Advances in small scale cryogenic magnetic refrigeration

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Abstract. General Engineering & Research (GE&R) has built an at-scale cryogenic magnetic refrigeration system and successfully demonstrated sustained sub 80 K (-193 °C) magnetocaloric cooling using a Halbach permanent magnet. The successful demonstration of cryogenic magnetic refrigeration using a permanent magnetic field with ZERO energy input requirements, validates this technology, and opens the door for its use in small and medium scale industrial applications, as well as fueling station infrastructure for fuel cell electric vehicles (FCEV). This paper provides an overview and status update of GE&R's magnetic refrigeration technologies.

1. Motivation

Hydrogen (H2) is expected to play a major role in meeting the nation's future energy needs. For fuel cell electric vehicle (FCEV) markets, studies have shown transport and storage of hydrogen in liquid form is likely the cheapest and safest method to achieve the Department of Energy (DOE) H2@scale economy, where H2 pump price needs to, eventually, be $5 per kg or lower [1]. Even so, the infrastructure for getting hydrogen into liquid form, and transporting and storing it in liquid form, has been slow to materialize. The cryogenic refrigeration systems needed to liquify hydrogen are both capital cost expensive and extremely energy intensive. Large scale H2 liquefaction plants achieve, at best, 10-20% of Carnot efficiencies (Carnot is theoretical maximum), and small and medium scale systems operate with 5-10% efficiencies. These high costs and poor efficiencies are a major pain point for existing industries requiring cryogenic temperatures, and they create an enormous barrier to entry for private investment into liquid H2 infrastructure for FCEV. Further, the hydrogen boil-off losses that occur along the delivery pathway adds to the price of H2 at the pump and complicates the economics for FCEV station owners to move to larger scale liquid hydrogen (LH2) storage. Many of these issues could be alleviated if energy efficient small scale H2 liquefaction existed.

Magnetic refrigeration is a promising technology, and likely the only technology, with the potential to significantly improve cryogenic refrigeration. Magnetic refrigeration utilizes the magnetocaloric effect (MCE), where a special solid state magnetic material, known as a magnetocaloric material, exhibits a variation in temperature when exposed to a changing magnetic field. GE&R is on the cutting edge of magnetic refrigeration technology. GE&R manufactures and sells a patented line of magnetocaloric materials and has built a small scale cryogenic magnetic refrigeration prototype and successfully demonstrated sustained sub 80 K (-193 °C) magnetocaloric cooling using a Halbach permanent magnet. GE&R's effort has validated

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the technology, and shows that with further development, achieving +50% efficiency in the sub 80 K temperature regime is possible.

The primary goal of our effort is to develop a small scale (~400 W cooling power at 20 K) hydrogen liquefaction magnetic refrigeration system for economical onsite re-liquefaction of up to 3 kg/hr of hydrogen boil-off losses at FCEV fueling stations. This type of system could be directly connected to the still cold (sub 30 K) vented boil-off from the dewar storage tank to completely eliminate these losses for <$1.50 per kg in electricity costs. Re-captured H2 at room temperature (300 K) could also be feed into the system and re-liquified for ~$3 per kg in electricity costs. Comparatively, this system would provide a 70-90% reduction in energy costs over the existing compression based refrigeration options.

Shell's recent announcement to close all of their H2 stations in California due to the high costs of getting H2 to the pump (currently averaging ~$33 per kg) has been a major blow to the market [2]. Clearly technological advances are needed for the H2 economy to move towards sustainability. Successful development of GE&R's small scale magnetic refrigeration system could immediately be useful to FCEV station owners to economically re-liquify boil-off losses. This would allow stations to move to larger storage capacities sooner (+3000 kg capacities), so more FCEV cars could be fueled, and manufacturers can sell more FCEV cars.

2. State of the Art - Cryogenic Refrigeration

The current options for manufactures to achieve cryogenic temperatures are to either use a liquid cryogen (such as liquid helium which is really expensive) or to use a compression based cryocooler system. Cryocoolers are refrigeration systems that can provide cooling down to cryogenic temperatures, typically defined as below ~120 K. They run the gamut in size and application and have had a slow, but steadily increasing market over that last few decades. The cost and efficiency of cryocoolers depends on the cooling power and the temperature that can be achieved (i.e. 80 K versus 10 K). In general, the smaller the cooling power the worse the efficiency, and the lower the temperature the system needs to achieve, the worse the efficiency. Over the last few decades major improvements in efficiency and cost of cryocoolers operating down to 80 K have been achieved, mainly due to the discovery and the use of mixed gas refrigerants. Cryocoolers operating at 80 K achieve efficiencies of 20-40%. Unfortunately, the ability to improve refrigerants below about 40 K may not be possible, with systems that can cool down to 10 K having efficiencies, at best, of ~5-10% [3].

Figure 1 illustrates how these system efficiencies translate into electrical cost for cooling. In the Figure 1 example, cooling of 1 kg of H2 down to its liquefaction temperature was evaluated. Electricity rates were assumed to be the average industrial rates of $0.08 per kW-hr. Assuming an efficiency of 5% of Carnot for a single system cryocooler to cool from 300 K down to 20 K, the electricity cost is ~$26. Utilizing a dual cryocooler system approach, where the efficiency of the first system (from 300 K to 80 K) and the second system (from 80 K to 20 K) are assumed to be 25% and 5%, respectively, reduces the energy cost by about 20% to ~$21. In practice, there are other costs associated with these systems that also need to be considered, such as capital cost and maintenance, which could increase especially with the use of dual or multiple systems.

Clearly, with the energy cost on the order of ~$20-30 per kg to re-liquefy H2 using existing small scale cryocooler technologies, these systems are totally unfeasible for FCEV stations to implement for boil-off loss mitigation. It should also be noted, the existing cryocooler systems

require maintenance (typically every ~2 years) and have operating life-times on the order of 5-10 years (where units which last longer are much higher cost).

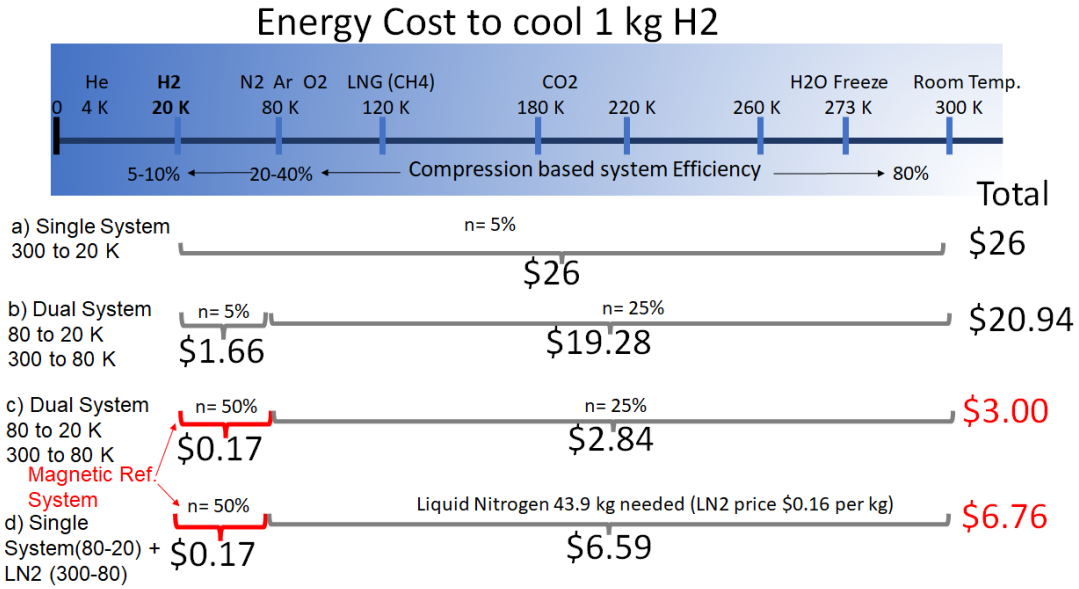

Figure 1. Calculated energy costs to cool 1 kg of H2 from room temperature (300 K) down to its liquefaction temperature (20 K) using commercially available compression based cryocooler systems in a) and b) and in c) replacing the low temperature stage with the proposed magnetic refrigeration system and in d) using liquid nitrogen as the heat sink to cool to 80 K (n is system efficiency, and calculations assume electricity cost of $0.08 per kW-hr and liquid nitrogen bulk delivery cost of $0.16 per kg).

3. GE&R Innovation

The magnetic refrigeration technology has been around for decades. It is currently available in commercial products which need sub 4 K temperatures, and it is one of the only technologies that can achieve these low temperatures. Magnetic refrigeration prototypes have also been developed for household refrigerators (General Electric), kitchen appliances (Camfridge), and building air conditioning (CoolTec Applications), and efforts to commercialize these systems are underway [4]. Magnetic refrigerators require two main components for operation:

1) MCE materials that function in the desired temperature range
2) Magnetic field force generated by superconducting, electro-, or permanent magnets.

The efficiency of magnetic refrigeration systems depends on the performance of the MCE material, the energy needed to generate the magnetic field (for permanent magnets this is ZERO!), the pumping power to flow a heat transfer fluid through the system, and the mechanical power needed to oscillate the magnetic field – all of which can be done much more efficiently, especially at cryogenic temperatures, than a compression based system. Further, GE&R currently exclusively owns and manufactures the only known MCE materials that will meet both cost and performance requirements to be viable in mass production of magnetic refrigeration systems. Access to our

own high performance MCE materials gives us a major competitive advantage in the development of magnetic refrigeration systems.

Why "fix" just sub 80K? We don't need to reinvent technology for the entire refrigeration range, because the existing compression based options for 300-80 K are actually pretty good. Figure 1 illustrates the case where a high efficiency magnetic refrigeration system with 50% of Carnot efficiency is used to cool from 80-20 K, and the cooling from 300-80 K is done by either a standard cryocooler with 25% efficiency (Figure 1c) or liquid nitrogen is used as a heat sink (Figure 1d). By replacing the most inefficient portion of compression based refrigeration (that is the portion from 80-20 K) with a more efficient magnetic refrigeration unit, the work input requirement of the second system (or liquid nitrogen) is significantly lower, which reduces both the electrical requirements and capital cost of the entire system – this translates to an ~80% reduction in electrical costs over the existing options.

An important aspect to note, Figure 1c and 1d calculations illustrate the costs associated with two different options for the high temperature stage (25% efficiency cryocooler or liquid nitrogen) with the assumptions of $0.08 per kW-hr electricity rates and $0.16 per kg bulk delivery of liquid nitrogen. Obviously, the electricity rates will vary significantly depending on location. In some areas in the U.S. industrial electricity costs run as low as $0.05 per kW-hr, whereas electricity costs in California could be $0.20 per kW-hr or higher depending on time of day. The liquid nitrogen will also range in price depending on location and scale purchased, or, in some cases it may be possible to generate the LN2 on site ($0.10 - $2.50 per kg). Additionally, the cryocooler system may require a larger up front capital expenditure, along with regular maintenance. The use of liquid nitrogen as the heat sink will require additional space for storage (which some FCEV stations may not have), and bulk deliveries, but there may be a lower upfront capital cost and very little maintenance requirements. The optionality to choose between a cryocooler or LN2 for the higher temperature stage may be an important component to have on a re-liquefaction system so that station owners can optimize the best fit for their location, facility size, and ability to scale with expected demand, while minimizing costs.

4. GE&R Technology Status

A schematic of the MCE assembly is shown in Figure 2, and a photograph of the interior of the LN2 tank with the actual magnetocaloric (MCE) assembly mounted into the system with the Halbach magnet is shown in Figure 3. The system has a custom designed heat transfer fluid (HTF) actuator system with a Halbach magnet with 2 in ID x 8 in length core, where the entire volume of the magnet core has magnetic field strength of ~1 T when measured at room temperature. For this prototype liquid nitrogen is used as the pre-cool heat sink because it is much easier and cheaper to scale the LN2 use as needed for testing different cooling powers during this development phase, versus needing to buy different sized cryocooling systems. The MCE assembly contains the GE&R MCE materials. The system operates as an Active Magnetic Regenerator (AMR), where during operation, the Halbach magnet oscillates between the left and right MCE beds in conjunction with the HTF actuator system pushing the helium back and forth across the beds. This AMR operation pumps the heat out to the LN2 heat sink, and the center of the MCE assembly (Tc) cools down. The vacuum layer surrounding the MCE assembly prevents heat gains into the MCE beds from the LN2.

Why use a permanent magnet? The ZERO energy requirements for a permanent magnet enable a smaller scale system with high efficiency (compared to a superconducting magnet which can only achieve high efficiency at large scale >100 kW/day cooling – this type of system is currently under development by Pacific Northwest National Lab) [5].

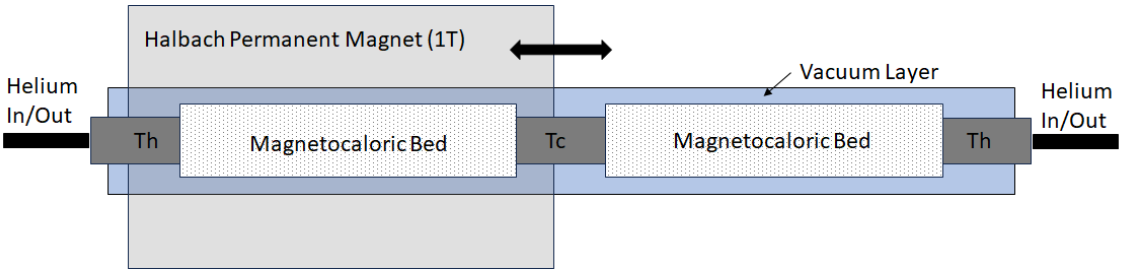

Figure 2. Schematic of the magnetocaloric (MCE) assembly where the MCE materials are contained in the magnetocaloric beds.

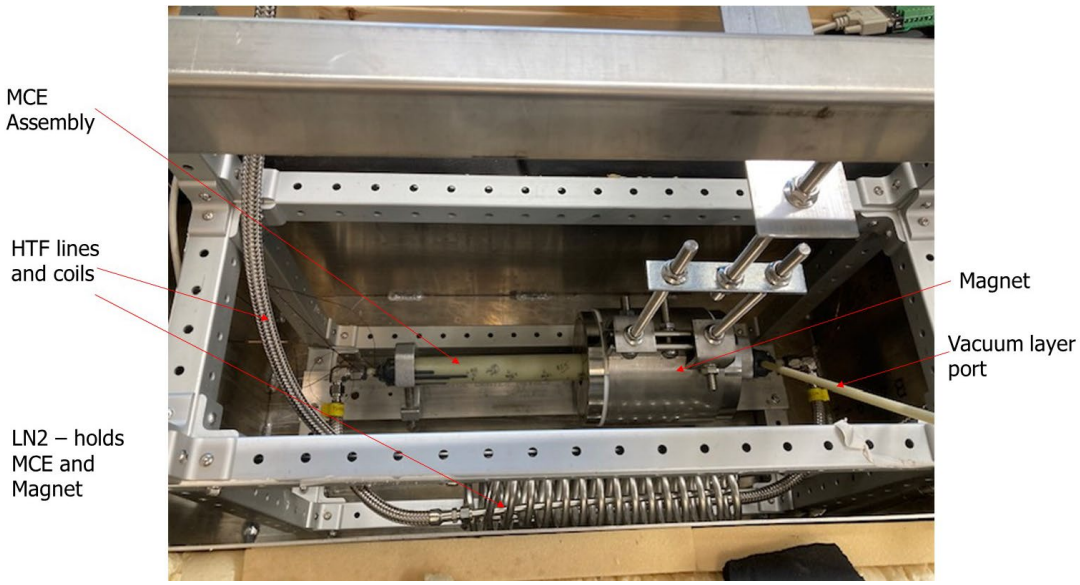

Figure 3. Photograph of interior LN2 tank containing the Halbach permanent magnet and MCE assembly.

Figure 4 shows the components of the MCE assembly which consists of a ~1/8 in vacuum layer created by dual garolite tubes (garolite is a composite material with low thermal conductivity great for cryogenic temperatures). Inside the vacuum layer are also radiation shields adhered to each tube to reduce heat gains into the inner MCE beds. The inner garolite tubing contains the MCE beds with 150 g of a single MCE composition (GE&R 75 K composition) in 150-300 μm powder form. Figure 5 shows the -ΔS versus temperature data for GE&R's 75 K MCE material, which is directly correlated to the adiabatic temperature change, and therefore, the performance of the refrigeration system. Figure 5 also shows an image of the powdered MCE materials. Our previous studies determined the 150-300 μm particle size range to be optimal for our system [6]. Platinum thermocouples are mounted along the inner MCE beds.

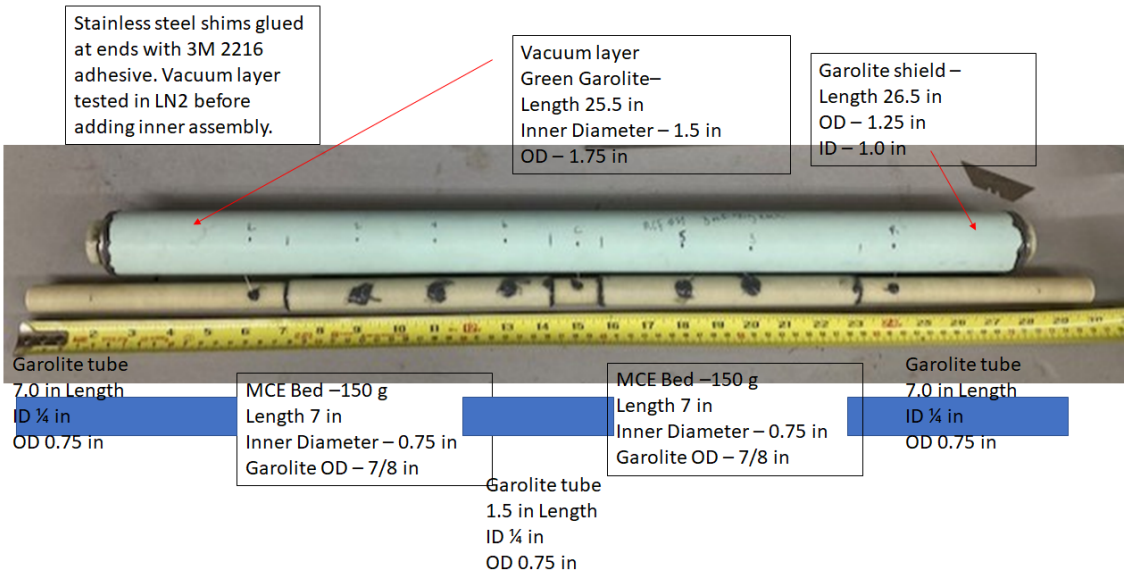

Figure 4. The components of the MCE assembly which achieved ~6-8 K of cooling below 80 K consisting of a dual garolite tube vacuum layer, and the inner garolite tubing containing the MCE beds. Platinum thermocouples are mounted along the inner MCE beds.

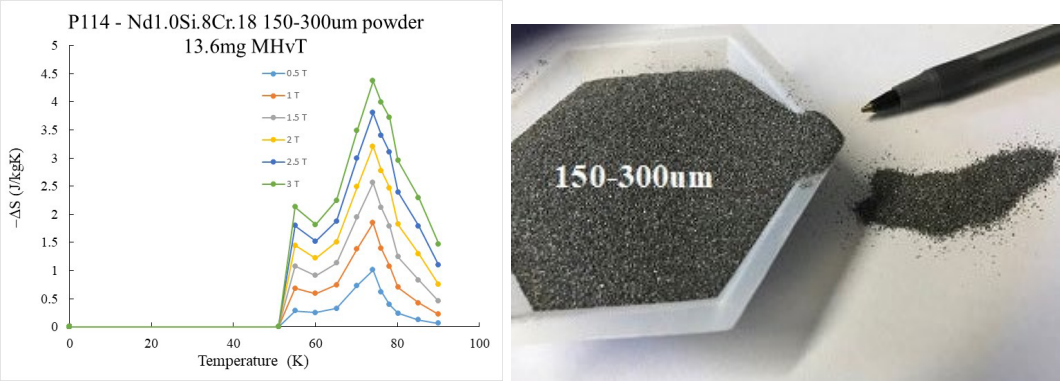

Figure 5. (Left) -ΔS versus temperature data for GE&R magnetocaloric material with peak functionality ~75 K and (Right) image of the 150-300 μm powder form used in the cryogenic magnetic refrigeration system.

Figure 6 shows the temperature versus time data for a recent test run on GE&R's magnetic refrigeration prototype, along with a photograph of the MCE assembly and magnet inside the liquid nitrogen tank during operation. This is the first ever AMR system built providing continuous magnetocaloric cooling below 80 K using a permanent magnet. The ~6-8 K of continuous cooling was achieved with only a partially functioning insulating vacuum layer (~380 mTorr). It is expected that achieving full vacuum layer functionality (<10 mTorr) will enable >15 K of sustained magnetocaloric cooling with the single-layer beds, and from the model predictions +40 K of sustained cooling below 80 K should be possible with multilayer beds used in this sized magnet system.

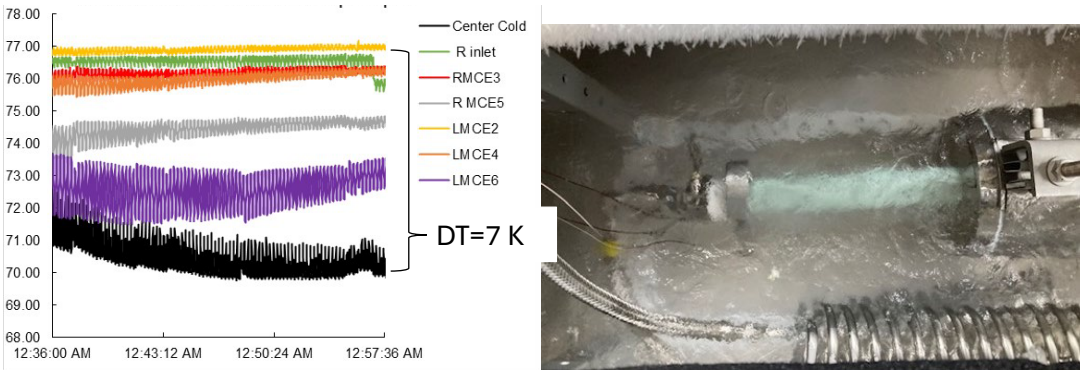

Figure 6. (Left) Temperature (K) versus time data and (Right) picture of the MCE assembly during operation.

5. Modelling and Future Work

The current system is only at 0.1% efficiency, so there is still a lot of work needed to reach the 50% efficiency target, as well as incorporation of the H2 liquefaction lines. Getting closer to the 50% efficiency target will be needed to attract the industrial investment to manufacture and deploy these systems commercially.

In collaboration with the University of California, San Diego (UCSD), a theoretical model of our system was also built which has been verified experimentally, and results recently published here [6]. Based on the model and sub 80 K experimental results, a pathway to achieve the 50% efficiency in the sub 80 K regime is provided in Table 1. The current prototype system (with 2 in ID magnet core) is expected to provide ~5-10% efficiency in the sub 80 K regime. This will be accomplished by fixing the vacuum layer on the MCE assembly to achieve <10 mTorr during operation and incorporating multilayer MCE materials into the assembly beds (currently only single layer). Increasing the magnet size to 3 in ID core will allow increased MCE material (>300 g per bed), so that the full 80 K down to 20 K temperature drop and 50% efficiency target can be achieved.

Table 1. Key operational parameters and performance targets.

Operational Parameters	Current (2024)	Expected w/ Current Magnet[a]			Possible w/ Larger Magnet[b]
System Pressure (psi)	50	50	50	100	100
Frequency (1/s)	0.08	0.17	0.17	0.17	1.17
Vacuum layer (mTorr)	381	10	10	10	10
Thot – Tcold (K)	77 – 70	77 - 60	77 - 40	77 – 30	77 – 18
# of MCE Layers	1	1	3	4	6-9
Qc (heat removed) (W)	5	27	49	125	419
Efficiency (% of Carnot)	0.1%	2%	4%	13%	52%

[a] Fix vacuum layer, increase frequency, multilayer MCE beds.
[b] Increase magnet core ID from 2 in to 3 in.

6. Conclusions

GE&R is on the cutting edge of magnetic refrigeration technology development. An at-scale cryogenic active magnetic regenerator refrigeration system has been built and successfully demonstrated continuous sub 80 K (-193 °C) magnetocaloric cooling using a Halbach permanent magnet. The successful demonstration of cryogenic magnetic refrigeration using a permanent magnetic field with ZERO energy input requirements, validates this technology, and opens the door for its use in small and medium scale industrial applications, as well as fueling station infrastructure for fuel cell electric vehicles (FCEV).

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