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Show Me the Road to Hydrogen

Non-Destructive Evaluation (NDE)

by

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A University Transportation Center Program at Missouri University of Science & Technology

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16. Abstract

Information is lacking about failure mechanisms associated with various hydrogen transportation systems, the types of typical failures, and critical locations where they may occur. Although one may consider these systems to be related to carbon-reinforced pressure vessels, their specific uses, material interactions with hydrogen, and unique in-service accumulated damages are expected to impose certain NDE restrictions and limitations that pressure vessels used in aerospace industry may not suffer from. Therefore, in consultation with public safety authorities and experts, researchers must evaluate, select and bring in various suitable NDE methods for an effective synergistically integrated approach to the NDE of these different components.

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SHOW ME THE ROAD TO HYDROGEN

Task 5: Nondestructive Evaluation (NDE)

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1. INTRODUCTION

This report summarizes the literature review carried out by the authors from June to December, 2007. The report summarizes various issues associated with manufacturing, transporting, re-fueling and nondestructive testing of hydrogen storage tanks. Hydrogen storage, and specifically compressed gas tanks, has been identified as an area where nondestructive testing will be particularly useful and is thus covered in much greater detail.

The rest of this report is structured as follows. Chapter 2 identifies the different hydrogen tank manufactures and Chapter 3 provides a brief description of the components of a typical hydrogen filling station along with some of the standards and codes that are followed to ensure safe operation. Chapter 4 discusses the different modes of hydrogen fuel storage on board vehicles. Destructive as well as nondestructive testing methods are also discussed. Chapter 5 provides a summary of the existing standards and codes for the inspection of hydrogen storage tanks and other components of the hydrogen infrastructure. Some of the deficiencies of the existing codes and standards for the hydrogen infrastructure have been summarized in Chapter 6 and a number of components of the hydrogen infrastructure which lack formalized codes and standards are identified. Effective maintenance of the hydrogen infrastructure requires the development of innovative products which will reduce inspection time and reduce the complexity involved in the inspection procedure. Two such state-of-the-art products are discussed in Chapter 7. Chapter 8 summarizes the findings of this literature survey study.

2. HYDROGEN TANK MANUFACTURERS

Four of the leading manufacturers of hydrogen storage tanks are described in this section.

2.1. Lincoln Composites

Lincoln Composites produces Tuffshell type IV compressed gas storage tanks. Their tanks are used for automobiles, busses, and stationary storage. They range in pressure from 3,000 psi to 10,000 psi [1].

2.2. Quantum Technologies Inc.

Quantum Technologies (QTWW) produces TriShield type IV compressed gas cylinders for hydrogen storage as well as fuel metering, electronic controls and fuel system integration. It has developed and demonstrated all-composite hydrogen storage tanks that store hydrogen at 10,000 psi (700 Bar) [2]. They produce automobile storage tanks, mobile fueling units, and other fueling products. Their tanks are used on Toyota cars. Quantum is examining using integrated sensors in their tanks [3].

2.3. Structural Composite Industries

Structural Composite Industries produces type III compressed gas cylinders. In the 1970s, SCI helped the United States Department of Transportation develop the first safety standards for composite fuel tanks, and SCI manufactured the first DOT approved composite fuel tank. SCI also developed the first composite fuel tank certified under European Standard ECE R110 [4].

2.4. Dynetek Industries Ltd.

Dynetek produces DyneCell type III compressed gas cylinders for storage of natural gas and hydrogen. Their tanks are used for automobiles, busses, mobile fueling stations, and stationary storage. They range in pressure from 3,000 psi to 10,000 psi. An integral part of Dynetek's expertise is its in-house testing facility used to validate and certify standard and/or custom designs effectively [5]. Dynetek has cylinders in use in the Citaro busses used by the Clean Urban Tranport for Europe (CUTE) project, the Ford Focus Fuel Cell vehicle, the Volkswagen type Bora, Nissan Xterra, 2000 Mercedes Benz Necar, Ford Focus FCV, Toyota FCHV and the Ford Hydrogen ICE vehicle.

3. HYDROGEN FILLING STATIONS

A hydrogen filling station is a refueling facility for hydrogen powered vehicles. Such filling stations are growing in number due an increased initiative to promote the use of hydrogen as an alternative energy source for passenger and commercial vehicles. Hydrogen filling sites are currently operational in almost all major U.S. cities and many more have been planned for the near future Figure 1 shows a typical hydrogen filling station.

Figure 1. Hydrogen filling station in Washington D.C. [6].

The California Fuel Cell Partnership (CaFCP), which is a collaboration of 31 member companies aimed at promoting the commercialization of hydrogen powered vehicles, has heralded the development of a number of hydrogen filling sties all over the state of California. The CaFCP currently has 16 operational filing stations and 15 more planned for the near future. A brief description of the hydrogen filling station at the West Sacramento headquarters of the CaFCP is given in the following sections [7].

The station has the capability to dispense hydrogen fuel in the liquid or gaseous form as required by a specific fuel cell vehicle type. The hydrogen fuel is delivered to the facility in tanker trucks and stored cryogenically at a temperature of -423 degree Fahrenheit.

Similar storage methods have been used in several industrial applications in the past but this is one of the first instances of such usage for hydrogen storage at a commercially operating filling station. The filling station has the flowing major components:

- One 4,500 gallon liquid hydrogen storage tank
- A vaporizer for warming the liquid hydrogen to its gaseous form
- A compressor to raise the gas pressure to 6250 psig (pounds per square inch gauge)
- Three tubes for storing gaseous hydrogen
- Two gaseous dispensers at 3600 psig and 5000 psig and a liquid hydrogen dispenser

3.1. Storage Tank

The storage tank is an ASME coded double walled pressure vessel. The inner steel wall is ½ inch in thickness and built to withstand a pressure of 150 psi and tested to 225 psi. The actual operating pressure of the tank is in the range of 50 psi. As a safety measure the tank has a number of redundant pressure valves which are designed to open in the event of over pressure and release the hydrogen through a 25 foot high vent stack.

3.2. High Pressure Storage Tubes

After compression hydrogen gas is stored in three steel storage tubes at 6250 psig. Like the storage tank the tubes are also equipped with safety valves to release the gas in the unlikely event of overpressure.

3.3. Hydrogen Dispenser

The fuel station has one liquid and two gaseous dispensers. The liquid dispenser siphons off liquid hydrogen directly from the storage tank and is vacuum jacketed in order to ensure that the operator is protected by an insulating barrier and liquid hydrogen fuel is delivered to the vehicle's storage tank at the correct temperature. The fuelling interface can be used with all of the three dispensers mentioned above and all hydrogen vehicles. It has been designed collaboratively by a number of major automobile companies participating in the CaFCPs hydrogen vehicle development program. Figure 2 shows a hydrogen fuel dispenser at an operational refueling station.

Figure 2. Hydrogen fuel dispenser at a filling station [8].

3.4. The Fueling Process

The CaFCP uses two protocols for filling the hydrogen fuel cell vehicles, the “fast-fill” protocol and the “slow-fill” protocol. For the “fast-fill” protocol the operator connects a data communication cable to the vehicles communication port and the computer at the filling site monitors the vehicles systems to make sure that the fueling standards set by the automobile manufacture and the filling station have been met. The operator then begins the actual fueling operation which can be completed in a span of less than five minutes. In case the vehicle to be refueled does not have a communication port the “slow-fill” protocol is used, the process takes about 15 minutes for safe completion.

3.5. Safety Standards and Procedures

The CaFCP has developed a safety protocol that allows the hydrogen filling site to operate with the same level of confidence as a modern day gasoline refueling station. The facility is monitored by ultraviolet and infrared sensors which can set of alarms to warn the attending staff in case of accidental fires. Also, the station employees are well instructed in the properties of hydrogen gas and imparted training for handling emergency situations. As an additional security measure the dispensers are operated only by the trained staff members of the filling station and activated by a unique Personal Identification Number (PIN).

4. NONDESTRUCTIVE EVALUATION FOR CONDITION MONITORING OF HYDROGEN POWERED VEHICLES

4.1. Modes of Onboard Hydrogen Storage

Hydrogen is very difficult to store. It is very light, requiring large volumes to store sufficient amounts in its natural state and pressure. It is also a small molecule, leaking through many materials. Furthermore, it will react with some materials, such as steel, weakening them. The U.S. Department of Energy has set several goals for hydrogen storage, as shown in Table 1.

Table 1. DOE goals for hydrogen storage [9].

Parameter	**2005**	**2010**	**2015**
Usable Specific Energy (kw hr / kg)	1.5	2	3
Usable Energy Density (kw hr / L)	1.2	1.5	2.7
Cost (165L bus tank) ($ / kw hr)	$6	$4	$2
Cycle Life (Cycle, 1/4 tank to full)	500	1,000	1,500
Refuleing Rate (kg H2 / min)	0.5	1.5	2.0

4.1.1. Compressed Gas

More than 90% of hydrogen powered vehicles in 2005 used compressed gas storage [10]. Compressed gas storage has been used for natural gas powered vehicles for years and the hydrogen industry has largely inherited from these designs. High pressure is used to reduce the volume of hydrogen. The most recent designs will operate up to 10,000 psi (700 bar). A liner is used to contain the hydrogen and a wrap of high strength fiber provides the strength to withstand the pressure. Disadvantages include large volume and safety concerns related to the high pressures. Compressing the hydrogen to 10,000 psi requires about 12% of the energy contained in that hydrogen. Four types of tanks have been developed for the compressed gas market; of these, type III and type IV tanks have been used for hydrogen storage.

4.1.1.1 Type III Tanks. A metal liner contains the gas and a complete fiber wrap provides most of the structural support against the pressure. Generally, in hydrogen applications, aluminum is used for the liner and carbon or a carbon/fiberglass hybrid for the fiber. Both loop and transverse wraps are used to provide strength in all directions.

4.1.1.2 Type IV Tanks. Type IV tanks are similar to the type III tanks except that a non-metal (generally plastic) liner is used. Plastic liners have increased fatigue resistance but provide less strength. They are also lighter then type III cylinders.

The Lincoln Composites Tuffshell tank is one example of a modern design for a type IV tank. A cutaway view of this tank is shown in figure 3. This tank has a High Density PolyEthylene (Plastic) liner wrapped with a carbon/glass hybrid fiber. This tank also features energy absorbing pads on the corners and a fiberglass outer layer to provide additional protection from impact damage. [11]

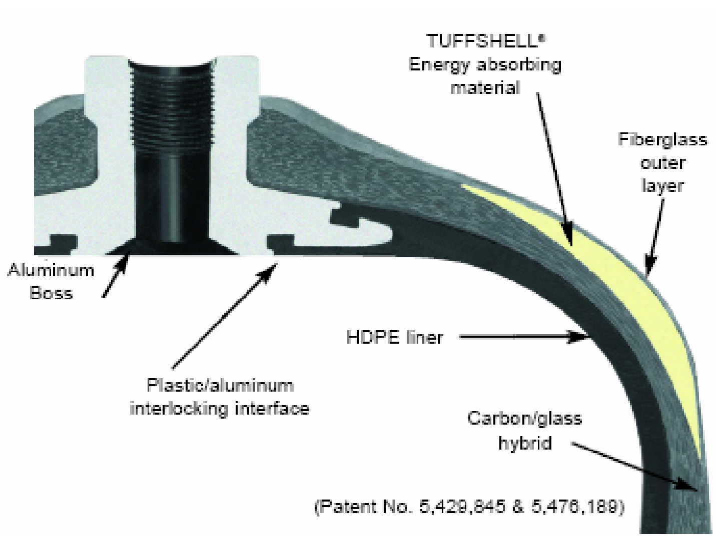


Figure 3. Cutaway view of a type IV cylinder [11].

4.1.1.3 Transportation/Long Term Storage. Stationary storage and transportation of compressed hydrogen generally uses racks of long, thin (e.g., 3.1 m length, 0.4 m diameter) tanks operating at lower pressures then automobile applications (2,500-6,500 psi). Stationary gaseous hydrogen storage tanks are shown in Figure 4.

Figure 4. Stationary gaseous hydrogen storage [12].

4.1.2 Liquid Hydrogen

The second type of hydrogen storage currently used in vehicles is liquefied hydrogen. Liquid hydrogen is denser than gaseous hydrogen, but hydrogen liquefies at 20° K, about ¼ the temperature of liquid nitrogen. About one third (28-40%) of the energy contained in hydrogen must be expended to liquefy it and cryogenic (very low temperature) tanks must be used to hold it. Boil-off, where heat leaking into the tank turns the hydrogen back into a gas, is a significant concern, which requires venting of the tank. About 3-4% of the hydrogen may boil-off in a day, though tanks using active cooling have improved this significantly.

4.1.2.1 Liquid Hydrogen Storage Systems. Modern liquid hydrogen storage provides the necessary insulation by isolating the tank by a vacuum, preventing heat conduction, and limiting heat absorbed through radiation with 70+ layers of insulation. The Linde tank, shown in Figure 5 is one example of a modern liquid hydrogen tank.

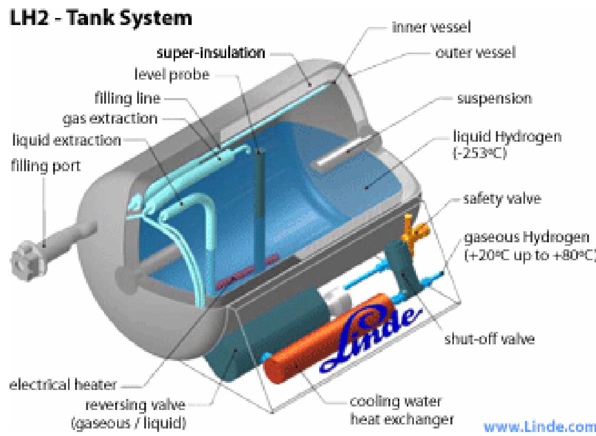


Figure 5. Liquid hydrogen tank [13].

4.1.2.2 Insulated Cryogenic Pressure Vessels. Lawrence Livermore National Laboratory is developing a tank taking advantage of both compressed and cryogenic storage. This is achieved by nesting a pressure vessel inside a cryogenic vessel. This tank can be operated as a pressure vessel, operated at low temperatures (~70° K) where the fiber in the pressure vessel has significantly higher strength, or as a cryogenic vessel storing liquid hydrogen. This would also allow the user to use compressed hydrogen for locale trips where car range is of less concern and the higher energy cost liquid hydrogen for longer trips. This system can also retain liquid hydrogen boil-off as compressed gas [14].

4.1.3 Hydrides

Hydrides chemically bond with hydrogen in a reversible process. The hydrogen can then be stored compactly and recovered as needed.

4.1.3.1 Metal Hydrides. Metal hydrides are metals that chemically combine with hydrogen, holding it in a small volume. The application of heat reverses the reaction and frees the hydrogen, and heat is generally available as a byproduct of the fuel cell. A typical application has powdered hydride metal and rods used to distribute heat contained in a metal box. Because the reaction is self limiting this is also a safe way to store hydrogen. Disadvantages include relatively large weight and the high cost.

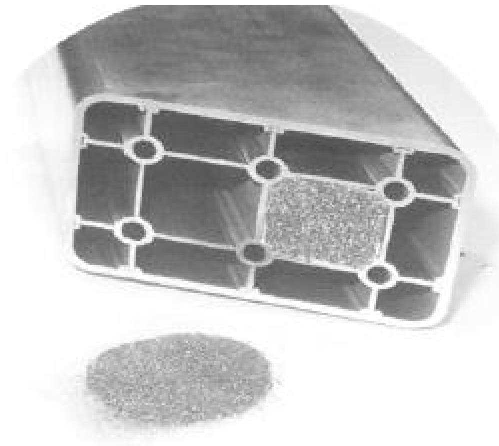


Figure 6. Metal hydride [15].

4.1.3.2 Chemical Hydrides. Chemical hydride slurry has been developed that is 15.3% hydrogen by weight. This slurry can be stored at room temperature and releases the hydrogen when combined with water. This slurry is stable for weeks, will not ignite, and is not contaminated by air. However, the reaction produces a hydroxide byproduct that must be returned to an industrial location to be recharged with hydrogen, which would require a much more extensive infrastructure [16].

4.1.4 Carbon Nanostructures

Carbon nanotubes bond with hydrogen increasing the amount of hydrogen that can be stored in a compressed gas tank. The best results have been obtained when metal atoms are bonded to the nanotube and then also bond with the hydrogen [17]. Hydrogen storage of 7% by weight has been achieved [15]. Other forms of carbon, such as activated carbon and nanohorns, have also show promise for storing hydrogen [18].

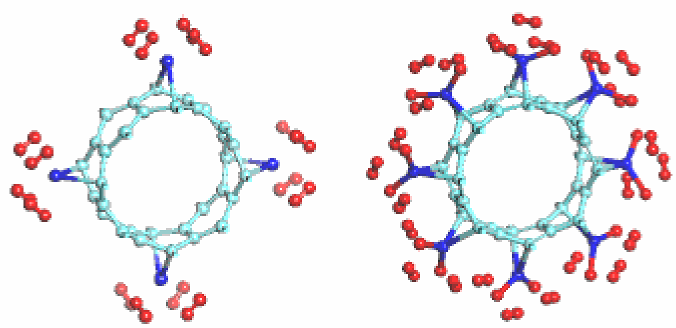


Figure 7. Hydrogen (red) bonded to carbon nanotube (light blue) using titanium (dark blue) [17].

4.1.5 Innovative Concepts

New and innovative solutions are constantly being proposed to improve hydrogen storage and meet the DOE goals. A few of these are included.

4.1.5.1 Zeolites. Zeolites are microporous inorganic compounds. Hydrogen is captured in micro pores to reduce volume. Thus far 0.7% hydrogen by weight has been achieved [15].

4.1.5.2 Replicants. Replicants are an alternative method of providing structural support to compressed gas tanks by repeatable small structures. One methods of this is macrolattices, passing support columns through the storage chamber to allow localized pressure support. A 4x4x4 strut cell has been built and it is expected that 20x20x20 will be necessary for use in vehicles. Another method uses microscopic structures within the tank to withstand high pressures [19].

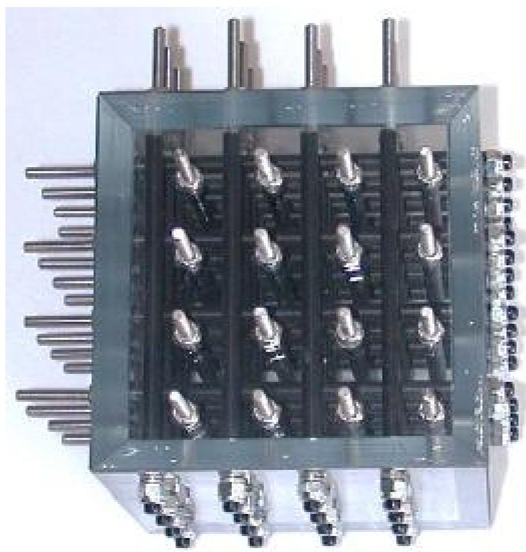


Figure 8. 4x4x4 macrolattice [19].

4.1.6 Tank Location in Vehicle

Tank location in vehicles is of particular concern because of the high volume required for current systems. Figure 9 shows nine possible tank locations in a car, for this discussion the first four have been grouped as floorboard storage, two have been grouped as trunk storage, and the roof storage is included. The tank placements in front of the instrument panel and in a trailer are not discussed, as these have not appeared in the other literature reviewed.

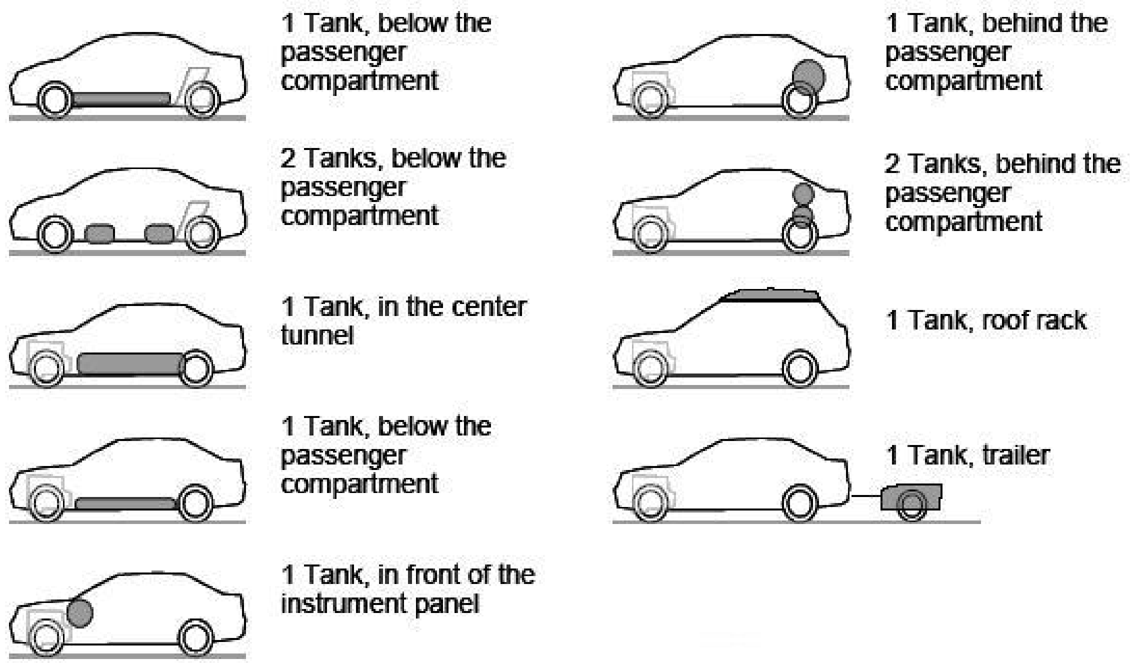


Figure 9. Potential tank locations [20].

4.1.6.1 Roof. Compressed gas hydrogen storage methods are particularly suited for busses, where large volume is not a problem. Most bus hydrogen storage systems mount to the roof a rack of compressed gas tanks. This location has not been widely used for cars.

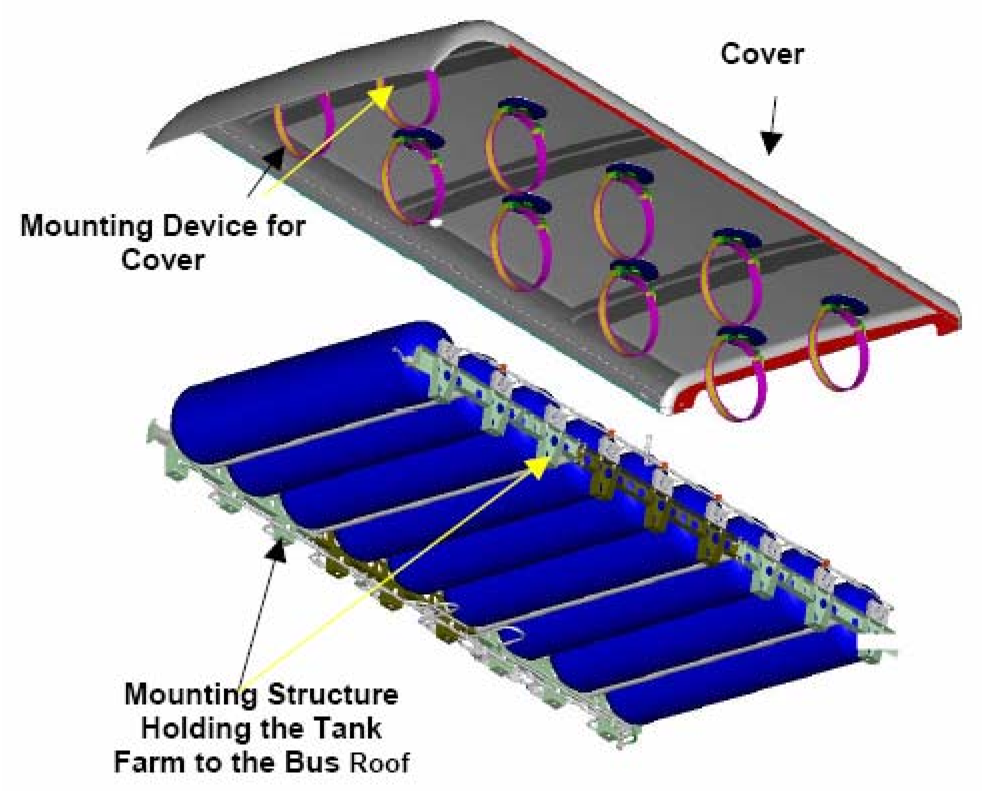


Figure 10. Hydrogen tank roof rack mount [21].

4.1.6.2 Trunk. A car trunk or truck bed is large empty space that can be used to hold the storage tank. This allows greater use of existing designs, but reduces the space available for use as a trunk.

4.1.6.3 Floorboard. Several new hydrogen vehicle designs place the tanks underneath the car floorboard. This is a fairly large area that can be devoted to hydrogen storage with limited interference with passenger areas. This is particularly attractive when using a by-wire system, such as the Auto-nomy by GM, which does not have a driveshaft.

Figure 11. GM Auto-nomy base [22].

4.1.6.4 Conformal Tanks. Research has begun on conformal tanks, both alternative shapes for compressed gas tanks and shaped liquid hydrogen tanks. Pillow shaped pressure vessels have achieved a burst pressure of 1,600 psi, about 7% of that achieved by cylindrical tanks [22-23]

Figure 12. Pillow shaped pressure tank [22].

4.2. Destructive Testing of Hydrogen Storage Tanks

A number of different tests are performed by tank manufacturers before the tanks are installed in the vehicles to ensure compliance with standards set by the DOT (Department of Transportation), SAE (Society of Automotive Engineers) and ISO (International Standards Organization). Studies have been conducted to ascertain if additional tests are required for ensuring that catastrophic failure does not occur under extreme operating conditions arising out of accidents such as collisions, fires etc. Table 2 lists some of the relevant additional tests [24]. The table is divided into three columns, the first column lists the type of test, the second column lists the specific activities performed during the test and the third column lists the criterion for successful completion of the test.

Table 2. Destructive tests performed on composite over wrapped hydrogen storage cylinders [24].

Type of Test	Test Description	Criteria for Success
Cycling, ambient temperature	10,000 cycles from less than 10% of service pressure to full service pressure, maximum 10 cycles/min	Cylinder must withstand the test with no visual indication of damage
Cycling, Environmental	• 5000 cycles from 0 to service pressure with tank at 60 degree Celsius with air at ambient temperature and 95% humidity • 5000 cycles from 0 to service pressure with tank at -51.1 degree Celsius with air at ambient temperature • 30 cycles from 0 to service pressure at ambient conditions • maximum 10 cycles/min • Burst test the cycled tank	Cylinder must withstand the cycling pressurization test with no visual indication of damage

Table 2 Destructive Tests performed on composite over wrapped hydrogen storage cylinders (Contd.) [24].

Type of Test	Test Description	Criteria for Success
Cycling, Thermal	• 10,000 cycles from 0 to service pressure at ambient temperature. • 20 thermal cycles with tank temperature varying from 93.3 degrees Celsius to -51.1 degrees Celsius at service pressure • Burst test the vessel	Cylinder must withstand the cycling pressurization test with no visual indication of damage
Gunfire Test	• Vessel is pressurized to service pressure with air/nitrogen • Impacted with an armor piercing projectile fired at a speed of 2800 ft/sec • Vessel is positioned such that the point of impact of the projectile is at an angle of 45 degrees with its longitudinal axis. • Firing range should not exceed 150 ft	Cylinder must not fail by fragmentation. Figure 13 shows a cylinder subjected to gunfire testing.
Bonfire Test	• Cylinder is pressurized to service pressure with air/nitrogen and relief valve is set to discharge at 83% of the service pressure Continued on next page	The gas should release primarily through the relief valve Figure 14 shows a cylinder subjected to bonfire testing.

Table 2 Destructive Tests performed on composite over wrapped hydrogen storage cylinders (Contd.) [24].

Type of Test	Test Description	Criteria for Success
Bonfire Test (contd.)	• Cylinder is exposed to fire such that the temperature at the surface is between 850-900 degree Celsius • The cylinder is exposed until the gas is fully vented	
Drop Test	• Drop height of 10m • Impact surface is unyielding • Cylinder is dropped onto its end • Cylinder is dropped horizontally onto its side wall • Cylinder is dropped onto a piece of angle iron measuring 3.8 cm x 0.48 cm • Cylinder is burst tested after the drops	The burst pressure of the cylinder should be 90% of the minimum burst pressure as specified by the manufacturer. Figure 15 shows a cylinder subjected to burst testing.

Figure 13. Cylinder subjected to gunfire test with no observable fragmentation [24].

Figure 14. Cylinder subjected to bonfire test [25].

Figure 15. Composite over wrapped tank after hydrostatic burst test [26].

4.3. Nondestructive Testing of Hydrogen Storage Tanks

The most popular Nondestructive Testing (NDT) method currently in use for periodic inspection of the hydrogen fuel tanks, once installed, is *visual testing*. The vehicle is periodically brought into an inspection bay, where a human operator visually assesses any damage that the tank may have suffered. Figure 16 shows a typical inspection bay. However, even though it is the most convenient and quickest nondestructive method, involving minimal operator training and data interpretation, it may not be a suitable testing method under most scenarios.

The structural integrity of the storage tank can be compromised if the composite over wrap is subjected to damage. A number of different NDT methods have been used for inspecting discontinuities in composites such as impact damage, disbond and delamination. Table 3 lists the different NDT techniques that have been investigated for inspecting composite cylinders [9, 27-33]. The table has five columns; the first column lists the name of the NDT technique, the second column describes briefly the rationale behind the inspection technique, the third and fourth columns summarize the advantages and disadvantages of the technique, respectively, while the fifth column states the applicability of the technique to inspection of composite cylinders.

Figure 16. Inspection bay for Ciatro busses in Madrid [12].

Table 3. Nondestructive testing methods for composite over wrapped hydrogen pressure vessels [9, 27-33].

NDT Technique	Rationale	Advantages	Disadvantages	Applicability to composite cylinder inspection
Visual Testing (VT)	Obvious damage to the cylinder is visible to the unaided eye.	• Less time consuming • Minimal operator training required	• Difficult to detect subtle damage • Almost impossible to detect hidden damage without any external manifestation • Unable to gauge the true extent of any damage detected	Currently the most commonly used NDT technique for inspection of hydrogen storage cylinders in service. Assessment of the cylinders condition may not always be accurate due to the inability to detect hidden and slight damage.
Eddy Current Testing (ECT)	An alternating current is set up in the test specimen and the flow of the induced current through the test specimen is monitored to reveal discontinuities.	• Well understood and documented technique • Portable equipment and easy operation • Minimal operator learning curve • Ability to detect hidden and subsurface anomalies	• Can only be used to inspect hydrogen cylinders with a composite over wrap which is high in carbon content • Some concern about the ability to detect subtle damage	Can be theoretically used to inspect cylinders in service but complex electrical conductivity issues coupled with the fact that the testing equipment requires access to the entire outer surface of the cylinder limits widespread commercial usage.

Table 3. Nondestructive testing methods for composite over wrapped hydrogen pressure vessel (contd.) [9, 27-33].

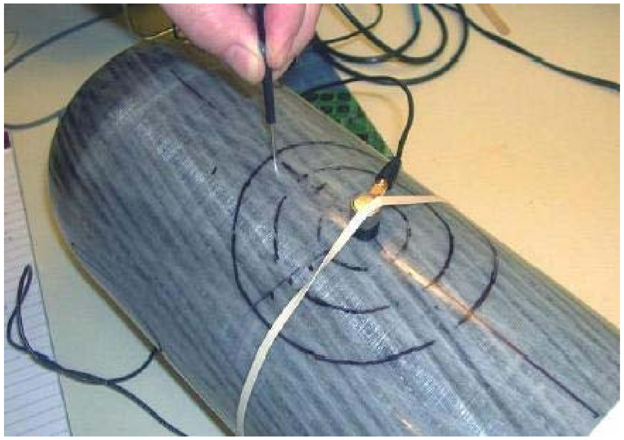
Ultrasound Testing (UT)	Ultrasound waves are introduced into a test specimen; properties of the test specimen affect the transmission of the wave through it.	• Extensively documented and well understood technique • Proven to detect discontinuities in composite materials • Requires couplant	• Access required to entire free surface of tank • Complex signal processing routines required for data interpretation • Dependent on shape of the inspected part • Problem with coupling the ultrasound waves into test medium	Found to be applicable to detecting damage in composite overwrapped cylinders, though complexities involved limit widespread use. Figure 17 (a), shows ultrasound the testing of a graphite-epoxy tank using a receiver and transmitter probe [29].
Laser Ultrasonics (LU)	Lasers are used to induce ultrasonic waves in the test cylinders, the damage condition determines the properties of the propagating wave.	• No coupling medium required • Ultrasound wave propagates perpendicular to the surface irrespective of the angle of incidence of the laser • Capable of inspecting complex shapes	• Access required to entire free surface of tank • Complex signal processing routines required for data interpretation • Considerable operator skill necessary	Found to be unable to generate ultrasound waves in translucent composites, which severely impairs its widespread usage Figure 17 (b), shows the setup of a laser ultrasound unit testing a complex duct [29].

Table 3. Nondestructive testing methods for composite over wrapped hydrogen pressure vessel (contd.) [9, 27-33].

Critically Reflected Longitudinal Waves (L_{CR})	L_{CR} waves are sensitive to stress conditions in the propagating medium which in turn are affected by discontinuities present.	Similar to UT	• The propagation of L_{CR} waves is affected by factors such as temperature and material texture • Suffers from some of the same drawbacks as UT	Able to demonstrate ultrasound wave propagation through composite medium, further studies required in order to ascertain the usefulness of this technique for detecting damage in composite cylinders.
Acoustic Emission (AE)	Damaged composites emit acoustic noise when pressurized. Piezoelectric transducers are used to monitor the emitted waves and ascertain extend of damage.	• Global technique • Can be used for continuous monitoring and dynamic tracking growth of defect growth	• AE transducers are sensitive to stress waves created by a number of different physical phenomenon such as friction, turbulence etc. • Difficult to separate signal of interest from background noise • Can only detect active damage	Can be used to inspect cylinders under controlled conditions, might not be possible to use without removing the cylinder from the vehicle. Further research currently being conducted.

Table 3. Nondestructive testing methods for composite over wrapped hydrogen pressure vessel (contd.) [9, 27-33].

Thermography	Damage to the cylinder results in differential heating of pristine and anomalous areas. An infrared camera can be used to capture hot and cold spots on the cylinder thereby revealing the affected region.	• Minimal operator training required • One shot imaging saves inspection time • Capability to detect subsurface defects	Needs visual access to the full inspection surface	Limited capability to penetrate composites, able to detect only near surface flaws. Sometimes has problems detecting flaws visible to the unaided eye. Figures 17 (c) and (d) show the comparison between a visual light image and thermographic image of an composite cylinder damaged by impact [29].
Shearography	It is an iterferometric technique in which two different images of the test surface illuminated by laser light are captured. The resulting interference pattern between the two images reveals discontinuities in the composite specimen.	• Capable of detecting impact damage and delamination • One shot imaging saves time • Easy operation requires minimal operator training	• High equipment cost • Limited application base at the current time	Has been shown to work for impact damage but is less suitable for more subtle damage. Is able to detect moisture in composites.



(a)

(b)

(c)

(d)

Figure 17. (a) Ultrasound testing of a graphite-epoxy tank using a receiver and transmitter probe, (b) a Lockheed Martin LaserUT™ laser ultrasound unit testing a complex composite duct, (c) visual light image of composite cylinder showing no apparent damage (d) thermographic image of the cylinder in part (c) clearly reveals subsurface damage [30].

The nondestructive evaluation techniques mentioned in Table 3 cannot be used for online condition monitoring of the hydrogen fuel cylinders. The cylinder to be inspected for damage has to be removed from the vehicle and tested under controlled conditions. However, the composite over wrap that provides the cylinder with its load bearing capability is light weight and very susceptible to impact damage which may lead to catastrophic failure of the cylinder without any warning. Therefore, on-line monitoring of the structural health of the cylinders is of immense practical importance. Table 4 provides a summary of such techniques employing embedded sensors which are currently under investigation [33].

Table 4. Health monitoring of composite hydrogen tanks using embedded sensors [33].

Condition Monitoring Scheme	**Rationale**	**Applicability to composite hydrogen cylinder inspection**
Resistance Strain Gauge Monitoring	Based on the piezo-resistive effect which results in the change in the electrical resistance of a material when mechanical stress is applied	• Traditional method of monitoring strain in the tank shell • Low cost sensor • Small inspection area • Needs a large number of sensors to be integrated into the tank shell
Fiber-optic Strain Gauge Monitoring	It is a fiber-optic based system which uses transmission from one fiber to another in a twisted pair to monitor localized strain.	• Application is limited to localized strain measurements • High cost involved hinders widespread commercial usage • Sensitive to environmental noise.
Acousto-Ultrasonic Monitoring	This is a combination of Acoustic-Emission and Ultrasonic monitoring, involving analysis of acoustic-emission events	• Low cost sensor which can monitor large areas of tank surface • Can be wound into the tank shell structure • Few real world tests

4.4. Design for Inspectability

Hydrogen storage tanks currently being used in compact passenger cars as well as larger vehicles such as busses and trucks are predominantly cylindrical in shape. These tanks are mostly stowed in the floorboard or the trunk of the smaller cars while busses usually have an array of roof mounted tanks. The shape of the tanks along with their installation location on the vehicles makes in-service inspection using traditional NDT techniques almost impossible.

Some of the changes suggested in order to make in-service inspection of the tanks a feasible proposition are:

- Design of conformal tanks which can be stowed in more accessible locations on the vehicle.
- Improved tank design to aid nondestructive testing methods such as ultrasound testing, which give poor results on test specimen with complex geometries.
- Use of embedded sensors, e.g. optical fiber based sensors, which can be wound into the matrix of the tanks' composite over wrap.
- Integrated nondestructive testing in tank manufacturing for improved quality assurance.

5. STANDARDS AND INSPECTION CODES

Table 5 provides a summary of the standards and codes for dealing with inspection of hydrogen storage tanks, piping and other parts of the hydrogen infrastructure [34]. Some of these standards are already in use while the others are currently being developed for use in the near future.

Table 5. Inspection codes and standards for hydrogen infrastructure [34].

Category	Standard	Scope	Status
Transportation Tanks	ASME Boiler and Pressure Vessel Code Section XII	This Section includes transport tanks currently covered under DOT specifications and 49 CFR requirements, specifically, Portable Tanks, Cargo Tanks and Rail Tank Cars.	Published in 2004. It is available through ASME. A “Project Team on Hydrogen Tanks” has been formed and is working to expand this standard to include requirements for hydrogen. The work of this team will also affect Section VIII Divisions 1 and 3, Code Case 2390 and possibly Section X. Key activities include: 1. Fracture resistance requirements, 2. Addition of new materials, 3. Design margins for composite vessels, 4. New code case for composite vessels, 5. Revision of Code Case 2390, 6. Metal hydride vessel design, and 7. Improved methods for in-service inspection.

Table 5. Inspection codes and standards for hydrogen infrastructure (contd.).

Category	Standard	Scope	Status
Vehicle Tanks			
1. Gaseous Storage	CSA- America, HGV2, Standard Hydrogen Vehicle Fuel Container	The NGV2 committee expanded its scope to address compressed hydrogen vehicle fuel containers. The containers under consideration are not over 1,000 liters in water capacity and may be metal or resin impregnated filament with metal or non-metallic liners.	Committee working with: 1. OEM's and tank manufacturers, and reviewing ISO requirements on the subject, and 2. ASME Steering Committee on issues of possible hydrogen embrittlement. Target date July 2007
2. Liquid	International Organization for Standardization (ISO) ISO TC197 WG#1 Technical Committee No. 197 – Hydrogen Technologies Work Group #1 Land Vehicle Fuel Tanks	The document specifies the construction requirements for refillable fuel tanks for liquid hydrogen used in land vehicles as well as the testing methods required to ensure that a reasonable level of protection from loss of life and property resulting from fire and explosion is provided.	Scheduled for publication before the end of 2006
Hydrogen Dispersing and Hydrogen Service Station Components	CSA America HGV4 Series for fuel dispensing equipments and components	The NGV 4 committee expanded its scope to address dispensing hydrogen for hydrogen gas powered vehicles. Further details of the activities are provided in Appendix A.	The TAG (Technical Advisory Group) for this series met in October to review working group drafts. The working groups continue to work on these drafts. Target date July 2007.

6. REQUIREMENTS FOR THE HYDROGEN INFRASTRUCTURE

The commercialization of Hydrogen powered vehicles will require the presence of a very strong supporting infrastructure comprised of hydrogen filling stations, hydrogen transportation pipelines, facilities for hydrogen storage at generation sites and filling stations, etc.

Nondestructive testing of the individual components of such an extensive infrastructure is a more complex and critical problem as compared to the testing of vehicular hydrogen storage tanks. Separate codes and inspection standards will be required along with a large number of skilled and semi-skilled operators having a proper understanding of the test procedures and the capability of interpreting test results. The critical nodes in the overall infrastructure will need to be identified and monitored closely to ensure smooth operation of the overall system. An exhaustive list of the existing hydrogen vehicle related codes and standards, along with the ones which are currently being developed can be found online at http://www.fuelcellstandards.com/Quick_Reference.htm [34].

The switch to an alternative energy source from a primarily hydrocarbon fuel dependent social and commercial setup will also have a number of socio-political implications, all of which are not clear at this point. With the expansion of the hydrogen infrastructure in the near future a number of these issues will come to the forefront and will have to be dealt with effectively.

7. DEMONSTRATIONS/PROOF OF CONCEPT

Field applications of NDT techniques to the inspection of hydrogen pressure vessels or other components of the hydrogen infrastructure (such as pipelines, hydrogen storage tanks at filling stations, etc.) have the following principal requirements:

- The inspection process should be completed in a short span of time
- Results generated should be easily displayable on commercially available CRT and LCD displays
- Operators with minimal training should be able to visually interpret the results

Most of the currently used NDT techniques such as ultrasound testing, eddy current testing etc. require that the part under inspection be raster scanned so that data for each scan point can be recorded. Only after the entire test surface has been scanned can a complete image be displayed. This process is time consuming and inconvenient and may be unsuitable for most in-service inspections. The following section briefly describes two innovations that are aimed at tackling the above mentioned drawbacks.

7.1. Laser Ultrasonic Camera

This novel camera developed by the researches at the Idaho National Engineering and Environmental Laboratory (INEEL) has the capability of producing a one shot image of ultrasonic motions in the sub-nanometers range on the surface of objects at frequencies ranging from Hz to GHz [35]. The one shot imaging approach produces a full field image of the entire test area without having to resort to raster scanning, thereby reducing inspection times drastically. The INEEL laser ultrasonic camera utilizes laser for ultrasonic generation and a photorefractive approach to interferometry to produce full field image of ultrasonic motion over a large area. The laser ultrasonic camera provides a non-contact inspection method which is desirable for most field applications. Appendix B provides more details on the INEEL laser ultrasonic camera.

7.2. Thermographic Camera

A thermographic camera, also sometimes referred to as an infrared camera, produces an image using infrared radiation [36]. All objects radiate heat naturally and a thermographic camera can be used to capture the differential heat distribution in them to reveal the presence of discontinuities. The test specimen can also be heated by an external energy source and then photographed with a thermographic camera [36]. The one shot imaging approach coupled with the fact that no contact is required with the object under test makes the thermographic camera a very practical tool for field applications. Figure 18 shows a handheld thermographic camera.

Figure 18. Handheld thermographic camera [30].

8. VISIT TO LINCOLN COMPOSITES, INC.

A visit was arranged and made to Lincoln Composites on November 20, 2006. The attendees were: Drs. Erickson and Zoughi from UMR, Dr. Washer and Mr. Blum (student) from UMC and Mr. Newhouse and Mr. Eihusen from Lincoln Composites, Inc. the primary purpose of this visit was to observe hydrogen tank manufacturing process and discuss the NDE methods that may be used for inspection of these tanks.

The tank consists of an HDPE (high-density polyethylene) liner. The tank ends are manufactured elsewhere and the HDPE is molded around the aluminum boss. The two ends are plastic-welded to the HDPE pipe that forms the length of the pipe. A combination of high strength carbon fiber and glass filaments are wound around this liner. The epoxy resin is applied as the fibers are wound. Three tanks are wound simultaneously on a particular machine. The winding mechanism was designed by Lincoln Composites and clearly limits their production rate. Though, they have plans to construct another winding mechanism. A foam piece is placed on the shoulders of the tank and then a final fiberglass layer is applied. The assembly is cured and then tested before being painted.

Lincoln Composites also manufactures modules consisting of tanks, pressure relief valves, piping, and support frame for roof- and chassis-mounting on busses and trucks.

The life span of fiber tanks is 20 years with a 3.3 or 3.5 safety margin (the safety margin is the design pressure divided by the service pressure). That is the ISO standard. Though there is some pressure to increase that to 25 years. There is some pressure to reduce the safety margin as well. The OEM's are driving for a long-term goal of a 1.8 safety factor, with a short term goal of 2.5 safety factor. However, a global reduction of 5-10% in the amount of glass fiber will show a failure in 6 months.

Currently, *visual inspection* is the NDE method of choice, but they know that not all failures can be detected visually. One of the engineers related one example of a tank with a dent that was detected by *feel and touch*.

NDE has been attempted, but has not shown Lincoln Composites that a failure can exist blind. In their opinion, on-board NDE could gain 10-15% on the safety margin. NDE is currently addressing steel bottles, but they do not recommend using these NDE techniques on composites. In their opinion, an acoustic emission sensor is probably the best NDE method. One would use a solenoid valve for an actuator and monitor the acoustic emissions for a leak. Another method of assessing damage is hearing the "tick" "tink" as the fibers break as the tank is being filled.

Embedded sensors in the tank have been tried by Powertech. Acoustic emission has been tried by Natural Resources Canada and others have looked at optical glass embedded in the tank. A paper by Robinson addresses the service versus the design pressure and the reliability of carbon and glass fibers.

9. SUMMARY

Nondestructive testing is needed for the hydrogen infrastructure in general and compressed gas hydrogen storage tanks, the current primary form of hydrogen storage, in particular. Visual testing is the current primary method of testing composite compressed gas tanks. Eddy current testing, ultrasound testing, laser ultrasonics, critically reflected longitudinal waves, acoustic emission, thermography, and shearography have all been studied for use on these tanks. Online condition monitoring has also been proposed using resistance strain gauge, fiber-optic strain gauge, and acousto-ultrasonic monitoring. No single nondestructive testing method was found to be able to provide a comprehensive snapshot of the structural health of the storage tanks. Online condition monitoring using embedded sensors seems to hold the most promise for the near future. An extensive collection of standard and codes for manufacturing, testing and maintenance of the hydrogen infrastructure is a critical requirement. A number of these are being currently developed for use in the very near future.

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Appendix A

Details of the various projects under the NGV4 committee involved in developing codes and standards for Hydrogen Dispensing and Hydrogen Service Components are provided below [34].

HGV 4.1 Hydrogen Dispensers

This standard contains safety requirements for the material, design, manufacture and testing of gaseous hydrogen dispensers constructed entirely of new unused parts and materials. This standards does not apply to the nozzle; vehicle to station communication, compression and ancillary equipment, compressed hydrogen gas storage containers, vehicle fueling appliances for HGV, remote station or kiosk consoles and remote sequencing equipment and other remote equipment not supplied as part of the dispenser.

HGV 4.2 Hose and Hose Assemblies for Hydrogen Vehicles and Dispensing Systems

This standard contains safety requirements for the material. Design, manufacture and testing of gaseous hydrogen hose and hose assemblies which are used for (1) connecting the dispenser to the refueling nozzle, (2) use as part of a vehicle on-board fuel system, or 93) use as vent lines which carry gas to a safe location for either vehicle or dispensing systems.

HGV 4.3 Temperature Compensation Devices for Hydrogen Dispensing Systems

This standard details safety performance requirements for gaseous hydrogen fueling station fueling station temperature compensation devices systems. It applies to newly manufactured systems designed primarily to adjust for full fill and to avoid over-pressurization of vehicle fuel storage containers under the operating temperature conditions specified in the standard. This standard does not apply to onboard vehicle temperature compensation systems or components.

HGV 4.4 Breakaway Devices for Hoses Used in Hydrogen Vehicle Fueling Stations

This standard contains safety requirements for the material, design, manufacture and testing of newly manufactured fueling hose breakaway devices. This is not applicable to "Vehicle Refueling Appliances," Dispenser Breakaway Devices or Vehicle Breakaway Components.

HGV 4.5 Priorities and Sequencing Equipment for Gaseous Hydrogen Dispensing Systems

This standard applies to priority and sequencing equipment which are part of a gaseous hydrogen vehicle fueling system. This standard contains safety requirements for the design, manufacture and testing of the priority and sequencing systems for gaseous hydrogen dispensers which are designed primarily to provide compressed hydrogen for vehicle fueling stations. This standard does not apply to the pressure swing absorber sequencing panel or the gas dryer sequencing panel.

HGV 4.6 Manually Operated Valves Used in Gaseous Hydrogen Vehicle Fueling Stations

This standard contains safety requirements for the design, manufacture and testing of manually operated valves for gaseous hydrogen vehicle fueling stations. This standard does not apply to fuel storage container shut-off valves or fueling nozzle valves.

HGV 4.7 Automatic Pressure Operated Valves for Use in Gaseous Hydrogen Vehicle Fueling Stations

This standard contains safety requirements for the design, manufacture and testing of automatic, pressure operated valves used in gaseous hydrogen vehicle fueling stations. This standard does not apply electrically actuated valves, hydraulically actuated valves, pressure regulating valves, pressure relief valves or fueling nozzle valves.

HGV 4.8 Hydrogen Gas vehicle Fueling Stations Compressor

This standard contains safety requirements for the design, manufacture and testing of gaseous hydrogen compressor packages used in fueling station service. This standard applies to newly manufactured equipment designed primarily to provide compressed hydrogen for vehicle fueling stations. This standard does not apply to vehicle fueling appliances for HGV or compressor packages used for non-vehicular fuel appliances

Appendix B

The following article on the INEEL laser ultrasonic camera was obtained from the fact sheet published online by The Idaho National Engineering and Environmental Laboratory at http://www.inl.gov/factsheets/industrial/ultrasoniccamera.pdf [34].

Idaho National Engineering and Environmental Laboratory

INEEL LASER ULTRASONIC CAMERA

Researchers at the Idaho National Engineering & Environmental Laboratory (INEEL) have developed a unique and versatile new method for detection of ultrasonic motion at surfaces. This method directly images, *without the need for scanning*, the surface distribution of subnanometer motions at frequencies from Hz to GHz. Applications include measurement of material properties of sheet materials such as paper, plastic, metal, as well as of bulk objects.

Ultrasonic waves form a useful nondestructive evaluation (NDE) probe for determining physical and mechanical properties of materials and parts. This is because ultrasonic waves or "sound" can be generated in all forms of matter: liquids, solids and gases and exhibit information about the material in which they travel. Measurement of the characteristics of ultrasonic wave motion, such as wave speed, attenuation and the presence of scattered waves from microstructural features or flaws are used to perform NDE for quality control. Laser ultrasonics refers to the process whereby lasers are used for both generation and detection of ultrasonic waves in materials, thereby providing a noncontacting method for performing ultrasonic NDE. The current state of the art utilizes a pulsed laser for ultrasonic generation through the process of thermoelastic expansion or weak ablation of material. Various methods of detection exist, involving interferometry of the Michelson, Fabry-Perot, and Photorefractive (adaptive) types. Commercially available systems utilize these interferometric methods and provide a "point and shoot" single point measurement capability. In order to perform measurements over a large surface, the laser generation and detection spots must be ***scanned*** in a raster fashion over the area recording ultrasonic signals at each location.

In contrast, the ***INEEL Laser Ultrasonic Camera*** employs a photorefractive (adaptive) approach to interferometry to provide full-field real-time images of ultrasonic motion over large areas. The basic information to be measured, the ultrasonic motion of the surface, is impressed onto the phase of the detection laser beam just as with the other passive methods. The entire optical image of the vibrating surface is formed inside the photorefractive material where it undergoes real time processing due to the dynamics of the photorefractive process. Nonlinear optical mechanisms within the photorefractive recording material are utilized to produce an output image that is a "picture" of the vibrating surface. The net effect is that interferometric detection is accomplished over the entire vibrating surface all at once without scanning, producing an output that can be viewed directly with the eye or with a television camera. No additional electronic or computational processing is required! By eliminating the need for scanning over large areas or complex parts, the inspection process is greatly speeded up.

Laser ultrasonic methods provide noncontacting approaches that are desirable for field applications, such as for remote measurements and in-situ manufacturing process monitoring. An example involves determination of the anisotropic properties of sheet materials by measuring the propagation of elastic

The INEEL is a facility operated for the U.S. Department of Energy

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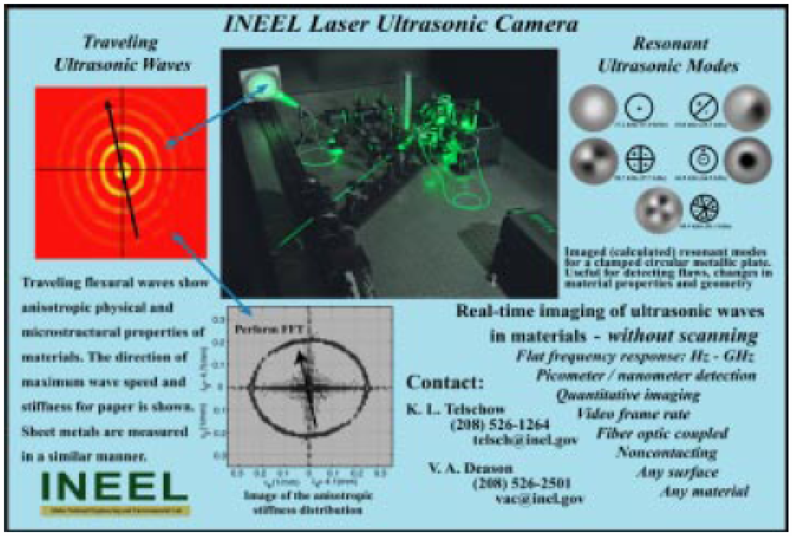
waves, known as Lamb waves, in different directions. The ***INEEL Laser Ultrasonic Camera*** produces a real-time image of propagating Lamb wave modes in all directions along the sheet simultaneously (see illustrations on reverse). The resultant image provides a direct quantitative determination of the phase velocity which depends on the material microstructure, density, and elastic properties in all directions simultaneously, thus showing plate anisotropy in the material. A second example is resonant ultrasonic spectroscopy (RUS), used to detect variations in material and geometry between fabricated parts. Ultrasonic motion of all types in most materials can be imaged and measured using this new approach developed at the INEEL.



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