturing.

NOTE: The bonfire test may also be carried out on cylinders installed in their transport frame. The fire and its position relative to the transport frame shall be approved by the Surveyor.

A.10 Penetration Tests

A cylinder pressurized to 250 bar ± 10 bar with the intended lading or compressed nitrogen shall be penetrated by an armour piercing bullet with a diameter of 7.62 mm or greater. The bullet shall completely penetrate at least one side wall of the cylinder. If the bullet does not penetrate, additional rounds shall be fired at the same location until the wall is penetrated. The projectile shall impact the sidewall at an approximate angle of 45°. The cylinder shall not rupture.

A.11 Composite Flaw Tolerance Tests

One finished cylinder, complete with protective coating, shall have flaws cut into the composite in the longitudinal direction. The flaws shall be greater than the visual inspection limits as specified by the manufacturer. As a minimum, one flaw shall be 130 mm long and 2.5 mm in depth, and another flaw shall be 1 000 mm long and 1.5 mm in depth, cut in the longitudinal direction into the cylinder sidewall.

The flawed cylinder shall then be pressure cycled between 25 bar and 325 bar at ambient temperature, initially for 3 000 cycles, then followed by an additional 12 000 cycles.

The cylinder shall not leak or rupture within the first 3 000 cycles, but may fail by leakage during the further 12 000 cycles. All cylinders which complete this test shall be destroyed.

A.12 High Temperature Creep Test

One finished cylinder shall be tested as follows:

a) the cylinder shall be pressurized to 375 bar and held at a temperature of 100 °C for not less than 200 h;
b) following the test, the cylinder shall meet the requirements of the hydrostatic expansion test (A.5), the leak test (A.4) and the hydrostatic pressure burst test (A.6).

A.13 Accelerated Stress Rupture Test

One cylinder shall be hydrostatically pressurized to 375 bar at 65 °C. The cylinder shall be held at this pressure and temperature for 1 000 h. The cylinder shall then be pressured to burst in accordance with the procedure described in A.6, except that the burst pressure shall exceed 85 % of the minimum design burst pressure.

A.14 Permeation Test

One finished cylinder shall be filled with the intended lading or suitable trace gas to working pressure, placed in an enclosed sealed chamber at ambient temperature, and monitored for leakage for 500 h.

The measured permeation rate shall be reported. If a trace gas is used, correlation between the trace gas and intended lading shall be provided.

The cylinder shall be sectioned and the internal surfaces inspected for any evidence of cracking or deterioration.

A.15 Tensile Properties of Plastics

The tensile yield strength and ultimate elongation of plastic liner material shall be determined at - 50 °C in accordance with ISO 527-2.

The test results shall demonstrate the ductile properties of the plastic liner material at temperatures of - 50 °C or lower by meeting the values specified by the manufacturer.

A.16 Softening Temperature of Plastics

Polymeric materials from finished liners shall be tested in accordance with a method described in ISO 306.

The softening temperature shall be at least 100 °C.

A.17 Coating Batch Tests

A.17.1 Coating Thickness

The thickness of the coating shall be measured in accordance with ISO 2808 and shall meet the requirements of the design.

A.17.2 Coating Adhesion

The coating adhesion strength shall be measured in accordance with ISO 4624:2002, and shall have a minimum rating of 4 when measured using either test method A or B, as appropriate.

A.18 Boss Torque Test

The body of the cylinder shall be restrained against rotation and a torque of twice the valve or PRD installation torque specified by the manufacturer shall be applied to each end boss of the cylinder. The torque shall be applied first in the direction of tightening a threaded connection, then in the untightening direction, and finally again in the tightening direction.

The cylinder shall then be subjected to a leak test in accordance with A.4.

A.19 Resin Shear Strength

Resin materials shall be tested on a sample coupon representative of the composite overwrap in accordance with ISO 14130, or an equivalent standard. Following 24 h boiling in water the composite shall have a minimum shear strength of 13.8 MPa.

A.20 Gas Cycling and Blow Down Test

Special consideration shall be given to safety when conducting this test. Prior to conducting this test, cylinders of this design shall have successfully passed the test requirements of A.4 (leak test), A.6 (hydrostatic pressure burst test), A.7 (ambient temperature pressure cycling test) and A.14 (permeation test).

One finished cylinder shall be cycle tested as follow:

a) fill the cvlinder to be tested with a non-corrosive fluid such as oil. inhibited water or glvcol:

b) cvcle the pressure in the cvlinder for 1 000 cvcles. between 25 bar and 250 bar:

c) release the pressure. drain the fluid and drv the interior of the cvlinder:

d) cvcle the pressure in the cvlinder for 5 cvcles. between 25 bar and 250 bar. with the intended lading:

e) following the high pressure hold of final cvcle. the gas shall be released freelv to atmosphere.

The pressure cvcling rate of b) shall not exceed 10 cvcles per minute. The pressure cvcling rate of g) shall provide at least a 2 hour hold at the high pressure portion of the cvcle.

The cvlinder shall then be subiected to a leak test in accordance with A.4 and meet the requirements therein. Following the completion of the test the cvlinder shall be sectioned and the liner and liner/end boss interface inspected for evidence of anv deterioration. such as fatigue cracking or electrostatic discharge.

Annex B
(informative)

ABS Application Forms & Certificates

B.1 ABS Application Forms

B.2 ABS Prototype Test Certificate For Each Design

B.3 ABS Production Certificate

B.4 Cylinder Certificate

ABS FOUNDED 1862

The American Bureau of Shipping Container Certification Application

Model Number:

Container Size and Description:

ABS Design Type Number: AB/ -

Manufacturer:	**TYPE OF SUBMITTAL:**
& Address:	☐ NEW DESIGN
Contact Person: Phone no.:	☐ ADDITIONAL UNITS
E-mail address: Fax no.:	☐ REVISION
Owner's Name:	**TYPE OF CONTAINER:**
& Address:	☐ GENERAL CARGO
User's Name:	☐ BULK
& Address:	☐ PLATFORM
Test Facility:	☐ TANK CONTAINER
Manuf. Facility:	☐ PORTABLE TANK ☐ UN
Quantity:	☐ THERMAL
Manufacturer's Nos.: thru	☐ MEGC ☐ UN
thru	**CERTIFICATIONS:**
thru	☑ ABS RULES
thru	☐ CSC (49 CFR 451.12)
Owner's Operating Nos.: thru	☐ CUSTOMS/TIR
thru	☐ UIC
thru	☐ ISO
thru	☐ ATO-DLO
Maximum Gross Mass: kg	☐ U.S. DOT
Tare: kg	☐ IMDG
Max. Permissible Payload: kg	☐ ATP
Allowable Stacking Weight: kg	☐ AAR
Other Information:	☐ USDA
	☐ TRANSPORT CANADA
	☐ RID/ADR
	☐ TPED
	☐ OTHER:

I, the undersigned, hereby apply for the certification of the above listed containers to be built in conformance with the above requested certifications. I warrant that I have the authority to present these containers to ABS for certification and the authority to use and distribute all information and data supplied in support of this application for ABS certification.

Printed Name: Date:

Agree - I have no objection to the information contained in my certification to be displayed publicly on the ABS website.

Please submit electronic copies of the completed and signed application, cover letter, drawings, calculations and any other additional information to the email address ABSContainers@eagle.org.

ABS
ABS PLAZA. 16855 NORTHCHASE DRIVE. HOUSTON. TX 77060 USA
TEL: 1-281-877-6000 FAX: 281-877-6001 EMAIL: abs-amer@eagle.org WEBSITE: www.eagle.org

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Data Form

Supplement for Tank Containers/Portable Tanks

AMERICAN BUREAU OF SHIPPING

Model Number:

Container Size and Description:

ABS Design Type Number: AB/ -

Overall Tank Length:		Seam to Seam Length:	
Inside Tank Diameter:		Head Material:	
Shell Material:		Head Thickness:	
Shell Thickness:		Lining Material:	
Equivalent Thickness in Reference Steel:		Insulation & Cladding:	
		Corrosion Allowance:	

MAWP:		psig	Test Pressure:		psig	Heating Coils: MAWP:		psig
		bar			bar			bar

Maximum Payload:		kg		lb	Liquid Capacity:		liters		gallons
Maximum Allowable Cargo Density:				S.G.	No. and Capacity of Compartments:				

Design temperature:

Min.:		°C		°F	Operating:		°C		°F	Max.:		°C	°F

Safety Valves: Quantity:		Model & Size:		Capacity of each:		m³/hr
Discharge Valves: Model & Size:		Top or Bottom:				

COMMODITY CHARACTERISTICS:

UN NO.	Substance Description and Proper Shipping Name	Class or Division	Packing Group	Physical State

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TEL: 1-281-877-6000 FAX: 281-877-6001 EMAIL: abs-amer@eagle.org WEBSITE: www.eagle.org

FOUNDED 1862 ABS

Data Form
Supplement for Thermal Containers

AMERICAN BUREAU OF SHIPPING

Model Number:

Container Size and Description:

ABS Design Type Number: AB/ -

Capacity: Cubic Feet: Cubic Meters:

INSULATION:

Material Density: Specific Heat:

K Factor per mm of Thickness: Kcal/m² (HR) (°C)

K Factor per Inch of Thickness: BTU/Ft²(HR) (°F)

Method of Installation:

Thickness:

Roof cm. in. Walls: cm. in. Floor: cm. in.

DESIGN HEAT LOAD:

Design Overall K Factor: Kcal/M² (HR) (°C) BTU/FT² (HR) (°F)

Mean Surface Area: m² ft² Est. Air Leakage m³/hr ft³/hr

Design Internal Temp: °C °F @ °C °F Ambient Max.

Total Design Heat Load to be Absorbed by Cooling Unit Kcal/hr BTU/hr

COOLING UNIT:

Model : Manufacturer:

Rating: Kcal/hr BTU/hr @ °C °F Max. Design Amb. Temp.

and @ °C °F Min. Design Amb. Temp.

Horse Power: Power Source

Refrigerant: Std. Refrigerant No.:

Condenser Cooled by: ☐ Water ☐ Air

Standard to which Refrigeration System is Constructed:

HEATING ARRANGEMENTS:

☐ Not Applicable ☐ Included with Cooling Unit ☐ Details Attached

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Data Form
Supplement for Multiple Element Gas Containers (MEGCS)

Model Number:

Container Size and Description:

ABS Design Type Number: AB/ -

Design standards: Dimensions: OAL: OD of elements:

Number of elements: Capacity/element Manufacturer

Element Material: Material Standard:

Element Thickness: Corrosion Allowance:

Min. Eq. Ref. Steel Thick: Lining Material:

Manifold Material: Material Standard:

Insulation Material

MAWP: psig Test Pressure: psig Liquid Capacity: liters

Bar gauge Bar gauge gallons

Maximum Payload: kg lb MPGM kg

Maximum Allowable Cargo Density: S.G. Mass of contents per Liter

Design Temperature: Minimum: °C °F Maximum: °C °F

Safety Valves: Quantity: Model/Size: Capacity of each: m^3/S

Discharge Valves: Model:

CARGO MATERIAL CHARACTERISTICS:			
UN NO.	Proper Shipping Name/Trade Name	Class Code	Packing Group

ABS
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ABS
FOUNDED 1862

AMERICAN BUREAU OF SHIPPING

Material Identification Form

Model Number:

Container Size and Description:

ABS Design Type Number: AB/ -

Component	Recognized National Standard* Material Specification/Grade	Dimensions of Profile	Thickness (mm)
Lower Side Rails			
Upper Side Rails			
Front Header			
Rear Header			
Front Sill			
Rear Sill			
Front Corner Post			
Rear Corner Post (Inner)			
Rear Corner Post (Outer)			
Front Panels			
Side Panels			
Door Panels			
Roof Panels			
Tunnel			
Crossmembers			
Forklift Pockets			

Corner Fittings: Foundry: Model (part no.):

Door Hardware: Mfr: Model (part no.):

Wood Flooring: Genus/Species Nominal Dimensions:

TCT (Chemical Treatment): Type of Joints:

Welding Consumables:

Welding wire specification/grade Process: Size:

Welding rods specification/grade Process: Size:

Additional information:

*Note: Generic descriptions such as "MCSS" and HIGH STRENGTH STEEL" are unacceptable.

ABS
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Prototype Test Certificate

Certificate No.: ____________

Design Type No.: AB/ ______ / ______ - ______

CSC Approval Reference: USA/AB- ______ / ______ - ______

This is to certify that the undersigned Surveyor to the American Bureau of Shipping did. at the request of Lincoln Composite ____________ . attend the test facility located at ____________ on ____________ and subsequent dates in order to examine and report upon a prototype cargo container which was tested in accordance with the ABS Rules for the Certification of Cargo Containers and the International Convention for Safe Containers. This container was constructed in accordance with General Arrangement drawing no. ____________ reviewed on (date) ____________ with reference no. T-8-7/________.

CONTAINER IDENTIFICATION

Manufacturer: ____________ Max. Gross Mass (MGM): ______ (kg) ______ (lb)

Model: ____________ Size: ____________ Tare: ______ (kg) ______ (lb)

Serial no.: ____________ Maximum Permissible Payload: ______ (kg) ______ (lb)

Refrigeration Machinery Manufacturer and Model: ____________

ABS TEST NO & DESCRIPTION		TEST FORCE	INTERNAL LOAD	SEQUENCE
7.11.1	Dimensional Check			
7. 11.2a	Stacking. Front			
7.11.2b	Stacking. Rear			
7.11.3	Lifting. Top			
7.11.4	Lifting. Bottom			
7.11.5	Lifting. FLP Loaded			
7.11.6	Lifting. FLP Unloaded			
7.11.7	Lifting. Grappler Arm			
7.11.8	Floor Strength, Concentrated			
7.11.9	Restraint			
7.11.10a	End Panel. Front			
7.11.10b	End Panel. Rear			
7.11.11	Side Panel			
7.11.12	Roof Strength			
7.11.13a	Racking. Transverse. Front			
7.11.13b	Racking. Transverse. Rear			
7.11.14	Racking. Longitudinal			
7.11.15	Cargo Securing Devices			
7.11.16	Weathertightness			

Additional tests (if any) listed on the reverse. Refer to test report no. ____________ for further details.

The container was examined before. during and after testing and was found to be satisfactory.

Issued on: ____________ at ____________ by ____________
(date) (place) (Surveyor)

NOTE: This certificate evidences compliance with one or more of the Rules, guides, standards or other criteria of American Bureau of Shipping and is issued solely for the use of the Bureau, its committees, its clients or other authorized entities. This certificate is a representation only that the container specified herein has been found to comply with one or more of the Rules, guides, standards or other criteria of American Bureau of Shipping. The validity, applicability and interpretation of this Certificate is governed by the Rules and standards of American Bureau of Shipping who shall remain the sole judge thereof. Nothing contained in this Certificate or in any Report issued in contemplation of this Certificate shall be deemed to relieve any designer, builder, owner, manufacturer, seller, supplier, repairer, operator or other entity of any warranty express or implied.

ABS PLAZA. 16855 NORTHCHASE DRIVE. HOUSTON. TX 77060 USA
TEL: 1-281-877-6000 FAX: 281-877-6001 EMAIL: abs-amer@eagle.org WEBSITE: www.eagle.org

B.2

Certificate No. ------------------

Test	Test Description	Specimens	Standard Reference and exceptions	Test results
Hydraulic Proof Pressure Test/Leak Check				
Hydraulic Volumetric Expansion Test				
Material test for plastic liners				
Hydrostatic Burst Tests				
Hydrostatic Burst Tests				
Ambient Cycle Test				
LBB				
Penetration Test				
Environmental Test				
Flaw Tolerance Test				
High Temp Creep				
Accelerated Stress Rupture				
Extreme Temp Pressure Cycling				
Resin Shear Strength				
Drop Test				
Boss Torque test				
Permeation				
Natural Gas Cycling Test				
Blowdown Test				
Bonfire				

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B.3

American Bureau of Shipping

CNG Container Certificate of Approval

Certificate No.:

Design Type No.: AB/108/07-02

CSC Approval Reference USA/AB/ /

Manufacturer & address		Serial No.	
Owner & address		Operating No.	

This is to certify that the multiple element gas container (MEGC) identified above has been inspected at each stage of manufacture and that its construction, including details of design, materials and workmanship, conforms to the ABS Rules for the Certification of Cargo Containers, to the International Convention of Safe Containers and ABS Guidance Notes on Review and Approval of Novel Concepts.

ELEMENT CHARACTERISTICS

Design Standard:	Design Temperature: Min: Max:
Dimensions (OAL):	OD:
No. of Elements :	Design Pressure:
Shell (Liner) Material:	Autofrettage Pressure:
Heads Material:	Service Pressure:
Nozzle Material:	Design Volume/element :
Laminate Material:	Safety Valve:
Skirt Material:	Discharge Valve:

CONTAINER CHARACTERISTICS

Overall dimensions: length 40' width 8' height 8'	Maximum Gross Mass: kg (lb)
Prototype unit test reference (certificate no.): (date)	Tare wt.: kg (lb)
Rail Impact Test (certificate no.): (date)	Maximum Permissible Payload: kg (lb)
Approved Commodities: Compressed Natural Gas (Methane)" (Hazard Class 2.1) UN 1971	

MANUFACTURER'S STATEMENT

I hereby affirm that the MEGC described above has been manufactured according to the drawings listed below, as approved by ABS on (date) _____ reference no. _____ under the effective quality control of the manufacturer identified above.

Drawing number (s): _____ Signed: _____________________ Date:

SHIPPER' RESPONSISIBILITY

- Maintain the operating pressure of the container below or up to design pressure and the settled pressure at 20 °C shall be no higher than _____ MPa.
- The container shall not be emptied to a pressure lower than _____ MPa.
- Gas quality shall be monitored to maintain within the threshold limits of water, carbon dioxide and hydrogen sulfide contents

Notes:
- Individual ABS certificates [AB 113] for each elements are to be appended to this certificates
- ABS Periodic inspection (element and piping) at intervals not exceeding 30 months is required by an ABS Surveyor.
- Subject container is considered "out-of-test" if a 30 month periodic inspection has become due.
- Container specified above that is "out-of-test" cannot be used (i.e., loaded with cargo) until it has undergone the following ABS prescribed periodic inspection in addition to any relevant regulations in the country of use.

Issued on: __________ at ______________________ By: ______________________________
(date) (place) (Surveyor)

NOTE: This certificate evidences compliance with one or more of the Rules, guides, standards or other criteria of American Bureau of Shipping and is issued solely for the use of the Bureau, its committees, its clients or other authorized entities. This certificate is a representation only that the container specified herein has been found to comply with one or more of the Rules, guides, standards or other criteria of American Bureau of Shipping. The validity, applicability and interpretation of this Certificate is governed by the Rules and standards of American Bureau of Shipping who shall remain the sole judge thereof. Nothing contained in this Certificate or in any Report issued in contemplation of this Certificate shall be deemed to relieve any designer, builder, owner, manufacturer, seller, supplier, repairer, operator or other entity of any warranty express or implied.

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TEL: 1-281-877-6000 FAX: 281-877-6001 EMAIL: abs-amer@eagle.org WEBSITE: www.eagle.org

FOUNDED 1862 ABS

American Bureau of Shipping
Cylinder Certificate of Compliance

Certificate No.: ____________________

Design Type No.: AB/ ______ / -

U.S. Department of Transportation No.:

Manufacturer & address:		
Owner & address:		

CYLINDER DESCRIPTION AND DESIGN CRITERIA:

DoT Specification or DoT Special Permit number: __________

Service pressure: ____________________

Nominal size: ______________ O.D. X __________ Long

Test pressure: ____________________

Nominal water capacity: ____________________

Minimum wall thickness: ______________

Calculated stress @ T.P.: ______________

MANUFACTURING PROCESS:
Construction (billet piece, tube, plate, etc.)

____

____

____

MATERIAL AND HEAT TREATMENT:

____

____

____

REPORT DETAILS:

Quantity: ____________________

Test date: ____________________

Serial no. range: ____________________

Heat no. or code: ____________________

Identifying symbol: ____________________

Lot number: ____________________

MARKINGS: ____________________

Consigned to: ____________________

I hereby certify that I have determined that the cylinders described on this report comply with the requirements of U.S. Department of Transportation specification: ____.

Comments:

Issued on: ____________________ at ____________________ by ____________________
(date) (place) (Surveyor)

NOTE: This certificate evidences compliance with one or more of the Rules, guides, standards or other criteria of American Bureau of Shipping and is issued solely for the use of the Bureau, its committees, its clients or other authorized entities. This certificate is a representation only that the tank container specified herein has been found to comply with one or more of the Rules, guides, standards or other criteria of American Bureau of Shipping. The validity, applicability and interpretation of this Certificate is governed by the Rules and standards of American Bureau of Shipping who shall remain the sole judge thereof. Nothing contained in this Certificate or in any Report issued in contemplation of this Certificate shall be deemed to relieve any designer, builder, owner, manufacturer, seller, supplier, repairer, operator or other entity of any warranty express or implied.

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Annex C
(informative)

Verification of Stress Ratios using Strain Gauges

This annex describes a procedure that may be used to verify stress ratios by use of strain gauges.

a) The stress-strain relationship for fibres is always elastic, therefore, stress ratios and strain ratios are equal.

b) High elongation strain gauges are required.

c) Strain gauges should be orientated in the direction of the fibres on which they are mounted (i.e. with hoop fibre on the outside of the cylinder, mount gauges in the hoop direction).

d) Verification Method

   1) Apply strain gauges and calibrate.

   2) Measure strains at working and minimum burst pressure.

   3) Confirm that the strain at burst pressure divided by the strain at working pressure meets the stress ratio requirements. For hybrid construction, the strain at operating pressure is compared with the rupture strain of cylinders reinforced with a single fibre type.

Annex D
(informative)

Instructions for Handling. Use and Inspection of Cylinders

D.1 General
The primary function of the manufacturer's instructions is to provide guidance to the cylinder purchaser. distributor. installer and user for the safe use of the cylinder over its intended service life.

D.2 Distribution
The manufacturer should advise the purchaser to supply these instructions to all parties involved in the distribution. handling. installation and use of the cylinders.

The document may be reproduced to provide sufficient copies for this purpose: however. it should be marked to provide reference to the cylinders being delivered.

D.3 Reference to Existing Codes. Standards and Regulations
Specific instructions may be stated by reference to national or recognized codes. standards and regulations.

D.4 Cylinder Handling
Handling procedures should be described which would ensure that the cylinders will not suffer unacceptable damage or contamination during handling.

D.5 Installation
Installation instructions should be provided which would ensure that the cylinders do not suffer unacceptable damage during installation and during normal operation over the intended service life.

Where the mounting is specified by the manufacturer. the instructions should. where relevant. contain details such as mounting design. the use of resilient gasket materials. the correct tightening torques and avoidance of direct exposure of the cylinder to the environment. chemicals and mechanical contacts. Cylinder locations and mountings should comply with recognized installation standards.

Where the mounting is not specified by the manufacturer. the manufacturer should draw the purchaser's attention to possible long-term impacts of the vehicle mounting system. e.g.. vehicle body movements and cylinder expansion/contraction under the pressure and temperature conditions of service.

Where applicable. the purchaser's attention should be drawn to the need to provide installations such that liquids or solids cannot be collected to cause cylinder material damage.

The correct pressure relieve device to be fitted should be specified.

Cylinder valves, pressure relief devices and connections should be protected against breakage in a collision. If this protection is mounted on the cylinder, the design and method of attachment should be approved by the cylinder manufacturer. Factors to be considered include the ability of the cylinder to support any transferred impact loads and the effect of localized strains on cylinder stresses and fatigue life.

D.6 Use of Cylinders

The manufacturer should draw the purchaser's attention to the intended service conditions specified in this Specification, in particular the cylinder's permissible number of pressure cycles, its life in years, the gas quality limits and the permissible maximum pressures.

D.7 In-service Inspection

The manufacturer should clearly specify the user's obligation to observe the required cylinder inspection requirements (e.g. reinspection interval, by authorized personnel). This information should be in agreement with the design approval requirements, and should cover the following aspects.

a) In-service Inspection

In addition to the required in-service inspection requirements in accordance with the regulations of the authority having jurisdiction, each cylinder should be visually inspected for external damage or deterioration prior to filling. Cylinders with damage should be removed from service until the severity of damage has been assessed and disposition determined.

b) Periodic requalification

Inspection and/or testing is required to be performed in accordance with the relevant regulations of the country(ies) where the cylinders are used.

Recommendations for periodic requalification by visual inspection or testing during the service life should be provided by the cylinder manufacturer on the basis of use under service conditions specified herein. Each cylinder should be visually inspected at least every 36 months, and at the time of any re-installation, for external damage and deterioration, including under the support straps. The visual inspection should be performed by a competent agency approved or recognized by the regulatory authority, in accordance with the manufacturer's specifications.

Cylinders without labels or stamps containing mandatory information, or with labels or stamps containing mandatory information that is illegible in any way should be removed from service. If the cylinder can be positively identified by manufacturer and serial number a replacement label or stamping may be applied, allowing the cylinder to remain in service.

c) Cylinders involved in collisions

Cylinders which have been involved in a vehicle collision should be re-inspected by an authorized inspection agency. Cylinders which have not experienced any impact damage from the collision may be returned to service, otherwise the cylinder should be returned to the manufacturer for evaluation.

d) Cylinders involved in fires

Cylinders which have been subject to the action of fire should be re-inspected by an authorized inspection agency, or condemned and removed from service.

APPENDIX D - DOT-SP 14951 (Third Revision)

U.S. Department
of Transportation

Pipeline and Hazardous
Materials Safety Administration

East Building, PHH-30
1200 New Jersey Avenue S.E.
Washington, D.C. 20590

DOT-SP 14951
(THIRD REVISION)

EXPIRATION DATE: 2017-10-31

(FOR RENEWAL, SEE 49 CFR § 107.109)

1. GRANTEE: Hexagon Lincoln, Inc.
Lincoln, NE

2. PURPOSE AND LIMITATIONS:

a. This special permit authorizes the manufacture, marking, sale, and use of a non-DOT specification fully wrapped fiber reinforced composite gas cylinder with a non-load sharing plastic liner that meets the ISO 11119-3 standard except for the design water capacity and working pressure. This special permit provides no relief from the Hazardous Materials Regulations (HMR) other than as specifically stated herein. The most recent revision supersedes all previous revisions.

b. The safety analyses performed in development of this special permit only considered the hazards and risks associated with transportation in commerce. The safety analyses did not consider the hazards and risks associated with consumer use, use as a component of a transport vehicle or other device, or other uses not associated with transportation in commerce.

3. REGULATORY SYSTEM AFFECTED: 49 CFR Parts 106, 107 and 171-180.

4. REGULATIONS FROM WHICH EXEMPTED: 49 CFR § 173.301(f) in that a fire protection system is used in lieu of a pressure relief valve and § 173.302(a) in that the use of a non-DOT specification cylinder is not authorized, except as specified herein.

5. BASIS: This emergency special permit is based on the application of Hexagon Lincoln, Inc. dated March 3, 2016, submitted in accordance with § 107.117 and a determination that it is necessary to prevent significant economic loss.

6. HAZARDOUS MATERIALS (49 CFR § 172.101):

Hazardous Materials Description			
Proper Shipping Name	**Hazard Class/ Division**	**Identi-fication Number**	**Packing Group**
Argon, compressed	2.2	UN1006	N/A
Helium, compressed	2.2	UN1046	N/A
Hydrogen, compressed	2.1	UN1049	N/A
Neon, compressed	2.2	UN1065	N/A
Nitrogen, compressed	2.2	UN1066	N/A
Methane, compressed *or* Natural gas, compressed *(with high methane content)*	2.1	UN1971	N/A

Note: See paragraph 7.c for cylinder service limitations.

7. SAFETY CONTROL MEASURES:

a. PACKAGING - Packaging prescribed is a non-DOT specification fully wrapped fiber reinforced composite gas cylinder with a non-metallic and non-load sharing plastic liner as described in the Lincoln Composites application on file with the Office of Hazardous Materials Safety Approvals and Permits Division (OHMSAPD). Each cylinder must meet all the design and construction requirements for UN composite cylinders specified in § 178.71(l) and of ISO Standard 11119-3 (Gas Cylinders of Composite Construction-Specification and Test Methods - Part 3: Fully wrapped fiber reinforced composite gas cylinders with non-metallic and non-load-sharing metallic liners), except as follows:

(1) Scope § 1 – Cylinders made under this special permit are limited to a minimum water volume of 450 liters and a maximum water volume of 8500 liters, and a working pressure up to 250 bar (3625 psi).

(2) Batch of non-metallic liners § 3.4 – A batch of non-metallic liners is the quantity of liners of the same nominal diameter, length, thickness and design, made successively from the same materials, and subjected to the same manufacturing process.

(3) Design (General Requirement) § 7.1.4 – The minimum fiber stress ratio for carbon fiber must be 2.40.

(4) Type approval procedure (General Requirement) § 8.1

(i) A DOT Independent Inspection Agency (IIA) approved in writing by the Associate Administrator for Hazardous Materials Safety (AAHMS) in accordance with 49 CFR Part 107, Subpart I must review the results of design qualification testing that was submitted in the application for special permit. The IIA must either verify that the cylinder design meets the requirements of the special permit based on the testing and other documentation submitted in the application for special permit, or the IIA may require additional testing and/or information from the manufacturer in order to verify the cylinder design meets all requirements of the special permit. Prior to production of cylinders, the IIA's verification of the cylinder design must be submitted to and acknowledged in writing by the OHMSAPD.

(ii) Prior to any manufacture of cylinders under this special permit, an IIA approved in writing by the AAHMS must provide inspections and verifications of all batch testing and all new design qualification testing in accordance with the requirements of this special permit.

(5) Prototype tests § 8.2.1, § 8.2.2 – The cylinders required to be manufactured for prototype testing must be representative of production units. A sufficient number of tubes shall be made available to complete the prototype testing or testing of the design variant. Subscale units are permitted as follows:

(i) Ambient cycling – One test unit must be full scale, additional unit must be full diameter, shorter length;

(ii) LBB – test unit must be full diameter and may be shorter length;

(iii) Environmental fluid – test unit may be smaller diameter and shorter length;

(iv) Environmental cycle – test unit may be smaller diameter and shorter length;

(v) High temperature creep and accelerated stress rupture – test unit may be smaller diameter and shorter length;

(vi) Flaw – test unit must be full diameter and may be shorter length;

(vii) Gunfire – test unit must be full diameter and may be shorter length;

(viii) Permeability – test unit may be smaller diameter and shorter length;

(ix) Torque – test unit must be full diameter and may be shorter length.

(6) Inspector § 8.2.7 - The IIA must witness all testing as specified in this special permit (see Table 2).

(7) Drop test § 8.2.7h, § 8.5.9 – Cylinders made under this special permit are not authorized for shipment unless mounted in a frame and must be handled in accordance with the operational controls listed in this special permit therefore they are exempt from drop test requirement of § 8.2.7h.

(8) Salt water immersion test § 8.2.7m, § 8.5.14 – Cylinders made under this special permit are not authorized for underwater use therefore cylinders are exempt from salt water immersion testing.

(9) New design § 8.3.2(d) - a minor change to a resin component that is within the same specification (i.e., from one epoxy to another) may be qualified as a design variant.

(10) Design Variant § 8.4 - Attached Table 2 (qualification tests) may be used in lieu of Table 2 of ISO 11119-3.

Table 2. Qualification tests for cylinders with maximum test pressure ≤ 375 bars, water volume greater than 450 liters and less than or equal to 8,500 liters.

Qualification for Design Variants															
Test	New Design	Length <= 50%	Length >50%	Diameter <=20%	Diameter >20% <= 50%	Liner thickness >20% or manufacture	Liner material	Equivalent fiber	Test Pressure <=20%	Test pressure >20% <=60%	Composite thickness or pattern	Boss-to-liner interface	Equivalent resin matrix	Resin Matrix	Pressure Relief Device
Liner material test							X								
Composite material test								X			X[1]		X[1]		
Hydraulic pressure	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Hydraulic burst	X	X[1]	X[1]	X[1]	X	X[1]	X[1]	X	X[1]	X	X	X[1]	X[1]	X[1]	
Ambient cycle	X			X[1]	X		X	X[1]	X[1]	X	X	X[1]			
Environmental cycle	X													X	
High temperature creep[1]	X				X[1]		X			X[1]a	X[1]a	Xa	Xa	Xa	
Flaw tolerance[1]	X				X									X	
High velocity impact (gunfire)	X				X[2]				X[1]	X[1]	X[1]			X	
Fire resistance	X		X[1]b		X[1]b					X					X
Permeability	X				X[2]	X	X			X[1]					
Torque	X						X					X		X	
Leak	X			X	X		X		X	X		X			
Pneumatic cycle	X				X[1]	1	X					X			

Notes:

1. For a new design of a cylinder with water volume larger than 450 L, a minimum of 1 cylinder may be used for each design change. For a change of boss-liner interface column, a leak check of the liner interface would be accepted. The pneumatic cycle test is not required if the boss- liner interface does not change.

a. Where the design variant’s burst pressure to test pressure ratio is over 20% greater than the same ratio for the approved design.

b. When length increases up to 50% and/or diameter increases up to 20%, Bonfire test may not be required if the volume stays the same or decreases and the same PRD system is used.

2. Test to be conducted for reduction in diameter only.

(11) Cylinder burst test § 8.5.3.1 – Two cylinders are required for the burst test. Pressurization rate is limited to 14 bar/sec at pressures above 80% of the minimum burst pressure. If the rate exceeds 3.5 bar/sec above 80% of the minimum burst pressure, then either the cylinder must be placed schematically between the pressure source and the pressure measurement device, or there must be a 5 second hold at the minimum design burst pressure.

(12) Burst test criteria § 8.5.3.2 - The burst pressure or pressure at failure, P_b, must be not less than 1.6 times the test pressure, P_h, of the composite cylinder.

(13) Ambient cycle test procedure § 8.5.4.1.1 – The cylinders must be cycled to 130 % of the working pressure or higher. At least one of these cylinders must be a full scale cylinder. One of these cylinders may be a subscale with full diameter, but shorter length. The cylinder must pass the LBB test, 8.5.19, with no leakage. Temperature monitoring of cylinder not required if temperature is maintained below 85 °C.

(14) Ambient cycle test criteria § 8.5.4.1.2 – The cylinder shall withstand a number of cycles equal to 750 times the design service life in years without leakage. The cylinder shall continue cycling until it leaks or reaches a total of 2250 times the service life in years. However, should failure during this second part of the test be by burst, then the cylinder shall have failed the test.

(15) Environmental cycle test procedure § 8.5.6.2 – The cylinder shall have an internal pressure of 10% of the working pressure during the temperature conditioning. The cylinder shall be pressure cycled between 10% and 100% of the working pressure during the extreme temperature exposure. Following the cycle testing at designated temperature (60-70 °C), the cylinder shall be subjected to 30 cycles from 10% of working pressure

to the test pressure at a rate not to exceed 10 cycles per minute.

(16) Environmental cycle test criteria § 8.5.6.3 – The burst pressure, p_b, must be not less than 1.4 times the test pressure, p_h.

(17) High temperature creep test procedure § 8.5.7.1, 8.5.7.2 – One cylinder shall be hydrostatically pressurized to test pressure at 65 °C. The cylinder shall be held at this pressure and temperature for 1,000 hours. The cylinder shall then be pressurized to burst in accordance with the procedure described in 8.5.3, except that the burst pressure shall exceed 100% of the minimum design burst pressure (1.6 times the test pressure, P_h). A second cylinder shall be pressurized to test pressure and held at a temperature of 100°C for not less than 200 hours. Following the test, the cylinder shall meet the requirements of the hydrostatic expansion test (8.5.2) and the burst test (8.5.3), with the minimum burst being 1.6 times the test pressure, P_h, of the composite cylinder.

(18) Flaw test criteria § 8.5.8.1 – One cylinder must be tested. A subscale tank with full diameter and shorter length may be used for the test.

(19) Flaw test criteria § 8.5.8.3 – The cylinder must not leak or rupture within the first 3,000 cycles, but may fail by leakage during the remainder of the cycles.

(20) Drop test § 8.5.9 – The drop test is not required. (See operational controls).

(21) High velocity impact test procedure § 8.5.10.1 – The cylinder may be filled with air, nitrogen, or the gas to be contained. If a single 7.62 mm (30 caliber) round will not penetrate the wall, additional rounds may be used, or a larger diameter round may be used.

(22) Fire resistance test § 8.5.11.2 – The cylinder (tube) assembly must be tested in a horizontal position. The bonfire test is designed to demonstrate that finished tubes, complete with the fire protection system (e.g., valve, pressure relief devices and/or integral thermal insulation) specified in the design, will prevent the rupture of the tube when tested under the specified fire conditions. A uniform fire source

of a minimum 1.65 m length must provide direct flame impingement on the cylinder surface. Any failure during the test of a valve, fitting or tubing that is not part of the intended protection system for the design shall invalidate the result. Direct flame impingement is not permitted on valves, fittings, and/or pressure relief devices. The fire and its position relative to the transport frame must be approved by the Inspector. Precautions shall be taken during fire testing in the event that tube rupture occurs.

(23) Fire resistance test criteria § 8.5.11.3 – The cylinder must vent through a pressure relief device, and without rupturing.

(24) Permeability test procedure § 8.5.12.2 – One cylinder must be tested. This may be the full scale cylinder or a subscale (shorter length with same diameter) using the same liner material. Pressure cycling prior to permeation testing is not required. The cylinder must be filled with the intended lading or suitable trace gas to working pressure, placed in an enclosed sealed chamber at ambient temperature, and monitored for leakage for 500 hours.

(25) Permeability test criteria § 8.5.12.3 – The measured permeation rate must be reported. If a trace gas is used, correlation between the trace gas and intended lading must be provided. If permeation exceeds the allowable rate of § 8.5.12.3, the cylinder must be sectioned and the internal surfaces inspected for any evidence of cracking or deterioration.

(26) Torque test on cylinder neck boss § 8.5.13.1 – The body of the cylinder must be restrained against rotation and a torque of twice the valve or PRD installation torque specified by the manufacturer must be applied to each end boss of the cylinder. The torque must be applied first in the direction of tightening a threaded connection, then in the un-tightening direction, and finally again in the tightening direction.

(27) Torque test criteria § 8.5.13.2 – Upon completion of all applied torques, the cylinder must be subjected to a leak test to confirm that no leakage occurred as a result of applied torque.

(28) Salt water immersion test § 8.5.14 – The salt water immersion test is not required, as the cylinder is not authorized for underwater applications.

(29) Leak test § 8.5.15 – An acceptable procedure for leak testing is to pressurize the cylinders with suitable fluid to working pressure and, with the cylinder having been pressurized for at least 15 minutes, carefully examine for signs of leakage (e.g., a visual indication or decrease in pressure).

(30) Pneumatic cycle test procedure § 8.5.16.1 – One finished cylinder shall be cycle tested as follows. Temperature monitoring of the cylinder is not required if the temperature is maintained below 85 °C:

(i) Fill the cylinder to be tested with a non-corrosive fluid such as oil, inhibited water or glycol;

(ii) Cycle the pressure in the cylinder for 1,000 cycles, between 10% of working pressure and working pressure. The pressure cycling rate shall not exceed 10 cycles per minute;

(iii) Release the pressure, drain the fluid, and dry the interior of the cylinder;

(iv) Cycle the pressure in the cylinder for 5 cycles, between 10% of working pressure and working pressure, with air, nitrogen or other gas determined by the inspector. The pressure cycling rate must provide at least a 2 hour hold at the high pressure portion of the cycle;

(v) Following the high pressure hold of the final cycle, the gas shall be released freely to atmosphere.

The cylinder must then be subjected to a leak test. Following the completion of the test, the cylinder must be sectioned and the liner and liner/end boss interface inspected for evidence of any deterioration, such as fatigue cracking or electrostatic discharge.

(31) Pneumatic cycle test criteria § 8.5.16.2 – The cylinder must have no signs of leakage or deterioration.

(32) Water boil test § 8.5.17 – The water boil test is not required.

(33) Batch inspection and testing sampling § 9.1.3 – Supplier's certification of the material properties may serve as verification of compliance.

(34) Batch inspection and testing criteria § 9.1.4 – Supplier's certification of the liner boss properties may serve as verification of compliance.

(35) Overwrap materials § 9.3 – Supplier's certification of the fiber properties may serve as verification of compliance.

(36) Batch testing procedure § 9.4.5 – One cylinder (tube) out of 5 batches or one year of cylinder production, whichever comes first. A batch here is defined to be production quantity of up to 200 finished cylinders (tubes) successively produced (plus finished cylinders required for destructive testing), of the same nominal diameter, length, thickness and design. The batch of finished tubes may contain different batches of liners, fibers and matrix materials.

(37) Batch testing criteria § 9.4.6 – The burst test may be conducted on the first unit of the batch. After reaching the minimum required burst pressure, and holding for 5 seconds, the cylinder shall have passed the test.

(38) Marking § 10.1 & 10.2 - marking must contain the following:

(i) DOT special permit number followed by working pressure expressed in bar (psig). Marking may be on a label permanently attached to the outside of the cylinder.

(ii) A serial number and the manufacturer's identification number or a symbol as obtained from the Associate Administrator for Hazardous Materials Safety, located just below or immediately following the DOT marking. The serial number and the manufacturer's identification number may be placed on the boss provided the markings are accessible for inspection.

(iii) The DOT Independent Inspector Agency (IIA) official mark must be placed near the serial number. The marking must contain date the (month and year) of the initial hydraulic proof pressure test for that cylinder.

(iv) The size of the letters and numbers used must be at least 0.64 cm (1/4 inch) high if space permits.

(v) The following are examples of an authorized format for marking:

DOT-SP AAAAA-YYYY
(where AAAAA is the special permit number and YYYY is the working pressure)
CCCC MMI
(where CCCC is the serial number and MMI is the manufacturer's mark or symbol)
DDD - MM/YY
(where DDD is the inspectors mark and MM/YY is the month and year of the hydraulic proof pressure test).

Additional markings are permitted, provided the additional markings do not obscure the required marking and are not detrimental to the integrity of the cylinder. Provisions for marking of the required requalification dates and RIN information must be made near the cylinder markings.

(39) **Additional requirements for each new design:**

(i) **Fire Protection System (FPS)** – Each tube assembly must be equipped with a Fire Protection System (FPS) as described in the Lincoln Composites application on file with the OHSMAPD. The FPS consists of:

(A) Plastic sensor lines that are energized from a low pressure reservoir, a pressure release mechanism, and vent lines. There are multiple sensor lines, and they run the length of the frame system. When the sensor lines are exposed to a fire, they melt or rupture, causing the air pressure inside the reservoir of the FPS system to drop. The pressure drop in the FPS reservoir activates the tube assembly pressure release mechanism, which vents all tubes or

(B) FPS system that uses a shape memory metal material as a trigger the vent valve during a fire scenario as specified in the Lincoln Composites patent application on file in the OHMSAPD.

(C) The vent lines direct the released gas upwards and outside of the frame system.

(ii) **Environmental fluids test -** One finished cylinder including coating if applicable must be tested in accordance with procedures described in the Lincoln Composites application on file with the OHMSAPD.

(iii) **Leak Before Burst (LBB) Test -** Two finished cylinders, of full scale diameter but may be shorter length, must be pressure cycled in accordance with the following procedure:

(A) Fill the cylinder to be tested with a non-corrosive fluid such as oil, inhibited water or glycol;

(B) Cycle the pressure in the cylinder between 25 bar and 375 bar at a rate not exceeding 10 cycles per minute;

(C) The number of cycles to failure must be reported, along with the location and description of the failure initiation; and

(D) All cylinders must either fail by leakage or exceed three times the design number of filling cycles.

(iv) **Resin Shear Strength -** Resin materials must be tested in accordance with procedures described in the Lincoln Composites application on file with the OHMSAPD.

(v) **Ultraviolent (UV) Testing -** One finished cylinder including coating if applicable must be UV tested in accordance with procedures described in the Lincoln Composites application on file with the OHMSAPD.

b. Requalification –

(1) Each cylinder must be requalified once every 5 years by a qualified person holding a valid DOT RIN in accordance with § 107.805 as follows:

(i) External and internal visual inspection in accordance with CGA pamphlet C-6.2 and with the Lincoln Composites Service Bulletin 10-01-002 and the Lincoln Composites CNG Bulk Hauling TITAN™ Module Inspection Manual on file with the OHMSAPD and hydraulic proof pressure test equal to 1.5 times the marked working pressure and hold the pressure for a minimum of 3 minutes without a loss of pressure.

(ii) A nondestructive examination (NDE) which is approved by the Approvals and Permits Division may be used in lieu of internal visual inspection and hydraulic proof pressure test.

(2) Persons who perform inspection and testing of cylinders subject to this special permit must comply with § 180.205(b) and with all the terms and conditions of this special permit and the HMR.

(3) Requalification date (month/year) must be permanently marked on the cylinder as specified in paragraph § 180.213. The marking of the RIN symbol on the cylinder certifies compliance with all of the terms and conditions of this special permit.

c. OPERATIONAL CONTROLS –

(1) Cylinders manufactured under this special permit are not authorized for use 15 years from the date of manufacture, except as specified under paragraph 8.a. of this special permit.

(2) A cylinder that has been subjected to fire may not be returned to service.

(3) Cylinders are permanently mounted:

(i) Inside of framing that is designed, marked (approval plate) and approved in accordance with the International Convention for Safe Containers (CSC) (49 CFR Part 451) as described in the Lincoln Composites application on file with the OHMSAPD. Structural framework has been evaluated for transportation of the tubes under this special permit by Finite Element Analysis (FEA) on file with OHMSAPD. The FEA has demonstrated the framework's ability to protect the tubes from damage due to front, rear, or side impact, and rollover. The frame designed meets the following:

(A) All requirement of § 173.301(i);

(B) The frame design must meet all requirements of CGA TB-25; or

(ii) In semitrailer for motor vehicle that is designed and analyzed using Finite Element Analysis (FEA) software. Analysis shall demonstrate the ability of the semitrailer structures to protect the tubes from damage due to front, rear, or side impact, and rollover. Structural framework Finite Element Analysis (FEA) on file with the OHMSAPD. This semitrailer design meets the following:

(A) All requirements of § 173.301(i);

(B) The frame design must meet all requirements of CGA TB-25.

(C) With the exception of the requirements for length, width, height and ISO/CSC markings, the frame is also tested in accordance with ISO 1496-3:1995(E) per the following sections:

1. Section 6.3 - Test No. 2, Top Lift;

2. Section 6.4 - Test No. 3, Bottom Lift;

3. Section 6.5 - Test No. 4, External Restraint (Longitudinal);

4. Section 6.6 - Test No. 5, Internal Restraint (Longitudinal);

5. Section 6.7 - Test No. 6, Internal Restraint (Lateral);

6. Section 6.8 - Test No. 7, Rigidity (Transverse);

7. Section 6.9 - Test No. 8, Rigidity (Longitudinal);

8. Section 6.11 - Test No. 10, Walkways (if applicable);

9. Section 6.13 - Test No. 12, Pressure Test.

(4) Cylinder (tube) handling – cylinder must be rejected if it drops from a height greater than 2' during the manufacturing and/or prior to being mounted to the CSC framing.

(5) Fire protection System (FPS) Inspection - Prior to each filling, the FPS and PRD must be inspected in accordance with the Lincoln Composites Service Bulletin 10-01-002 on file with the OHMSAPD to ensure adequate reservoir pressure for full operation of the FPS/PRD.

(6) Cabinet Flammability Limit – Lower Level Flammability Limit (LEL) of each gas or gas mixtures must be calculated for the highest pressure and temperature and to ensure the cabinet of the cylinder assembly is equipped with proper ventilation to avoid a fire or explosion during transportation.

(7) Prior to use in Offshore Service under the terms of this special permit, additional information justifying such use must be submitted to and acknowledged in writing by the AAHMS.

(8) Low pressure/temperature prior to filling – the following procedure must be followed in case the pressure of a cylinder (tube) dropped below 100 psig (7 bar) while the ambient temperature was below -12°C:

> Prior to filling - either the tube must be held at or above 16°C for 8 hours, or the tube must be filled to 435 psig (30 +/- 3 bar) from a compressor, and held for one hour, before returning to normal fill procedures.

(9) Transportation of Division 2.1 (flammable gas) is not authorized aboard cargo vessel unless specifically authorized in the Hazardous Materials Table (§ 172.101).

(10) When transported by cargo vessel, the cylinders must be stowed on deck only and are prohibited from passenger ships (Stowage Category D).

8. SPECIAL PROVISIONS:

a. Service Life Extension Program.

(1) Cylinders manufactured under this special permit are authorized for a maximum service life of 15 years from the date of manufacture in accordance with the Lincoln Composites service life extension program dated February 14, 2013 on file with the OHMSAPD. The service life extension program must be implemented for each design type that is intended for additional service life beyond 15 years to determine the

additional years of service life. If cylinders are authorized for extended service life, the maximum service life of each cylinder under this special permit is 30 years from the date of manufacture.

(2) Under the service life extension program, the grantee must randomly recall a minimum of thirty cylinders of each design type which have been in service for 10 and 13 years. Cylinders recalled after 10 years shall be designated "Group A" and cylinders recalled after 13 years shall be designated "Group B". All recalled cylinders must be subjected to design requalification as specified Sections 8.5.4, 8.5.5, 8.5.7 and 8.5.8 of ISO 11119-3. Acceptance criteria shall be as defined in ISO 11119-3 except $P_b = 1.6P_h$ and the design life (y) must be greater than or equal to 20 years. All cylinders that fail to meet the requalification requirements must be condemned, removed from service and rendered incapable of retaining pressure. In the case that some units from the initial minimum lot size are condemned, an additional 30 cylinders must be selected and subjected to the same design requalification as specified above (Sections 8.5.4, 8.5.5, 8.5.7 and 8.5.8 of ISO 11119-3). An Independent Inspection Agency must witness all testing.

(3) The complete test report including original test data must be submitted to the Associate Administrator for Hazardous Materials Safety for assessment within 30 days of completion. Failure to meet the acceptance criteria specified in this section shall result in the design being restricted to a maximum life of 15 years.

b. In accordance with the provisions of Paragraph (b) of § 173.22a, persons may use the packaging authorized by this special permit for the transportation of the hazardous materials specified in paragraph 6, only in conformance with the terms of this special permit.

c. A person who is not a holder of this special permit, but receives a package covered by this special permit, may reoffer it for transportation provided no modification or change is made to the package and it is offered for transportation in conformance with this special permit and the HMR.

d. A current copy of this special permit must be maintained at each facility where the package is offered or reoffered for transportation.

e. A current copy of this special permit must be maintained at each facility where the package is manufactured under this special permit and must be made available to a DOT representative upon request.

f. Each packaging manufactured under the authority of this special permit must be either (1) marked with the name of the manufacturer and location (city and state) of the facility at which it is manufactured or (2) marked with a registration symbol designated for a specific manufacturing facility.

9. MODES OF TRANSPORTATION AUTHORIZED: Motor vehicle, rail freight and cargo vessel.

10. MODAL REQUIREMENTS: A current copy of this special permit must be carried aboard each cargo vessel or motor vehicle used to transport packages covered by this special permit. For transportation by cargo vessel, see paragraphs 7.c.(9) and 7.c.(10).

11. COMPLIANCE: Failure by a person to comply with any of the following may result in suspension or revocation of this special permit and penalties prescribed by the Federal hazardous materials transportation law, 49 U.S.C. 5101 et seq:

- o All terms and conditions prescribed in this special permit and the Hazardous Materials Regulations, 49 CFR Parts 171-180.

- o Persons operating under the terms of this special permit must comply with the security plan requirement in Subpart I of Part 172 of the HMR, when applicable.

- o Registration required by § 107.601 et seq., when applicable.

Each "Hazmat employee", as defined in § 171.8, who performs a function subject to this special permit must receive training on the requirements and conditions of this special permit in addition to the training required by §§ 172.700 through 172.704.

No person may use or apply this special permit, including display of its number, when this special permit has expired or is otherwise no longer in effect.

Under Title VII of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)—"The Hazardous Materials Safety and Security Reauthorization Act of 2005" (Pub. L. 109-59), 119 Stat. 1144 (August 10, 2005), amended the Federal hazardous materials transportation law by changing the term "exemption" to "special permit" and authorizes a special permit to be granted up to two years for new special permits and up to four years for renewals.

12. REPORTING REQUIREMENTS: Shipments or operations conducted under this special permit are subject to the Hazardous Materials Incident Reporting requirements specified in 49 CFR §§ 171.15 Immediate notice of certain hazardous materials incidents, and 171.16 Detailed hazardous materials incident reports. In addition, the grantee(s) of this special permit must notify the Associate Administrator for Hazardous Materials Safety, in writing, of any incident involving a package, shipment or operation conducted under terms of this special permit.

Issued in Washington, D.C.:

for Dr. Magdy El-Sibaie
Associate Administrator for Hazardous Materials Safety

Address all inquiries to: Associate Administrator for Hazardous Materials Safety, Pipeline and Hazardous Material Safety Administration, U.S. Department of Transportation, East Building PHH-30, 1200 New Jersey Avenue, Southeast, Washington, D.C. 20590.

Copies of this special permit may be obtained by accessing the Hazardous Materials Safety Homepage at http://hazmat.dot.gov/sp_app/special_permits/spec_perm_index.htm
Photo reproductions and legible reductions of this special permit are permitted. Any alteration of this special permit is prohibited.

PO: MMToughiry/TG

APPENDIX E - SU 9806 (Ren. 2) - Transport Canada Equivalency Certificate

Transport
Canada
Safety and Security

Transportation of Dangerous
Goods Directorate
330 Sparks Street
Ottawa ON K1A 0N5

Transports
Canada
Sécurité et sûreté

Direction générale du transport
des marchandises dangereuses
330, rue Sparks
Ottawa ON K1A 0N5

Equivalency Certificate
(Approval issued by the competent authority of Canada)

Certificate No.: SU 9806 (Ren. 2)

Certificate Holder: Hexagon Lincoln, Inc.

Mode of Transport: Road, Rail, Marine

Issue Date: December 12, 2016

Expiry Date: December 31, 2021

CONDITIONS

This Equivalency Certificate authorizes:

1) Hexagon Lincoln, Inc. (formerly known as Lincoln Composites, Inc.), to design, manufacture, sell, offer for sale, deliver, or distribute in Canada, means of containment used or intended to be used in importing, offering for transport, handling, or transporting dangerous goods in a manner that does not comply with section 5.1 and Part 8 of the *Transportation of Dangerous Goods Act, 1992*,

2) any person to sell, offer for sale, deliver, distribute, import, or use a standardized means of containment in a manner that does not comply with Part 8 of the *Transportation of Dangerous Goods Act, 1992*, and

3) any person to handle, offer for transport, transport, or import, by road or railway vehicle, or by ship on a domestic voyage, dangerous goods included in Class 2 in a means of containment in a manner that does not comply with section 5(*a*) in relation to safety requirements only, (*c*), and (*d*) of the *Transportation of Dangerous Goods Act, 1992*, and subsections 1.7(a) and (c), sections 5.1 and 5.2, subparagraphs 5.10(1)(a)(ii), 5.10(1)(b)(iii), and 5.10(1)(d)(iii), and subsection 5.10(2) of the *Transportation of Dangerous Goods Regulations*, in relation to the manufacture, selection, and use of means of containment only, if:

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Selection and Use

(a) subject to conditions (b) to (z) of this certificate, the requirements with respect to specification TC-3FCM cylinders in CSA Standard B340-08, *"Selection and use of cylinders, spheres, tubes, and other containers for the transportation of dangerous goods, Class 2",* March 2008, cited in the rest of this certificate as CSA B340-08, are complied with;

(b) subject to conditions (c) and (d) of this certificate, each means of containment is a multiple-element gas container (i.e. an assembly of tubes interconnected by a manifold and assembled within a framework) that meets the definition of "container" within the terms of the International Maritime Organization's (IMO) "*International Convention for Safe Containers, 1972*", 1996 Edition, cited in the rest of this certificate as the International Convention for Safe Containers, 1972;

(c) each container is in conformity with the International Convention for Safe Containers, 1972, and a Safety Approval Plate conforming to the specifications set out in the Appendix to Annex I of the International Convention for Safe Containers, 1972 is permanently affixed to the container at a readily visible place;

(d) for containers transported by rail, a prototype of the container was subjected to and has met the requirements of the dynamic longitudinal impact test set out in Appendix C of CSA Standard B625-08, "*Portable tanks for the transport of dangerous goods*", July 2008;

(e) despite conditions (b) to (d) of this certificate, each means of containment may be a container that has been tested in accordance with sections 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.11, and 6.13 of International Standard ISO 1496-3:2015, "*Series 1 freight containers – Specification and testing – Part 3: Tank Containers for liquids, gases and pressurized dry bulk".* Such containers shall not be stacked and shall not be transported by railway vehicle;

(f) the tubes, valves, manifolds, pressure-relief devices, and other accessories are protected against damage resulting from lateral and longitudinal impact and overturning;

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(g) despite Clause 4.6.2 of CSA B340-08, the tubes are used only for:

(i) gases in Class 2.2,
(ii) UN1971, METHANE, COMPRESSED; or NATURAL GAS, COMPRESSED with high methane content,
(iii) UN1049, HYDROGEN, COMPRESSED,
(iv) UN1964, HYDROCARBON GAS MIXTURE, COMPRESSED, N.O.S.,
(v) UN1954, COMPRESSED GAS, FLAMMABLE, N.O.S.;

(h) when used in natural gas service, methanol or glycol is not deliberately added to the natural gas and the composition of the natural gas meets one of the following conditions:

(i) for dry gas, the maximum gas contaminant limits apply:

a) 32 mg/m^3 of water vapour,
b) 23 mg/m^3 of hydrogen sulphide, and
c) 1% by volume of oxygen, or

(ii) for wet gas, the maximum gas contaminant limits apply:

a) 23 mg/m^3 of hydrogen sulphide and other soluble sulphides,
b) 115 mg/m^3 total sulphur,
c) 1% by volume of oxygen,
d) 3% by volume of carbon dioxide, and
e) 0.1% by volume of hydrogen;

(i) the dangerous goods are compatible with the materials of containment under the conditions of use;

(j) each tube is fitted with a shut-off valve that is closed during transport;

(k) the manifold valves are closed during transport;

(l) the manifold is depressurized before transport;

(m) a minimum pressure is maintained in each tube while in service and during unloading operations in accordance with Hexagon Lincoln, Inc.'s Service Bulletin 14-02-005, "Hexagon Composites CNG Bulk Hauling TITAN® Module Operation and Inspection Manual With NC Gas Venting System", cited in the rest of the certificate as Hexagon Lincoln, Inc.'s Service Bulletin 14-02-005,

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and filed by the certificate holder with the Executive Director, Regulatory Frameworks and International Engagement, Transportation of Dangerous Goods Directorate, Transport Canada;

(n) subject to condition (o) of this certificate, the top of the framework is covered by opaque panels;

(o) the covered area surrounding the tubes and the enclosed area where manifold, piping, and valves are located are vented to the outside;

(p) despite Clause 4.3.1 of CSA B340-08, the container is equipped with a pressure-relief device system designed to vent all tubes in the event of a fire. The system consists of a thermally activated sensing device at several locations within the container running continuously along the full length of the framework which actuates when exposed to direct flame or a constant heat of 177°C or greater. Upon actuation of the pressure-relief device system, the contents of the tubes shall be vented. The vent ports are arranged to discharge upward and unobstructed to the open air in such a manner as to prevent any impingement of escaping gas upon the tubes and are located such that they will not be blocked in the event of a rollover of the container;

(q) despite Clause 4.3.2 of CSA B340-08, the pressure-relief device system is capable of preventing the rupture of normally filled tubes when subjected to a fire test conducted in accordance with paragraph (ax) of this certificate;

(r) the requirements in Clause 5.1.3 and 5.1.4 of CSA B340-08 do not apply;

(s) the tubes are not filled:

- (i) if they are due for requalification,
- (ii) unless they and their structural and service equipment have been examined and found to be in good working order,
- (iii) if they are damaged to such an extent that their integrity or structural or service equipment could be affected. The tubes are evaluated for damage at time of filling in accordance with Hexagon Lincoln, Inc.’s Service Bulletin 14-02-005,
- (iv) if they were exposed to ambient temperatures below -12°C with less than 0.7 MPa of internal pressure, unless they have been:
  - a) conditioned at a temperature above 16°C for at least 8 hours, or
  - b) conditioned in accordance with the cold fill procedure specified in the Hexagon Lincoln, Inc.’s Service Bulletin 14-02-005, and
- (v) unless the required markings specified in condition (bk) and condition (bl)(iii) of this certificate are legible;

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(t) the tubes are operated and maintained in accordance with Hexagon Lincoln, Inc.'s Service Bulletin 14-02-005;

(u) before transport, the pressure-relief device system is inspected in accordance with Hexagon Lincoln, Inc.'s Service Bulletin 14-02-005;

(v) when the means of containment are transported by ship, they are stowed on deck in a well-ventilated area;

(w) tubes that have been subjected to fire are not returned to service;

(x) means of containment that have been involved in a vehicle collision are removed from service until they, their service and structural equipment, and the tubes comprising the means of containment have been inspected for damage and determined to be in good working order by the certificate holder;

(y) the tubes are not used for underwater applications;

(z) not more than 15 years has elapsed since the original manufacturing test date for each tube;

Manufacture and Requalification

(aa) subject to conditions (ab) to (bm) of this certificate, each tube was designed, constructed, and initially inspected and tested in accordance with the requirements applicable to fully-wrapped composite cylinders with non-load-sharing non-metallic liners specified in International Standard ISO 11119-3:2002, "*Gas cylinders of composite construction – Specification and test methods – Part 3: Fully wrapped fibre reinforced composite gas cylinders with non-load-sharing metallic or non-metallic liners"*, published by the International Organization for Standardization (ISO), cited in the rest of this certificate as ISO 11119-3:2002;

(ab) each tube was manufactured by Hexagon Lincoln, Inc.,
5117 N.W. 40th Street or 5150 N.W. 40th Street, Lincoln, Nebraska, U.S.A., in accordance with the quality systems manual, the specific procedures, the design qualification test reports, and drawings for the part numbers specified in Appendix C of this certificate, filed by the certificate holder, with the Executive Director, Regulatory Frameworks and International Engagement, Transportation of Dangerous Goods Directorate, Transport Canada;

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(ac) despite Clause 3.4 of ISO 11119-3:2002, a batch of non-metallic liners is the quantity of liners of the same nominal diameter, length, thickness and design, made from the same materials and subjected to the same manufacturing process;

(ad) despite Clause 3.5 of ISO 11119-3:2002, a batch of finished tubes is a production quantity of up to 200 finished tubes serially produced (plus finished tubes required for destructive testing) or 12 months of production, whichever occurs first, of the same nominal diameter, length, thickness, wrapping pattern, and design;

(ae) each tube consists of a plastic liner wrapped with resin-impregnated carbon fibre filament windings in both longitudinal and circumferential directions and an optional outer layer of polyurethane paint. An end boss is integrally molded into the pole of each end of the liner to provide interface for connecting the tube to the gas system and for mounting to the framework;

(af) subject to conditions (ag) and (ah) of this certificate, the plastic liner is made from a high-density polyethylene (HDPE) copolymer and is an assembly of two injection molded domes and an extruded pipe joined together at two places by butt fusion welding copolymer. The wall thickness of each assembly shall be specified in the design qualification test reports filed by the certificate holder, with the Executive Director, Regulatory Frameworks and International Engagement, Transportation of Dangerous Goods Directorate, Transport Canada;

(ag) the yield strength and the ultimate elongation of each batch of the plastic liner material is determined at –50°C in accordance with International Standard ISO 527-2:1993, "*Plastics – Determination of tensile properties – Part 2: Test conditions for moulding and extrusion plastics*" (incorporating Technical Corrigendum 1:1994), published by the International Organization for Standardization (ISO). The minimum yield strength is 20.7 MPa and the ultimate elongation is 5%. A material certificate of conformance from the plastic manufacturer is deemed acceptable;

(ah) the softening temperature of each batch of the plastic liner material is determined in accordance with International Standard ISO 306:2004, "*Plastics – Thermoplastic materials – Determination of Vicat softening temperature (VST)*, published by the International Organization for Standardization (ISO), and is at least 105°C. A material certificate of conformance from the plastic manufacturer is deemed acceptable;

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(ai) each tube has a working (service) pressure of 25.0 MPa;

(aj) an optional protective coating of paint is applied to the external surface of each tube;

(ak) inspections and verifications are in accordance with the requirements of ISO 11119-3:2002 and carried out by an Independent Inspector registered with Transport Canada in accordance with Clause 25.4 of CSA Standard B339-08, "*Cylinders, spheres, and tubes for the transportation of dangerous goods*", March 2008, cited in the rest of this certificate as CSA B339-08. In addition, the Independent Inspector:

(i) performs, verifies, or witnesses the burst test, the high velocity impact (gunfire) test, the fire resistance test, the torque test, and the additional design qualification tests specified in Appendix A of this certificate,

(ii) for each new tube design, prepares a report that includes, as a minimum, all information shown in Annex A of ISO 11119-3:2002, and

(iii) for each tube batch, prepares a report that includes, as a minimum, all information shown in Annex B of ISO 11119-3:2002. The reports are retained by the manufacturer and by the Independent Inspector for the service life of the tubes;

(al) despite Clause 8.2.1 and 8.2.2 of ISO 11119-3:2002, a sufficient number of tubes shall be made available to complete the prototype testing or testing of the design variant;

(am) unless otherwise specified in this certificate, the prototype tubes shall be full-scale tubes representative of the new design;

(an) despite Table 2 referenced in Clause 8.2.3, 8.2.8, and 8.4.4 of ISO 11119-3:2002, Table 1 of Appendix B of this certificate is used for determining the level of reduced testing for design variants;

(ao) as an alternative to the requirements specified in Clause 8.5.1 or 8.5.2 of ISO 11119-3:2002, the hydraulic volumetric expansion test is performed in accordance with Hexagon Lincoln, Inc.'s documented proof test procedure that has been approved and release within their ISO 9001 Quality Management System and in accordance with the following conditions:

(i) the test pressure is maintained for at least 30 s without leakage or burst,

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(ii) the expansion at test pressure is determined by measuring total axial growth and the total diameter growth in 2 places using strain gauge,

(iii) the expansion per 6.9 MPa during testing does not exceed 0.162% for diameter and 0.123% for length, and

(iv) the test may be repeated if the test pressure cannot be maintained due to failure of the test apparatus;

(ap) despite Clause 8.5.3 of ISO 11119-3:2002, the burst test is performed as follows:

(i) two representative tubes are tested hydrostatically to destruction by pressurizing at a rate not exceeding 14 bar/s at pressures in excess of 80% of the minimum design burst pressure,

(ii) if the rate of pressurization at pressures in excess of 80% of the minimum design burst pressure exceeds 3.5 bar/s, then either the tube is placed schematically between the pressure source and the pressure measurement device, or there is a 5 s hold at the minimum design burst pressure,

(iii) the burst pressure is a least 1.6 times the test pressure;

(aq) the ambient cycle test is performed in accordance with Clause 8.5.4 of ISO 11119-3:2002, except as follows:

(i) two representative tubes are pressure-cycled,

(ii) one shorter tube may be used as an alternative to a full-scale tube. The shorter tube is manufactured with the same process, materials, wrapping pattern, has the same nominal outside diameter as the full-scale production tube, and has a length-to-diameter ratio not less than 2.5,

(iii) the upper cyclic pressure is at least equal to 130% of the service pressure,

(iv) the design life is 20 years,

(v) the cylinders withstand a number of cycles equal to 750 times the design life without leakage,

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(vi) the cylinders continue cycling until leakage occurs or after reaching a total number of cycles equal to 2250 times the design life, and

(vii) failure occurs by leakage and not by burst;

(ar) the vacuum test specified in Clause 8.5.5 of ISO 11119-3:2002 is not required;

(as) the environmental cycle test is performed in accordance with Clause 8.5.6 of ISO 11119-3:2002, except as follows:

(i) a shorter tube with smaller diameter may be used as an alternative to a full-scale tube. The shorter tube shall be manufactured with the same process, materials, wrapping pattern, shall have the same stress level as the full-scale production tube at test pressure, and shall have a length-to-diameter ratio not less than 2.5;

(at) despite Clause 8.5.7 of ISO 11119-3:2002, a finished prototype tube is subjected to a high temperature creep test in accordance with section 2 of Appendix A of this certificate;

(au) one representative tube is subjected to the flaw test in accordance with Clause 8.5.8 of ISO 11119-3:2002, except as follows:

(i) a shorter tube may be used as an alternative to a full-scale tube. The shorter tube is manufactured with the same process, materials, wrapping pattern, has the same nominal outside diameter as the full-scale production tube, and has a length-to-diameter ratio not less than 2.5,

(ii) the tube is subjected to the ambient cycle test specified in Clause 8.5.4 of ISO 11119-3:2002, but the upper cyclic pressure is the working pressure and the test is suspended after 5000 cycles if the tube has not failed, and

(iii) the tube does not leak or rupture within the first 3000 cycles, but may fail by leakage during the remainder of the cycles;

(av) the drop test specified in Clause 8.5.9 of ISO 11119-3:2002 is not required. However, any tube that is dropped from a height greater than 0.6 m during the manufacturing process or prior to assembly within the framework shall be condemned;

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(aw) one representative tube is subjected to the high velocity impact (gunfire) test in accordance with Clause 8.5.10 of ISO 11119-1:2002, except as follows:

(i) a shorter tube may be used as an alternative to a full-scale tube. The shorter tube is manufactured with the same process, materials, wrapping pattern, has the same nominal outside diameter as the full-scale production tube, and has a length-to-diameter ratio not less than 2.5,

(ii) the armour-piercing bullet has a diameter of 7.62 mm or greater, and

(iii) if there is no penetration of the wall, additional bullets may be shot at the same point until penetrated;

(ax) as an alternative to the fire resistance test specified in Clause 8.5.11 of ISO 11119-3:2002, one representative container consisting of a quantity of tubes containing the maximum quantity of gas to be vented per single pressure-relief manifold within the container design is subjected to a bonfire test specified in section 1 of Appendix A of this certificate;

(ay) as an alternative to the permeability test specified in Clause 8.5.12 of ISO 11119-3:2002, one representative tube is subjected to a permeability test as follows:

(i) a shorter tube with a smaller diameter may be used as an alternative to a full-scale tube if differences in liner thickness and diameter have been accounted for by calculation,

(ii) the tube is filled with the intended lading or suitable trace gas to working pressure, placed in an enclosed sealed chamber at ambient temperature, and monitored for permeation for 500 h,

(iii) the measured permeation rate is reported. If a trace gas is used, correlation between the trace gas and intended lading is provided, and

(iv) the permeation rate is less than or equal to 0.25 ml of natural gas per hour per litre water capacity of the tube or less than the equivalent of 2 ml of hydrogen gas per hour per litre water capacity of the tube;

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(az) as an alternative to the torque test specified in Clause 8.5.13 of ISO 11119-3:2002, one representative tube is subjected to a torque test as follows:

(i) a shorter tube may be used as an alternative to a full-scale tube. The shorter tube is manufactured with the same process, materials, wrapping pattern, has the same nominal outside diameter as the full-scale production tube, and has a length-to-diameter ratio not less than 2.5,

(ii) the body of the tube is restrained against rotation and a torque of twice the valve or PRD installation torque specified by the certificate holder is applied to each end boss of the tube. The torque is applied first in the direction of tightening a threaded connection, then in the untightening direction, and finally again in the tightening direction,

(iii) there is no visible damage to any combination of the boss, liner, and composite interfaces,

(iv) the tube is then subjected to a leak test where it is pressurized hydraulically to the working pressure for at least 15 minutes and examined for leakage in accordance with Hexagon Lincoln, Inc.'s documented proof test procedure that has been approved and release within their ISO 9001 Quality Management System;

(ba) the saltwater immersion test specified in Clause 8.5.14 of ISO 11119-3:2002 is not required;

(bb) as an alternative to the leak test specified in Clause 8.5.15 of ISO 11119-3:2002, the leak test is performed in accordance with Hexagon Lincoln, Inc.'s documented proof test procedure that has been approved and release within their ISO 9001 Quality Management System and the following:

(i) the tubes are pressurized hydraulically to working pressure,

(ii) the tubes are held at working pressure for at least 15 minutes and examined for signs of leakage, and

(iii) tubes showing evidence of leakage are rejected;

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(bc) instead of the pneumatic cycle test specified in Clause 8.5.16 of ISO 11119-3:2002, a finished prototype tube is subjected to a gas cycling and blowdown test in accordance with section 3 of Appendix A of this certificate;

(bd) a finished prototype tube is subjected to an environmental fluids test in accordance with section 4 of Appendix A of this certificate;

(be) a finished prototype is subjected to an accelerated stress rupture test as specified in section 5 of Appendix A of this certificate;

(bf) two finished prototype tubes are subjected a leak-before-burst (LBB) test as specified in section 6 of Appendix A of this certificate;

(bg) the resin system is tested on sample coupons representative of the composite overwrap, in accordance with International Standard ISO 14130:1997, "*Fibre-reinforced plastic composites – Determination of apparent interlaminar shear strength by short-beam method*", or an equivalent standard. Following 24 hour boiling in water the composite shall have a minimum shear strength of 13.8 MPa;

(bh) the glass transition temperature of the resin material is determined in accordance with ASTM D 3418-08, "*Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry*" and is greater than 104°C;

(bi) despite Clause 9.4.4 of ISO 11119-3:2002, each completed tube is subjected to a hydraulic volumetric expansion test in accordance with condition (an) of this certificate;

(bj) despite Clause 9.4.5 of ISO 11119-3:2002, an ambient cycle test is performed on one finished tube from each production quantity of up to 1000 finished tubes serially produced or one year of production, whichever occurs first, in accordance with condition (aq) of this certificate, except as follows:

(i) a shorter tube may be used as an alternative to a full-scale tube. The shorter tube is manufactured with the same process, materials, wrapping pattern, has the same nominal outside diameter as the full-scale production tube, and has a length-to-diameter ratio not less than 2.5;

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(bk) each tube is permanently marked in accordance with Clause 4.17 of CSA B339-08, except the Transport Canada mark, the specification designation and the service pressure are replaced with "TC-SU 9806" followed by the service pressure expressed in bar. In addition to these marks, each tube must be permanently and legibly marked with:

(i) the text "WARNING – THIS TUBE MUST NOT BE USED IN VACUUM SERVICE" or "WARNING – 7 BAR (100 PSIG) MUST BE MAINTAINED IN TUBE WHILE IN SERVICE AND DURING UNLOADING OPERATIONS", and

(ii) the text "tube service life expires 15 years from date of manufacture",

The size of the marks must be not less than 12 mm in height;

(bl) each tube is requalified at least every five years in accordance with the Hexagon Lincoln, Inc.'s Service Bulletin 14-02-005, except as follows:

(i) the requalification is performed by a facility registered pursuant to Clause 25.3 of CSA B339-08,

(ii) each tube is subjected to a proof pressure test in accordance with CGA C-1-2006, "*Methods for Hydrostatic Testing of Compressed Gas Cylinders*", Ninth Edition, 2006, published by the Compressed Gas Association, Inc., and is also visually inspected both internally, inasmuch as the size of the openings permit, and externally. The test pressure shall be held for at least 3 minutes,

(iii) a requalification marking is applied in accordance with Clause 24.6.3 of CSA B339-08. The marking is applied on a label securely affixed to the dome of the tube and overcoated with epoxy or polyurethane. Stamping of any part of the tube is prohibited, and

(iv) the requalification report is kept for the service life of the tube. The report shall include, as a minimum, the inspection results for each type of damage described in Hexagon Lincoln, Inc.'s Service Bulletin 14-02-005. The owner of the tube and the person who prepared the report shall each keep a copy of the report for the service life of the tube;

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CONDITIONS

(bm) the certificate holder, tube owner, or user reports any incident involving loss of contents or failure of the tubes to the Executive Director, Regulatory Frameworks and International Engagement, Transportation of Dangerous Goods Directorate, Transport Canada;

(bn) before the expiry date of this certificate, the certificate holder reports a summary of the tube manufacturing and performance experience to the Executive Director, Regulatory Frameworks and International Engagement, Transportation of Dangerous Goods Directorate, Transport Canada; and

(bo) each side of the means of containment as well as the rear cabinet of the means of containment is marked with the letters and numbers “TC-SU 9806” that are of a colour contrasting with the background and not less than 50 mm in height.

Note: The issuance of this Equivalency Certificate in no way reduces the certificate holder's responsibility to comply with any other requirements of the *Transportation of Dangerous Goods Regulations,* the *Technical Instructions for the Safe Transportation of Dangerous Goods by Air,* the *International Maritime Dangerous Goods Code*, and the *Canadian Aviation Regulations* not specifically addressed in this certificate.

Signature of Issuing Authority

(see last page for signed copy)

David Lamarche P. Eng., ing.
Chief
Approvals and Special Regulatory Projects

Equivalency Certificate
(Approval issued by the competent authority of Canada)
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(*The following is for information purposes only and is not part of the certificate.)*

Contact Person: Norman L. Newhouse
Vice President, Technology
Hexagon Lincoln Inc.
5117 N.W. 40th Street
Lincoln, Nebraska 68524
U.S.A.

Telephone: 402-470-5035
Facsimile: 402-470-0019
E-mail: norman.newhouse@hexagonlincoln.com

Explanatory Note

This Equivalency Certificate authorizes the handling, offering for transport and transport of tubes in a manner that does not comply with Part 5 of the *Transportation of Dangerous Goods Regulations.* The tubes are interconnected by a manifold and assembled within a framework. Such an assembly of tubes is typically known as a multiple-element gas container. The certificate holder has demonstrated that when used and tested under the stipulated conditions, the tubes could be used with an equivalent level of safety.

An extension of the tube service life up to a maximum of 20 years might be considered upon the submission by the certificate holder, (i.e. the cylinder manufacturer) of supporting data and test reports pertaining to these tubes from the time of manufacture and from the time in service.

Legend for Certificate Number

SH - Road, SR - Rail, SA - Air, SM - Marine
SU - More than one Mode of Transport
Ren. – Renewal

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NOTE

Under Canadian Law, a foreign manufacturer of non-specification means of containment cannot be charged with an offence under the *Transportation of Dangerous Goods Act, 1992* for failure to comply with the conditions of an Equivalency Certificate. However, certain remedies under the Act are available to Transport Canada in this eventuality.

These include:

1. detention of dangerous goods and consequently the means of containment containing them (subsection 17(1));

2. detention of the means of containment whether full or empty (subsection 17(1));

3. directions not to import the means of containment or to return them to origin (subsection 17(3));

4. inspectors’ directions (section 19);

5. directions to importers of the means of containment to issue notices of defective construction or recall (subsection 9(2)); and

6. revocation of the equivalency certificate, thereby making any use of the means of containment an offence (subsection 31(6)).

If none of the foregoing are adequate, Protective Directions may be issued to prohibit or to control the use of the means of containment (section 32).

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APPENDIX A

Prototype Tests

1. Bonfire Test

1.1 General

The bonfire test shall be designed to demonstrate that finished tubes while mounted within their transport framework, and complete with the fire protection system (tube valves, pressure relief devices and/or integral thermal insulation) specified in the design, will prevent the rupture of the tubes when tested under the specified fire conditions.

Precautions shall be taken during fire testing in the event that tube rupture occurs.

1.2 Tube set-up

One representative container consisting of a quantity of tubes containing the maximum quantity of gas to be vented per single pressure-relief manifold within the container design shall be placed on a support structure approximately 300 mm above the fire source.

Metallic shielding shall be used to prevent direct flame impingement on tube valves, fittings, and/or pressure relief devices. The metallic shielding shall not be in direct contact with the specified fire protection system (pressure relief devices or tube valves).

Any failure during the test of a valve, fitting or tubing that is not part of the intended protection system for the design shall invalidate the result.

1.3 Fire source

A uniform fire source of at least 0.6 m in length shall provide direct flame impingement on the tube or transport container surface.

Any fuel may be used for the fire source provided it supplies uniform heat sufficient to maintain the specified tube temperatures until the tubes are vented. The selection of a fuel should take into consideration air pollution concerns. The arrangement of the fire shall be recorded in sufficient detail to ensure that the rate of heat input to the tubes is reproducible.

Any failure or inconsistency of the fire source during a test shall invalidate the result.

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APPENDIX A

Prototype Tests (cont'd)

1.4 Temperature and pressure measurements

Surface temperatures shall be monitored by at least three thermocouples located along the bottom of the tubes and spaced not more than 0.75 m apart.

Thermocouple temperatures and the tube pressures shall be recorded at intervals of every 30 seconds or less during the test.

1.5 General test requirements

The tubes shall be pressurized to working pressure with the intended lading or compressed nitrogen.

Within 5 minutes of ignition the temperature at least one thermocouple shall indicate a temperature ≥590°C. This minimum temperature shall be maintained for the remainder of the test.

The centre of the tube assembly shall be positioned over the centre of the fire source.

1.6 Acceptable results

Each tube shall completely vent through a pressure-relief device, and without rupturing.

2. **High Temperature Creep test**

2.1 Procedure

One finished tube shall be tested as follows:

A shorter tube with smaller diameter may be used as an alternative to a full-scale tube. The shorter tube shall be manufactured with the same process, materials, general wrapping pattern, shall have the same stress level as the full-scale production tube at test pressure, and shall have a length-to-diameter ratio not less than 2.5. The tube shall be pressurized to test pressure and held at a temperature of 100°C for not less than 200 hours.

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APPENDIX A

Prototype Tests (cont'd)

2.2 Acceptable Results

Following the test procedure, the tube shall meet the requirements of the hydraulic volumetric expansion test (condition (an)), the leak test (condition (ba)) and the burst test (condition (ao)) specified in this certificate.

3. **Gas Cycling and Blow Down Test**

3.1 Procedure

One finished tube shall be cycle tested as follows:

a) a shorter tube may be used as an alternative to a full-scale tube. The shorter tube shall be manufactured with the same process, materials, wrapping pattern, shall have the same nominal outside diameter as the full-scale production tube, and shall have a length-to-diameter ratio not less than 2.5,
b) the tube shall be filled with a non-corrosive fluid such as oil, inhibited water or glycol,
c) the pressure in the tube shall be cycled for 1000 cycles, between 10% of service pressure and service pressure. Pressurization shall be performed at a maximum rate of 10 cycles per minute,
d) the pressure shall be released, the fluid shall be drained, and the interior of the tube shall be dried,
e) the pressure in the tube shall be cycled for 5 cycles, between 10% of service pressure and service pressure, with air, nitrogen, or the intended lading. During each cycle, the pressure shall be held at the upper cyclic pressure for at least 2 hours,
f) following the high pressure hold of the final cycle, the gas shall be released freely to the atmosphere, and
g) the cylinder shall then be subjected to a leak test.

3.2 Acceptable results

Following the above test sequence, the tube shall be sectioned and the liner and liner/end boss interface shall be inspected and not show evidence of any deterioration, such as fatigue cracking or electrostatic discharge.

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APPENDIX A

Prototype Tests (cont'd)

4. Environmental Fluids Test

4.1 Container Set-Up and Preparation

A shorter tube with smaller diameter may be used as an alternative to a full-scale tube. The shorter tube shall be manufactured with the same process, materials, general wrapping pattern, shall have the same stress level as the full-scale production tube at test pressure, and shall have a length-to-diameter ratio not less than 2.5.

One tube shall be tested, including coating if applicable. The upper section of the tube shall be divided into five distinct areas and marked for pendulum impact preconditioning and fluid exposure. The areas shall be nominally 100 mm (4 in.) in diameter. The areas may not be oriented along a single line, but shall not overlap. Although preconditioning and other fluid exposure is performed on the cylindrical section of the tube, all of the tube, including the domed sections, shall be as resistant to the exposure environments as the exposed areas.

4.2 Pendulum Impact Preconditioning

The impact body shall be of steel and have the shape of a pyramid with equilateral triangle faces and a square base, the summit and the edges being rounded to a radius of 3 mm (0.12 in.). The center of percussion of the pendulum shall coincide with the center of gravity of the pyramid; its distance from the axis of rotation of the pendulum shall be 1000 mm (39.37 in.). The total mass of the pendulum referred to its center of percussion shall be 15 kg (33 lbs.). The energy of the pendulum at the moment of impact shall be not less than 30 Nm (22.1 ft-lb) and as close to that value as possible. During pendulum impact, the tube shall be held in position by the end bosses. Each of the five areas shall be preconditioned by impact of the pendulum body summit at the center of the area. The tube shall be unpressurized during preconditioning.

4.3 Environmental Fluids for Exposure

Each marked area shall be exposed to one of five solutions.

The five solutions are:

Sulfuric acid - 19 percent solution by volume in water.

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APPENDIX A

Prototype Tests (cont'd)

Sodium hydroxide - 25 percent solution by weight in water.

Methanol/gasoline - 5/95 percent concentration of M5 fuel meeting the requirements of *ASTM D4814, Standard Specification for Automotive Spark-Ignition Engine Fuel*.

Ammonium nitrate - 28 percent by weight in water.

Windshield washer fluid (50 percent by volume solution of methyl alcohol and water).

When exposed, the test sample shall be oriented with the exposure area uppermost. A pad of glass wool approximately 0.5 mm (1/64 in.) thick and between 90 and 100 mm (3.5 and 4.0 in.) in diameter shall be placed on the exposure area. A sufficient amount of the test fluid shall be applied to the glass wool to ensure that the pad is wetted evenly across its surface and through its thickness for the duration of the test, and to ensure that the concentration of the fluid is not changed significantly during the duration of the test.

4.4 Pressure Cycle and Pressure Hold

The tube shall be hydraulically pressure cycled between less than or equal to 10 percent of service pressure and 130 percent of service pressure for a total of 3000 cycles. The maximum pressurization rate shall be 27.5 bar (400 psi) per second. After pressure cycling, the tube shall be pressurized to 130 percent of service pressure, and held at that pressure a minimum of 24 hours and until the elapsed exposure time (pressure cycling and pressure hold) to the environmental fluids equals 48 hours.

4.5 Acceptable Results

Following the above test sequence, the residual burst strength of the tube shall be no less than 1.8 times the service pressure when tested in accordance with condition (ap) of this certificate.

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APPENDIX A

Prototype Tests (cont'd)

5. Accelerated Stress Rupture Test

5.1 Procedure

One finished tube shall be tested as follows:

A shorter tube with smaller diameter may be used as an alternative to a full-scale tube. The shorter tube shall be manufactured with the same process, materials, general wrapping pattern, shall have the same stress level as the full-scale production tube at test pressure, and shall have a length-to-diameter ratio not less than 2.5.

The tube shall be hydrostatically pressurized to test pressure and held at 65°C.

The tube shall be held at this pressure and temperature for 1000 h. The tube shall then be pressurized to burst in accordance with condition (ap) of this certificate.

5.2 Acceptable Results

The burst pressure shall exceed 85% of the minimum design burst pressure.

6. Leak-Before-Burst (LBB) Test

6.1 Procedure

Two finished tubes shall be tested as follows:

A shorter tube may be used as an alternative to a full-scale tube. The shorter tube shall be manufactured with the same process, materials, wrapping pattern, shall have the same stress level as the full-scale production tube at test pressure, and shall have a length-to-diameter ratio not less than 2.5.

The tubes shall be filled with a non-corrosive fluid and subjected to successive reversals between 2.5 MPa and 37.5 MPa at a rate not exceeding 10 cycles per minute.

The number of cycles to failure shall be reported, along with the description of the failure initiation.

6.2 Acceptable Results

The tubes shall either fail by leakage or exceed three times the design number of filling cycles (45000 cycles).

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APPENDIX B

Table 1: Design Qualification Tests

Test	Design Variant Changes														
	New Design	Length <= 50%	Length >50%	Diameter <=20%	Diameter >20% <= 50%	Liner thickness >20% or manufacture	Liner material	Equivalent fiber	Test Pressure <=20%	Test pressure >20% <=60%	Composite thickness or pattern	Boss-to-liner interface	Equivalent resin matrix	Resin Matrix	Pressure Relief Device
Liner material test							X								
Composite material tests								X			X[1]		X[1]		
Hydraulic pressure	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Hydraulic burst	X	X[1]	X[1]	X[1]	X	X[1]	X[1]	X	X[1]	X	X	X[1]	X[1]	X[1]	
Ambient cycle	X			X[1]	X		X	X	X[1]	X	X	X[1]			
Environmental cycle	X													X	
High temperature creep[1]	X				X[1]		X			X[1]a	X[1]a	Xa	Xa	Xa	
Flaw tolerance[1]	X				X									X	
High velocity impact (gunfire)	X				X[2]				X[1]	X 1	X[1]			X	
Fire resistance	X		X[1]		X[1]b					X					X
Permeability	X				X[2]	X	X			X					
Torque	X						X					X		X	
Leak	X			X	X		X		X	X		X			
Pneumatic cycle	X				X[1]	1	X					X			

Notes

1. For a new design of a cylinder with water volume larger than 450 L, a minimum of 1 cylinder may be used for each design change. For a change of boss-liner interface column, a leak check of the liner interface would be accepted. The pneumatic cycle test is not required if the boss-liner interface does not change.
    a. Where the design variant's burst pressure to test pressure ratio is over 20% greater than the same ratio for the approved design.
    b. When length increases up to 50% and/or diameter increases up to 20%, Bonfire test may not be required if the volume stays the same or decreases and the same PRD system is used.
2. Test to be conducted for reduction in diameter only.

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APPENDIX C

Container and Tube Part Numbers

240253-006
240253-007
240253-008
240140-0101 (Titan™ tank)
240140-0401
240245 (SmartStore™ Container)
240251 (Titan® XL40 Trailer)

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CONDITIONS

(bm) the certificate holder, tube owner, or user reports any incident involving loss of contents or failure of the tubes to the Executive Director, Regulatory Frameworks and International Engagement, Transportation of Dangerous Goods Directorate, Transport Canada;

(bn) before the expiry date of this certificate, the certificate holder reports a summary of the tube manufacturing and performance experience to the Executive Director, Regulatory Frameworks and International Engagement, Transportation of Dangerous Goods Directorate, Transport Canada; and

(bo) each side of the means of containment as well as the rear cabinet of the means of containment is marked with the letters and numbers “TC-SU 9806” that are of a colour contrasting with the background and not less than 50 mm in height.

Note: The issuance of this Equivalency Certificate in no way reduces the certificate holder's responsibility to comply with any other requirements of the *Transportation of Dangerous Goods Regulations,* the *Technical Instructions for the Safe Transportation of Dangerous Goods by Air,* the *International Maritime Dangerous Goods Code*, and the *Canadian Aviation Regulations* not specifically addressed in this certificate.

Signature of Issuing Authority

David Lamarche, P.Eng.

David Lamarche P. Eng., ing.
Chief
Approvals and Special Regulatory Projects

APPENDIX F - Powertech Labs - Test Report Number: TR-00672-01R1 - Project: PL-00672 - Hydrogen Cycling of TITAN Tanks

Powertech

Prepared For:

Hexagon Lincoln

HYDROGEN CYCLING OF TITAN TANKS

Project: PL-00672

Test Report Number: TR-00672-01R1

Prepared By:

Powertech Labs Inc.

Project Lead: Graham Meadows, P.Eng.

Revision 1

November 5, 2015

Contents

1 Introduction

Hydrogen gas cycle testing of Titan tanks was performed by Powertech Labs Inc. at the request of Hexagon Lincoln. The test was conducted on two Titan tanks that were instrumented with pressure sensors, internal temperature sensors, and internal cameras. An additional four Titan tanks assembled as a module were used as hydrogen gas accumulators during each transfer cycle.

A total of four gas cycles per Titan tank were completed for a total of eight transfers. Hydrogen sensors monitored the dome areas for leakage during the transfers followed by a hands-on inspection at the completion of each cycle.

2 Test Setup

A dedicated hydrogen gas cycle system was designed and configured for the purposes of this test. The test setup was comprised of six Titan tanks per the arrangement shown in Figure 1. Titan #1 and #2 were the two test tanks. Titan #3 through #6 were the accumulator storage tanks.

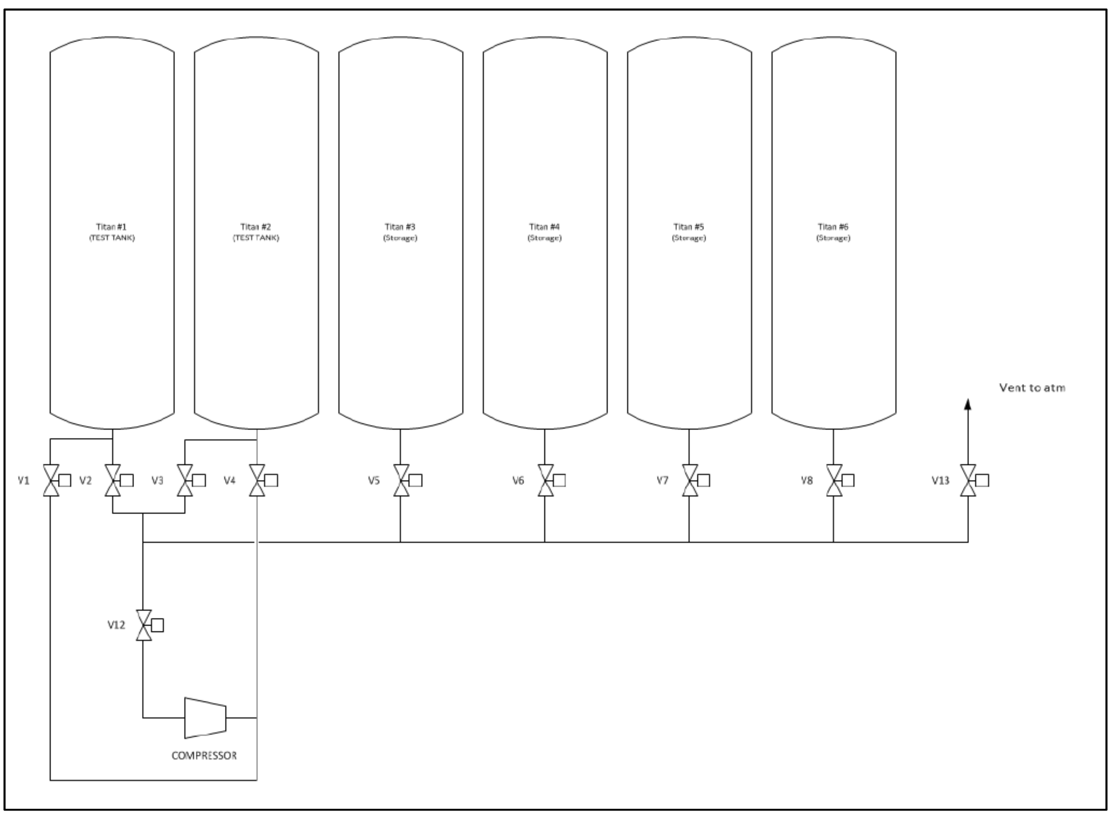

Figure 1 – Titan Test Schematic

The two test tanks were supported on custom mounting cradles with an ultra-high-molecular-weight (UHMW) polyethylene layer to allow the tanks to expand and contract during cycling as shown in Figure 2.

Figure 2 – Test Tanks Supported on Cradles

All of the tanks where connected to pressure transducers at the inlet fittings to monitor tank pressure throughout the test. Titan #1 and #2 also were equipped with internal thermocouples and cameras provided by Hexagon Lincoln as shown in Figure 3 and Figure 4. The two test tanks also had hydrogen detectors installed on each end near the end boss connections.

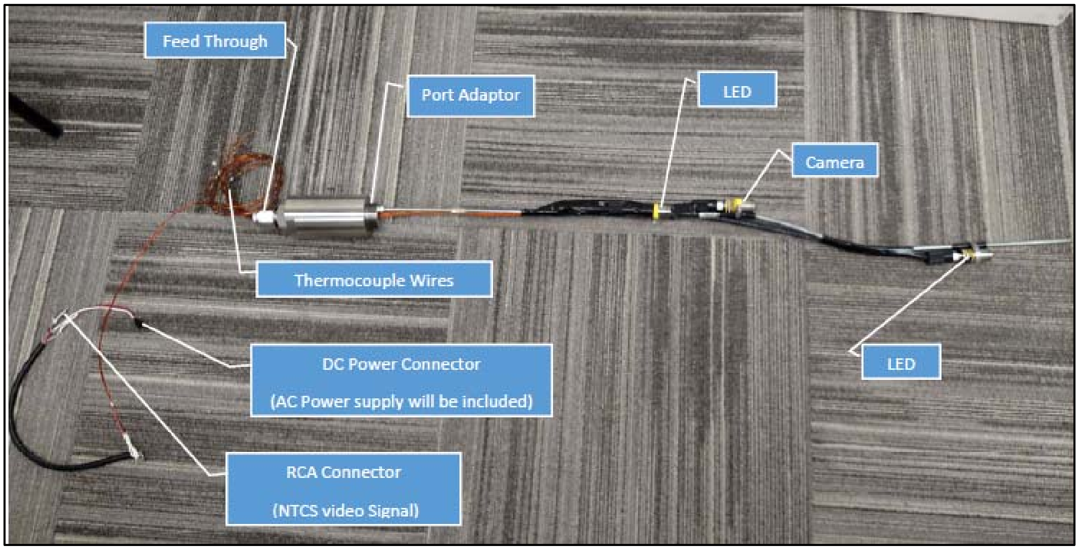

Figure 3 – Thermocouples and Cameras for Test Tanks

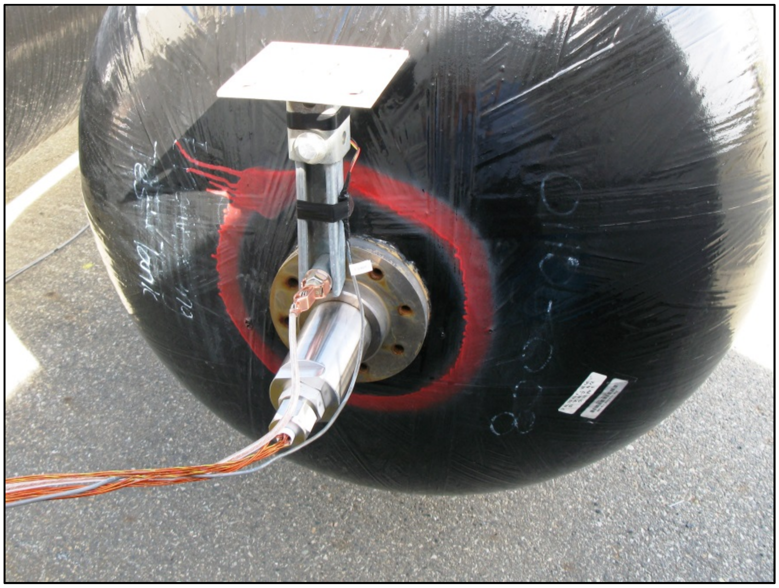

Figure 4 – End Fittings with Cameras installed in Titan #1

The tanks were connected with ¾” stainless steel tubing. Two actuated ball valves were installed on each test tank (one for fueling and one for defueling) as shown in Figure 5. Manual ball valves were installed on the Titan module as shown in Figure 6.

Figure 5 – Test Titans connected with Actuated Valves

Figure 6 – Test Titans connected to Module

All of the six Titans were purged with nitrogen then filled with hydrogen to the initial condition of 25 barg (lower pressure bound). Hydrogen was then compressed into Titan #1 to 250 barg (upper pressure bound).

3 Test Procedures and Conditions

The following test procedure was performed:

1) All tanks were set to initial conditions as follows:
    a. Titan #1: 250 barg
    b. Titan #2: 25 barg
    c. Titan Module (Titans #3/#4/#5/#6): 25 barg

2) Titan #1 was subjected to a pressure hold at 250 barg (upper pressure bound) for a minimum 3 days before the first transfer.

3) Hydrogen gas was depressurized from Titan #1 into Titan #2, then Titan #3, then Titan #4, Titan #5 and finally into Titan #6. Once equalized, with Titan #6, the remaining pressure in Titan #1 was released through a vent stack until the pressure had been reduced to 25 barg. The overall time to depressurize to 25 barg was to be less than 1 hour regardless of internal gas temperature in the test tank.

4) During the transfer period, the hydrogen gas detectors were monitored for any sign of leakage from the end fittings or dome region of the test tanks.

5) Following the transfer, the test tanks were inspected with a handheld hydrogen detector and/or Snoop solution.

6) The compressor was operated to compress hydrogen into Titan #2 from the gas stored in the Titan Module (Titan #3, #4, #5, and #6).

7) Titan #2 was then subjected to a pressure hold at 250 barg (upper pressure bound) for a minimum 3 days.

8) Hydrogen gas was depressurized from Titan #2 into Titan #1, then Titan #3, then Titan #4, Titan #5 and finally into Titan #6. Once equalized, with Titan #6, the remaining pressure in Titan #2 was released through a vent stack until the pressure had been reduced to 25 barg. The overall time to depressurize to 25 barg was to be less than 1 hour regardless of internal gas temperature in the test tank.

9) Steps 2 to 8 were repeated for a total of 4 pressure cycles each on Titan #1 and Titan #2 (8 total transfers) as shown in Table 1.

Table 1 – Transfer Sequence Summary

Transfer #	Titan #1 Initial Pressure	Titan #2 Initial Pressure	Cycle #
1	250	25	1
2	25	250	
3	250	25	2
4	25	250	
5	250	25	3
6	25	250	
7	250	25	4
8	25	250	

10) When all transfers were complete, Titan #1 and Titan #2 were vented and purged with nitrogen for the return shipment.

4 Test Results

4.1 Transfer 1, Titan #1 to Titan #2

The first transfer was performed by defueling Titan #1. The initial starting pressure was 256 barg and the total depressurization time to 25 barg was 30 minutes. While defueling Titan #1 into Titan #2, the flow was paused multiple times as the temperature in Titan #2 approached the upper limit rating of +85°C. The gas temperature continued to rise above +85°C after the stoppage in flow reaching temperatures as high as +120°C. In a post-Transfer #1 discussion with Hexagon Lincoln, it was determined that future transfers should require the pauses in flow to occur at a lower temperature, selected to be +60°C, to ensure temperature peaks occur at +85±5°C. The coldest temperature recorded in Titan #1 was -55°C near the end of the transfer. The data for this transfer is shown in Figure 7 and Figure 8.

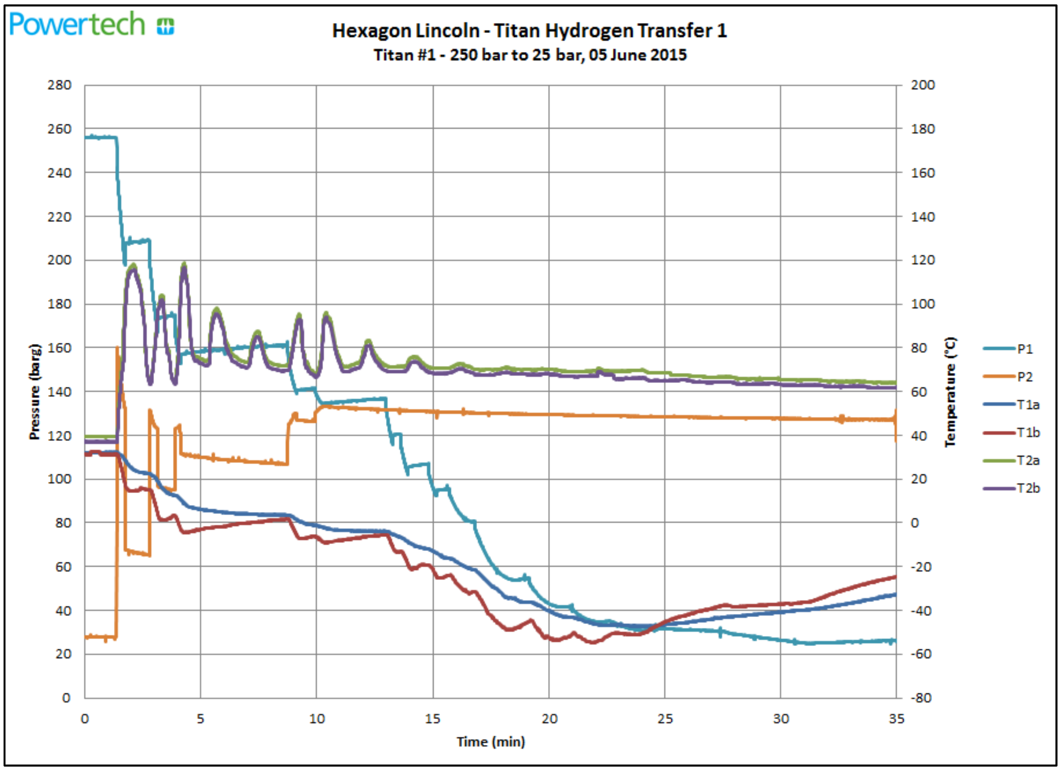

Figure 7 – Transfer 1, Data Summary

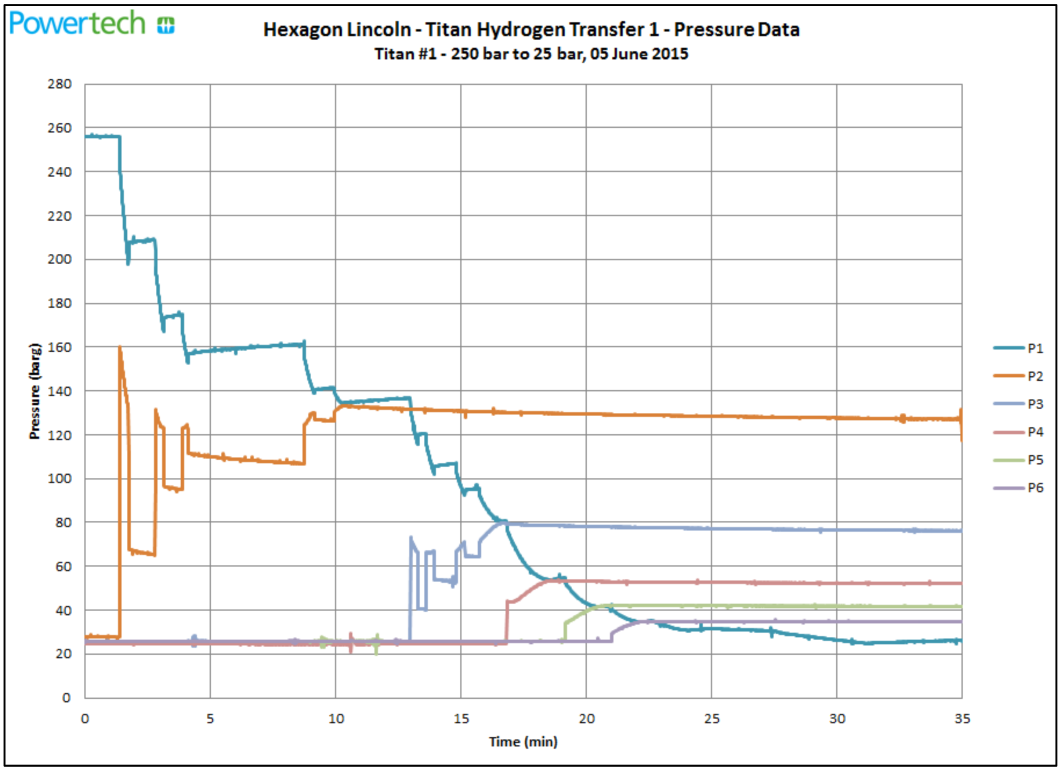

Figure 8 – Transfer 1, Pressure Data

During the transfer, the internal cameras were recording activity and monitoring for buckling within the test tanks. Camera 1 (inside Titan #1) was monitoring the defuel and Camera 2 (inside Titan #2) was monitoring fueling. As the hydrogen gas was flowing from Titan #1, the internal temperatures started to drop and moisture in the tank began to form a cloud formation. Figure 9 through Figure 15 show the various states of the cloud formation throughout the transfer period. Approximately halfway through the transfer period, the internal temperatures became cold enough for the Camera 1 to stop working as shown in Figure 16. This camera remained off for the remainder of the transfer. During the settling period following the transfer, as the internal temperatures warmed, the camera started to function again and revealed no issues with the liner.

Figure 9 – Camera 1, Titan 1, Start of Transfer 1

Figure 10 – Camera 1, Titan 1 during Transfer 1

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Figure 11 - Camera 1, Titan 1 during Transfer 1

Figure 12 - Camera 1, Titan 1 during Transfer 1

Figure 13 - Camera 1, Titan 1 during Transfer 1

Figure 14 - Camera 1, Titan 1 during Transfer 1

Figure 15 - Camera 1, Titan 1 during Transfer 1

Figure 16 - Camera 1, Titan 1 during Transfer 1 – Camera failing

Camera 2 monitored the inside of Titan #2 as shown in Figure 17. As Titan #2 was being filled, the internal temperatures reached the upper limit of +85°C and though the flow was paused at that point, the temperature continued to increase. As the camera heated with the warm gas, the picture went dark as shown in Figure 18, then ultimately failed and went completely black for the remainder of the transfer. The wiring connections were checked but Camera 2 remained non-operational for the remainder of the test cycles. It is believed that the high temperature peaks seen in Titan #2 contributed to the failure of the camera. As previously outlined, measures to keep the high temperature peak within typical service conditions were put in place for the remaining cycles.

Figure 17 - Camera 2, Titan 2 during Transfer 1

Figure 18 – Camera 2, Titan 2 just before failure

In addition to the internal cameras, Camera 3 (IR video) monitored the temperature profile during the transfer. The thermal image shows Titan #1 becoming cold while defueling and Titan #2 becoming hot as it was filled as shown in Figure 19 to Figure 21. Camera 4 was a standard video camera that captured the expansion of Titan #2 and the contraction of Titan #1 (Figure 22). This expansion/contraction is best viewed by fast forwarding or "skipping" through the video footage.

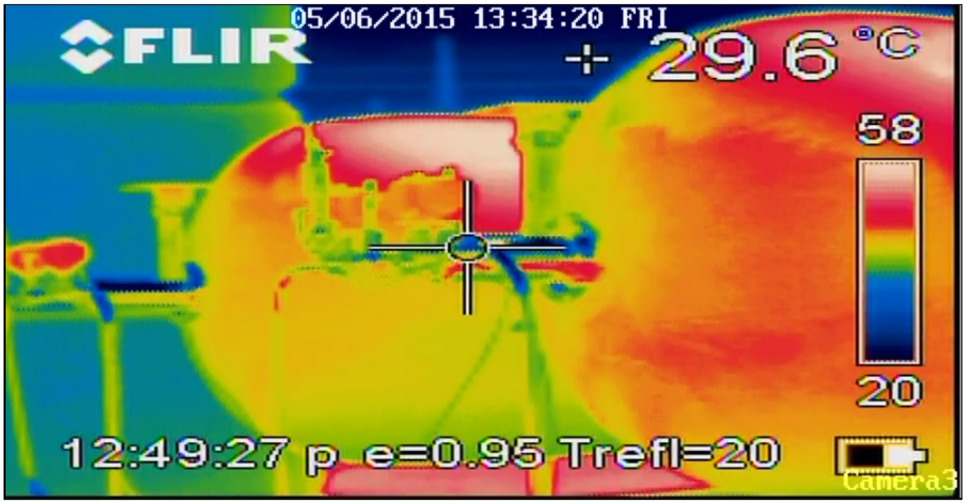

Figure 19 – Camera 3, Transfer 1 (start of transfer)

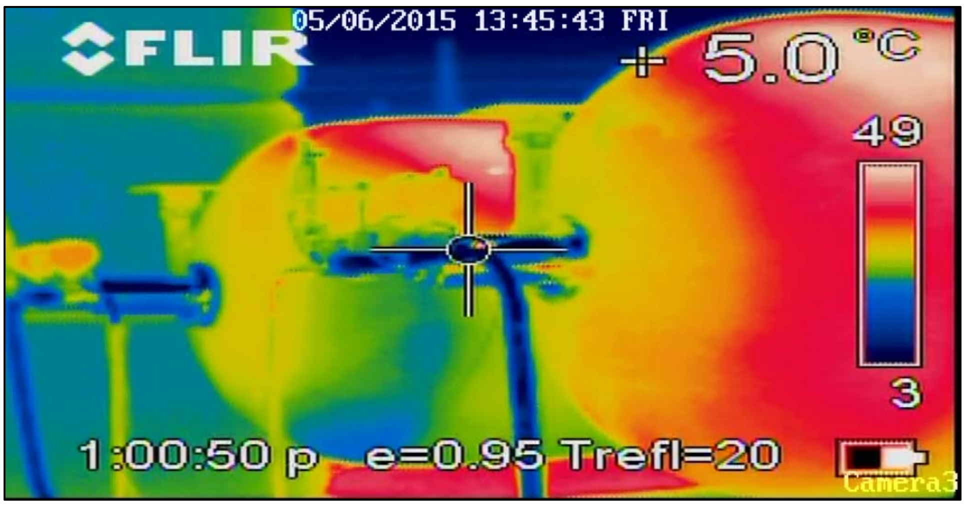

Figure 20 – Camera 3, Transfer 1 (middle of transfer)

Figure 21 – Camera 3, Transfer 1 (end of transfer)

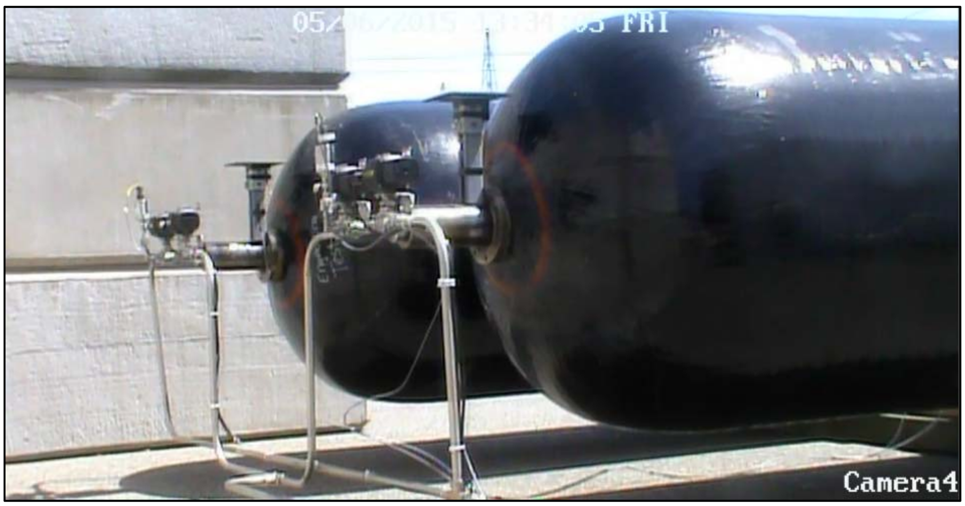

Figure 22 – Camera 4, Transfer 1

During the transfer there was no evidence of any leakage on any of the hydrogen detectors. There was also no leakage noticed when inspecting the tanks following the transfer.

Titan #2 was then pumped up to 250 barg in preparation for Transfer 2.

4.2 Transfer 2, Titan #2 to Titan #1

The second transfer was performed by defueling Titan #2. The initial starting pressure was 254 barg and the total depressurization time to 25 barg was 30 minutes. While defueling Titan #2 into Titan #1, the flow was paused multiple times as the temperature in Titan #1 approached the upper limit rating of +85°C. The coldest temperature recorded in Titan #2 was -58.9°C near the end of the transfer. The data for this transfer is shown in Figure 23 and Figure 24

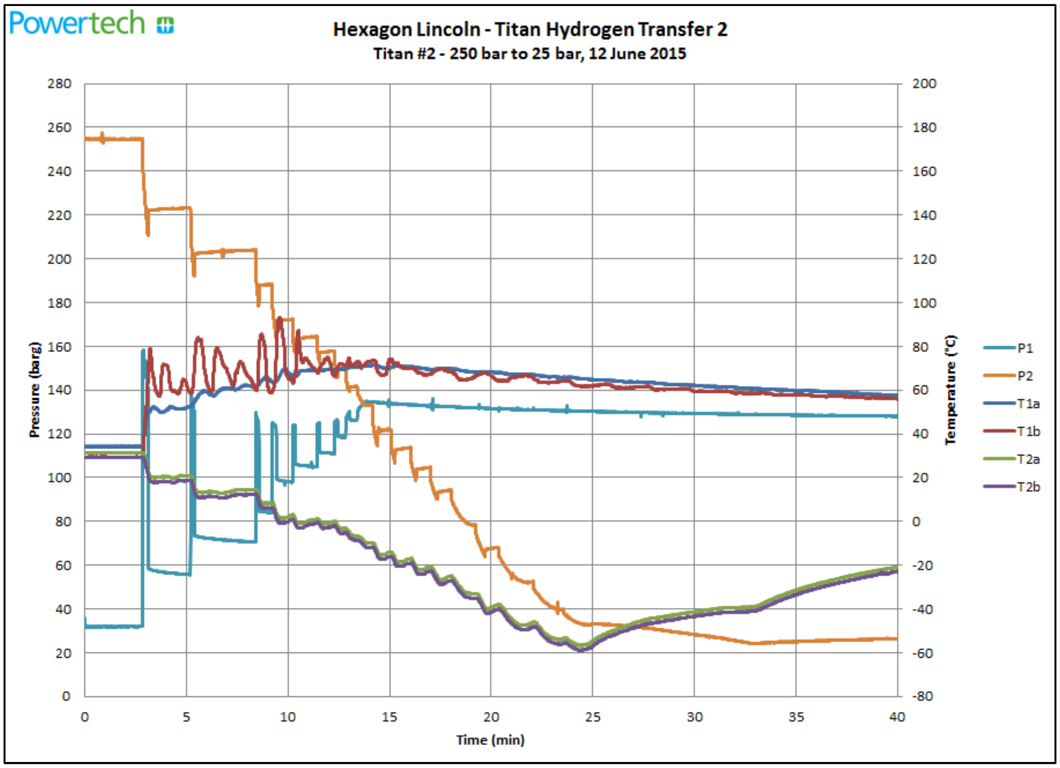

Figure 23 - Transfer 2, Data Summary

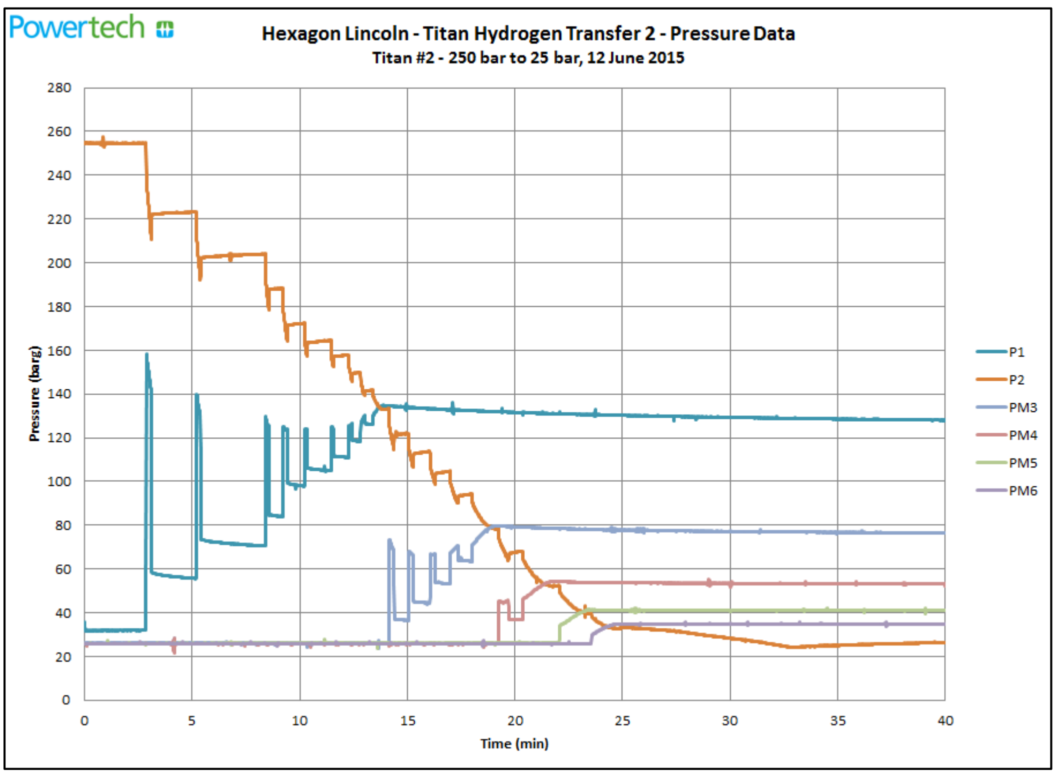

Figure 24 - Transfer 2, Pressure Data

Camera 1 monitored Titan #1 as it was being filled as shown in Figure 25. There was no sign of anything abnormal during this transfer. Camera 4 monitored the expansion/contraction of the test tanks as shown in Figure 26.

Figure 25 – Camera 1, Transfer 2

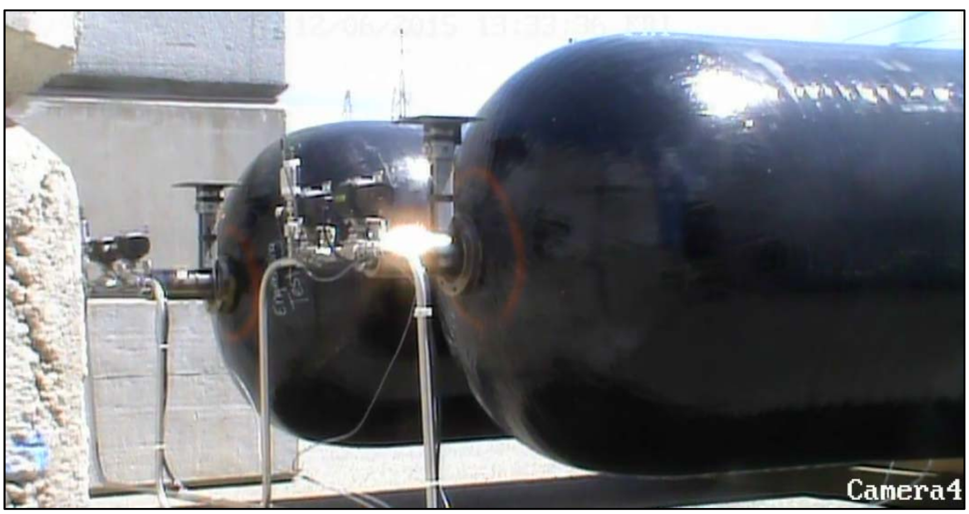

Figure 26 – Camera 4, Transfer 2

Camera 3 (IR video) monitored the thermal profile during the transfer as shown in Figure 27 to Figure 29. The thermal profile was the opposite of Transfer 1 as Titan #2 cooled down during defueling and Titan #1 became hot as it was filled.

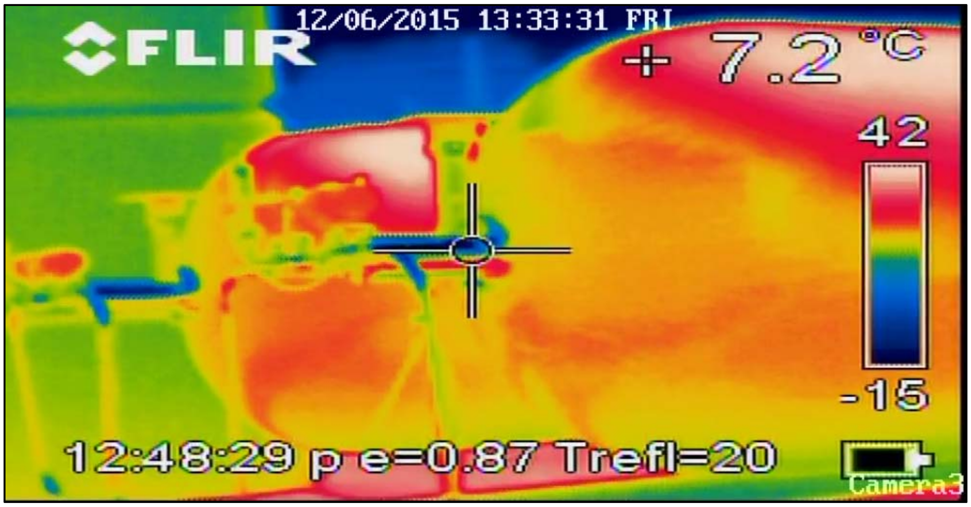

Figure 27 - Camera 3, Transfer 2 (start of transfer)

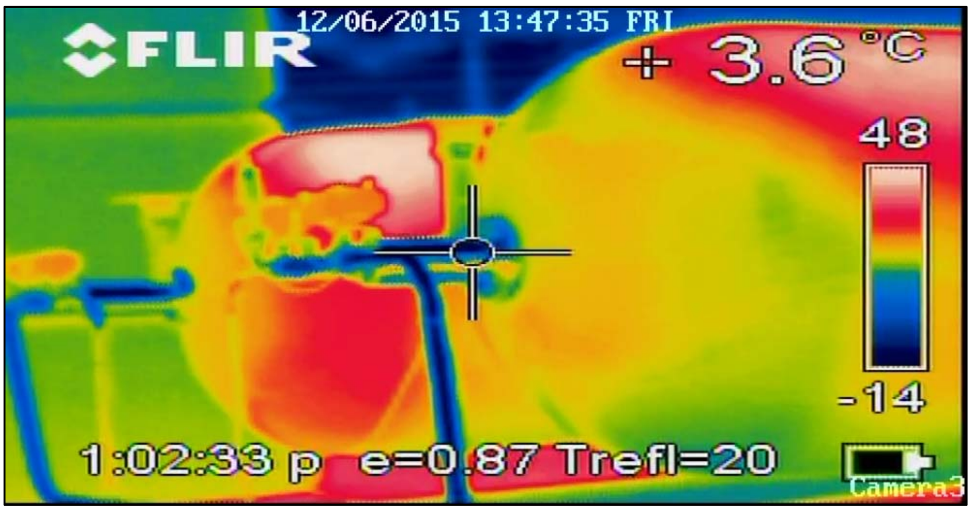

Figure 28 - Camera 3, Transfer 2 (middle of transfer)

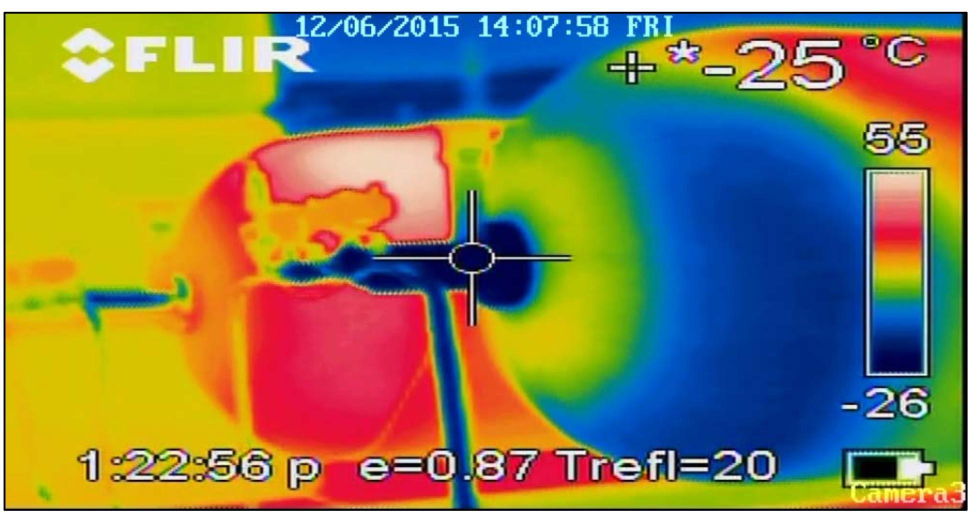

Figure 29 - Camera 3, Transfer 2 (end of transfer)

There was no sign of any leakage on the hydrogen detectors during the transfer. Following the transfer, the test tanks were inspected with a handheld detector and Snoop as shown in Figure 30 and Figure 31. There were a couple areas showing a small formation of Snoop bubbles. The handheld detector was able to measure 10 – 250 ppm when sniffing right at the bubbling location but dissipated to a negligible level when the sensor head was moved approximately 1 cm away from the bubbling locations. The bubbling seemed to disappear within a 30 minute period from the end of the transfer.

Figure 30 – Handheld detector after transfer (Titan #2)

Figure 31 – Snoop bubbles after transfer (Titan #2)

Titan #1 was then pumped up to 250 barg in preparation for Transfer 3.

4.3 Transfer 3, Titan #1 to Titan #2

The third transfer was performed by defueling Titan #1. The initial starting pressure was 254 barg and the total depressurization time to 25 barg was 26 minutes. While defueling Titan #1 into Titan #2, the flow was paused multiple times as the temperature in Titan #2 approached the upper limit rating of +85°C. The coldest temperature recorded in Titan #1 was -63°C. The data for this transfer is shown in Figure 32 and Figure 33.

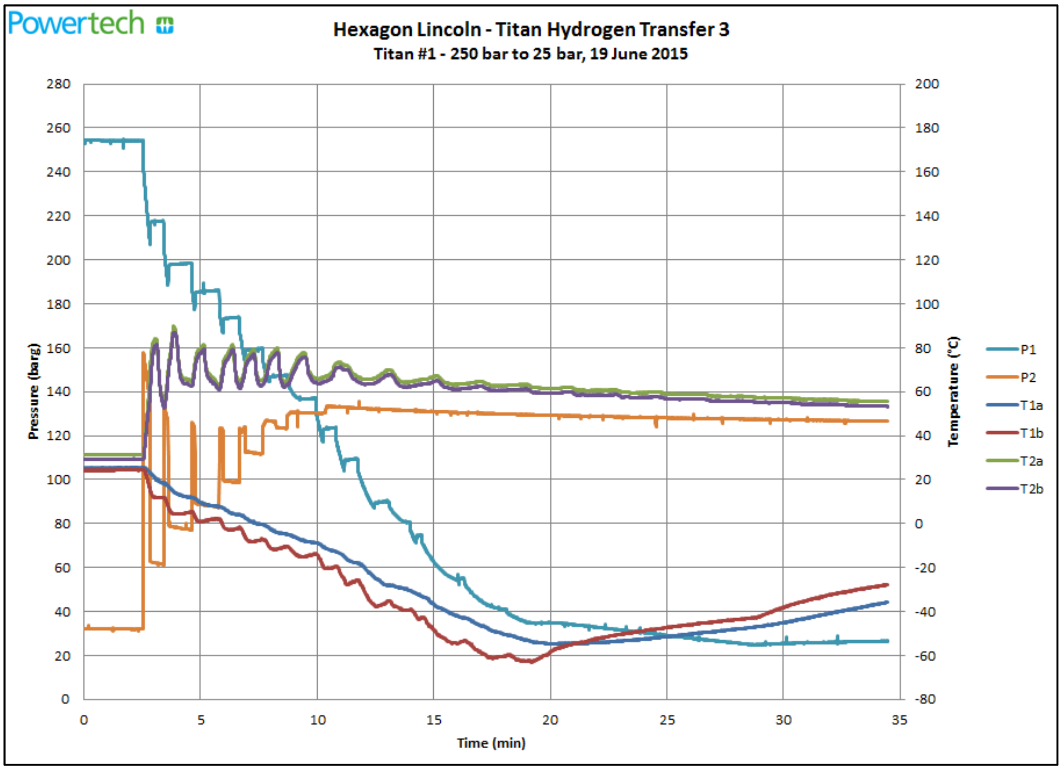

Figure 32 - Transfer 3, Data Summary

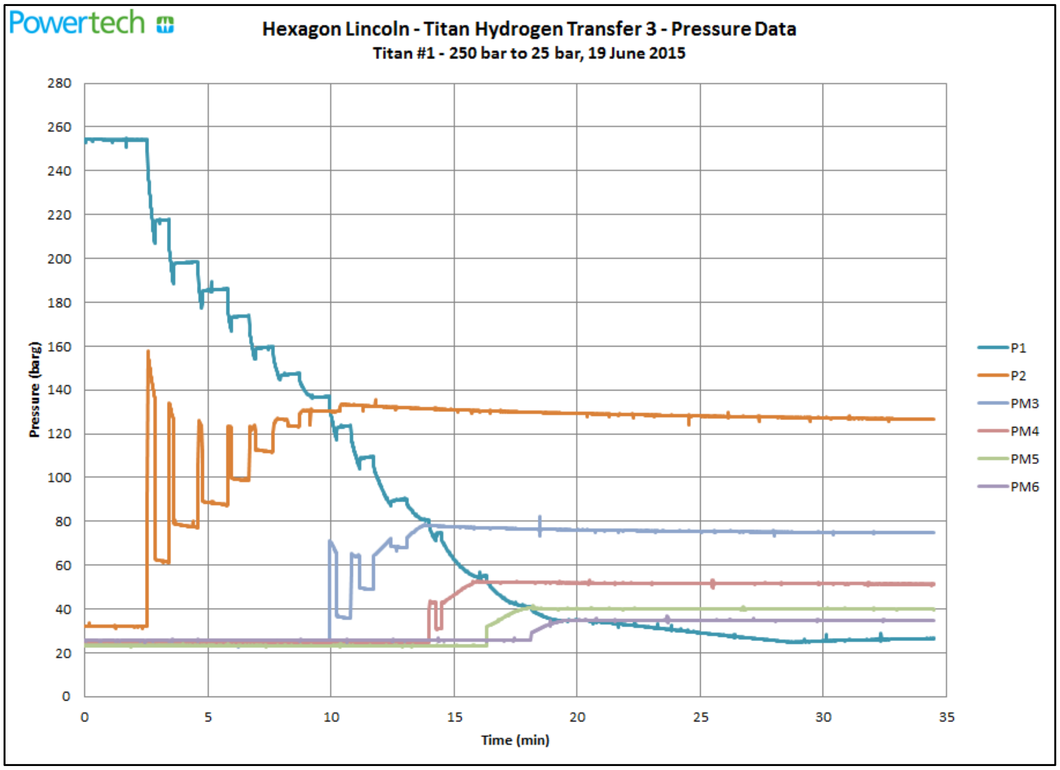

Figure 33 - Transfer 3, Pressure Data

Camera 1 monitored the inside of Titan #1 as it was defueled (Figure 34). The same cloud formation as discovered during Transfer 1 also occurred during this transfer as shown in Figure 35 and Figure 36.

Figure 34 – Camera 1, Transfer 3 (inside Titan #1)

Figure 35 – Camera 1, Transfer 3 (during transfer)

Figure 36 – Camera 1, Transfer 3 (during transfer)

Camera 3 (IR video) monitored the thermal profile of Titan #1 from above as it was defueled as shown in Figure 37 to Figure 38. Camera 4 was also installed above the test tanks to monitor for expansion/contraction as shown in Figure 39.

During the transfer there was no evidence of any leakage on any of the hydrogen detectors. There was also no leakage noticed when inspecting the tanks following the transfer.

Titan #2 was then pumped up to 250 barg in preparation for Transfer 4.

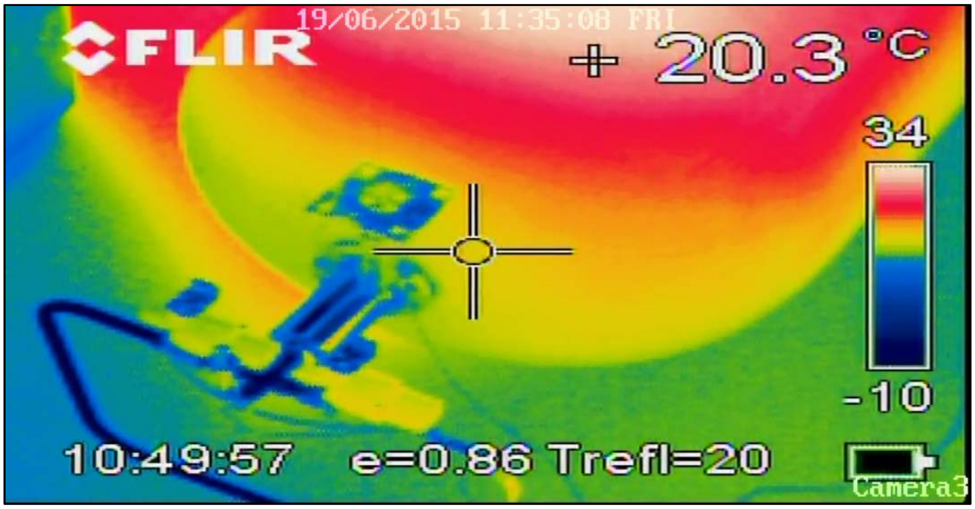

Figure 37 – Camera 3, Transfer 3 (start of defuel)

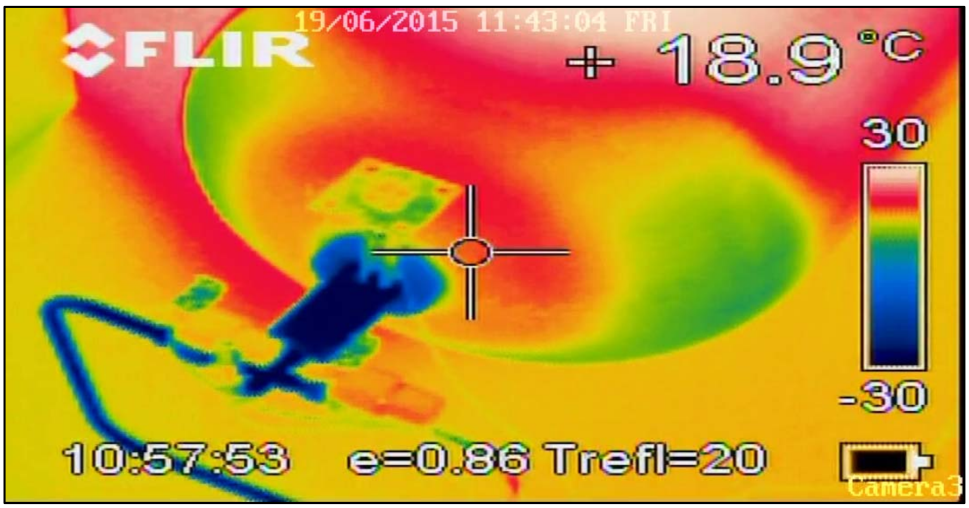

Figure 38 – Camera 3, Transfer 3 (during defuel)

Figure 39 – Camera 4, Transfer 3

4.4 Transfer 4, Titan #2 to Titan #1

The fourth transfer was performed by defueling Titan #2. The initial starting pressure was 258 barg and the total depressurization time to 25 barg was 36.5 minutes. While defueling Titan #2 into Titan #1, the flow was paused multiple times as the temperature in Titan #1 approached the upper limit rating of +85°C. The coldest temperature recorded in Titan #2 was -52.4°C near the end of the transfer. The data for this transfer is shown in Figure 40 and Figure 41.

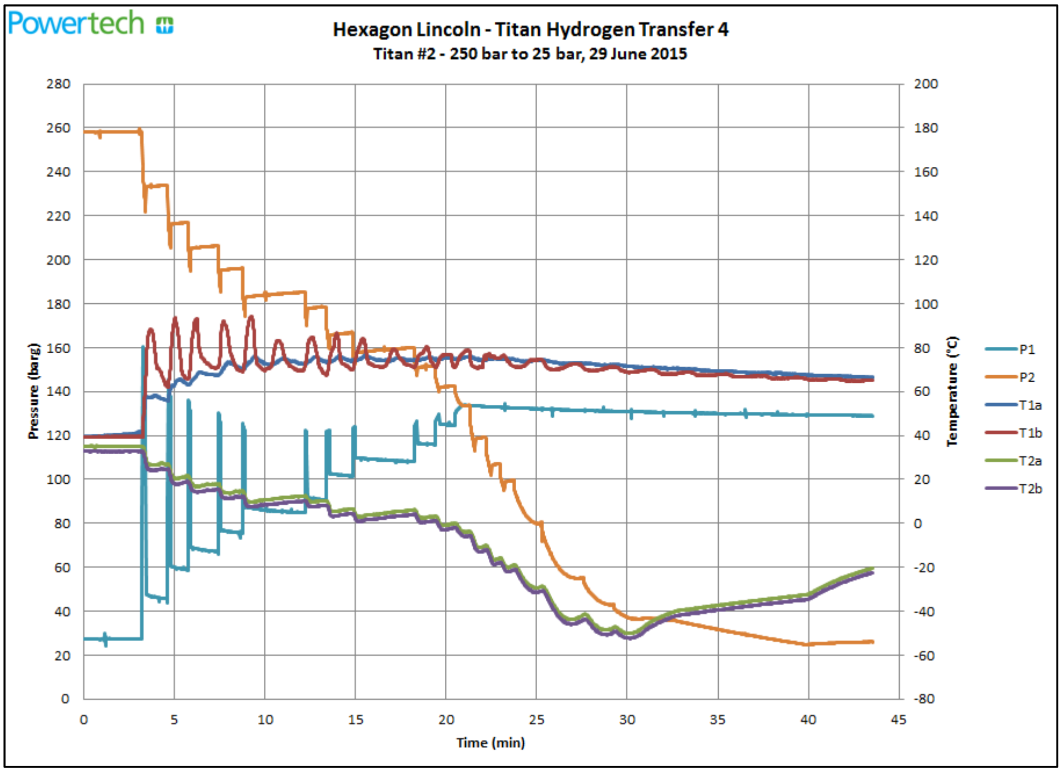

Figure 40 - Transfer 4, Data Summary

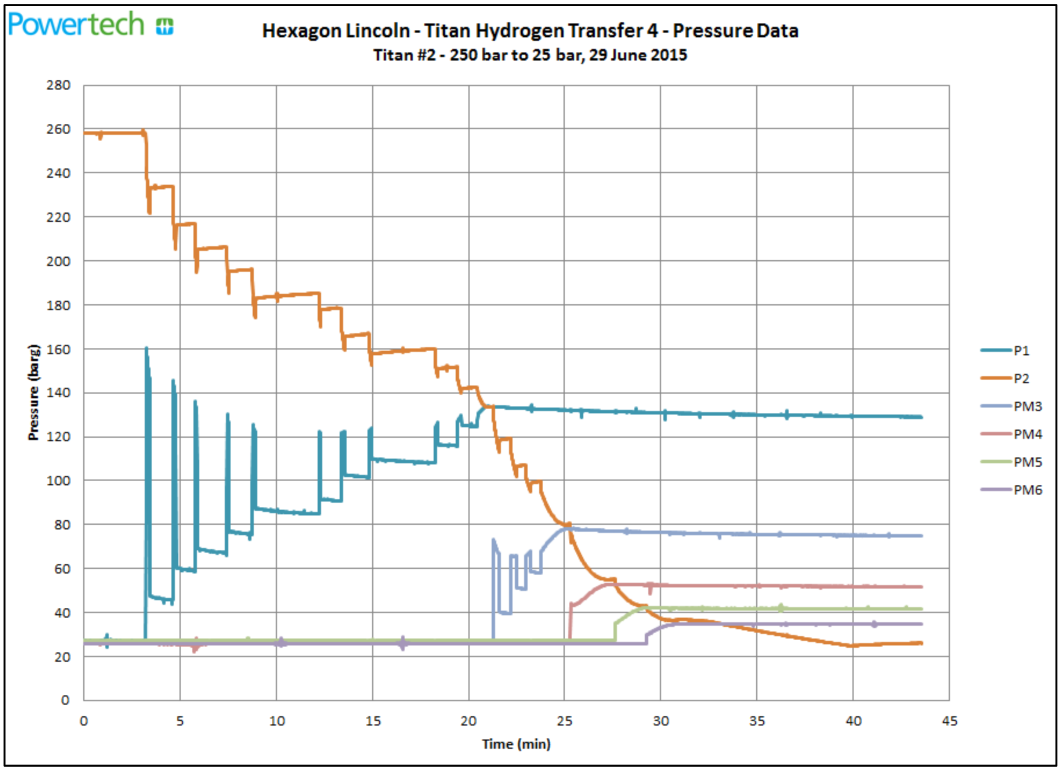

Figure 41 - Transfer 4, Pressure Data

Camera 1 monitored Titan #1 as it was being filled as shown in Figure 42. There was no sign of anything abnormal during this transfer.

Figure 42, Camera 1, Transfer 4

Camera 3 (IR video) monitored the thermal profile during the transfer as shown in Figure 43 to Figure 45. The thermal profile shows that Titan #2 cooled down during defueling and Titan #1 became hot as it was filled.

Figure 43 - Camera 3, Transfer 4 (start of transfer)

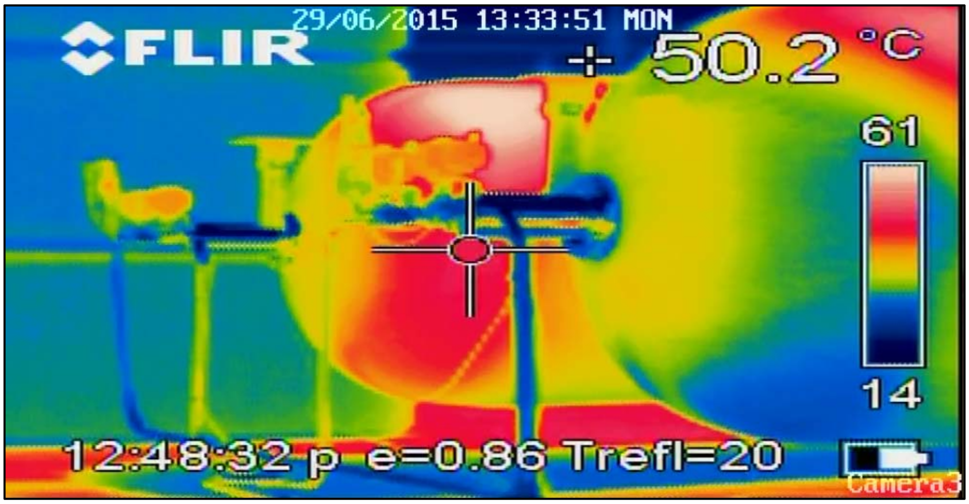

Figure 44 - Camera 3, Transfer 4 (middle of transfer)

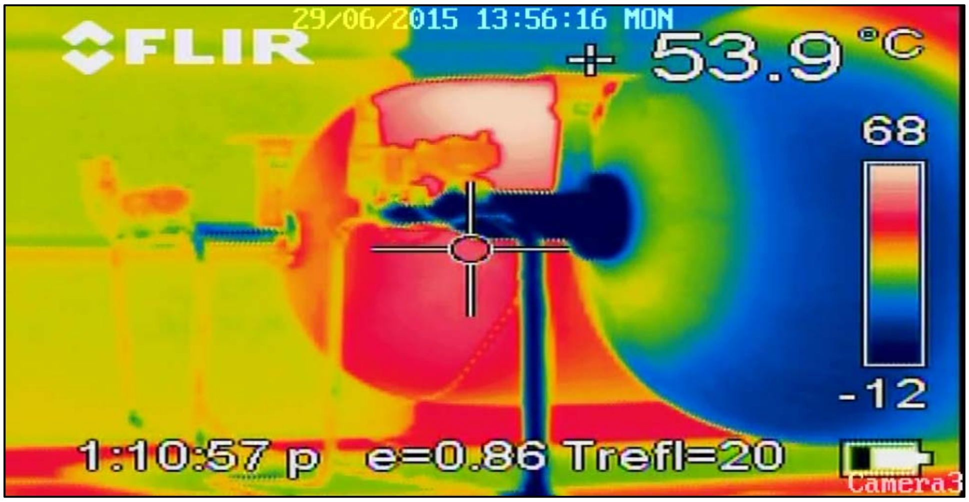

Figure 45 - Camera 3, Transfer 4 (end of transfer)

Camera 4 monitored the expansion/contraction of the test tanks as shown in Figure 46.

Figure 46 – Camera 4, Transfer 4

Following the equalization of Titan #2 into the module, the remaining pressure was vented to atmosphere through the vent stack as shown in Figure 47 until the pressure had reached 25 barg.

Figure 47 – Venting Titan #2 to 25 barg

There was no sign of any leakage on the hydrogen detectors during the transfer. Following the transfer, the test tanks were inspected with a handheld detector and Snoop as shown in Figure 48 and Figure 49. There were a couple areas showing a small formation of Snoop bubbles on Titan #2 that were similar to Transfer 2. Nothing was detected on Titan #1. The bubbling seemed to disappear within a 30 minute period from the end of the transfer.

Figure 48 – Snoop bubble formation on Titan #2 (front)

Figure 49 – Handheld sniffer at Titan #2 (rear dome)

Titan #1 was then pumped up to 250 barg in preparation for Transfer 5.

4.5 Transfer 5, Titan #1 to Titan #1

The fifth transfer was performed by defueling Titan #1. The initial starting pressure was 253 barg and the total depressurization time to 25 barg was 34 minutes. While defueling Titan #1 into Titan #2, the flow was paused multiple times as the temperature in Titan #2 approached the upper limit rating of +85°C. The coldest temperature recorded in Titan #1 was -49.8°C. The data for this transfer is shown in Figure 50 and Figure 51.

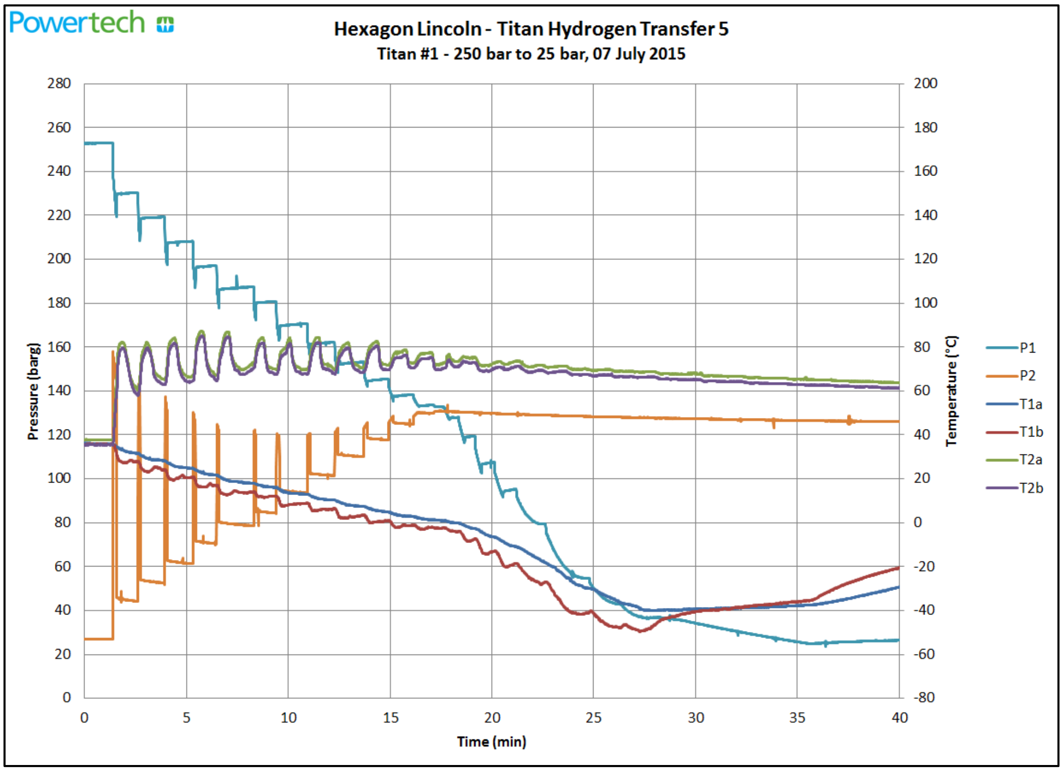

Figure 50 - Transfer 5, Data Summary

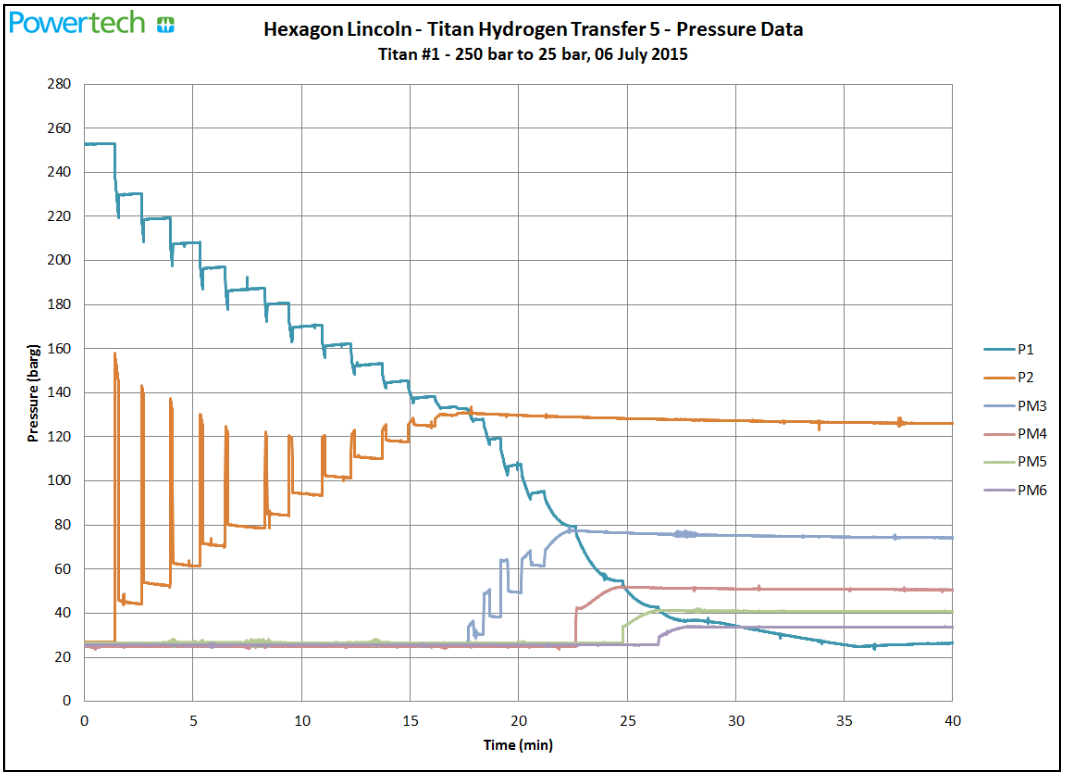

Figure 51 - Transfer 5, Pressure Data

Camera 1 monitored the inside of Titan #1 as it was defueled (Figure 52). The same cloud formation as discovered during Transfer 1 and Transfer 3 also occurred during this transfer as shown in Figure 53.

Figure 52 – Camera 1, Transfer 5 (inside Titan #1)

Figure 53 - Camera 1, Transfer 5 (inside Titan #1)

For this transfer, Camera 4 was positioned to monitor down the length of the tanks between Titan #1 and Titan #2 as shown in Figure 54.

Figure 54 – Camera 4, Transfer 5

Camera 3 (IR Video) was also located in the same position to monitor the thermal profile as shown in Figure 55 and Figure 56.

Following the transfer, there were no significant leaks detected on either test tank. Titan #2 was then pumped to 250 barg in preparation for Transfer 6.

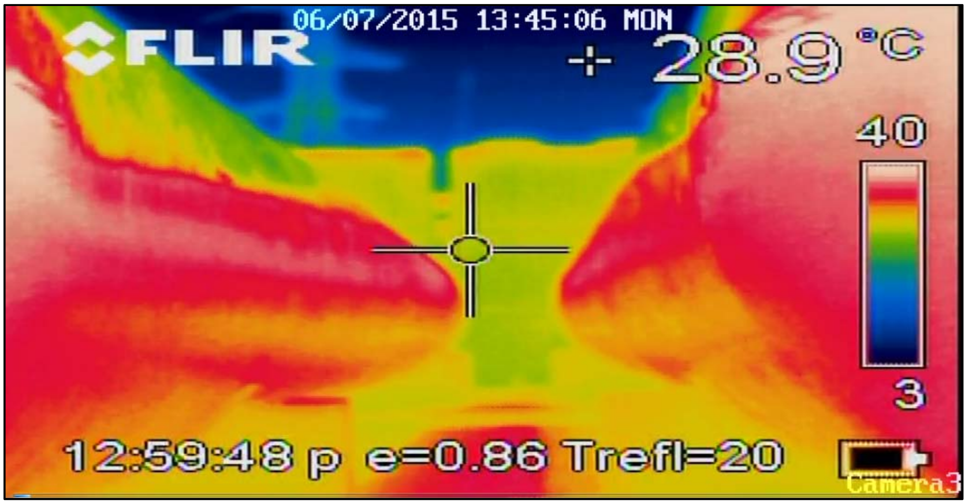

Figure 55 – Camera 3, Transfer 5 (start of transfer)

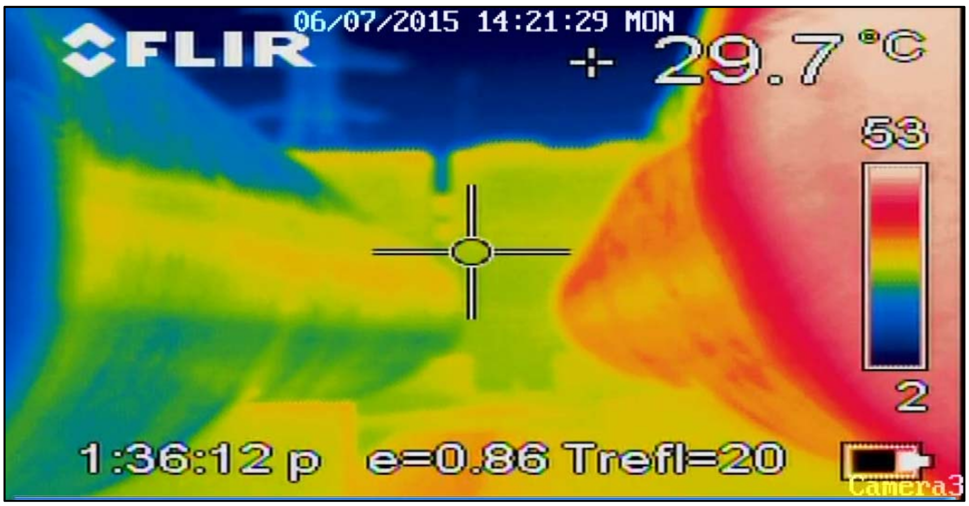

Figure 56 – Camera 3, Transfer 5 (end of transfer)

4.6 Transfer 6, Titan #2 to Titan #1

The sixth transfer was performed by defueling Titan #2. The initial starting pressure was 257 barg and the total depressurization time to 25 barg was 28 minutes. While defueling Titan #2 into Titan #1, the flow was paused multiple times as the temperature in Titan #1 approached the upper limit rating of +85°C. The coldest temperature recorded in Titan #2 was -59.7 °C. The data for this transfer is shown in Figure 57 and Figure 58.

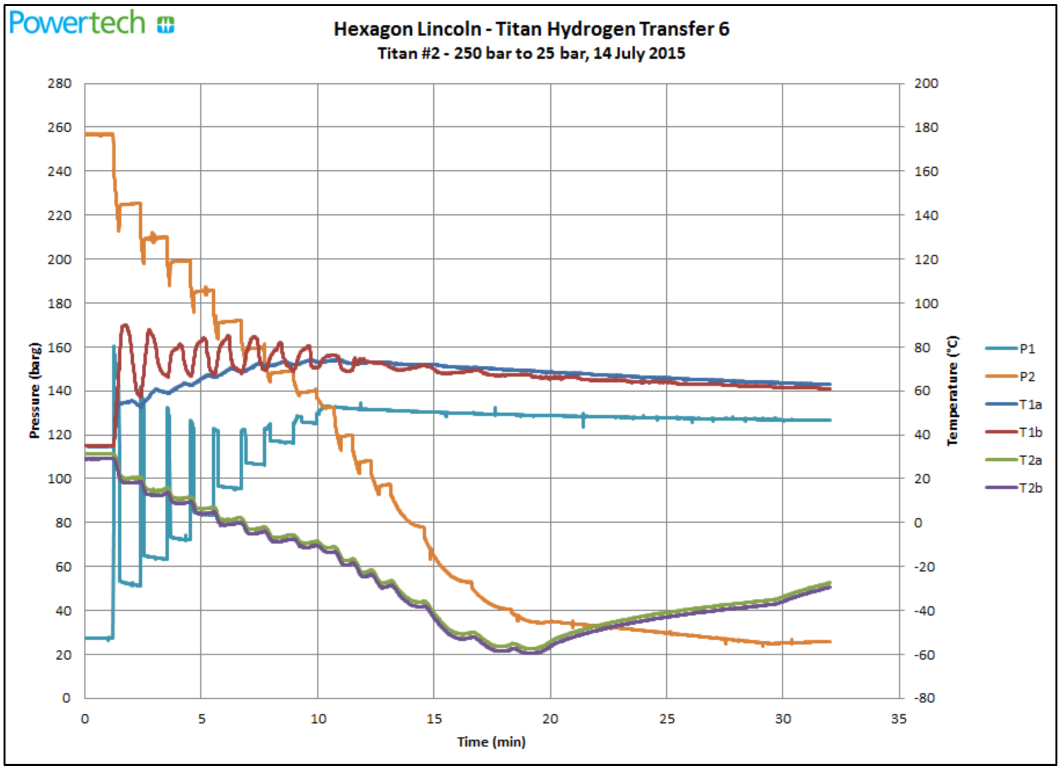

Figure 57 – Transfer 6, Data Summary

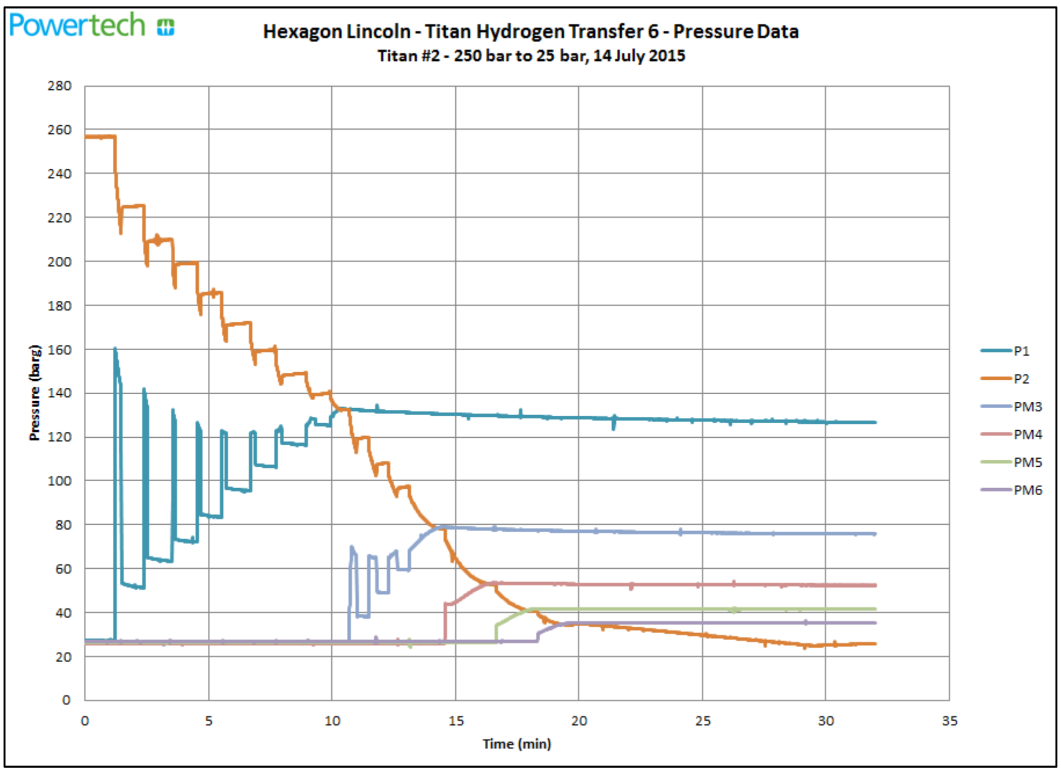

Figure 58 – Transfer 6, Pressure Data

Camera 1 monitored Titan #1 as it was being filled as shown in Figure 59. There was no sign of anything abnormal during this transfer.

Figure 59 – Camera 1, Transfer 6

Camera 4 monitored the expansion/contraction of the test tanks as shown in Figure 60.

Figure 60 – Camera 4, Transfer 6

Camera 3 (IR video) monitored the thermal profile during the transfer as shown in Figure 61 to Figure 63. The thermal profile shows that Titan #2 cooled down during defueling and Titan #1 became hot as it was filled.

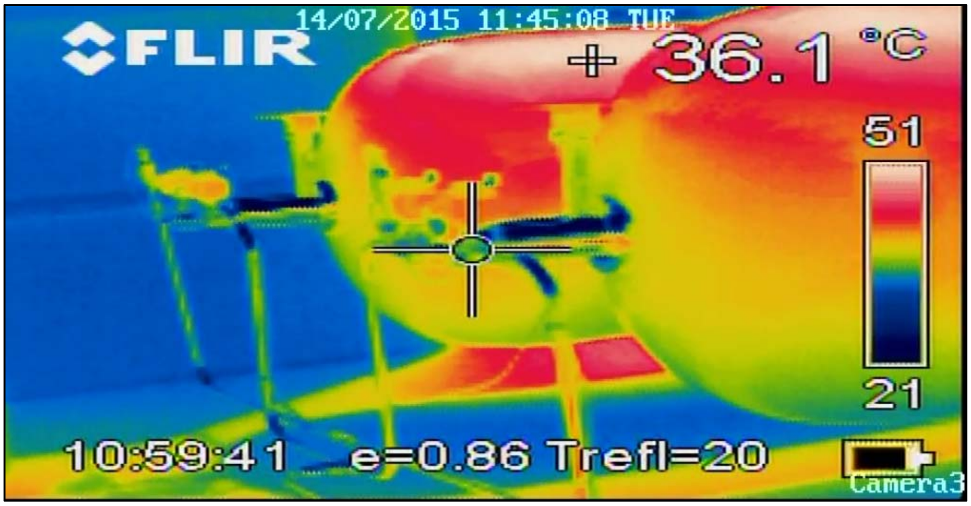

Figure 61 - Camera 3, Transfer 6 (start of transfer)

Figure 62 - Camera 3, Transfer 6 (middle of transfer)

Figure 63 - Camera 3, Transfer 6 (end of transfer)

There was no sign of any leakage on the hydrogen detectors during the transfer. Following the transfer, the test tanks were inspected with a handheld detector and Snoop as shown in Figure 64 through Figure 67. There were a few areas showing a small formation of Snoop bubbles. The handheld detector was able to measure a maximum level of 0.6 vol% immediately after the transfer when sniffing right at a specific bubbling location. The measurement dropped to 20-100 ppm when measuring 1 cm from the bubbling location and 0-20 ppm at a distance of 2 cm. Over the next few hours, the measurement in the 1-2 cm range became negligible (<5 ppm) and remained negligible when the tank was inspected over the next few days.

Figure 64 – Snoop Bubbles at Titan #2, after Transfer 6

Figure 65 – Handheld detector, Titan #2 immediately after Transfer 6 (0.5 vol%)

Figure 66 – Handheld detector, Titan #2 (0 ppm, 1-2 cm from bubbles)

Figure 67 - Snoop bubble formation, Titan #2 (rear) after Transfer 6

4.7 Transfer 7, Titan #1 to Titan #2

The seventh transfer was performed by defueling Titan #1. The initial starting pressure was 253 barg and the total depressurization time to 25 barg was 27 minutes. While defueling Titan #1 into Titan #2, the flow was paused multiple times as the temperature in Titan #2 approached the upper limit rating of +85°C. The coldest temperature recorded in Titan #1 was -57.8°C. The data for this transfer is shown in Figure 68 and Figure 69.

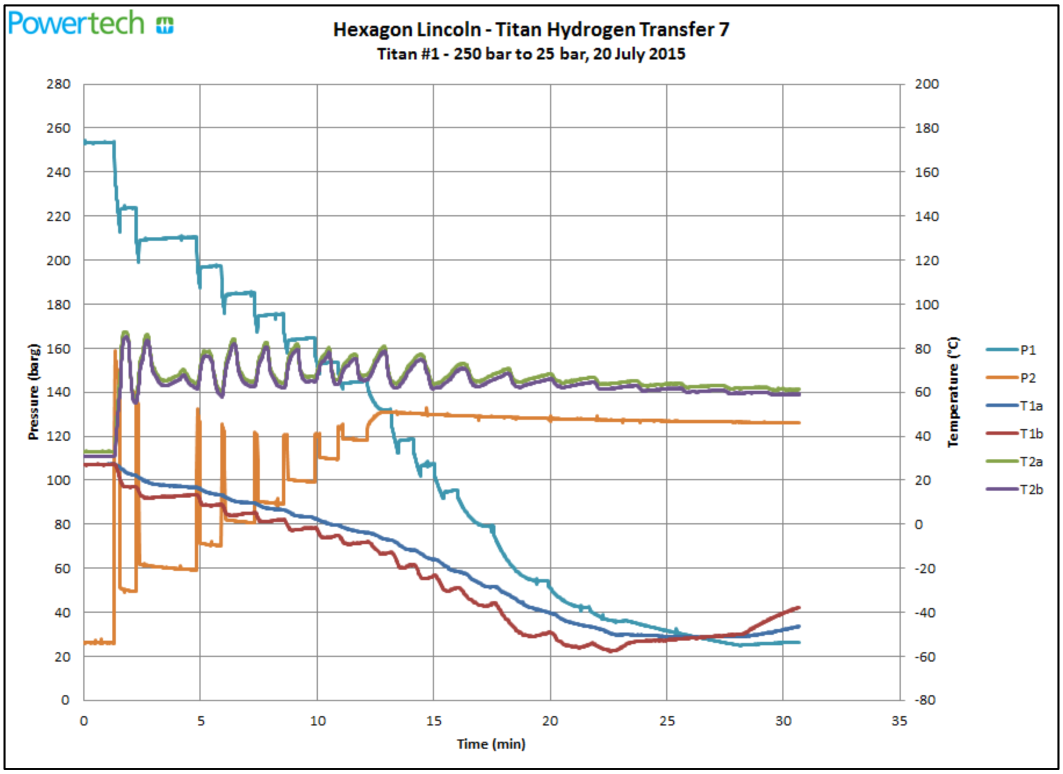

Figure 68 – Transfer 7, Data Summary

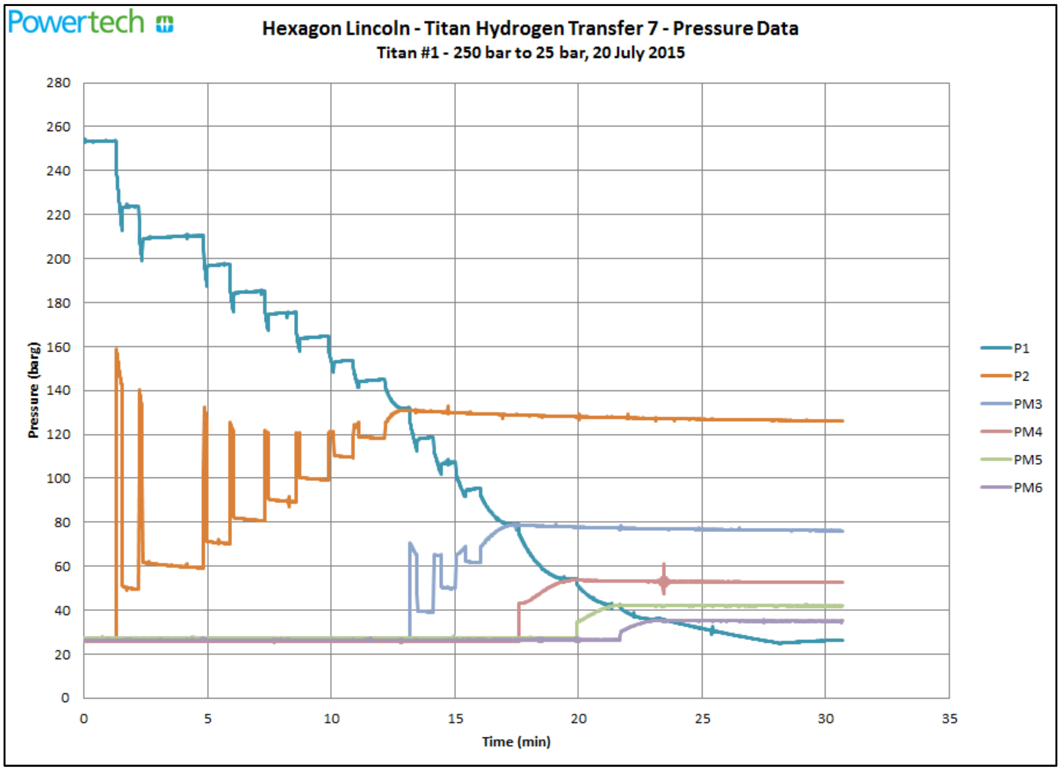

Figure 69 – Transfer 7, Pressure Data

Camera 1 monitored the inside of Titan #1 as it was defueled. The same cloud formation as previously discovered also occurred during this transfer as shown in Figure 70.

Figure 70 – Camera 1, Transfer 7

Camera 3 (IR video) monitored the thermal profile during the transfer as shown in Figure 71 to Figure 73. The thermal profile shows that Titan #1 cooled down during defueling and Titan #2 became hot as it was filled. Camera 4 monitored the expansion/contraction of the test tanks as shown in Figure 74.

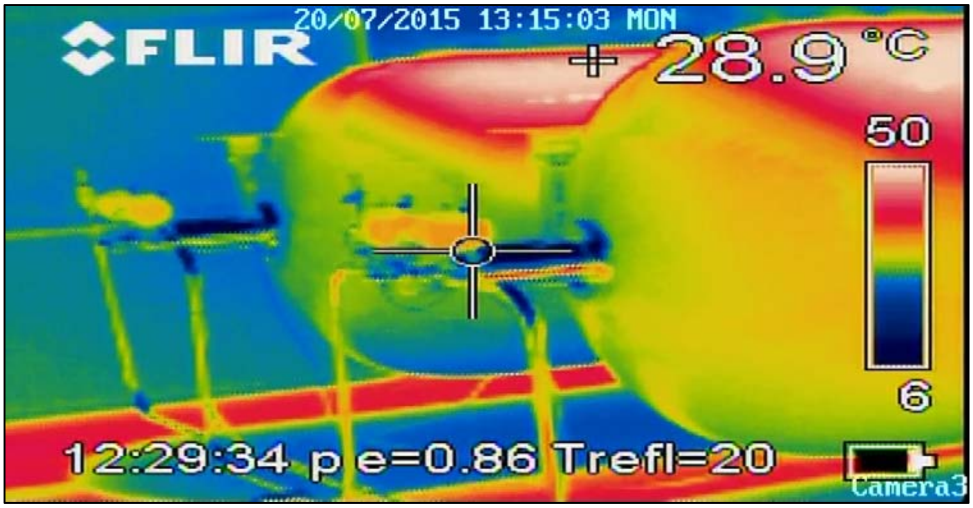

Figure 71 - Camera 3, Transfer 7 (start of transfer)

Figure 72 - Camera 3, Transfer 7 (middle of transfer)

Figure 73 - Camera 3, Transfer 7 (end of transfer)

Figure 74 – Camera 4, Transfer 7

4.8 Transfer 8, Titan #2 to Titan #1

The eighth and final transfer was performed by defueling Titan #2. The initial starting pressure was 254 barg and the total depressurization time to 25 barg was 23 minutes. While defueling Titan #2 into Titan #1, the flow was paused multiple times as the temperature in Titan #1 approached the upper limit rating of +85°C. The coldest temperature recorded in Titan #2 was -57.8 °C. The data for this transfer is shown in Figure 75 and Figure 76.

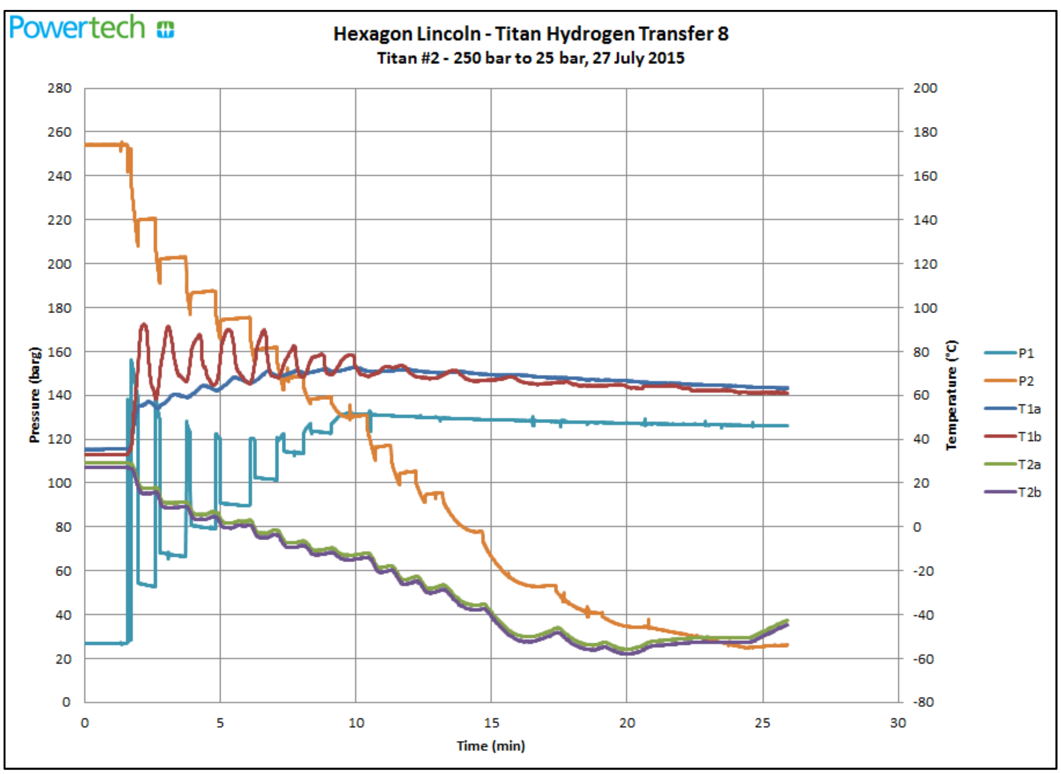

Figure 75 – Transfer 8, Data Summary

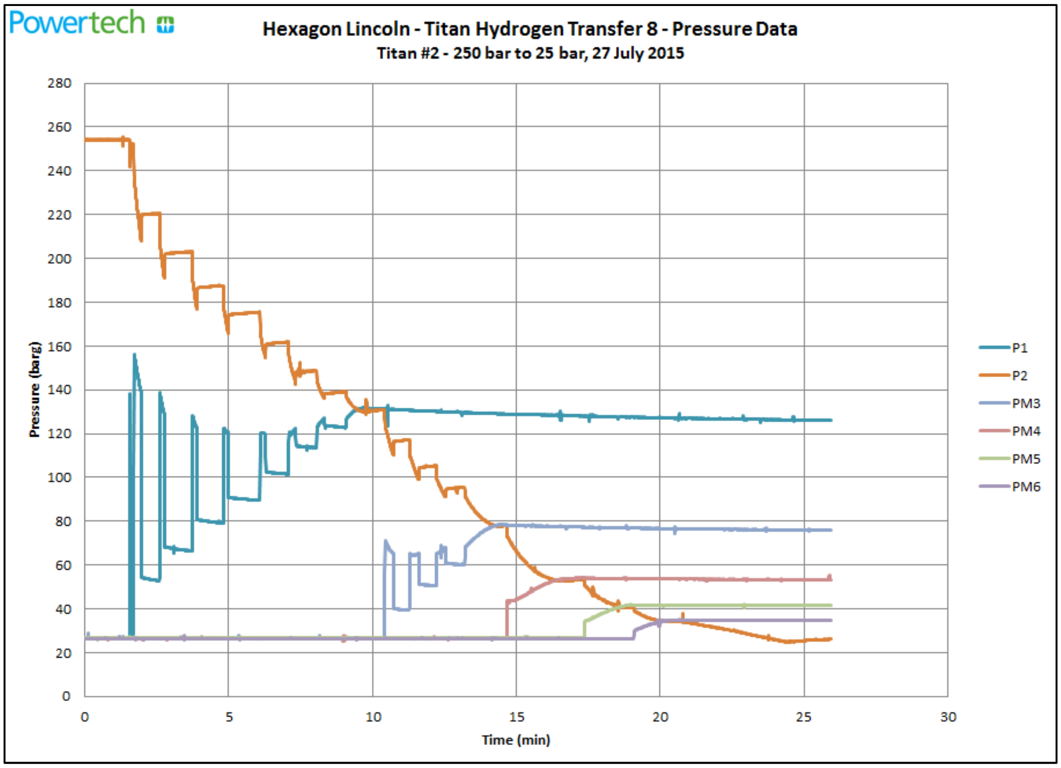

Figure 76 – Transfer 8, Pressure Data

Camera 1 monitored Titan #1 as it was being filled as shown in Figure 77. There was no sign of anything abnormal during this transfer.

Figure 77 – Camera 1, Transfer 8

Camera 3 (IR video) monitored the thermal profile during the transfer as shown in Figure 78 to Figure 80. The thermal profile shows that Titan #2 cooled down during defueling and Titan #1 became hot as it was filled.

Figure 78 - Camera 3, Transfer 8 (start of transfer)

Figure 79 - Camera 3, Transfer 8 (middle of transfer)

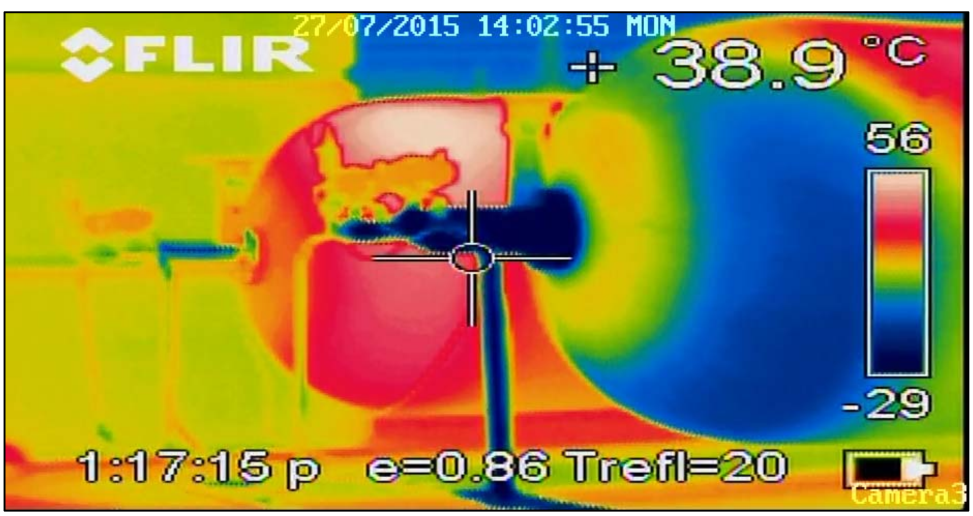

Figure 80 - Camera 3, Transfer 8 (end of transfer)

Camera 4 monitored the expansion/contraction of the test tanks as shown in Figure 81.

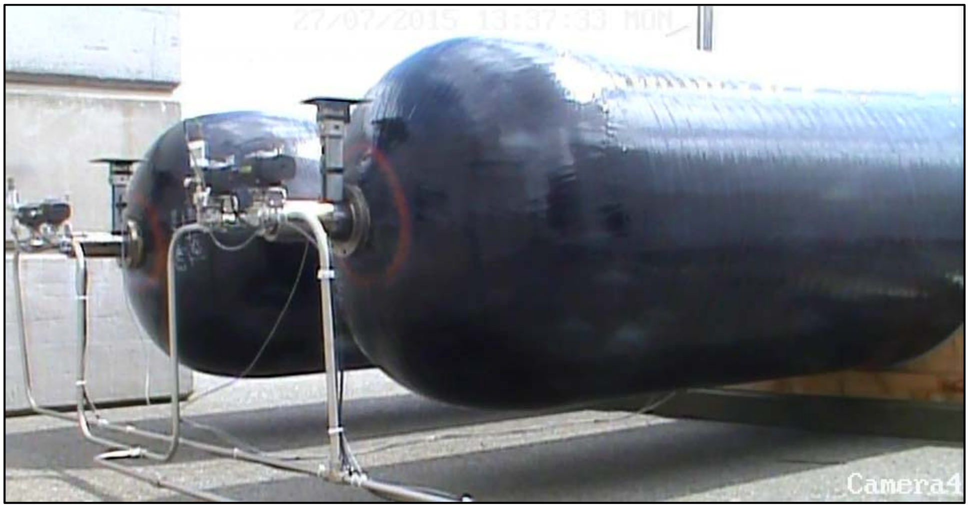

Figure 81 – Camera 4, Transfer 8

There was no sign of any leakage on the hydrogen detectors during the transfer. Following the transfer, the test tanks were inspected with a handheld detector and Snoop as shown in Figure 82 through Figure 85. There were a few areas showing a small formation of Snoop bubbles. The handheld detector was able to measure a maximum level of 0.2 vol% immediately after the transfer when sniffing right at a specific bubbling location. The measurement dropped to a negligible (<5 ppm) level when sniffing at 1-2 cm from the bubbling locations.

Figure 82 – Leak Check at Titan 2 (654 ppm right at bubble location, rear)

Figure 83 - Leak Check at Titan 2 (0 ppm at 1 cm from bubble location, rear)

Figure 84 – Transfer 8, Snoop bubbles at front of tank

Figure 85 – Transfer 8, Snoop bubbles at rear of tank

Following Transfer 8, all of the Titan tanks were defueled completely and purged with nitrogen. The cameras were removed from the tanks to allow for a post-test inspection with a borescope.

4.9 Post Test Inspection and Test Summary

Following the completion of hydrogen cycling, a borescope was used to inspect the inside of Titan #1 and Titan #2. There was some water/fluid that was confirmed to be resting in the bottom of Titan #1 which explains the moisture and cloud formation during the defuels of this tank. There was no evidence of any liner damage and the cylinders appear to remain in good condition.

In summary, all eight transfers were completed successfully with no major issues. There were some minor leaks found following the rapid defueling process when the tanks were still cold, but the concentration amounts were minimal especially when the detection point was greater than 1 cm from the leak location.

All of the data and video files have been submitted to Hexagon Lincoln electronically.

Tested By:	Approved By:
Paul Obrovac	Graham Meadows, P.Eng.
Date: November 5, 2015	