19

Compact Hydrogen Storage in Cryogenic Pressure Vessels

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CONTENTS

19.1 Introduction ........................................................................................................................ 651
19.2 Historical Perspective ......................................................................................................... 652
19.3 Thermodynamics of Cryogenic Pressure Vessels ........................................................... 654
19.4 Potential Safety Advantages ............................................................................................... 658
19.5 Technology Validation ......................................................................................................... 659
19.6 Increasing Packaging Efficiency with Dual-Volume Vessels ......................................... 661
19.7 Conclusions ......................................................................................................................... 663
Acknowledgments ..................................................................................................................... 663
References .................................................................................................................................... 664

19.1 Introduction

As a universal transportation fuel that can be generated from water and any energy source, hydrogen is a leading candidate to supplant petroleum with the potential to ultimately eliminate petroleum dependence, associated air pollutants, and greenhouse gases [1]. The predominant technical barrier limiting widespread use of hydrogen automobiles is storing enough hydrogen fuel on board to achieve sufficient (500+ km) driving range in a compact, lightweight, rapidly refuelable, and cost-effective system.

There are three major conceptual approaches to storing hydrogen on board automobiles: (1) gas compressed to high pressures (e.g., 350–700 atm) [2,3], (2) lower pressure absorption of hydrogen within porous and/or reactive solids [4,5], or (3) cryogenic liquid (LH₂) at temperatures near its boiling point (20.3 K) [6]. Each approach faces fundamental limits. Hydrogen stored as a compressed gas occupies a relatively large volume at ambient temperature, while materials to absorb hydrogen add significant weight, cost, and thermal
complexity to onboard storage systems. Finally, liquid hydrogen (LH$_2$) evaporates very easily, pressurizing quickly as it absorbs heat from the environment (typically venting after 3 days of inactivity) or from distribution, transfer, and refueling operations.

A new approach has been developed over the last decade that combines existing storage technologies to capture the advantages of both: cryogenic pressure vessels [7–9]. Cryogenic vessels comprise a high-pressure vessel enclosed in high-performance vacuum multilayer thermal insulation (Figure 19.1), enabling hydrogen storage at cryogenic temperatures (as cold as 20 K) and high pressures (e.g., ∼350 atm). For a pressure vessel of given size and cost, a cryogenic pressure vessel stores substantially more hydrogen than a vessel at ambient temperature without the additional weight and cost of hydrogen-absorbent materials but with far greater thermal endurance than conventional (i.e., low pressure) cryogenic LH$_2$ tanks. Cryogenic pressure vessels can essentially eliminate evaporative losses for practical automotive refueling and driving scenarios. High-density storage enables inexpensive, long-range hydrogen-fueled automobiles, and cryogenic operation reduces isentropic expansion energy, potentially improving safety of operation.

19.2 Historical Perspective

When initially proposed in the early 1970s, hydrogen-fueled vehicles demanded low-pressure LH$_2$ [10,11]. Pressurized hydrogen storage was not considered viable. Metallic tanks were extremely heavy and bulky, and composite materials were not available for automotive applications due to technical maturity and cost issues.
Progress in cryogenic technology (a factor of 1000 improvement on cryogenic insulation over 50 years [12]) made a compelling case for LH$_2$ vehicles. BMW, Linde, and Magna Steyr demonstrated LH$_2$ vessels with world-leading weight, volume, and cost performance [6,13]. However, while viable for large vehicles (>10 kg H$_2$), LH$_2$ tanks suffer from considerable evaporative losses when reduced in size due to lower thermal mass that magnifies the effect of environmental heat transfer.

The aerospace industry, more sensitive to weight and less sensitive to cost, did consider composite materials for multiple structural applications. In particular, storage of cryogenic propellants and oxidizers is a key application that was researched from the 1960s [14]. While light and efficient for space travel, cryogenic fluids suffer from evaporative losses during long missions, and minimizing these losses is critical for reducing launch weight. While most efforts have been dedicated to zero boil-off systems where high-performance thermal insulation is complemented by active cryocooling to eliminate evaporative losses [15,16], the concept of storing cryogens in a vessel rated for high pressure (34–120 atm) was also considered for this application [17]. The authors observed the thermodynamic potential for trading-off vessel strength (pressure rating) versus insulation performance: greater pressure rise allows more heat transfer and less insulation. Conversion between the two phases of hydrogen nuclear spin (para to ortho) is endothermic, and the authors also considered the use of catalysts to promote the reaction and further reduce evaporative losses. The results indicate an advantage for cryogenic pressure vessels versus low-pressure cryogenic vessels for Mars exploration due to lower evaporative losses.

Progress in composite pressure vessel technology enabled automotive application starting in the early 1990s and leading to the development of high-performance pressure vessels capable of storing hydrogen at large weight fraction (>10% H$_2$) [18]. However, volumetric performance—critical for efficient packaging within a vehicle—was still limited by the low density of compressed gas.

The first automotive cryogenic pressure vessels were developed at Concordia University (Montreal, Canada) in the early 1990s [19,20]. The concept for these thermocontrolled vessels consisted of filling insulated pressure vessels (rated for 300 atm) with LH$_2$, which was subsequently evaporated, initially from contact with the warm tank and finally by circulating warm gases (e.g., engine exhaust) through an in-tank heat exchanger. Aside from the capacity advantage of storing high-density LH$_2$, thermocontrolled vessels provide a source of high-pressure hydrogen that can be used for direct injection into a hydrogen spark-ignited engine, eliminating power loss that would otherwise occur due to hydrogen displacing ambient air [21]. The potential for evaporative losses for infrequent drivers or during long periods of inactivity was not considered and may be an issue when the cryogenic vessel is pressurized through intentional heat transfer.

Detailed thermodynamic modeling of cryogenic pressure vessels was first conducted at Lawrence Livermore National Laboratory [8]. The analysis revealed the potential for high-capacity vessels that eliminate evaporative losses during regular use. The margin afforded by the high-pressure rating combined with the cooling that occurs as gaseous hydrogen is extracted reduces sensitivity to environmental heat transfer by an order of magnitude when compared to LH$_2$ vessels. It may also enable insulation simplification. While LH$_2$ tanks demand very-high-performance insulation (<3 W heat transfer), cryogenic pressure vessels can operate at higher heat transfer rates (possibly as much as 10 W), enabling thinner and/or simpler insulations that improve packaging efficiency and reduce system cost.
19.3 Thermodynamics of Cryogenic Pressure Vessels

Cryogenic pressure vessels address three key problems stemming from the high volatility of LH$_2$: evaporative losses after a short period of inactivity (dormancy), cumulative evaporative losses for short daily driving distances, and risk of being stranded due to fuel evaporation after long-term parking.

The dormancy (period of inactivity before a vessel releases hydrogen to reduce pressure buildup) is an important parameter for LH$_2$ vehicle acceptability. Dormancy can be calculated from the first law of thermodynamics [22] and the properties of H$_2$ [23] and can be illustrated with a diagram of hydrogen thermodynamic properties (Figure 19.2) to simplify visualization and graphical calculation of dormancy for hydrogen vessels.

Figure 19.2 uses axes of internal energy and density instead of more traditional temperature and pressure. A dormancy calculation begins by identifying the initial thermodynamic state in Figure 19.2 (density and internal energy) of the hydrogen contained in the vessel. From this initial point (e.g., point A), the thermodynamic state of hydrogen fuel on board a parked vehicle moves horizontally to the right (warming at constant density) as

![Figure 19.2](image-url)

**FIGURE 19.2**

Phase diagram for hydrogen showing density (right vertical axis) and internal energy (horizontal axis), with lines for constant pressure (thick lines), temperature (dotted lines), and entropy (thin lines). The figure also shows a thick dashed saturation line that separates the supercritical phase (right) from the two-phase (liquid and vapor) region (left). A second vertical axis in the left shows the mass of hydrogen contained in a vessel with 140 L internal volume, which would store 10 kg of LH$_2$ at 20 K and 1 atm. The figure also shows letters and areas representing dormancy (in Watt days) of conventional LH$_2$ tanks (AB, medium-gray area) and cryogenic pressure vessels (B to E, medium + light + dark-gray areas).
heat enters from the environment, until the hydrogen pressure reaches the vessel maximum and some hydrogen needs to be used or vented. The cumulative thermal energy absorbed while a car is parked can be calculated by multiplying the amount of hydrogen in the vessel by the total change in its specific internal energy. This total thermal energy is shown as the area in Figure 19.2 under the horizontal line joining the initial and final points in the process (neglecting temperature stratification and vessel thermal capacity). Dormancy is then equal to the total heat absorbed (the area under the line) divided by the heat entry rate.

An appropriate choice of scales in Figure 19.2 radically simplifies dormancy calculations. The grid scale in the internal energy (horizontal) axis is set at 86.4 kJ/kg H$_2$, which converts to 1 W-day/kg H$_2$ (1 day = 86,400 s). The grid scale in the vertical axis represents 1 kg H$_2$. Therefore, the area of a grid square represents 1 W-day of heating. The total change in internal energy (in Watt-days) can be easily calculated by counting the squares under the horizontal line representing the parking process. Dormancy is calculated by dividing the internal energy change (in Watt-days) by the rate of heat transfer (in Watts).

As an illustration, consider a parked hydrogen automobile with a conventional LH$_2$ tank with 140 L internal volume and 6 atm maximum working pressure, which is 80% full with 8 kg LH$_2$ at 20 K and 1 atm (point A in Figure 19.2). Once the vehicle is parked, heat entry warms the hydrogen, increasing both its temperature and pressure. Dormancy ends in this case when the pressure reaches 6 atm (point B in Figure 19.2), when hydrogen venting becomes necessary to maintain pressure within the vessel’s limits. Total heat absorbed during this process from point A to point B can be calculated by counting the number of squares (8 W-days) in the area marked in green. Dormancy can then be calculated by dividing 8 W-days by the heat transfer rate (e.g., 2 days for a vessel absorbing heat at a rate of 4 W).

Figure 19.2 illustrates the dramatic dormancy advantage of automobiles with cryogenic pressure vessels. An auto initially filled with 8 kg LH$_2$ at 1 atm and 20 K can remain parked until the pressure reaches 340 atm (point C in the figure) without venting any hydrogen. Counting squares under the line joining point A and point C, we obtain $8 + 48 = 56$ W-days, seven times greater thermal endurance than a conventional LH$_2$ tank.

Furthermore, unlike conventional LH$_2$ vessels, cryogenic pressure vessels dramatically extend dormancy as the vehicle is driven. For example, if the parked vehicle is driven when the hydrogen is at state C (Figure 19.2) consuming 2 kg of H$_2$ fuel, the remaining hydrogen in the vessel expands and cools following a constant entropy line from point C to point D, extending the thermal endurance of the vessel by an additional 48 W-days before any losses occur (at point E in Figure 19.2). Further driving substantially extends dormancy, essentially eliminating fuel evaporation for even very moderate driving patterns.

In principle, Figure 19.2 enables simple analyses of arbitrary cycles of driving and parking periods. Evaporative losses and dormancy are easily calculable, given a driving schedule, vessel volume, and thermal performance (i.e., heat transfer leak rate).

Figure 19.2 is somewhat conservative because it neglects secondary effects such as vessel heat capacity and heat potentially absorbed by conversion between the two states of nuclear spin arrangement (i.e., para-hydrogen conversion to ortho-hydrogen) of hydrogen molecules. Both of these effects tend to increase the dormancy of the vessels but are most significant only for warmer temperatures (T > 77 K) and partially full vessels where thermal endurance is a substantially easier challenge. Both effects are negligible at the very low (i.e., 20–30 K) temperatures where conventional LH$_2$ tanks operate.

From Figure 19.2, it is clear that insulation performance can be traded off versus vessel pressure rating: dormancy can be increased by either improving insulation or by
strengthening the vessel. This trade-off is better illustrated in Figure 19.3, which shows contour lines of dormancy versus heat transfer rate (x-axis) and vessel rated pressure (y-axis) for an initially full vessel (140 L internal volume and 10 kg LH\textsubscript{2} at 1 atm). The figure shows that a pressure vessel may reach acceptable dormancy (5 days) through either (1) high-performance insulation (∼3 W) at low rated pressure (∼167 atm) or (2) high rated pressure (700 atm) at low-performance insulation (∼17 W). Even larger heat transfer rates would be allowable in continuously driven vehicles (e.g., taxis, buses) since strong vessels (>500 atm rated pressure) deliver 1 day of dormancy at heat entry rates over 60 W. The optimum design point depends on the relative cost of fiber and insulation, as well as the particular mission requirements.

It should also be noted that Figure 19.3 assumes a completely full vessel—the best case for low-pressure vessels and the worst case for high-pressure vessels. Low-pressure vessels (<10 atm) have maximum dormancy when full because the thermal inertia of the evaporating LH\textsubscript{2} slows down pressure rise. On the other hand, cryogenic pressure vessels gain most of their dormancy from containing the hydrogen as they heat up and therefore have longest dormancy at low fill levels where the vessel can heat up more before reaching the rated pressure. Dormancy is infinite when ambient temperature hydrogen at rated pressure is denser than the cryogenic hydrogen stored in the vessel.

Considering that (1) vehicles are typically not filled to full capacity before extended parking and (2) even short distance driving plays a considerable role in cryogenic pressure vessel dormancy (Figure 19.2), it is important to consider all factors for enabling quick visualization of thermal performance and dormancy. Figures 19.4 (vessel rated for 135 atm) and 19.5 (vessel rated for 350 atm) assume a 140 L vessel (10 kg LH\textsubscript{2} when full) with 5 W heat transfer rate, installed on board an efficient vehicle (100 km/kg H\textsubscript{2}). For any given vessel pressure (x-axis) and hydrogen mass (y-axis), the figures give (1) dormancy, (2) daily driving distance necessary to eliminate evaporative losses, (3) temperature, and (4) entropy.
As an example of the application of these figures, assume that a vessel with a 140 L internal volume and 135 atm rated pressure contains 6 kg H\textsubscript{2} at a pressure of 105 atm. Finding the location of this point in Figure 19.4, we determine that the vessel contains hydrogen at \( \sim 60 \) K and will start venting in \( \sim 1 \) day if left unused and driving \( \sim 45 \) km/day will suffice for eliminating all evaporative losses.

A comparison between Figures 19.4 and 19.5 illustrates the thermal performance advantages of stronger vessels. The infinite dormancy region more than doubles in size as the pressure rating is increased to 350 atm (Figure 19.5) due to the higher ambient temperature storage capacity. Even in the regions where evaporative losses are possible, dormancy is considerably longer, and minimum daily driving distance is much shorter as the rated pressure is raised, eliminating evaporative losses under practical driving scenarios. These advantages of cryogenic pressure vessels must be balanced against the added cost and weight of structural materials and the cost of high-performance insulation.

It is worth noting that there is no risk of being stranded due to evaporative losses during cryogenic pressure vessel long-term parking. Even when thermal equilibrium with the environment is reached (after months of parking), a substantial fraction of the original hydrogen remains (15% at 135 atm and 30% at 350 atm, infinite dormancy limit in Figures 19.4 and 19.5). This is sufficient for reaching a refueling station even in remote locations.
19.4 Potential Safety Advantages

Cryogenic pressure vessels offer a number of potential safety advantages. The most dramatic and perhaps counterintuitive is the radically lower theoretical burst energy of low-temperature H₂. Figure 19.6 shows the theoretical maximum mechanical energy released by a sudden adiabatic expansion to atmospheric pressure (e.g., in a vessel rupture) of high-pressure hydrogen gas from three temperatures (80, 150, and 300 K). H₂ stored at 70 atm and 300 K will release a maximum mechanical energy of 0.55 kWh/kg H₂ if suddenly (i.e., adiabatically) expanded to atmospheric pressure (cooling substantially in the process). Counterintuitively, this maximum energy release increases only slightly with much higher H₂ pressures. Raising vessel pressure to 1000 atm (1400% increase from 70 atm) increases maximum mechanical energy release by only 10% while shrinking vessel volume and strengthening (thickening) vessel walls many times over. The low burst energy and high hydrogen storage density of cryogenic temperatures combine synergistically, permitting smaller vessels that can be better packaged on board to withstand automobile collisions. The vacuum jacket surrounding a cryogenic pressure vessel (Figure 19.1) offers a second layer of protection, eliminating environmental impacts over the life of the pressure vessel. Vacuum jacketing also provides expansion.
Compact Hydrogen Storage in Cryogenic Pressure Vessels

volume to mitigate shocks from hydrogen release. Cryogenic vessels avoid the fast fill heating and overpressures (up to 25%) typical of ambient temperature vessels, consequently operating at higher safety factors, especially as driving the automobile cools the remaining hydrogen fuel and reduces average hydrogen pressures further over typical driving and refueling cycles. Finally, due to the high density of cryogenic hydrogen and the relatively low refueling pressure, the number and amplitude of pressure peaks in a cryogenic pressure vessel can be lower than in ambient high-pressure vessels.

19.5 Technology Validation

Three generations of cryogenic pressure vessels incorporating aluminum-lined, composite-wrapped vessels, an outer vacuum vessel, and multilayer vacuum insulation to minimize heat transfer have been designed, assembled, and demonstrated at LLNL (Figure 19.7). The designs also included instrumentation for pressure and temperature as well as safety devices to prevent vessel failure. The figure shows specific weight and volume performance for the three vessels (weight fraction and grams of H₂ per liter), as well as the Department of Energy (DOE) 2010, 2015, and ultimate weight and volume targets [24].
The latest prototype cryogenic pressure vessel (generation 3) takes advantage of the insensitivity to environmental heat transfer to considerably reduce insulation thickness (to ∼1.5 cm vs. ∼3 cm typical of LH$_2$ vessels), significantly reducing system volume. This more compact vessel is expected to still provide acceptable dormancy.

Table 19.1 lists detailed component weight and volume breakdown for the generation 3 cryogenic pressure vessel. Thin insulation produces a very compact and light design that meets the very challenging DOE 2015 weight and volume targets and is within 3 kg of meeting the DOE ultimate weight target. Further gains in packaging density may be obtained by pressurizing LH$_2$, theoretically increasing hydrogen storage capacity by ∼20% for isothermal compression (84 kg/m$^3$ hydrogen density at 20 K and 250 atm), although 5%–10% density increase is more likely once pumping inefficiencies and compression heating are considered.

The US DOE has also established cost targets for hydrogen storage systems [24]. While cryogenic pressure vessels are projected to be cost competitive with respect to alternatives [25], they still cost three to four times more than the DOE 2010 target ($13.6/kWh vs. $4/kWh). Cost may therefore be the most challenging of DOE targets, even though future improvements on vessel materials, manufacture, and insulation may reduce expense below projected values.
#### TABLE 19.1

Weight and Volume of the Main System Components for the Generation 3 Cryogenic Pressure Vessel and for the Dual-Volume System

<table>
<thead>
<tr>
<th>Components</th>
<th>Generation 3</th>
<th>Dual Volume (Projected)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight (kg)</td>
<td>Volume (L)</td>
</tr>
<tr>
<td>Hydrogen inside cylindrical vessel(s)</td>
<td>10.7</td>
<td>151</td>
</tr>
<tr>
<td>Hydrogen within low-pressure vessel</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total hydrogen stored</td>
<td>10.7</td>
<td>151</td>
</tr>
<tr>
<td>High-pressure vessel(s)</td>
<td>61</td>
<td>28</td>
</tr>
<tr>
<td>Low-pressure (interstitial) vessel</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Insulation and vacuum shell</td>
<td>57</td>
<td>46</td>
</tr>
<tr>
<td>Total, vessel and vacuum shell</td>
<td>118</td>
<td>74</td>
</tr>
<tr>
<td>Total, vessel(s), vacuum shell, and hydrogen</td>
<td>129</td>
<td>225</td>
</tr>
<tr>
<td>Total for accessories</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Total, storage system</td>
<td>145</td>
<td>235</td>
</tr>
<tr>
<td>$H_2$ weight fraction</td>
<td>7.38%</td>
<td>45.49</td>
</tr>
</tbody>
</table>

The generation 3 vessel was built and installed on board a Toyota Prius experimental vehicle. The dual-volume system has been designed and analyzed, but it has not been built. For comparison, the DOE 2010 targets are 4.5% weight fraction and 30 g H$_2$/L; DOE 2015 targets are 6% weight fraction and 40 g H$_2$/L; ultimate DOE targets are 7.5% weight fraction and 70 g H$_2$/L [24]. Storage calculations assume 70.7 kg/m$^3$ hydrogen density (LH$_2$ at 20 K and 1 atm). The table assumes that all stored hydrogen is usable, although driving at high power for a long time may drop the vessel pressure below the necessary level to run the engine or fuel cell, reducing the net hydrogen storage density by a few percent [26].

#### 19.6 Increasing Packaging Efficiency with Dual-Volume Vessels

Cryogenic pressure vessels store high-density LH$_2$ while avoiding evaporative losses with thin insulation resulting in high system storage density. However, even LH$_2$ is only a fourth as energetically dense as gasoline, and the generation 3 vessel is approximately six times larger than a gasoline tank with the same energy storage. While there is still potential for improving cryogenic pressure vessels through more compact construction, we also see the possibility of using conformable designs that may package better inside the vehicle than conventional cylindrical shapes.

Conformable vessels hold the promise of better filling box-shaped or even irregularly shaped spaces, improving packaging efficiency by 20%–40% over conventional cylindrical vessels. However, conformable vessels remain a structural challenge [27,28]. Noncylindrical, nonspherical shapes suffer from bending stresses that quickly exceed the strength of structural materials—even ultrastrong carbon fiber. Applicability of conformable box-shaped vessels is therefore limited to low pressures (~6 atm), typically too low for compact hydrogen storage.

We can, however, take advantage of low-pressure conformable vessels through a new concept: dual-volume containers. The concept of a dual-volume container (Figure 19.8...
combines two high-pressure (∼250 atm) cylindrical vessels enclosed within a low-pressure (∼6 atm) box-shaped conformable container that can be filled with low-pressure LH₂, enabling utilization of interstitial spaces and corners that are normally wasted in cylindrical vessels. The low-pressure container is then surrounded with thin (6.5 mm) vacuum multilayer insulation for reducing heat transfer into the vessel.

The geometry of dual-volume vessels is synergistic with hydrogen properties because the interstitial space can store LH₂ at low pressure and high density. While the low-pressure container will have reduced thermal endurance (∼2 days), it can be used for extending vehicle range when most needed—during long trips. Continuous driving quickly consumes hydrogen before any evaporative losses may occur. The driver may then fill only the cylindrical pressure vessels with LH₂ and leave the interstitial vessel empty when little driving is anticipated, avoiding evaporative losses while still maintaining a reasonable driving range.

The dual-volume design in Figure 19.8 has improved packaging efficiency due to interstice utilization. A system with 11.4 kg H₂ storage capacity would store 5.4 kg LH₂ in 76.7 L of interstitial space, often wasted in cylindrical vessels. Each of the inner high-pressure linerless vessels stores 3 kg LH₂ in 43.3 L of internal volume.

The dual-volume vessel in Figure 19.8 has been analyzed and designed by finite element. Table 19.1 lists the projected weight and volume of the vessel and accessories. The table shows that the dual-volume vessel has potential for producing very high weight and volume performance, and it is projected to meet or exceed the DOE 2015 targets.

Vessel volume listed in Table 19.1 is the total external volume (i.e., the shrink-wrap volume). However, considering that spaces in vehicles are typically box-shaped rather than cylindrical, it may be appropriate to define vessel’s effective volume performance not in terms of total external volume but rather in terms of the volume of a box that encloses the system. It would therefore make sense to define a conformability credit as the hydrogen volume stored in a conformable vessel that occupies a box-shaped space divided by the hydrogen volume in cylindrical vessels that can be packaged within the same box-shaped space. This criterion would give the dual-volume vessel a 22% conformability credit that would
increase the volumetric performance from 53 to 64 g H₂/L—over 90% of the density of pure LH₂ at ambient pressure (70.7 g/L).

It may be possible to reach the DOE ultimate volume target (70 g/L) by filling the cylindrical vessels with pressurized LH₂ and the interstitial vessel with low-pressure LH₂. At 84 g/L (LH₂ at 20 K and 250 atm), the total amount of hydrogen in the cylindrical vessels would grow to 7.3 kg, for a total of 12.7 kg once the interstitial vessel is considered. This would raise weight and volume performance metrics to 7.3% H₂ and 72 g H₂/L (assuming 22% conformability credit). If packaged into a vehicle, this dual-volume system would provide an unprecedented level of storage performance, potentially enabling practical range in most hydrogen vehicles.

19.7 Conclusions

Unlike other fuels, hydrogen can be produced and consumed without generating carbon dioxide. If generated using renewable energy, hydrogen becomes a versatile, storable, and universal carbonless energy carrier that does not pollute. The greatest engineering challenge associated with hydrogen fuel is storing enough hydrogen on board the vehicle for a reasonable range (500 km).

First developed for aerospace applications, cryogenic pressure vessels are now being researched for automotive use. Cryogenic pressure vessels can store high-density hydrogen, similar to LH₂ vessels, without the evaporative losses. They are more compact than compressed hydrogen, therefore reducing the need for expensive carbon fiber. They are light and offer potential safety advantages due to reduced isentropic expansion energy at low temperature.

The versatility and flexibility of cryogenic pressure vessels enable high hydrogen storage density while avoiding evaporative losses, maintaining reasonable cost, and allowing fast refueling. The recent generation 3 prototype is the first automotive hydrogen vessel to meet the DOE 2015 weight and volume targets.

Conformable dual-volume vessels store hydrogen in interstitial and corner spaces that typically go unused in cylindrical vessels, thereby improving packaging efficiency and providing even higher hydrogen storage performance, leading to unprecedented levels of volume storage capacity. Predicted storage packaging density would enable long-range hydrogen transportation in a broad line of today’s vehicles. Ongoing and planned work is addressing the technical challenge of simultaneously improving insulation performance and packaging efficiency while maintaining low cost.

Acknowledgments

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Compact Hydrogen Storage in Cryogenic Pressure Vessels
