2.4 Gaseous Storage of Hydrogen

2.4.1 Compressed Hydrogen Storage (CH$_2$).

5700 g of CH$_2$ (with installed volume of 397 liters) at 300 K and 3000 psi is required to provide the work potential of 7.5 gallons (28.4 liters) of gasoline (providing 300-mile range in a 40 mpg vehicle). According to Gordon (68), compressed hydrogen storage cylinders constructed out of composite materials could be made available by 1990 as the commercial technology improves. These composite cylinders will hold pressures of 6000 to 10,000 psi and could ultimately enjoy a volumetric density of about 21 kg/m^3 (at ~10,000 psi) and a mass density of 5.5 wt% H$_2$. Therefore, an advanced composite container holding 5.7 kg of CH$_2$ would provide a range of 300 miles in a hydrogen vehicle, but will require a storage space of 260 liters (69 gallons) and weigh about 230 lb (104 kg). This will then be about nine times bulkier and three times heavier than a typical 7.5-gallon gasoline tank. Such a CH$_2$ storage system will still be comparable to the metal hydride systems and LH$_2$ tanks providing a 300-mile range (62).

Table XIII					
Approximate Total CH$_2$ Storage System[1] Mass (Kg) and Volume (Liters) as a Function of Vehicle Range and Storage Pressure (62)					
Pressure (psi)					
Range (miles)	3000 W V	6000 W V	8000 W V	10000 W V	Comparable Gasoline Tank[2] W V
250	65 409	72 273	78 246	85 228	26 25
300	77 489	85 327	92 295	101 271	30 31
350	91 574	101 383	109 346	119 319	34 36

[1] Carbon/aluminum compressed gas vessel.
[2] Six lb per gallon; 20-lb tank for 250 miles, 21.7-lb tank for 300 miles, 23.3-lb tank for 350 miles and 25-lb tank for 400 miles. 40-mpg vehicle and an outer to inner storage tank ratio of 1.075 is assured.

Table XIII depicts the installed volume and weight of CH$_2$ systems using the data of Gordon (68). The data are obtained for the performance of carbon/aluminum vessels, which are the strongest and most expensive per unit of weight of any developed to date (62, 69). Cheaper Kevlar-wrapped cylinders can also be used but their burst pressure is only 60 to 70% of that for carbon/aluminum vessels

unit weight of the container (70). Therefore, for Kevlar-wrapped tanks, the total storage system weight (including approximately 6 lb of hydrogen fuel) should be about 1.6 times those shown in Table XIII for carbon/aluminum vessels.

2.4.2 Compressed Methane Gas Storage (CCH₄)

2.4.2.1 Advanced Storage Technology for Compressed Methane Vehicles.
A comprehensive review of the current technology is given by DeLuchi et al. (62). Aluminum tanks wrapped with fiberglass, Kevlar or carbon fibers provide one-half to one-quarter of the weight of that of steel tanks in common use today. A dedicated Ford compressed methane vehicle with 5 spun-aluminum, Kevlar-wrapped tanks (weighing 28.5 pounds each) had an interior capacity of 26.5 liters (71). The five tanks store 40.9 lb of methane, had a volume of about 174 liters, and weighed about 208 lb (62). Pressurized to 2500 psi, these tanks could provide a 200-mile range, giving an apparent vehicle efficiency of about 25 mpg. One can compare the size and weight of this storage system with that of a gasoline tank of equal range. A small gasoline tank, holding on the order of 10 gallons, weighs about 26 lb (72, 73) and gasoline weighs ~6 lb per gallon, then gasoline tanks displace about 5 to 10% more space in the vehicle than their material volume. Therefore, an 8.5 gallon tank, which in a 40 mpg vehicle provides a 340-mile range (comparable to the Ford's vehicle) weighs about 76 lb and displaces 9.0 to 9.5 gallons (34 to 36 liters). Thus, the Ford's storage system is about five times larger and weighs an extra 132 lb. As a result of these extra pounds, a slight decrease in efficiency may occur.

Compressed methane cylinders will be required to have a burst pressure of 2.7 to 3.0 times their normal operating pressure (62). The minimum burst pressure of the cylinders used by Ford was 9000 psi. It is noted that Canada and Italy would not allow maximum operating pressures in compressed gas storage tanks exceeding 3000 psi. This will then eliminate one of the original five tanks used in the Ford vehicle, reducing its range to 310 miles. The overall weight would be reduced to 171 lb and overall storage volume to 139 liters. The equal-range 8-gallon gasoline tank would weigh about 73 lb and displace around 33 liters. The weight difference thus would be reduced to 98 lb.

The use of carbon fiber instead of Kevlar will further reduce the weight of the storage system (with the same vehicle range and storage volume) (68). But, carbon-wrapped vessels are three times as expensive as Kevlar-wrapped and ten times as expensive as fiberglass vessels (62). The sizes and weights of composite pressure vessels as a function of range and pressure, for the technologies discussed above, are given in Tables XIV and XV. Based on these data, it appears that using higher storage pressures, above 3000 psi, would, up

to a point, reduce the volume of the system for a given range, relative to lower pressure systems, and also would increase the weight. The weight would increase because increased storage pressure results in an increased vessel weight gain which is much more rapid than the increase in the amount of gas contained (because of nonideal gas behavior at high pressures). Therefore, for methane there would be no advantage to using storage pressures above 4500 psi which can be considered the volumetrically optimal storage pressure. A 4500-psi storage system would weigh 13 to 25 lb more than a 3000 psi system providing the same 300-mile range, but would displace 20 liters less. The extra 20 lb or so would not affect handling or efficiency of the vehicle appreciably, while an extra 20 liters of storage space is gained.

The least expensive cylinders, fiberglass/aluminum composites, would be about 3.45 times larger and 144 lb heavier than a gasoline tank, for a 300-mile range and storage at 4500 psi (62). The most expensive cylinder, a carbon/aluminum composite, would have the same displacement as the fiberglass-wrapped cylinder, but would weigh only 35 lb more than the gasoline vehicles. Unfortunately, these vessels would be prohibitively expensive. High-pressure tanks are more expensive than lower pressure tanks, primarily due to the increased wall thickness, and would be more expensive to refill, because of the extra energy needed to reach the much higher pressures. They also might take longer to refill on an energy-unit basis. Replacing four cylinders with one of equal total capacity, or replacing the cylinder with a sphere is unlikely to improve the storage efficiency (70). Containers should be made compatible with the minimum required for the desired service pressure to minimize the cost. Furthermore, the required ratio of burst to operating pressure should be as low as is safe.

Table XIV

The Volume (liter) of Compressed Methane Systems as a Function of Range and Pressure (62)

Range (miles)	Service pressure (psi)					Gasoline Tank
	2500	3000	4500	6000	10000	
250	117	106	90	86	86	25
300	140	127	107	103	106	31
350	164	149	124	120	120	36
400	187	170	143	137	137	41
Ratio to Gasoline Tank	4.55:1	4.15:1	3.45:1	3.35:1	3.35:1	1:1

The compressed methane storage systems are still several times larger than gasoline tanks providing the same range. It is probable that compressed methane vehicles would have a shorter range than gasoline and perhaps methanol vehicles. With advanced technology, commercially available today, and moderately higher storage pressures, the volume and especially the weight difference between compressed methane vessels and gasoline tanks can be greatly reduced relative to using USDOT all-steel cylinders.

According to DeLuchi et al. (62), mass-produced, fiberglass-wrapped cylinders (providing a 300-mile range in a 350-miles/10^6Btu vehicle) would add about $700 to $850 to the price of the vehicle. This estimate includes the additional support components (i.e. values, vapor seal, mounting brackets, etc.) as necessary. It is also foreseen that composite vessels would last at least 30 to 40 years with a salvage value of 25 to 45% at the end of the life of the vehicle (62).

<table>
<tr><td colspan="7" align="center">**Table XV**
Mass[1] (kg) of Compressed Methane Storage Systems[2] as a Function
of Range, Pressure and Technology[3] (62)</td></tr>
<tr><td rowspan="2">**Range
(miles)**</td><td rowspan="2">**Weight of
gas (kg)**</td><td colspan="4" align="center">**Service pressure (psi)**</td><td rowspan="2">**Gasoline
Tank[4]
(kg)**</td></tr>
<tr><td align="center">**2500
K / C / F**</td><td align="center">**3000
K / C / F**</td><td align="center">**4500
K / C / F**</td><td align="center">**6000
K / C / F**</td></tr>
<tr><td align="center">250</td><td align="center">13.65</td><td align="center">53.1 / 37.2 / 65.8</td><td align="center">54.9 / 38.6 / 68.9</td><td align="center">68 / 43.5 / 79.8</td><td align="center">73 / 49.4 / 93</td><td align="center">26.3</td></tr>
<tr><td align="center">300</td><td align="center">16.37</td><td align="center">63.5 / 44.9 / 79.8</td><td align="center">65.8 / 46.3 / 84.4</td><td align="center">76.2 / 52.2 / 95.7</td><td align="center">87.5 / 59 / 111</td><td align="center">30.39</td></tr>
<tr><td align="center">350</td><td align="center">19.1</td><td align="center">74.4 / 52.2 / 92.5</td><td align="center">76.7 / 53.5 / 95.7</td><td align="center">88 / 60.3 / 110.7</td><td align="center">102 / 69 / 130</td><td align="center">34.47</td></tr>
<tr><td align="center">400</td><td align="center">21.82</td><td align="center">84.8 / 59.4 / 105.2</td><td align="center">87.5 / 61.2 / 109.3</td><td align="center">101.2 / 69.4 / 127.5</td><td align="center">116.6 / 79 / 148.8</td><td align="center">38.56</td></tr>
</table>

[1] Includes mounting brackets at 17% of empty tank mass and fuel.

[2] Estimates (within 10 or 15%) using outer/inner volume ratios. 1.157-1.331 for 3000 and 1.561-1.728 for 10000-psi containers.

[3] (C): carbon/aluminum system; (K): Kevlar/aluminum system and (F): Fiberglass (S-glass)/aluminum syste.

[4] See note 2, Table XIII.