TBD

Charles Hoes, System Safety Engineer

For years, *TBD* has been a regular feature in the *Journal of System Safety*, covering key trends, insights, and updates in the world of system safety. Interestingly, TBD actually began as a placeholder title because we couldn't decide whether the column should have a specific "topic" or be more free-form. But as time went on, the title stuck because it's a reminder that system safety is an ongoing journey – to be determined.There's always more to learn, new challenges to tackle, and fresh insights to uncover. So every time you see TBD, think of it as a nod to the ever-evolving nature of safety science—where the work is never quite "done."

HYDROGEN VERSUS LITHIUM BATTERIES FOR ENERGY STORAGE

Currently the two best candidates for chemical energy storage are the two lightest metals – sort of. Lithium, a light highly reactive metal, it is the main component of the lithium batteries used to power many portable electronic devices and electric cars. Hydrogen is also a metal that at normal conditions is nonmetallic, but becomes a metal at high pressures (very high pressures). Both of these elements can be used to create efficient, light weight, high energy density electrical storage systems. However, from the safety and environmental (and cost) point of view they are very different.

It might be worth taking a few minutes to dispel some myths concerning the safety of hydrogen. Perhaps the first myth that needs to be dispelled is the popular idea that hydrogen is "extremely dangerous" as evidenced by the Hindenburg fire. Granted, the burning of the Hindenburg was a great tragedy and very spectacular, but it was not "just" a hydrogen fire as is widely reported. The fire resulted from a combination of factors, not the least of which was the use of highly flammable coatings on the fabric of the dirigible. There is a lot of debate concerning the details of the Hindenburg disaster, so many that a "true" story may never be told. However, it seems clear that the magnitude of the fire and speed of spread was a combination of the presence of very large quantities (over 7 million cubic feet) of highly flammable hydrogen gas and the highly flammable covering.

When hydrogen burns the flame is almost invisible. The photographs of the fire clearly show very large colored flames. This means that something besides hydrogen was burning, and that "something" contributed greatly to the intensity and spread of the fire. The bulk of the hydrogen wasn't burning, and probably never did because it consisted of 100% hydrogen gas which requires mixing with oxygen in order to burn. It is my guess that most of the released hydrogen escaped into the atmosphere and mixed with air and diluted below the flammable range and therefore didn't ignite. Some of the hydrogen burned, but probably not all of it. The burning hydrogen may well have ignited the structural elements of the craft but it wasn't just a "hydrogen fire" – it was a fire that resulted from a complex interaction of many features of the design of the entire system. The Hindenburg was designed and built as a helium filled set of balloons. Switching to using hydrogen instead of inflammable helium resulted in an extremely dangerous situation. Hydrogen can be used safely, but only if done so properly – just as with any other energetic material.

One feature of hydrogen fires is that they don't radiate much infrared thermal energy; in fact they emit so little visible light and "heat" that workers in hydrogen facilities sometimes walk holding brooms in from of them so they can detect a large hydrogen fire before walking into the invisible flame. Hydrogen fires don't emit infrared energy that can cause flammable materials to catch on fire at a distance from radiation. The Hindenburg fire probably spread as fast as it did because the brightly glowing particles from the burning structure emitted large amounts of infrared ("heat") energy that ignited unburned fabric well in advance of the flame front. My guess is that it spread so rapidly because the ignition was spread by thermal radiation reaching far in advance of the flame front.

While hydrogen gas can undoubtedly be quite dangerous, that does not mean that it is unacceptably dangerous, or as dangerous as other sources of high-density energy. For example, the Space Shuttle safely burned the equivalent of over 34 billion cubic feet of hydrogen (5,000 times the volume of the Hindenburg) during a launch. The risk isn't because of the use of hydrogen; it is HOW it is used. The Hindenburg had many serious design flaws with respect to the use of large quantities of hydrogen that almost guaranteed a disaster such as the Hindenburg fire. Gasoline is considered "acceptable" only because systems have been designed to effectively control the risks. Now and then a large, highly destructive gasoline fire occurs, but this is amazingly rare. It is my engineering judgement (as a System Safety Engineer) that hydrogen gas can be made much safer than gasoline, while they both clearly have significant risks. My point isn't that there are no risks; it is that the risks are comparable to, and often much less, than risks that we accept as a matter of course.

Hydrogen gas comes from many sources, some of which could be called "green" sources, and others not so green. Today, most hydrogen is made from "black" sources of hydrocarbons such as oil, coal or natural gas. There are also largely untapped sources of "white" hydrogen in underground naturally occurring, pockets of geological hydrogen. The most promising source of "green" hydrogen comes from the decomposition (electrolysis) of water into hydrogen and oxygen using power from non-polluting sources such as solar, wind, wave, hydroelectric or geothermal electrical generation systems. This approach uses hydrogen as a type of chemical battery where the energy can be stored in pressurized containers indefinitely until it is needed, at which point it is re-combined with oxygen to form water, releasing energy in the form of heat or electricity.

High capacity storage batteries (such as lithium batteries) are certainly not "safe" or "environmentally friendly." They are highly dangerous both from the potential for them to burn or explode, and from the point of view of containing very large quantities of stored electricity. A major hazard with using high voltage, high capacity batteries in vehicles is related to what happens following an accident that damages the batteries and/or electrical system. The stored energy doesn't just "dissipate" it remains potentially resulting in an explosion or fire, or presenting a high power electrical hazard to first responders and the accident victims. Many interesting, and horrifying, scenarios are possible when these systems become damaged in unpredictable ways.

Perhaps the largest problems with the use of lithium batteries are related to the highly negative impact on the environment associated with mining, refining and disposing of the lithium and various other materials (including graphite, cobalt, manganese and nickel) used in the batteries. With the possible exception of cobalt, there are sufficient amounts of these materials to supply the short term future market, but mining and refining these materials come with substantial negative environmental impacts in terms of size of mining sites, potential for pollution and the use of large quantities of water. Lithium production is particularly problematic because it is found in low concentration surface deposits in arid regions necessitating the destruction of vast areas of environmentally sensitive desert. In addition, large amounts of water are required in the extraction/refining process that can damage already limited sources of surface and ground water.

The most likely use of energy storage in the near future will be to meet the demand for powering electric vehicles. Currently, the two most "market ready" approaches are using rechargeable lithium batteries or lightweight PEM (Polymer Electrolyte Membrane) Hydrogen Fuel Cells. Hydrogen can also be used directly to produce heat or run internal combustion engines, very similar to using natural gas. The airlines are currently doing a lot of research to design jet engines that can use hydrogen fuel in place of jet fuel. Internal combustion engines have made to work quite nicely using hydrogen fuel. Hydrogen is an extremely flexible fuel source that can fill many, if not most, of our current uses for gaseous and liquid fuels, and as a medium for electrical storage without the hazardous voltages inherent in the storage device presented by batteries.

I think most people have a grasp of how rechargeable batteries work, so I won't go into much detail here. The one thing that people might not be aware of is their tendency to catch fire and burn, or explode. These problems have been minimized, but not eliminated, with the current designs used in electric cars. PEM hydrogen fuel cells are generally unknown to the public. I want to briefly describe how they work.

My first encounter with a PEM fuel cell was in a small research laboratory at Humboldt State University (now Cal Poly Humboldt). The fuel cell was in the form of a cube about four inches on a side. It consisted of layers of graphite and a thin membrane resembling "plastic wrap." The graphite layers had been machined to form a serpentine grove allowing air or hydrogen to flow to the surfaces of the graphite layer. The thin membrane (the PEM membrane) was sandwiched between the graphite. It was impervious to relatively large hydrogen molecules, but the tiny amount of catalyst embedded into the membranes allowed the nucleus of hydrogen atoms (protons) to flow through to the other side of the membrane where it combined with the oxygen in air flowing through the other side, creating an electrical charge and thus an electrical current (emitting water as the only byproduct). The hydrogen was "dead headed" into the groves at a pressure of around 1 psi. It didn't need to flow through the stack, it just needed to get to the surfaces. A small fan directed room air through the groves on the "oxygen side" of the stack. The air flowed through the stack to maintain a steady source of oxygen and to exhaust the byproducts of this process (pure water vapor). During operation, the cell felt mildly warm. The striking part was the pair of 1/2 inch thick copper electrodes connected to each side of the fuel cell stack. They had to be that size because of the very large amount of power and electrical current delivered by the cell.

All of the large automobile manufacturers have PEM fuel cell cars ready to manufacture if, or when, the market turns to them. I have seen several of these vehicles by various manufacturers and they are beautiful. The fuel cell modules are around one cubic foot, taking up little of the space "under the hood" of the car. High pressure hydrogen storage tanks are located under the floor of the passenger compartment, similar to the location of batteries in electric cars. I have a friend that had the job of testing many of these cars on the roads of California's highways, byways, deserts and mountains. He said they are wonderful to drive. I suppose just about the same as a modern electric vehicle, which they are.

One of the major advantages of PEM fuel cells for this application is that they are quickly scalable with respect to available sources of fuel. Very large quantities of hydrogen are created from various sources, including fossil fuels. At first this sounds bad, but it provides an easy means of transitioning to hydrogen while green sources of hydrogen are being created. We don't have to wait until enough "green" electrical power it available on the grid. In fact, electric cars change from the grid, they are not using "green" sources of power, they are just using whatever is there from whatever sources are available.

One of the best features of hydrogen as a fuel is that it can easily be made using solar, wind and other sources of "green" energy by the electrolysis of water. For example, solar electricity can be used to make hydrogen, which can then be stored for future use, or shipped via pipeline or tanker to where it is needed (such as filling stations). Not only can it be easily created, stored and transported, but it can be used for a variety of additional purposes to replace the use of hydrocarbons. If produced locally (such as at the site of a home solar system), the hydrogen can be stored for months until needed, or could be used to fuel an automobile during night time hours. Commercial airlines don't think they can use batteries because of weight restrictions, but they can store enough hydrogen – so they can join the "green" energy revolution by converting to hydrogen fuel.

The materials used in the construction of a PEM Hydrogen Fuel Cell system are mostly "normal" construction materials (iron, aluminum, copper) with a very small amount of catalyst similar in quantity to a catalytic converter in a car. All of these materials can easily be recycled and pose no new environmental threats.

The point of this is that we are at a point where hydrogen presents a very flexible and robust solution to moving toward a truly "green" energy economy, while batteries are just taking us down the normal path to excessive environmental damage.