End-of-Life Evaluation of Compressed Natural Gas Vehicle Fuel Tanks

Aaron Williams and Lauren A. Lynch

National Renewable Energy Laboratory

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List of Acronyms

ANSI	American National Standards Institute
CGA	Compressed Gas Association
CNG	compressed natural gas
CSA	CSA Group
EOL	end of life
FMVSS	Federal Motor Vehicle Safety Standards
Hz	hertz
ISO	International Organization for Standardization
LA	Los Angeles
MAE	modal acoustic emission
NGV	natural gas vehicle
NGV2	*CSA/ANSI NGV 2-2019* standard
NREL	National Renewable Energy Laboratory
PHMSA	Pipeline and Hazardous Materials Safety Administration
psig	pounds per square inch gauge

Executive Summary

The end-of-life (EOL) requirement of compressed natural gas (CNG) fuel tanks can vary from the variable service life of the vehicle, compelling the vehicle owner to replace the fuel tank in compliance with the tank manufacturer's EOL requirements. CNG fuel tanks that need to be replaced before the end of the vehicle's service life are a financial burden to the vehicle owner and increases acute hazards related to the removal and reinstallation of the tanks, such as improper fitment of replacement fuel tanks, brackets, and mounting components. Federal Motor Vehicle Safety Standards (FMVSS) No. 304 requires a visual inspection of CNG fuel tanks (e-CFR 2020), avoiding unnecessary removal and reinstallation of tanks to prevent such hazards. Removal and replacement of expired CNG fuel tanks also introduces concerns of resale of expired tanks or incorrect disposal of CNG fuel tanks.

There are no FMVSS that define the EOL requirement for CNG fuel tanks as they are defined by the manufacturer, and there are limited and inconsistent enforcement efforts to ensure vehicle owners adhere to the EOL requirements for CNG fuel tanks. Therefore, it is not uncommon for CNG vehicles to continue utilizing CNG fuel tanks that have surpassed their defined EOL requirements.

The U.S. Department of Energy undertook this project to investigate the structural integrity of CNG fuel tanks under routine operating conditions at the end of their defined useful life. This information would allow the industry to better identify, understand, and mitigate safety risks and address barriers and opportunities related to CNG storage onboard vehicles.

This study evaluated the structural integrity of Type III and Type IV CNG fuel tanks from the Los Angeles (LA) County Metropolitan Transportation Authority to characterize the fuel tank conditions after experiencing a full service life of 15 years in transit bus application. The data produced provide insight about the condition of the CNG fuel tanks at the conclusion of their defined EOL and potential risks of continued operation of the CNG vehicle without replacement of the expired fuel tanks. In addition to physical testing performed on the fuel tanks, a nondestructive evaluation of modal acoustic emission (MAE) was utilized to assess the structural integrity of the tanks. The CNG fuel tanks were evaluated in their received condition and after experiencing artificial damage. The MAE results were then compared to visual inspection results of the procedures defined in the Compressed Gas Association's (CGA's) C-6.2 and C-6.4 standards (Compressed Gas Association 2013; 2012) to better understand the effectiveness of the visual inspection and potential safety risks of continued use of the tanks.

A total sample size of 60 CNG fuel tanks were tested to characterize the structural integrity at their defined EOL of 15 years in comparison to the CSA Group/American National Standards Institute's (CSA/ANSI's) design and performance standard, *CSA/ANSI NGV 2-2019* (NGV2) (CSA/ANSI 2019). Twenty of the 60 tanks were burst-tested without being subjected to any additional damage to establish a baseline understanding of the tank's structural integrity at EOL. An additional 20 tanks were subjected to artificial notch and impact damage followed by fatigue cycling and burst pressure testing to understand structural durability. Another 20 tanks were subjected to hydraulic fatigue cycling followed by a burst test to simulate continued use of the tanks beyond their defined EOL. Two of these 20 tanks were also leak-tested to understand

potential for additional failure modes. An outline summary of the CNG fuel tanks tested and their results follows:

60 of 101 Tanks Initial Visual and MAE Inspection
60 Passed

20 of 60 Tanks Burst Pressurized as Received
20 Passed

Number of Tanks Tested	Minimum Burst Pressure Test Pass/Fail	
20 of 20 Tanks as Received from LA County Metro Transportation Authority	20 Tested 20 Passed	10 Type III 10 Type IV

20 of 60 Tanks Artificially Damaged and Burst Pressurized
14 Passed, 6 Failed

Number of Tanks Tested	Hydraulic Fatigue Tested to 15,000 Cycles Pass/Fail		Minimum Burst Pressure Test Pass/Fail	
8 of 20 Tanks Notch Damaged	4 Tested 4 Passed	2 Type III 2 Type IV	8 Tested 8 Passed	4 Type III 4 Type IV
4 of 20 Tanks Impact Damaged	2 Tested 2 Passed	1 Type III 1 Type IV	4 Tested 4 Passed	2 Type III 2 Type IV
4 of 8 Tanks Local Impact Damaged at Standard Height	2 Tested 2 Passed	1 Type III 1 Type IV	4 Tested 2 Passed 2 Failed	2 Type III 2 Type IV
4 of 8 Tanks Local Impact Damaged at Double Height	2 Tested 2 Passed	1 Type III 1 Type IV	4 Tested 4 Failed	2 Type III 2 Type IV

20 of 60 Tanks Hydraulically Fatigued to 18,000 Cycles
20 Passed

Number of Tanks Tested	Hydraulic Fatigue Tested to 18,000 Cycles Pass/Fail		Minimum Burst Pressure Test Pass/Fail	
2 of 20 Tanks Leak-Tested	2 Tested 2 Passed	1 Type III 1 Type IV	None Tested	
20 of 20 Tanks Burst Pressurized	20 Tested 20 Passed	10 Type III 10 Type IV	20 Tested 20 Passed	10 Type III 10 Type IV

The results of the structural integrity testing of the Type III and Type IV CNG fuel tanks at the end of their defined useful life of 15 years from the LA County Metro Transportation Authority suggests potential opportunity of continued use of tanks, as the majority of the sample size met the minimum pressure requirements of NGV2 at EOL, as well as after additional hydraulic fatigue cycling and some artificial damage. Additional research and development with an expanded CNG fuel tank sample size to characterize tank integrity after experiencing a full service life in a variety of applications could further verify such potential. Visual inspection was not sufficient in identifying damage inflicted by a localized impact test on Type III and Type IV CNG fuel tanks, whereas a nondestructive evaluation method successfully assessed the structural integrity of the tanks and would not have compromised the original installation.

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1 Introduction

The end-of-life (EOL) requirement of compressed natural gas (CNG) fuel tanks can vary from the variable service life of the vehicle, compelling the vehicle owner to replace the fuel tank in compliance with the tank manufacturer's EOL requirements. CNG fuel tanks that need to be replaced before the end of the vehicle's service life are a financial burden to the vehicle owner and increases acute hazards related to the removal and reinstallation of the tanks, such as improper fitment of replacement fuel tanks, brackets, and mounting components. Federal Motor Vehicle Safety Standards (FMVSS) No. 304 requires a visual inspection of CNG fuel tanks (e-CFR 2020), avoiding unnecessary removal and reinstallation of tanks to prevent such hazards. Removal and replacement of expired CNG fuel tanks also introduces concerns of resale of expired tanks or incorrect disposal of CNG fuel tanks.

There are no FMVSS that define the EOL requirement for CNG fuel tanks as they are defined by the manufacturer, and there are limited and inconsistent enforcement efforts to ensure vehicle owners adhere to the EOL requirements for CNG fuel tanks. Therefore, it is not uncommon for CNG vehicles to continue utilizing CNG fuel tanks that have surpassed their defined EOL requirements.

In support of the U.S. Department of Energy, the National Renewable Energy Laboratory (NREL) led this study to investigate the integrity of CNG fuel tanks under routine operating conditions at the end of their defined useful life in order to better identify, understand, and mitigate safety risks and address barriers and opportunities related to CNG storage onboard vehicles. This section provides an overview of the background and objective of the project.

1.1 Background

Natural gas was designated as an alternative fuel to gasoline under the Energy Policy Act of 1992 (AFDC 2020). Due to its domestic abundance, low cost, and lower engine emissions, CNG is a widely used alternative fuel for both light- and heavy-duty vehicles. Currently, there are approximately 150,000 natural gas vehicles in service in the United States, while an estimated 15.2 million vehicles operate on natural gas worldwide (CSA/ANSI 2019).

Compressed gas cylinders are an integral part of a CNG vehicle's fuel system. These fuel tanks are typically manufactured to meet CSA Group/American National Standards Institute's (CSA/ANSI's) *CSA/ANSI NGV 2-2019* (NGV2) standard as it defines design and certification requirements for natural gas vehicle (NGV) onboard fuel tanks. NGV2 is an American National Standard processed under the canvass method, in accordance with procedures of ANSI. NGV2 states that the defined useful life of the CNG fuel tanks shall be specified by the tank manufacturer and shall be greater than 10 years and less than 25 years.

There are four CNG fuel tank cylinder types. Type I CNG cylinders are completely made of either aluminum or steel metal. Type II CNG cylinders are manufactured with a metal liner reinforced by glass or carbon fiber composite wrap around the middle (also referred to as "hoop wrap"). Type III CNG cylinders are also manufactured with a metal liner but are reinforced with a full composite wrap encompassing the entire cylinder. Type IV cylinders are manufactured with a plastic, gastight liner reinforced by a full composite wrap encompassing the entire cylinder.

The vehicle owner is required to replace CNG fuel tanks in compliance with the tank manufacturer's EOL requirements. However, the removal and replacement of the fuel tanks may introduce critical hazards such as improper fitment of the tanks, brackets, and mounting components that could potentially cause probable failure modes to the system. In addition to safety hazards, removal and replacement of expired fuel tanks on CNG vehicles with remaining service life is a burdened expense to the vehicle owner and tends to compound for fleets with multiple CNG vehicles that likely have multiple CNG fuel tanks per vehicle. Removal and replacement of CNG tanks tend to be cost-prohibitive for fleets, sometimes resulting in utilization of CNG tanks beyond defined EOL.

1.2 Objective

Due to the continued use of CNG fuel tanks beyond their defined EOL, NREL initiated this study on behalf of the U.S. Department of Energy to investigate the integrity of CNG fuel tanks under routine operating conditions at the end of their defined useful life. These data will assist the industry to better identify, quantify, and alleviate the safety risks associated with CNG tanks in operation beyond their defined EOL, in addition to addressing barriers and opportunities related to CNG storage onboard vehicles.

2 Methodology

2.1 Subcontract Award

On July 1, 2016, NREL submitted a request for proposal number RGJ-6-62575-01 for characterization of CNG fuel tanks at the end of their defined service life. The winning subcontractor was responsible for identifying transit agencies or fleets that would be able to provide CNG fuel tanks at their defined EOL, provide a list of fuel tanks to be tested, provide a test plan for characterization of the fuel tanks to understand their structural integrity, conduct the testing, and produce a final report of the test results. On September 30, 2016, subcontract number AGJ-7-62575-01 was awarded to Digital Wave Corporation of Centennial, Colorado.

In October 2017, a work stop order was put in place due to unforeseen budget impacts. The subcontractor was not able to complete the defined test plan and paused the work in hopes of being able to continue once funding was available again. Approximately one year after work ceased, the contract was reinstated, and the subcontractor agreed to complete the testing with minimal changes to the originally defined test plan. Testing resumed in March 2019 and was complete per the contract deliverables in October 2019.

2.2 Characterization Approach

The physical durability of Type III and Type IV CNG fuel tanks from the Los Angeles (LA) County Metropolitan Transportation Authority were evaluated to characterize the fuel tank's structural integrity after experiencing a full service life of 15 years in transit bus application. In addition to the durability testing performed on the fuel tanks, modal acoustic emission (MAE), a nondestructive evaluation method, was utilized to assess the structural integrity of the tanks where the results were then compared to visual inspection results.

A total of 101 CNG fuel tanks at the end of their defined useful life were provided by the LA Metro Transportation Authority. Fifty tanks were Type III cylinders and 51 were Type IV cylinders. Each tank was used in transit bus applications, where they were stored onboard in covered housing. The exact service history of each fuel tank was unknown. However, each tank was estimated to have been cycled from 1,000 to 4,400 pounds per square inch gauge (psig), 6 times per week for 15 years, resulting in an estimated total of 4,680 fatigue cycles over the useful life of each tank. A total sample size of 60 tanks—30 Type III and 30 Type IV—were subjected to testing. Ten tanks of each design type were concluded to be statistically significant for EOL burst pressurization and hydraulic fatigue cycling as defined by the subcontractor, and the number of tanks subjected to artificial damage provided a single replicate of each design type for sample control.

Once selected at random for testing, all 60 CNG fuel tanks were visually inspected according to the U.S. fuel system inspection standard Compressed Gas Association (CGA) C-6.4, and CGA C-6.2 if the tank was a Type III cylinder. All tanks were then examined by MAE to further assess the structural integrity before testing. Twenty of the tanks, 10 Type III and 10 Type IV, were pressurized until burst according to NGV2 to establish a baseline understanding of the tank's structural integrity at the defined EOL, in their as received condition. Table 1 summarizes the tests conducted on the tanks as received from LA Metro Transportation Authority.

Table 1. Summary of Tests Conducted on Tanks as Received from LA Metro

Tank Count	Design Type	Serial Number	Manufacture Date	Visual & MAE Inspection	Artificial Damage	Burst Pressure
1	III	ALT810N-2565	Nov. 2001	YES	NO	YES
2	III	ALT810N-3991	March 2002	YES	NO	YES
3	III	ALT810N-3993	March 2002	YES	NO	YES
4	III	ALT810N-1976	Sept. 2001	YES	NO	YES
5	III	ALT810N-2099	Oct. 2001	YES	NO	YES
6	III	ALT810N-2107	Oct. 2001	YES	NO	YES
7	III	ALT810N-3858	March 2002	YES	NO	YES
8	III	ALT810N-3884	March 2002	YES	NO	YES
9	III	ALT810N-4049	March 2002	YES	NO	YES
10	III	ALT810N-2189	Oct. 2001	YES	NO	YES
11	IV	314-051	Oct. 2000	YES	NO	YES
12	IV	314-144	Oct. 2000	YES	NO	YES
13	IV	316-007	Oct. 2000	YES	NO	YES
14	IV	319-037	Oct. 2000	YES	NO	YES
15	IV	305-163	Aug. 2000	YES	NO	YES
16	IV	309-181	Aug. 2000	YES	NO	YES
17	IV	314-050	Oct. 2000	YES	NO	YES
18	IV	309-026	Aug. 2000	YES	NO	YES
19	IV	305-160	Aug. 2000	YES	NO	YES
20	IV	319-012	Oct. 2000	YES	NO	YES

An additional 20 tanks were then subjected to artificial damage via notch and impact procedures followed by hydraulic fatigue cycling and burst pressure tests to understand the tank's structural integrity at the defined EOL in comparison to the NGV2 design and performance standard. The test procedure used to inflict notch damage was defined in Section A.17 of International Organization for Standardization (ISO) 11439 (ISO 2000) and the test procedure to inflict impact damage was done according to Section A.20 of ISO 11439 with additional modifications to increase the severity of the impact damage to better represent risks from in-service operating conditions. After artificial damage, some tanks were then additionally cycled per hydraulic fatigue cycling defined in Sections A.17 and A.20 of ISO 11439. Finally, all 20 of the artificially damaged tanks were burst-tested according to NGV2. The tests conducted on the artificially damaged and additionally cycled tanks are summarized in Table 2 and Table 3.

Table 2. Summary of Tests Conducted on Artificially Damaged Type III CNG Fuel Tanks

Tank Count	Serial Number	Pre-Damage Visual & MAE Inspection	Artificial Damage Type	Hydraulic Fatigue Cycling	Post-Damage Visual & MAE Inspection	Post-Damage Burst Testing
1	ALT810N-3324	YES	Impact	NO	YES	YES
2	ALT810N-2188	YES	Impact	YES	YES	YES
3	ALT810N-4105	YES	Localized Impact	NO	YES	YES
4	ALT810N-2562	YES	Localized Impact	YES	YES	YES
5	ALT810N-2191	YES	Localized Impact at Double Height	NO	YES	YES
6	ALT810N-2104	YES	Localized Impact at Double Height	YES	YES	YES
7	ALT810N-3651	YES	Notched	NO	YES	YES
8	ALT810N-3742	YES	Notched	NO	YES	YES
9	ALT810N-1995	YES	Notched	YES	YES	YES
10	ALT810N-2744	YES	Notched	YES	YES	YES

Table 3. Summary of Tests Conducted on Artificially Damaged Type IV CNG Fuel Tanks

Tank Count	Serial Number	Pre-Damage Visual & MAE Inspection	Artificial Damage Type	Hydraulic Fatigue Cycling	Post-damage Visual & MAE Inspection	Post-Damage Burst Testing
1	309-022	YES	Impact	NO	YES	YES
2	305-164	YES	Impact	YES	YES	YES
3	305-159	YES	Localized Impact	NO	YES	YES
4	319-001	YES	Localized Impact	YES	YES	YES
5	309-023	YES	Localized Impact at Double Height	NO	YES	YES
6	313-047	YES	Localized Impact at Double Height	YES	YES	YES
7	319-006	YES	Notched	NO	YES	YES
8	316-008	YES	Notched	NO	YES	YES
9	316-014	YES	Notched	YES	YES	YES
10	309-117	YES	Notched	YES	YES	YES

Another 20 tanks were subjected to hydraulic fatigue cycling followed by a burst pressurization test to simulate continued use of the tanks beyond their defined EOL and understand the tank's structural integrity in comparison to NGV2 design and performance standard for tank burst requirement at the time of manufacture. The hydraulic fatigue cycling consisted of a total of 18,000 cycles per FMVSS No. 304 to simulate approximately 24 years of additional service, assuming 750 fills per year. Two of the tanks that were hydraulically fatigued were also leak-tested according to NGV2 before being burst-tested. Table 4 is a summary of the tests conducted on the tanks that were hydraulically fatigued.

Table 4. Summary of Tests Conducted on Hydraulically Fatigued Tanks

Tank Count	Design Type	Serial Number	Manufacture Date	Initial Visual & MAE Inspection	Artificial Damage	Hydraulic Fatigue Cycled	Post-Cycling Visual & MAE Inspect-ion	Burst Pressure	Leak Tested
1	III	ALT810 N-3653	Feb. 2002	YES	NO	YES	YES	YES	NO
2	III	ALT810 N-2351	Oct. 2001	YES	NO	YES	YES	YES	YES
3	III	ALT810 N-3733	March 2002	YES	NO	YES	YES	YES	NO
4	III	ALT810 N-2353	Oct. 2001	YES	NO	YES	YES	YES	NO
5	III	ALT810 N-2740	Dec. 2001	YES	NO	YES	YES	YES	NO
6	III	ALT810 N-2403	Oct. 2001	YES	NO	YES	YES	YES	NO
7	III	ALT810 N-3735	March 2002	YES	NO	YES	YES	YES	NO
8	III	ALT810 N-3323	Feb. 2002	YES	NO	YES	YES	YES	NO
9	III	ALT810 N-2996	Dec. 2001	YES	NO	YES	YES	YES	NO
10	III	ALT810 N-3326	Feb. 2002	YES	NO	YES	YES	YES	NO
11	IV	313-063	Oct. 2000	YES	NO	YES	YES	YES	NO
12	IV	309-032	Aug. 2000	YES	NO	YES	YES	YES	NO
13	IV	319-020	Oct. 2000	YES	NO	YES	YES	YES	NO
14	IV	313-046	Sept. 2000	YES	NO	YES	YES	YES	NO
15	IV	309-025	Aug. 2000	YES	NO	YES	YES	YES	NO
16	IV	309-186	Aug. 2000	YES	NO	YES	YES	YES	YES
17	IV	313-045	Sept. 2000	YES	NO	YES	YES	YES	NO

Tank Count	Design Type	Serial Number	Manufacture Date	Initial Visual & MAE Inspection	Artificial Damage	Hydraulic Fatigue Cycled	Post-Cycling Visual & MAE Inspect-ion	Burst Pressure	Leak Tested
18	IV	319-007	Oct. 2000	YES	NO	YES	YES	YES	NO
19	IV	319-051	Oct. 2000	YES	NO	YES	YES	YES	NO
20	IV	314-048	Oct. 2000	YES	NO	YES	YES	YES	NO

3 Test Procedures

This section summarizes the test procedures conducted on the 60 CNG fuel tanks for EOL characterization.

3.1 Visual Inspection

Prior to any testing, all 60 CNG fuel tanks were visually inspected according to CGA C-6.4 and CGA C-6.2 if the tank was a Type III cylinder. The fuel system inspection standard in the United States utilized by the CNG fuel vehicle industry is CGA C-6.4. It provides guidance on assessing the fuel storage containers (fuel tanks) for dents, dings, cuts, gouges, and scrapes, and other such damage, as well as signs of leakage of the fuel tanks or compromised cap, valve, cover, shield, regulator, lines, filtration, brackets, and mounting components. The visual inspection is typically conducted while the fuel tank remains mounted on the vehicle, where cameras and/or mirrors may be used as tools for the inspection. A qualified CNG fuel system inspector typically conducts the visual inspection of the CNG fuel system once per year, as required by FMVSS No. 304, as well as before the CNG vehicle is placed in service and after any thermal event or accident. CGA C-6.2 standard addresses the techniques for visual inspection and requalification of composite overwrapped high-pressure cylinders and provides guidance on internal visual inspection of liners specific to Type III cylinders that is not covered in CGA C-6.4.

3.2 Modal Acoustic Emission

All 60 CNG fuel tanks were inspected by MAE examination both before and after artificial damage and hydraulic fatigue cycling. Criteria for the MAE acceptance or rejection of the fuel tanks were defined by ISO Technical Standard 19016 and U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) standard "Modal Acoustic Emission (MAE) Examination Specification for Requalification of Composite Overwrapped Pressure Vessels (cylinders and tubes)." During MAE examination, the tanks were pressurized to a defined schedule and piezoelectric sensors were attached to the external surface of the tank, where they passively detected stress waves emanating from a given damage mechanism. Figure 1 illustrates the sensor location for both Type III and Type IV cylinders during MAE examination.

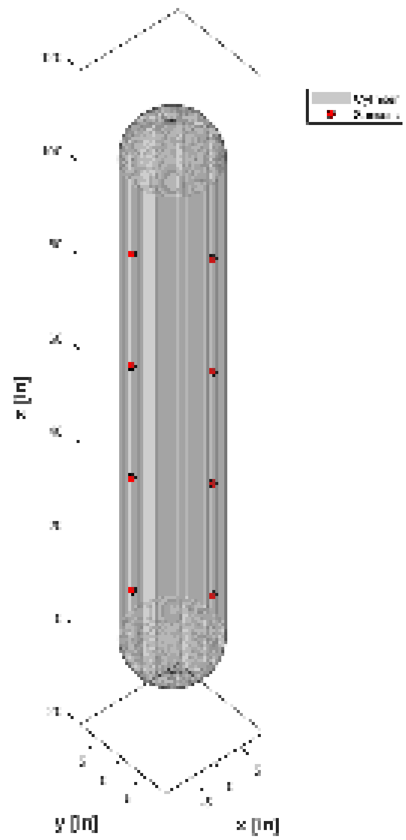

Figure 1. Sensor position diagram during MAE examination

Frequency and damage mechanics analyses were conducted to determine the type of damage, as well as the significance of the damage to the structural integrity of the tank. For this study, a Digital Wave Corporation digital module system was used to capture the stress waveforms and facilitate the MAE examination.

Figure 2 illustrates the pressure schedule used to perform the MAE examination on all the CNG tanks that underwent inspection. All tanks had a defined service pressure of 3,600 psig. Therefore, 4,700 psig was the pressure level for the 130% hold, and 5,400 psig was the pressure level for the holds at 150%.

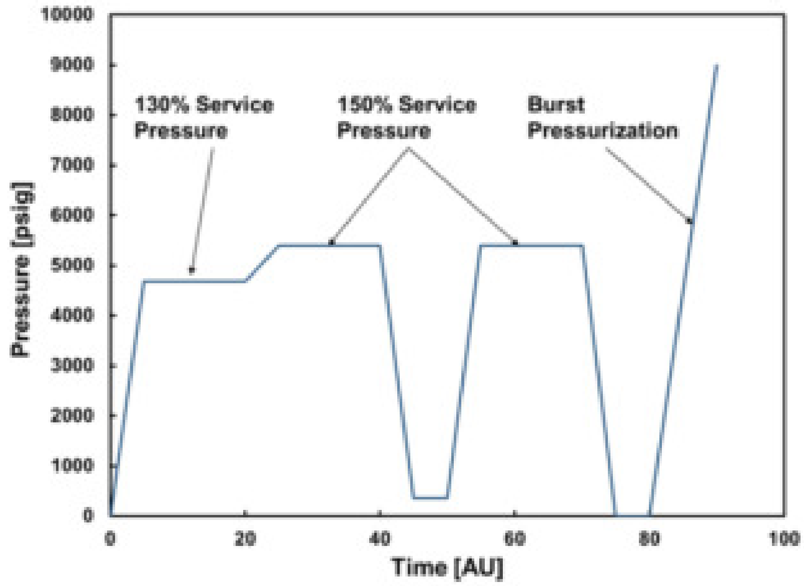

Figure 2. Pressure schedule for MAE examination followed by burst pressurization

3.3 Burst Pressurization

Twenty CNG tanks—10 Type III and 10 Type IV—were randomly sampled from the total population of 101 tanks for EOL burst pressurization testing. Prior to burst testing, all tanks were visually inspected per CGA C-6.2 and CGA C-6.4, where all tanks passed according to the acceptance criteria.

A 20,000-psig full-scale pressure transducer was used to monitor the tank's pressure during testing. The pressure transducer was connected at the end of the tank, opposite the hydraulic pump, to avoid "pressure hammering" from the hydraulic pump and to achieve a clear pressure signal. The cylinders were hydrostatically pressurized until burst, where the minimum burst pressure requirement of 8,100 psig from NGV2 was referenced as the acceptance criteria.

3.4 Artificial Damage by Notching

Eight of 20 artificially damaged tanks were notched before pressurized until burst. Two notches were imposed along the axial direction of four Type III cylinders and four Type IV cylinders according to Section A.17 of ISO 11439. One notch was shorter in length with a deeper depth, and the second notch was longer in length with a shallower depth. The shorter notch was 1.0 inch long and 0.05 inches deep, whereas the longer notch was 8.0 inches long and 0.03 inches deep, as show in Figure 3.

Figure 3. (a) Representative short notch with deep depth and (b) representative long notch with shallow depth

3.5 Artificial Damage by Impact

Twelve of the 20 CNG fuel tanks were artificially damaged through horizontal impact events as defined in Section A.20 of ISO 11439. Four of the tanks—two Type III cylinders and two Type IV cylinders—were subjected to impact damage as specified in the test procedure by dropping the tanks from the specified height onto a flat concrete surface. In order to represent a worst-case scenario of real-world failure modes of impact damage experienced by CNG fuel tanks in service, the remaining cylinders were dropped onto a modified surface from an adjusted height from that defined in the test procedure. Two Type III and two Type IV fuel tanks were dropped onto a 4 in. x 6 in. x 36 in. piece of angled steel located on the ground at the impact location. The angled steel localized the impact onto the tank to increase the severity of the damage. Another two additional Type III and two Type IV fuel tanks were dropped from twice the defined height onto a 4 × 6 × 36-in. piece of angled steel located on the ground at the impact location, as the increased height from which the tanks were dropped doubled the amount of potential energy of the impact event. These modified test conditions were a better representation of severe damage inflicted onto CNG fuel tanks in actual operating environments. Figure 4 depicts a time lapse of the representative localized impact event onto the steel angle iron.

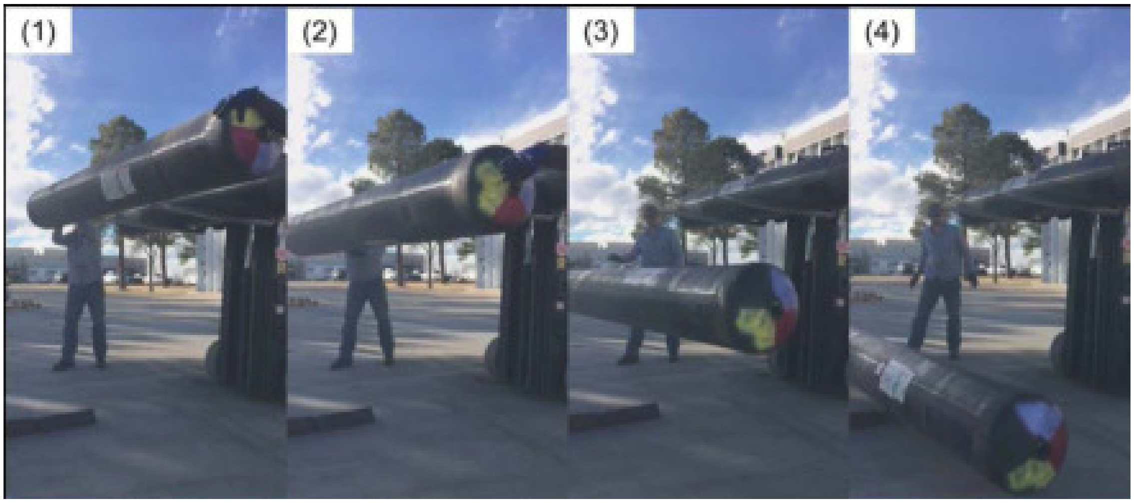

Figure 4. (1) Tank at testing height; (2) drop initiation of the tank; (3) tank dropping; (4) impact of the tank onto the steel angle iron

3.6 Hydraulic Fatigue Cycling

Hydraulic fatigue cycling was conducted in order to simulate extended service life for the CNG fuel tanks. Two different methods were used for hydraulic fatigue cycling: the internationally recognized design standard ISO 11439 (ISO 2000) for the 10 tanks that had been artificially damaged, and U.S. FMVSS No. 304 for the 20 tanks that were cycled as received from LA Metro Transportation Authority. The method defined in ISO 11439 was used for the artificially damaged tanks in continuation of the notching and impact protocols, as FMVSS No. 304 does not include requirements for impact or notch tolerance testing.

In order to monitor the mechanical stiffness during hydraulic fatigue cycle testing according to both test methods and to quantify the total accumulated microstructural damage of the tanks, the subcontractor defined and calculated a damage parameter. The details of these methods and the damage parameter are further described in the following sections.

3.6.1 ISO 11439 Fatigue Cycle Method

Following artificial damage procedures of notch and impact events, 10 of the 20 damaged tanks were subjected to hydraulic fatigue cycling according to the requirements of Sections A.17 and A.20 of ISO 11439. These tanks were hydraulically pressurized from a minimum of 10% of defined service pressure (360 psig) to a maximum of 105% of defined service pressure (a high pressure set point of 3,780 psig). This fatigue cycling consisted of a total of 15,000 cycles at a rate of approximately 0.007 Hz. Figure 5 illustrates the measured pressure trace of four of these representative fatigue cycles.

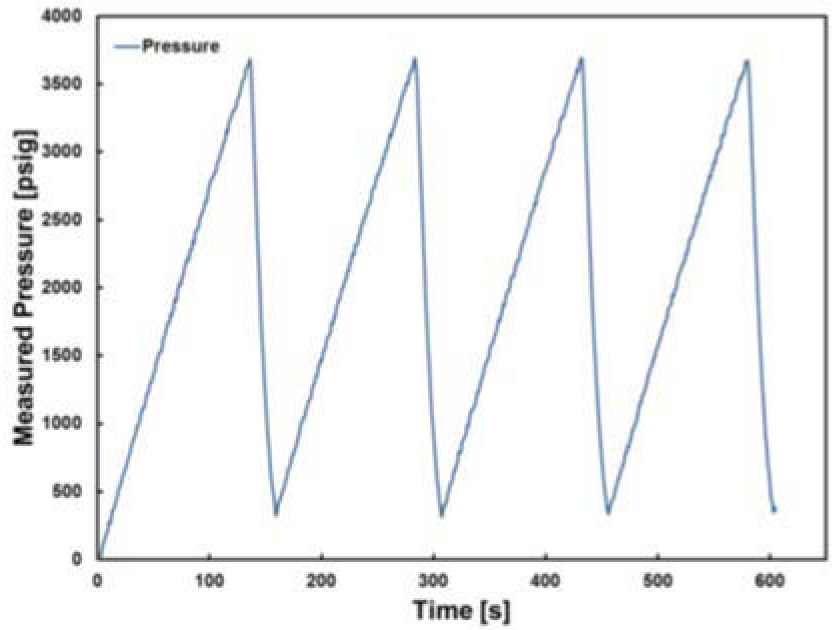

Figure 5. Pressure trace of four fatigue cycles

The total 15,000 cycles simulated approximately 20 years of additional service, assuming 750 fills per year. Every 2,250th cycle, representative of 3 years of service life, an overload fatigue cycle to 150% of service pressure (resulting in 5,400 psig, representative of a test pressure cycle) was placed on the cylinders to represent real-world periodic pressurization inspection of the tank to test pressure.

3.6.2 FMVSS No. 304 Pressure Cycle Method

The 20 tanks that were subjected to hydraulic fatigue cycling followed by a burst test to simulate continued use of the tanks beyond their defined EOL were pressure cycled according to Section 8.1.1 of FMVSS No. 304 (e-CFR 2020).

Each tank was subjected to 13,000 fatigue cycles from a service pressure of 3,600 psig to a maximum of 10% of the service pressure (resulting in 360 psig). Every 2,250th cycle, representative of 3 years of service life, an overload fatigue cycle to 150% of service pressure (resulting in 5,400 psig, representative of a test pressure cycle) was introduced to represent a periodic pressurization inspection. After the 13,000 cycles to service pressure, including the overload cycle, the tanks were subjected to 5,000 cycles of 125% of service pressure to a maximum of 10% of the service pressure (resulting in 360 psig). These 5,000 cycles included two overload cycles every 2,250 cycles. Figure 6 illustrates the pressure trace of these fatigue cycles.

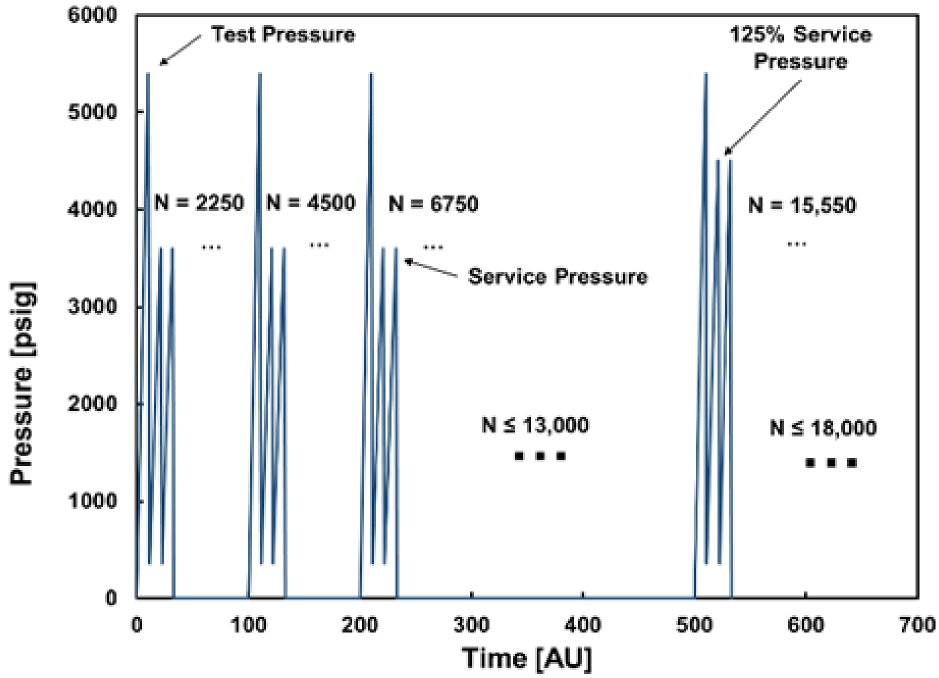

Figure 6. Fatigue test protocol

3.6.3 Damage Parameter

In order to monitor the mechanical stiffness during hydraulic fatigue cycle testing and to quantify the total accumulated microstructural damage of the tanks, the subcontractor defined and calculated a damage parameter. Strains from two gauges were attached to each tank, one oriented axially and one oriented in the hoop direction. These measured forces from each strain gage were used to calculate and monitor the damage parameter, *D*, for the tanks:

$$D = E_i/E_0 \quad (1)$$

D = damage parameter
E_i = the measured modulus from a given channel on the i^{th} cycle
E_0 = the measured modulus from a given strain channel on the initial fatigue cycle.

A damage parameter value of one or greater indicated that the tank was not accumulating gross microstructural damage and therefore was not experiencing any degradation of the tank stiffness. A damage parameter value of less than one indicated that the tank was losing mechanical stiffness during the hydraulic fatigue cycle testing and accumulating gross microstructural damage. The damage parameter was further analyzed to determine the damage mechanism and assess the structural durability of the cylinder.

3.7 Leak Test

One randomly selected Type III and Type IV tank was subjected to a leak test after hydraulic fatigue cycling according to CGA C-6.4 (CGA 2012). The leak test was conducted to determine if the liner of the tanks had been damaged, which would have resulted in degraded structural integrity of the tank. Both tanks passed the leak test according to the acceptance criteria and were not deemed as damaged from additional hydraulic fatigue cycling of the defined 18,000 cycles.

4 Test Results

This section summarizes the results from each of the test procedures conducted on the CNG fuel tanks for EOL characterization.

4.1 Visual Inspection Results

All 60 CNG fuel tanks were visually inspected per CGA C-6.2 and CGA C-6.4 if Type III. The visual inspection was conducted on the tanks as they were received, before any testing, as well as a second time following artificial damage and hydraulic fatigue cycling. With the exception of the Type III tanks that experienced the localized impact event at double height, every tank passed the visual inspection, according to the defined criteria, both before and after testing. Table 5 and Table 6 summarize cylinder type, manufacture date, and inspection results for all tanks that were visually inspected.

Table 5. Summary of Visual Inspection Results of Type III CNG Fuel Tanks

Tank Count	Serial Number	Manufacture Date	Internal Visual Inspection	External Visual Inspection
1	ALT810N-3324	Feb. 2002	PASS	PASS
2	ALT810N-2188	Oct. 2001	PASS	PASS
3	ALT810N-4105	April 2002	PASS	PASS
4	ALT810N-2562	Oct. 2001	PASS	PASS
5	ALT810N-2191	Oct. 2001	FAIL	FAIL
6	ALT810N-2104	Oct. 2001	FAIL	FAIL
7	ALT810N-3651	Feb. 2002	PASS	PASS
8	ALT810N-3742	March 2002	PASS	PASS
9	ALT810N-1995	Sept. 2001	PASS	PASS
10	ALT810N-2744	Dec. 2001	PASS	PASS
11	ALT810N-3653	Feb. 2002	PASS	PASS
12	ALT810N-2351	Oct. 2001	PASS	PASS
13	ALT810N-3733	March 2002	PASS	PASS
14	ALT810N-2353	Oct. 2001	PASS	PASS
15	ALT810N-2740	Dec. 2001	PASS	PASS
16	ALT810N-2403	Oct. 2001	PASS	PASS
17	ALT810N-3735	March 2002	PASS	PASS
18	ALT810N-3323	Feb. 2002	PASS	PASS
19	ALT810N-2996	Dec. 2001	PASS	PASS
20	ALT810N-3326	Feb. 2002	PASS	PASS
21	ALT810N-2565	Nov. 2001	PASS	PASS
22	ALT810N-3991	March 2002	PASS	PASS
23	ALT810N-3993	March 2002	PASS	PASS

Tank Count	Serial Number	Manufacture Date	Internal Visual Inspection	External Visual Inspection
24	ALT810N-1976	Sept. 2001	PASS	PASS
25	ALT810N-2099	Oct. 2001	PASS	PASS
26	ALT810N-2107	Oct. 2001	PASS	PASS
27	ALT810N-3858	March 2002	PASS	PASS
28	ALT810N-3884	March 2002	PASS	PASS
29	ALT810N-4049	March 2002	PASS	PASS
30	ALT810N-2189	Oct. 2001	PASS	PASS

Table 6. Summary of Visual Inspection Results of Type IV CNG Fuel Tanks

Tank Count	Serial Number	Manufacture Date	Internal Visual Inspection	External Visual Inspection
1	313-063	Aug. 2000	PASS	PASS
2	309-032	Aug. 2000	PASS	PASS
3	319-020	Aug. 2000	PASS	PASS
4	313-046	Oct. 2000	PASS	PASS
5	309-025	Aug. 2000	PASS	PASS
6	309-186	Sept. 2000	PASS	PASS
7	313-045	Oct. 2000	PASS	PASS
8	319-007	Oct. 2000	PASS	PASS
9	319-051	Oct. 2000	PASS	PASS
10	314-048	Aug. 2000	PASS	PASS
11	309-022	Aug. 2000	PASS	PASS
12	305-164	Aug. 2000	PASS	PASS
13	305-159	Aug. 2000	PASS	PASS
14	319-001	Oct. 2000	PASS	PASS
15	309-023	Aug. 2000	PASS	PASS
16	313-047	Sept. 2000	PASS	PASS
17	319-006	Oct. 2000	PASS	PASS
18	316-008	Oct. 2000	PASS	PASS
19	316-014	Oct. 2000	PASS	PASS
20	309-117	Aug. 2000	PASS	PASS
21	314-051	Oct. 2000	PASS	PASS
22	314-144	Oct. 2000	PASS	PASS
23	316-007	Oct. 2000	PASS	PASS
24	319-037	Oct. 2000	PASS	PASS

Tank Count	Serial Number	Manufacture Date	Internal Visual Inspection	External Visual Inspection
25	305-163	Aug. 2000	PASS	PASS
26	309-181	Aug. 2000	PASS	PASS
27	314-050	Oct. 2000	PASS	PASS
28	309-026	Aug. 2000	PASS	PASS
29	305-160	Aug. 2000	PASS	PASS
30	319-012	Oct. 2000	PASS	PASS

4.2 Modal Acoustic Emission Results

All 60 CNG fuel tanks were subjected to MAE examination, where the criteria for the MAE acceptance or rejection were defined by ISO Technical Standard 19016 and PHMSA standard "Modal Acoustic Emission Examination Specification for Requalification of Composite Overwrapped Pressure Vessels (cylinders and tubes)" (U.S. DOT 2018) The nondestructive examination was conducted on the tanks as they were received, as well as a second time following artificial damage and hydraulic fatigue cycling.

4.2.1 Examination of Tanks in Received Condition

All MAE inspections of as-received tanks passed the examination according to the acceptance criteria. Table 7 and Table 8 summarize cylinder type, manufacture date, and MAE examination results for all tanks.

Table 7. Summary of MAE Examination Results of Type III CNG Fuel Tanks in Received Condition

Tank Count	Serial Number	Manufacture Date	MAE Acceptance (Pass/Fail)
1	ALT810N-3324	Feb. 2002	PASS
2	ALT810N-2188	Oct. 2001	PASS
3	ALT810N-4105	April 2002	PASS
4	ALT810N-2562	Oct. 2001	PASS
5	ALT810N-2191	Oct. 2001	PASS
6	ALT810N-2104	Oct. 2001	PASS
7	ALT810N-3651	Feb. 2002	PASS
8	ALT810N-3742	March 2002	PASS
9	ALT810N-1995	Sept. 2001	PASS
10	ALT810N-2744	Dec. 2001	PASS
11	ALT810N-3653	Feb. 2002	PASS
12	ALT810N-2351	Oct. 2001	PASS
13	ALT810N-3733	March 2002	PASS
14	ALT810N-2353	Oct. 2001	PASS
15	ALT810N-2740	Dec. 2001	PASS
16	ALT810N-2403	Oct. 2001	PASS

Tank Count	Serial Number	Manufacture Date	MAE Acceptance (Pass/Fail)
17	ALT810N-3735	March 2002	PASS
18	ALT810N-3323	Feb. 2002	PASS
19	ALT810N-2996	Dec. 2001	PASS
20	ALT810N-3326	Feb. 2002	PASS
21	ALT810N-2565	Nov. 2001	PASS
22	ALT810N-3991	March 2002	PASS
23	ALT810N-3993	March 2002	PASS
24	ALT810N-1976	Sept. 2001	PASS
25	ALT810N-2099	Oct. 2001	PASS
26	ALT810N-2107	Oct. 2001	PASS
27	ALT810N-3858	March 2002	PASS
28	ALT810N-3884	March 2002	PASS
29	ALT810N-4049	March 2002	PASS
30	ALT810N-2189	Oct. 2001	PASS

Table 8. Summary of MAE Examination Results of Type IV CNG Fuel Tanks in Received Condition

Tank Count	Serial Number	Manufacture Date	MAE Acceptance (Pass/Fail)
1	313-063	Aug. 2000	PASS
2	309-032	Aug. 2000	PASS
3	319-020	Aug. 2000	PASS
4	313-046	Oct. 2000	PASS
5	309-025	Aug. 2000	PASS
6	309-186	Sep. 2000	PASS
7	313-045	Oct. 2000	PASS
8	319-007	Oct. 2000	PASS
9	319-051	Oct. 2000	PASS
10	314-048	Aug. 2000	PASS
11	309-022	Aug. 2000	PASS
12	305-164	Aug. 2000	PASS
13	305-159	Aug. 2000	PASS
14	319-001	Oct. 2000	PASS
15	309-023	Aug. 2000	PASS
16	313-047	Sep. 2000	PASS
17	319-006	Oct. 2000	PASS
18	316-008	Oct. 2000	PASS

Tank Count	Serial Number	Manufacture Date	MAE Acceptance (Pass/Fail)
19	316-014	Oct. 2000	PASS
20	309-117	Aug. 2000	PASS
21	314-051	Oct. 2000	PASS
22	314-144	Oct. 2000	PASS
23	316-007	Oct. 2000	PASS
24	319-037	Oct. 2000	PASS
25	305-163	Aug. 2000	PASS
26	309-181	Aug. 2000	PASS
27	314-050	Oct. 2000	PASS
28	309-026	Aug. 2000	PASS
29	305-160	Aug. 2000	PASS
30	319-012	Oct. 2000	PASS

4.2.2 Examination of Tanks Following Notch Damage

After the eight tanks—four Type III and four Type IV—were artificially damaged via notching, they were subjected to MAE examination. None of the eight tanks passed the acceptance criteria and would have been denied for continued use. MAE examination confirmed that a stress concentrator had been introduced into each composite cylinder's microstructure and that the tank's burst strength was degraded as compared to an undamaged cylinder. A summary of the MAE examination results and the identified specific cause of rejection is shown in Table 9.

Table 9. Summary of MAE Results of Tanks Following Notch Damage

Tank Count	Design Type	Serial Number	Artificial Damage Type	Burst Pressure (psig)	Burst Pressure (Pass/Fail)	MAE Result (Pass/Fail)	MAE Rejection Cause
1	III	ALT810N-3651	Notched	10,510	Pass	Fail	BEO, FTF, FE
2	III	ALT810N-3742	Notched	10,655	Pass	Fail	FE
3	III	ALT810N-1995	Notched + Fatigue Cycled	9,830	Pass	Fail	BEO
4	III	ALT810N-3651	Notched + Fatigue Cycled	10,510	Pass	Fail	BEO, FE
5	IV	319-006	Notched	10,000	Pass	Fail	BEO, FE
6	IV	316-008	Notched	9,460	Pass	Fail	BEO, FE
7	IV	316-014	Notched + Fatigue Cycled	9,240	Pass	Fail	BEO, FE
8	IV	309-117	Notched + Fatigue Cycled	9,220	Pass	Fail	BEO, FTF

BEO: background energy oscillation
FTF: energy greater than the allowable for fiber tow fracture
FE: fretting emission energy violated

4.2.3 Examination of Tanks Following Impact Damage

After the 12 tanks (six Type III and six Type IV) were artificially damaged via impact, they were subjected to MAE examination per in Section A.20 of ISO 11439. MAE evaluation was conducted directly after the impact events, prior to additional fatigue or burst testing. Four Type III tanks passed the MAE examination: two with impact damage inflicted per ISO 11439 and two with localized impact damage as inflicted per the modified procedure with an angled steel iron. Two Type IV tanks passed the MAE examination, both with impact damage inflicted per ISO 11439. MAE examination confirmed that a stress concentrator had been introduced into the six other composite cylinder's microstructure and that the tank's burst strength was degraded as compared to an undamaged cylinder. The four Type III and two Type IV tanks that passed the MAE examination also passed the burst pressurization test. The fatigue and burst tests that followed the MAE examination of the impacted tanks confirmed that the MAE criteria were valid predictors of which tanks experienced degraded structural integrity and ultimately failed the following burst pressure test. A summary of the MAE examination results of the impacted tanks and the identified specific cause of rejection is shown in Table 10.

Table 10. Summary of MAE Results of Tanks Following Impact Damage

Tank Count	Design Type	Serial Number	Artificial Damage Type	Burst Pressure (psig)	Burst Pressure (Pass/Fail)	MAE Result (Pass/Fail)	MAE Rejection Cause
1	III	ALT810N-3324	Impact per ISO 11439	11,345	Pass	Pass	-
2	III	ALT810N-2188	Impact per ISO 11439 + Fatigue	10,220	Pass	Pass	-
3	III	ALT810N-4105	Localized Impact	9,625	Pass	Pass	-
4	III	ALT810N-2562	Localized Impact + Fatigue	8,700	Pass	Pass	-
5	III	ALT810N-2191	Localized Impact at Double Height	6,110	Fail	Fail	BEO, FE
6	III	ALT810N-2104	Localized Impact at Double Height + Fatigue	7,440	Fail	Fail	FTF, BEO, FE
7	IV	309-022	Impact per ISO 11439	10,215	Pass	Pass	-
8	IV	305-164	Impact per ISO 11439 + Fatigue	8,715	Pass	Pass	-
9	IV	305-159	Localized Impact	5,400	Fail	Fail	FTF, BEO, FE
10	IV	319-001	Localized Impact + Fatigue	5,400	Fail	Fail	FTF, BEO
11	IV	309-023	Localized Impact at Double Height	6,160	Fail	Fail	BEO
12	IV	313-047	Localized Impact at Double Height + Fatigue	7,160	Fail	Fail	FTF, BEO

BEO: background energy oscillation
FTF: energy greater than the allowable for fiber tow fracture
FE: fretting emission energy violated

4.3 Burst Pressurization Results of As-Received Tanks

After visual inspection and MAE examination, 20 tanks—10 Type III and 10 Type IV—were subjected to hydraulic burst pressurization according to NGV2 to establish a baseline understanding of the tank's structural integrity at the end of its 15 year life in comparison to NGV2 design and performance standard. Burst strength distributions for both tank design types, of all 20 tanks, revealed that each maintained the initial design strength required at time of manufacturing. Table 11 outlines the burst pressure test results of tanks as received from LA Metro Transportation Authority.

Table 11. Summary of Initial Burst Pressure Testing Results

Tank Count	Design Type	Serial Number	Manufacture Date	Visual Inspection (Pass/Fail)	MAE Acceptance (Pass/Fail)	Burst Pressure (Pass/Fail)	Burst Pressure (psig)
1	III	ALT810N-2565	Nov. 2001	PASS	PASS	PASS	10,780
2	III	ALT810N-3991	March 2002	PASS	PASS	PASS	10,870
3	III	ALT810N-3993	March 2002	PASS	PASS	PASS	10,560
4	III	ALT810N-1976	Sept. 2001	PASS	PASS	PASS	11,110
5	III	ALT810N-2099	Oct. 2001	PASS	PASS	PASS	10,560
6	III	ALT810N-2107	Oct. 2001	PASS	PASS	PASS	10,460
7	III	ALT810N-3858	March 2002	PASS	PASS	PASS	11,150
8	III	ALT810N-3884	March 2002	PASS	PASS	PASS	10,700
9	III	ALT810N-4049	March 2002	PASS	PASS	PASS	10,780
10	III	ALT810N-2189	Oct. 2001	PASS	PASS	PASS	10,490
11	IV	314-051	Oct. 2000	PASS	PASS	PASS	10,430
12	IV	314-144	Oct. 2000	PASS	PASS	PASS	10,690
13	IV	316-007	Oct. 2000	PASS	PASS	PASS	10,460
14	IV	319-037	Oct. 2000	PASS	PASS	PASS	10,300
15	IV	305-163	Aug. 2000	PASS	PASS	PASS	10,070
16	IV	309-181	Aug. 2000	PASS	PASS	PASS	10,110
17	IV	314-050	Oct. 2000	PASS	PASS	PASS	10,230
18	IV	309-026	Aug. 2000	PASS	PASS	PASS	10,050
19	IV	305-160	Aug. 2000	PASS	PASS	PASS	N/A
20	IV	319-012	Oct. 2000	PASS	PASS	PASS	N/A

4.4 Artificially Damaged Tanks Tolerance Results

This section summarizes the test results of hydraulic fatigue cycling, leak test, and burst pressurization of the 20 tanks subjected to artificial damage via notch and impact events.

4.4.1 Hydraulic Fatigue Cycling of Notched Tanks

Of the four Type III and four Type IV CNG fuel tanks subjected to notch tolerance testing defined in ISO 11439, two of each tank design type were subjected to MAE examination followed by hydraulic fatigue cycle testing for 15,000 cycles per ISO 11439, concluded by EOL burst pressurization test. MAE results successfully detected a stress concentrator that existed in the microstructure of the cylinder after the notch procedure. All four tanks that were hydraulically fatigue cycled did not experience degradation of the tank's stiffness according to the monitored damage parameter of accumulated gross microstructural damage. Table 12 summarizes these results.

Table 12. Hydraulic Fatigue Cycling Test Results of Notched Tanks

Tank Count	Design Type	Serial Number	Artificial Damage Type	Post-Damage MAE Examination (Pass/Fail)	15,000 Fatigue Cycles (Pass/Fail)
1	III	ALT810N-1995	Notched + Fatigue Cycled	PASS	PASS
2	III	ALT810N-2744	Notched + Fatigue Cycled	PASS	PASS
3	IV	316-014	Notched + Fatigue Cycled	PASS	PASS
4	IV	309-117	Notched + Fatigue Cycled	PASS	PASS

The subcontractor estimated that the simulated additional 20 years of service via hydraulic fatigue cycling, when assuming 750 fills per year, reduced the residual burst strength by 7% of Type III tanks and by 5% of Type IV tanks when compared to the notched tanks not subjected to additional fatigue cycles. These results suggest that the tanks had additional service life remaining beyond the defined EOL following the artificial damage by notching.

4.4.2 Burst Pressurization of Notched Tanks

All eight CNG fuel tanks subjected to notch damage, including the four that were hydraulic fatigue cycled per ISO 11439, underwent EOL burst pressurization as defined in NGV2. All eight tanks met the burst pressure minimum of 8,100 psig, the same requirement for CNG fuel tanks at the time of manufacture. These burst pressure test results are summarized in Table 13.

Table 13. Burst Pressure Test Results of Notched Tanks

Tank Count	Design Type	Serial Number	Artificial Damage Type	Post-Notch MAE Examination (Pass/Fail)	Burst Pressure (psig)	Burst Pressure Met (Pass/Fail)
1	III	ALT810N-3651	Notched	PASS	10,510	PASS
2	III	ALT810N-3742	Notched	PASS	10,655	PASS
3	III	ALT810N-1995	Notched + Fatigue Cycled	PASS	9,830	PASS
4	III	ALT810N-2744	Notched + Fatigue Cycled	PASS	9,860	PASS
5	IV	319-006	Notched	PASS	10,000	PASS
6	IV	316-008	Notched	PASS	9,460	PASS
7	IV	316-014	Notched + Fatigue Cycled	PASS	9,240	PASS
8	IV	309-117	Notched + Fatigue Cycled	PASS	9,220	PASS

4.4.3 Hydraulic Fatigue Cycling of Impacted Tanks

Of the 12 tanks subjected to impact damage, two Type III and two Type IV CNG fuel tanks were damaged by impact as defined in ISO 11439. A total of two tanks, one of each design type, were then hydraulically fatigued, followed by the EOL burst pressurization test. Both tanks were subjected to 15,000 cycles as previously defined and did not experience degradation of the tank's stiffness according to the monitored damage parameter of accumulated gross microstructural damage.

Eight of the remaining tanks—four Type III and four Type IV—were subjected to a localized impact event of the cylinder sidewall, a modified impact event to ISO 11439, where two tanks of each design type were then subjected to MAE examination followed by hydraulic fatigue cycle testing for 15,000 cycles to 105% of service pressure. All four tanks were subjected to 15,000 cycles as previously defined and did not experience degradation of the tank's stiffness according to the monitored damage parameter of accumulated gross microstructural damage. These results suggest that the tanks had additional service life of approximately 20 years remaining beyond the defined EOL following the artificial damage by impact. Table 14 summarizes results of all six tanks that were fatigue-cycled following impact events.

Table 14. Fatigue Cycling Test Results of Impacted Tanks

Tank Count	Design Type	Serial Number	Artificial Damage Type	Post Fatigue MAE Result (Pass/Fail)	15,000 Fatigue Cycles (Pass/Fail)
1	III	ALT810N-2188	Impact per ISO 11439 + Fatigue	Pass	Pass
2	III	ALT810N-2562	Localized Impact + Fatigue	Pass	Pass
3	III	ALT810N-2104	Localized Impact at Double Height + Fatigue	Fail	Pass
4	IV	305-164	Impact per ISO 11439 + Fatigue	Pass	Pass
5	IV	319-001	Localized Impact + Fatigue	Fail	Pass
6	IV	313-047	Localized Impact at Double Height + Fatigue	Fail	Pass

4.4.4 Burst Pressurization of Impacted Tanks

Of the 12 tanks subjected to impact damage, two Type III and two Type IV CNG fuel tanks were subjected to impact damage as defined in ISO 11439, followed by the EOL burst pressurization test. All four tanks met the minimum required burst strength according to the acceptance criteria defined in NGV2 of 8,100 psig.

The remaining eight tanks, four Type III and four Type IV were subjected to a modified localized impact event on the cylinder sidewall. Two tanks of each design type from this sample of eight were then subjected to MAE examination, followed by hydraulic fatigue cycle testing and burst pressurization. The remaining four tanks were only exposed to burst pressurization after the impact events.

The visual inspection of the tanks following the impact events revealed that only the two Type III cylinders subjected to the highest energy impact event exhibited visual indications, and did not meet the acceptance criteria. The other four Type III cylinders did not exhibit any visual indications. Of further significance, none of the six Type IV cylinders had visual damage that did not meet acceptance criteria, even though the burst strength had been significantly compromised in some instances.

The four tanks—two Type III and two Type IV—subjected to the standard impact event defined in ISO 11439 passed the minimum required burst pressure of 8,100 psig after being damaged and/or fatigue cycled. The two Type III tanks subjected to the modified procedure of localized impact events also met the minimum required burst pressure after damage and/or fatigue cycling. However, the two Type IV tanks subjected to the modified procedure of localized impact events did not meet the minimum burst strength requirement of 8,100 psig. All four tanks—two Type III and two Type IV tanks—subjected to the modified procedure with a doubled drop height failed to meet the minimum required burst strength. Therefore, the higher energy impact from local impact events drastically reduced the burst strength performance of both design types of cylinders, especially Type IV. Table 15 summarizes results of all 12 tanks that were pressurized until burst following impact events and fatigue cycling.

Table 15. Burst Pressure Test Results of Impacted Tanks

Tank Count	Design Type	Serial Number	Artificial Damage Type	Burst Pressure (psig)	Burst Pressure (Pass/Fail)	MAE Result (Pass/Fail)	MAE Rejection Cause
1	III	ALT810N-3324	Impact per ISO 11439	11,345	Pass	Pass	-
2	III	ALT810N-2188	Impact per ISO 11439 + Fatigue	10,220	Pass	Pass	-
3	III	ALT810N-4105	Localized Impact	9,625	Pass	Pass	-
4	III	ALT810N-2562	Localized Impact + Fatigue	8,700	Pass	Pass	-
5	III	ALT810N-2191	Localized Impact at Double Height	6,110	Fail	Fail	BEO, FE
6	III	ALT810N-2104	Localized Impact at Double Height + Fatigue	7,440	Fail	Fail	FTF, BEO, FE
7	IV	309-022	Impact per ISO 11439	10,215	Pass	Pass	-
8	IV	305-164	Impact per ISO 11439 + Fatigue	8,715	Pass	Pass	-
9	IV	305-159	Localized Impact	5,400	Fail	Fail	FTF, BEO, FE
10	IV	319-001	Localized Impact + Fatigue	5,400	Fail	Fail	FTF, BEO
11	IV	309-023	Localized Impact at Double Height	6,160	Fail	Fail	BEO
12	IV	313-047	Localized Impact at Double Height + Fatigue	7,160	Fail	Fail	FTF, BEO

BEO: background energy oscillation
FTF: energy greater than the allowable for fiber tow fracture
FE: fretting emission energy violated

4.5 Hydraulic Fatigue Cycling Results

Of the 20 tanks subjected to hydraulic fatigue cycling per FMVSS No. 304, all 20 successfully completed the additional 18,000 cycles simulating 20 years of continued service. Two of these

20 tanks that were hydraulically fatigued were also leak-tested according to NGV2. Each of the 20 tanks was then subjected to a burst pressurization test, where they all exceeded the minimum burst pressure requirement of 8,100 psig. Table 16 summarizes the tests conducted on the tanks that were hydraulically fatigued.

Table 16. Results of Tanks Hydraulically Fatigued Without Additional Damage

Tank Count	Design Type	Serial Number	Manufacture Date	Hydraulic Fatigued (cycles)	Burst Pressure (psig)	Burst Pressure Met (Pass/Fail)
1	III	ALT810N-3653	Feb. 2002	15,000	10,720	PASS
2	III	ALT810N-2351	Oct. 2001	15,000	LEAK TESTED	NA
3	III	ALT810N-3733	March 2002	15,000	10,800	PASS
4	III	ALT810N-2353	Oct. 2001	15,000	10,120	PASS
5	III	ALT810N-2740	Dec. 2001	15,000	10,620	PASS
6	III	ALT810N-3735	March 2002	15,000	10,380	PASS
7	III	ALT810N-3323	Feb. 2002	15,000	11,010	PASS
8	III	ALT810N-2996	Dec. 2001	15,000	11,130	PASS
9	III	ALT810N-3326	Feb. 2002	15,000	11,150	PASS
10	III	ALT810N-2403	Oct. 2001	15,000	10,610	PASS
11	IV	313-063	Oct. 2000	15,000	9,750	PASS
12	IV	309-032	Aug. 2000	15,000	9,830	PASS
13	IV	319-020	Oct. 2000	15,000	10,150	PASS
14	IV	313-046	Sept. 2000	15,000	10,100	PASS
15	IV	309-025	Aug. 2000	15,000	10,360	PASS
16	IV	309-186	Aug. 2000	15,000	10,100	PASS
17	IV	313-045	Sept. 2000	15,000	LEAK TESTED	NA
18	IV	319-007	Oct. 2000	15,000	10,070	PASS
19	IV	319-051	Oct. 2000	15,000	10,740	PASS
20	IV	314-048	Oct. 2000	15,000	9,310[a]	PASS

[a] The burst pressure for S/N 314-048 was not considered valid for distribution determination due to a mechanical pump failure resulting in a mixed mode burst/static fatigue failure as the cause of failure.

4.6 Leak Test

Both tanks, one Type III and one Type IV, did not display any signs of leak according to CGA C-6.4 and passed the test according to the defined criteria after being fatigue cycled according to FMVSS No. 304.

Table 17. Summary of Leak Test Results

Tank Count	Tank Type	Serial Number	Manufacture Date	Hydraulic Fatigue (cycles)	Visual Inspection
1	III	ALT810N-2351	Oct. 2001	18,000	PASS
2	IV	314-045	Sept. 2000	18,000	PASS

Each tank met the acceptance criteria defined in CGA C-6.4 confirming that the additional simulated service life from 18,000 cycles did not cause degradation of the tank resulting in a leak failure mode.

5 Conclusion

All 60 CNG fuel tanks that were visually inspected once received from the LA Metro Transportation Authority passed per CGA C-6.2 and CGA C-6.4. They also passed the MAE examination according to ISO Technical Standard 19016 and PHMSA standard "Modal Acoustic Emission Examination Specification for Requalification of Composite Overwrapped Pressure Vessels (cylinders and tubes)." The 60 tanks were all beyond their defined useful life of 15 years but seemed to be structurally sound based on the results of the initial visual inspection and MAE examination.

The 20 tanks—10 Type III and 10 Type IV—subjected to hydraulic burst pressurization to establish a baseline understanding of the tank's structural integrity at the end of their 15 year life according to NGV2 design and performance standard all exceeded the minimum burst strength requirement. These results indicate that the tanks maintained the required strength for burst pressurization at the time of manufacture and did not experience any significant strength degradation during their use in service.

Visual inspections did not effectively identify tanks with compromised structural integrity. Ten of the 12 tanks subjected to artificial damage passed visual inspection; the remaining two tanks subjected to artificial damage by notching did not. Both tanks that failed were Type III cylinders. The remaining tanks did not exhibit any rejectable visual indications, although 4 of the 10 tanks' structural integrity was compromised and later failed to meet the burst pressurization requirement.

MAE examination successfully detected the compromised structural integrity of all eight tanks subjected to artificial damage by notch events. Four Type III tanks and two Type IV tanks, of the 12 total tanks subjected to artificial damage by impact events, passed the MAE examination after the impact events. MAE examination confirmed that a stress concentrator had been introduced into the six other composite cylinders' microstructure and that the tanks' structural integrity had been compromised and would not meet minimum burst pressurization requirements. The four Type III and two Type IV tanks that passed the MAE examination also passed the burst pressurization test, and therefore did not have damage that affected the tank's structural integrity. Although not all of the artificial damage events resulted in failure modes of the CNG fuel tanks, those that did have compromised structural integrity were accurately predicted by MAE examination.

Of the 20 tanks subjected to hydraulic fatigue cycling as defined in FMVSS No. 304, all 20 successfully completed the additional 18,000 cycles that simulated 24 years of continued service when assuming 750 fills per year. Two of the tanks that were hydraulically fatigued also passed the leak test according to NGV2, showing no degradation that resulted in a leak failure mode after the additional service. Each of the 20 tanks then exceeded the minimum burst pressurization requirement for tanks at the time of manufacture. The results of burst pressurization following hydraulic fatigue cycling of the tanks that were not subjected to latent damage suggest the potential of additional service life for CNG tanks beyond their defined EOL.

The potential opportunity of continued use of CNG tanks that have not been subjected to potential physical damage could be supported by additional research and development. An expanded CNG fuel tank sample size to characterize tank integrity after experiencing a full service life in a variety of applications could further verify such potential. Visual inspection was not sufficient in identifying damage inflicted by a localized impact test on Type III and Type IV CNG fuel tanks, whereas a nondestructive evaluation method of MAE successfully assessed the structural integrity of the tanks. MAE examination does not require that tanks be removed from the vehicle assembly and could potentially validate tank integrity beyond visual inspection.

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