Hydrogen is the most abundant element in the universe and on the earth. However, most of it is in the form of water, and less than 1% exists as molecular hydrogen.\(^1\)\(^2\) Hydrogen is an important potential alternative fuel because it has many attractive properties, such as non-toxicity, clean combustion, and high energy density.\(^2\) The chemical energy per mass of hydrogen is at least three times larger than that of liquid hydrocarbons.\(^1\)\(^2\) However, there are some problems in using hydrogen as a fuel. The most crucial one is to develop safe and efficient storage for it. The U.S. Department of Energy has set the target capacity for storage units as 6.5% hydrogen by mass and 62 kg \(H_2\) m\(^3\) for cars using fuel cells.\(^1\)\(^2\) High-pressure containers and liquid-hydrogen containers conventionally used for hydrogen storage have some dangerous parts and can lose some hydrogen.\(^1\) Also, the capacity for these storage units is only about 4% hydrogen by mass.\(^1\) Thus, many researchers have tried to find better methods for hydrogen storage.

Many metals and alloys have been studied and show the ability of adsorbing hydrogen.\(^1\)\(^3\)-\(^5\) Well-known metals and alloys are enlisted in Table 1.\(^1\)\(^3\) Generally, however, metal hydrides have low mass density and sometimes show unfavorable kinetics which are inappropriate for hydrogen storage.\(^1\)\(^5\) Light-metal hydrides show high hydrogen capacity, such as 7.4 wt% hydrogen for NaAlH\(_4\).\(^7\) However, the light-metal hydrides generally produce the hydrogen at high temperature, above about 200 °C. Bogdanovic et al. showed that the desorption temperature can be decreased by doping NaAlH\(_4\) with Ti catalysts.\(^6\)-\(^11\) They also demonstrated the reversibility for several adsorption and desorption cycles.\(^9\)\(^11\) However, they have not discovered the identity and mechanism of the Ti catalyst in the reaction, which will have to be known for further progress.\(^6\)

**Table 1. Metal hydrides and their hydrogen-storage properties**

<table>
<thead>
<tr>
<th>Type</th>
<th>Metal</th>
<th>Hydride</th>
<th>Mass%</th>
<th>Peq, T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elemental</td>
<td>Pd</td>
<td>PdH(_{0.6})</td>
<td>0.56</td>
<td>0.02 bar, 298 K</td>
</tr>
<tr>
<td>Elemental</td>
<td>Mg</td>
<td>MgH(_2)</td>
<td>7.66</td>
<td>5 bar, 620 K</td>
</tr>
<tr>
<td>AB5</td>
<td>LaNi(_5)</td>
<td>LaNi(_5)H(_6)</td>
<td>1.37</td>
<td>2 bar, 298 K</td>
</tr>
<tr>
<td>AB2</td>
<td>ZrV(<em>2) (</em>{2.5})</td>
<td>ZrV(<em>2)H(</em>{2.5})</td>
<td>3.01</td>
<td>10(^9) bar, 323 K</td>
</tr>
<tr>
<td>AB</td>
<td>FeTi</td>
<td>FeTiH(_2)</td>
<td>1.89</td>
<td>5 bar, 303 K</td>
</tr>
<tr>
<td>A2B</td>
<td>Mg(_2)Ni</td>
<td>Mg(_2)NiH(_2)</td>
<td>3.59</td>
<td>1 bar, 555 K</td>
</tr>
<tr>
<td>Body-centered cubic</td>
<td>TiV(_2)</td>
<td>TiV(_2)H(_4)</td>
<td>2.6</td>
<td>10 bar, 313 K</td>
</tr>
</tbody>
</table>

Yaghi et al. synthesized MOF-5 in 1999, consisting of \([\text{O}Zn]\)\(^{6+}\) groups assembled into the cubic lattice by the organic connectors, BDC(1,4-benzenedicarboxilate), as
shown in Figure 1. They designed and synthesized various isoreticular MOFs by changing the organic connectors. MOF-5 showed 4.5 wt% at 78 K and 1.0 wt% at 298 K and 20 bar in hydrogen capacity. MOF-5 has two different hydrogen-binding sites: one is the \([OZn]^{5+}\), and the other is an organic connector, BDC. Yaghi et al.

Carbon nanotubes, found by Iijima in 1991, were expected to be good for hydrogen storage due to low specific weight and their structure, which is microporous and contains capillaries. Dillon et al. estimated the hydrogen-storage capacity of carbon nanotubes to be 5-10 wt% based on their experimental results. After that, many researchers studied in this area and produced much experimental data. However, this data showed large differences in hydrogen capacity, from 0.01 to 10 wt% for the same material, single-walled carbon nanotubes. In some cases, the controversy is caused by non-reliable characterization of the carbon nanotubes used in the experiments, as well as improper analytical methods. Some groups claimed that hydrogen-storage capacity of carbon nanostructures is proportional to the specific surface area by 1.5 wt% per 1000 m²/g. Also, many theoretical calculations have been performed for understanding adsorption processes and maximum possible storage capacity for carbon nanotubes. By theoretical calculation, the maximum capacity is 4.2 wt% for physisorption and about 14 wt% for chemisorption of hydrogen.

In conclusion, light-metal hydrides and metal organic frameworks showed promising results. Further research of carbon nanotubes is needed to establish whether they are suitable materials for hydrogen storage.
References


