

**RELIABILITY TECHNIQUES TO REDUCE THE RISK OF FAILURE IN CNG COMPOSITE
PRESSURE VESSEL**

(Recibido 05-06-2017. Aprobado el 07-09-2017)

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Abstract .This paper is devoted to present reliability techniques as a best failure mitigation tool for CNG composite pressure vessels. As far as composite materials are so sensitive to environmental working conditions, design methodology must be established based on reliability considerations .Because of over using of car fuel tanks, CNG should be properly substituted as an alternative fuel. Safety and cost are the most critical points in developing CNG-CPV to public usage. Meeting optimum point, design criteria must be followed by reliability criteria. In this paper, author tried to persuade CNG-CPV developer to take care of mentioned risks. Reliability testing is introduced as a feasible and reliable solution in order to assure desired safety .

Keywords: Reliability, FMEA, CNG, CPV, Failure, reliability testing.

1.INTRODUCTION

CNG is an alternative fuel that is stored under high pressure on the vehicle (20,7- or 24,8 Mpa) from -30°C to 45°C. Safety and cost are two factors that have prevented significant natural gas vehicle penetration in the automotive market. In other words, the use of natural gas as an alternative fuel in automotive applications is not widespread primarily because of the high cost and durability of carbon fiber composite storage tanks. Composite materials are an enabling technology for reducing the weight of CNG fuel tanks. Carbon fiber composites are relatively expensive because of the raw material cost of the carbon fiber, which accounts for approximately 40% of the total tank cost. By introducing large tow-size carbon fiber in the tank design there is the potential for a tremendous cost savings. The cost of large tow-size carbon fiber is approximately one-half the cost of conventional tow-size carbon fiber. However, not all of these savings is realized in the final overall tank cost because of the lower fiber strength and lower strength translation that has been demonstrated in large tow-size carbon fiber composite structures. Composite CNG tanks are typically fabricated using the wet-filament winding process. This is a process where the fiber tow is passed through a resin bath to

impregnate the tow and then wrapped around a mandrel prior to curing in an oven at elevated temperature.

Types of CNG Storage Tanks Desired types of CNG storage tanks should be satisfied essential requirements (e.g. lower Cost, lighter weight, more durable and improved safety). According to Fig.1, for weight sensitive applications (transit bus and passenger cars) Type 4 composite tanks are attractive. Reinforcement used in over-wrapping a tank is typically either a carbon fiber or glass fiber. The main advantages are low weight, corrosion resistance and fatigue resistance.

However, disadvantages of carbon fiber can be anticipated relatively expensive and poor resistance to impact damage Cost analysis of a typical Type 4 tank showed that 40% of the total cost is attributed to the carbon fiber raw material cost. Cost and durability of Type 4 CNG storage tanks are major factors that have inhibited the growth of CNG as an alternative fuel. Additional process trials are needed to achieve lower void contents and to increase the strength translation. Strength data was generated for designing CNG tanks with the required safety factor. Fatigue was identified as not being a critical failure mode.[1]

	<u>Materials</u>	<u>Equivalent Gal. Gas/Weight Ratio</u>
I	Metal	1 Steel
II	Metal lined Hoop wrapped w/ fiber composite	1.7 Steel/Glass fiber 2.1 Alum/Glass fiber
III	Metal lined Fully wrapped w/ fiber composite	2.3 Alum/Glass fiber
IV	Plastic lined Fully wrapped w/ fiber composite	4.0 Thermoplastic/ Carbon/Glass fiber

Fig1. Different types of materials in CNG tanks



Fig2. Composite over wrapped Pressure Vessels (COPVs)

2.SAFETY FACTORS IN CNG TANKS

The most controversial part of tank design rules is the selection of safety factor. Safety factors on

Table1. Safety factors in different standards

Standards Safety Factors	Standards Safety Factors
0•USCG 4	0•USCG 4
0•IGC Code 3	0•IGC Code 3
57•DNV CNG Rules 1	57•DNV CNG Rules 1
ASME VIII div 3 1,73	ASME VIII div 3 1,73

Safety is not proportional to the value of the safety factor.

3.FAILURE MODES IN CNG PRESSURE VESSELS(PVS)

3.1.Failure modes in PVs

PVs are fracture critical regardless of use and susceptible to impact damage and frequency of catastrophic failure. PVs required either proof test or damage tolerance test program regardless of mission

tensile strength for pressure tanks can selected from different standards(Table 1).

type. Some failure modes are presented in Table2. the main cause of these failures can be:

- Faulty design fabrication and installation
- Corrosion or erosion
- Operator error or poor maintenance
- Burner failures
- Pressure control failure

Table2. Some Failure modes of CPV

Failures Modes
Burned or overheated
Collapsed inward
Combination explosion
cracked
Torn assunders(rupture)
leakage
Catastrophic failure of vehicle or station hardware
components
Degraded failure of vehicle or station hardware
components
Electrostatic discharge of CNG

3.2.Failure modes in fiber reinforced composite

In recent years, these materials have seen applications ranging from mass produced tennis rackets to relatively complex structures, such as compressed pressure vessel. As the use of these materials expands, so also does the likelihood of eventual fracture. As with their metal counterparts, the occurrence of fracture is likely to represent a relatively rare event that is not encountered with most hardware usage. However, when such fractures occur, the ability to determine their origin and cause constitutes a critical step that is necessary in providing valuable engineering feedback and ensuring the continued integrity of the components during service.

3.3.Failure causes in composites

Because of their relatively recent usage, new causes of failure in composite materials are still being uncovered as service experience is gained. Current knowledge, however, indicates that many of the basic sources of failure that occur in metals are likely to be observed in composites. These sources include three basic categories of causes: errors in design,

fabrication and processing deficiencies, and anomalous service conditions. Given the construction properties, and sensitivities of composite materials, the specific causes that may occur and should be considered during an analysis are worth reviewing.

3.4.Design Errors

Composite materials are somewhat unique in that both the fundamental properties of the material and the configuration of the component to be fabricated are subject to design. Correspondingly, design errors can be made at both the material and structural levels of design. Engineering errors of the material may include a variety of problems. The more common of these include errors in analyzing the effect of individual ply anisotropies or the inadequate assessment of material damage and environmental sensitivities. Because the level of stress carried by each ply in a uniformly strained laminate depends upon its modulus, large stress gradients and internal shear stresses can exist between plies oriented at significant angles to one another. Such stress gradients can lead to premature fracture, particularly where the magnitude of these gradients is large. Such

large gradients are particularly common where groups of adjacent plies with the same orientation are oriented at 90° to another group of adjacent plies. The highly anisotropic coefficient of thermal expansion of composite materials represents another area where design errors can be made at a material level. Many composite materials exhibit significantly large differences in thermal-expansion coefficients, depending upon their fiber orientation. As a result, changes in temperature, that is, temperatures that differ significantly from the curing temperature, can induce internal stress gradients where plies are oriented at significant angles to one another. These internal stress gradients are analogous to those generated under applied mechanical loads. Because many high-performance composites are cured or formed at elevated temperatures, the cooling of these parts during processing to ambient conditions can induce these internal stresses in the as-fabricated condition. For many designs, the magnitude of these stresses and those generated by additional temperature variations may be relatively inconsequential. However, high internal stress levels may develop in laminates with groups of adjacent plies oriented at large angles to one another or in such structures as space vehicles, in which extreme variations in temperature occur. On a more general level, errors in material design can include many of the same problems encountered in metals. Fractures can be caused by inadequate understanding of environmental sensitivities, the effect of damage, or the fatigue sensitivity of the material used. Because the properties of composites depend upon their ply, or fiber, orientation and stacking sequences, the sensitivity of each design may vary significantly, posing a potential problem for design. In addition, synergistic effects may exist between these factors, giving rise to further sensitivities not considered during normal design practices. Design errors relating to the component itself are likely to include unconsidered load sources. Stress concentrations and unanticipated buckling instabilities or modes. As with their metal counterparts, such failures may occur as a result of oversight. In most cases, thorough trying during design uncovers most of these errors. However, those related to fatigue or rarely attained load conditions may not become apparent until well into the life of the part.

3.5.Fabrication and Processing Deficiencies

Typically, the occurrence of defective or anomalous conditions is controlled and prevented by manufacturing controls and material inspection testing imposed during the fabrication process. However, because absolute control and inspection are generally economically infeasible and because human errors do occur, these control and inspection methods sometimes allow occasional errors.

Continuous fiber reinforced composites are usually fabricated by laminating together and curing multiple plies impregnated with unreacted matrix resin. Within this fabrication operation, a number of errors can occur. Because each of the individual plies involved in a laminated composite has highly anisotropic properties, their placement and orientation can be critical in achieving the desired engineering properties. This is particularly true for composites in which each individual ply constitutes a significant percentage of the total laminate, that is, thin gage structures. For example, in a unidirectional laminate, a variation in overall fiber orientation of 15° can generate up to a 50% reduction in ultimate strength. For thermosetting matrices, reacting the matrix resin represents one of the more critical steps. Either improper amounts of the two resin components or the inadequate application of heat during curing can produce conditions of under cure. Such conditions, when extensive, can significantly degrade the properties of the matrix and its resistance to chemical or environmental exposure. Similarly, inadequate compaction during the lamination process can result in extensive porosity and reductions in material strength and durability.

3.6.Anomalous Service Conditions

Particular service anomalies include improper operation or use, faulty maintenance and repair, overloads due to failure of a related part, and environmental- or service-incurred damage beyond that reasonably anticipated. Many of these causes are not unique to composite materials. However, because of their construction, composites are particularly affected by some conditions more than other materials. The engineering properties of composites can be significantly reduced by variations in temperature, foreign object impact damage, and, with some resin systems, chemical attack. With thermosetting matrices, the effect of temperature can become quite detrimental,

particularly if moisture has been absorbed into the resin system. Property reductions due to foreign object damage can also be equally extreme. Studies have shown that moderate levels of impact energy can reduce material strength up to 60%.

3.7. Fracture Modes in Composites

Because of their laminated anisotropic construction, fractures in composites can occur in a number of complex ways. The types and modes of fracture that can be encountered depend upon both the direction of applied load and the orientation of fibers (plies) making up the composite material. The definition of fracture modes on a macroscopic scale, however, provides a relatively useful means of classifying failure modes and fracture types in much the same way as with metals. Fractures in continuous fiber reinforced composites can be divided into three basic fracture types: inter laminar, Intra laminar, and Trans laminar.

4. THE FAILURE ASSESSMENT

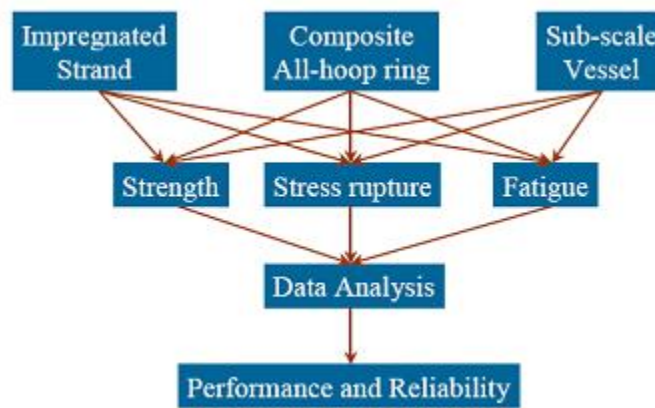


Fig.3 Durability analysis

4.2. Preventive actions against failure

When pressure vessels are to be put into storage, the following must be provided for:

- Prevention of mechanical damage, such as scratches, dents, dropping, etc.
- Protection against exposure to adverse environments which could cause corrosion or stress corrosion.

4.1. CNG Storage Tank Diagnostic

Imbedded fiber optic sensors and modal analysis techniques can be as candidate technologies for in service NDE of CNG composite fuel tanks in the modal analysis technique, structural modal parameters are used as global indicators of complete structures including composite cylinders. The modal parameters such as natural frequency and damping can characterize the health or structural integrity of a component and may be used to detect defects in the material. Modal parameters may not be able to determine the exact location of the defect, but studies have shown that the defect size in composite materials can be correlated with changes in natural frequency and damping. These parameter changes (from baseline) are used to identify defects in the material. Future directions are determining damage criteria for an “unsafe” tank condition, and manufacturing prototype composite tanks and conduct field demonstrations. In Fig.3 durability analysis can be carried out for fatigue failure.

- Prevention of induced stresses due to storage fixture constraints.

4.3. Reliability tests as failure removing tools

There are some alternative tools to improving reliability levels. According to available facilities two procedures can be purposed. The end effects of the procedures should be anticipated reduction failure severity and occurrences with optimum cost. To be more effective, the procedures must be applied in whole life cycle of the product. Increasing

reliability levels in design stage with well-established guidelines (so-called design for x(x stand for manufacturability, Testability, serviceability, safety, reliability and so on)) can be best solution. Developing techniques in manufacture process to ensure meeting the established reliability requirements in design stage is a complementary action. Planning reliability test can be best solution tool. General goal in reliability test is detecting failure and removing the cause of the failure in design or manufacturing processes.

4.4.Environmental Stress Screening (ESS)

A series of tests conducted under environmental stresses to disclose weak parts and workmanship defects for correction. Environmental stress screening (also known as preconditioning, burn-in, et cetera) shall be conducted on parts, subassemblies, and complete units for both developmental and production items. During development, ESS test procedures, taking into consideration the equipment design, part/component technology, and production fabrication techniques, shall be formulated.

4.5.Reliability Developing/Growth Testing (RDGT)

A series of tests conducted to disclose deficiencies and to verify that corrective actions will prevent recurrence in the operational inventory (Also known as “TAAF” testing). Growth testing will emphasize performance monitoring, failure detection, failure analysis, and the incorporation and verification of design corrections to prevent recurrence of failures.

4.6.Reliability Qualification Test (RQT)

A test conducted under specified conditions, by, or on behalf of, the government, using items representative of the approved production configuration, to determine compliance with Specified Reliability requirements as a basis for production approval. (Also known as a “Reliability Demonstration or “Design Approval”, test.)

4.7.Production Reliability Acceptance Test (PRAT)

A test conducted under specified conditions, by, or on behalf of, the government, using delivered or deliverable production Items, to determine the producer’s compliance with Specified reliability requirements.

5.RELIABILITY TEST IN PRESSURE VESSELS

5.1.Testing Requirements (Metal PV)

A set of full scale fatigue and burst tests shall be performed and it must be documented that the cylinder wall, end cap and welding has:

- Sufficient reliability against fatigue. Two fatigue tests are required to document that the fatigue capacity is in excess of 15x the number of stress cycles during the design life time.
- The cylinder possesses sufficient burst resistance after 2x the number of pressure induced stress cycles
- Process prototype testing shall be carried out to document that the system functions as specified with respect to accumulation and disposal of liquids.
- Small scale fatigue test
 - Longitudinal welds
 - Circumferential welds
- Full scale (end-capped pipe) fatigue test
 - Fatigue test of construction detail
- Burst test with full scale end-capped pipe
- Cool-down testing
- Process testing
 - Full scale verification of loading/unloading process testing
- Qualification test

5.2.Testing Requirements (CPV)

Fatigue testing of CPV storage vessel components and materials engineering using composite glass and

carbon fiber materials is essential. The cylinders will be subject to a variety of stresses and risk analyses. Some will be bursted as they are, while others will be bursted to the strength of five to 10 years, which is their expected life span. The cylinders will also be burst-tested to confirm their integrity. Some will be previously damaged, like from the drop of a hammer, to simulate a non-recognized, pre-installation impact, and then subject to the same testing. Some will even be shot with a bullet to show safe rupture characteristics.

5.3. Acceptance Test Requirements

Requirements shall be satisfied by completion of leak and/or proof test requirements for the assembled pressurized system as dictated by the applicable range safety documentation, and or procuring agency, requirements, Re-Certification Test Requirements, Re-certification of lines, fittings and components shall be as delineated as applied to the refurbished systems. Qualification testing shall include life cycle testing, random vibration testing, and burst testing. The following delineates the required tests:

- Pressure Testing

Requirement for application of external loads in combination with internal pressures during testing must be evaluated based on the relative magnitude and/or destabilizing effect of stresses due to the external load. If limit combined tensile stresses are enveloped by test pressure stresses, the application of external loads shall not be required. If the application of external loads is required, the load shall be cycled to limit for four times the predicted number of operating cycles of the most severe design condition (e.g., destabilizing load with constant minimum internal pressure, or maximum additive load with constant maximum expected operating pressure). Qualification test procedure shall be approved by the procuring agency and the appropriate launch or test range approval authority.

- Random Vibration

Random vibration qualification testing shall be performed per requirements of MIL-STD-1540 unless it can be shown the vibration requirement is enveloped by other qualification testing performed.

6. CONCLUSION

- CNG pressure vessel in cars, as a critical product to man-user, must be designed and manufactured based on reliability considerations.
- CNG pressure vessel in cars, as a daily usage, have a high rate charging and discharging, consequently working in a safe situation in specific useful life is the most critical point in design.
- Periodic inspection especially after harsh car accident must be scheduled. To this end, design must be followed reliability criteria.
- Reliability testing is the best solution to remove failure causes from design and/or manufacturing stage in order to reducing probability of the failure occurrence and severity during service in estimated life time.
- Composite pressure vessels are very sensitive to environmental working conditions so it is necessary to simulate real conditions during developing and final stage. RDGT can be only recommendation.

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