HOW MEA DESIGN CAN MAKE FUEL CELLS A VIABLE OPTION FOR HEAVY-DUTY VEHICLES

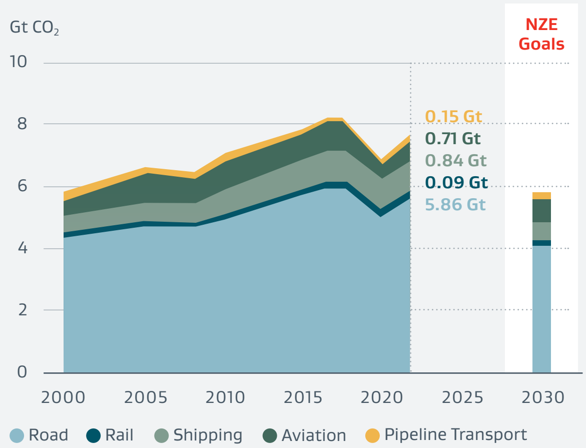
Shinichi Nishimura is a global product specialist for fuel cell technologies at W. L. Gore & Associates (Gore) and has more than 20 years of experience in polymer electrolyte membranes for fuel cells and other applications. We sat down with Shinichi to discuss decarbonisation in the transportation industry, the potential to significantly reduce emissions from the heavy-duty sector with hydrogen vehicles, and the challenges membrane electrode assembly (MEA) manufacturers have to overcome in these operating conditions.

Q: What role does the transportation sector have to play in achieving the world's net-zero ambitions?

A: The importance of the transportation industry as a decarbonisation lever cannot be overstated. Historically almost entirely dependent on fossil fuels and internal combustion engines, this sector was responsible for 37% of global CO_2 levels in 2021 alone. There is a tremendous urgency to lower carbon emissions from transportation to meet international net-zero targets (Figure 1).

Figure 1.

Global CO_2 emissions from transport by sub-sector in the Net Zero Scenario, 2000–2030



Improving the sustainability of passenger and freight transport, IEA, 2022, https://www.iea.org/topics/transport

The heavy-duty vehicle (HDV) sector has an especially critical role to play in decarbonisation. Medium-duty and heavy-duty trucks represent 25% of annual vehicle fuel use and produce 23% of total carbon emissions in the United States. More importantly, annual freight truck miles are projected to significantly increase by 2050 – so developing and commercializing alternative, low-carbon energy sources is critical.

How have PEM fuel cells emerged as a suitable technology for heavy-duty vehicles (HDVs)?

Recent advancements and innovations in proton exchange membrane (PEM) technology in hydrogen fuel cells have started generating real interest as a viable alternative solution to diesel engines. PEM's unique properties of scalability, durability, and power density are an attractive proposition to heavy-duty, long-haul commercial transportation.

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New roads and challenges for fuel cells in heavy-duty transportation, Cullen et al., 2021, https://www.osti.gov/pages/servlets/purl/1777401

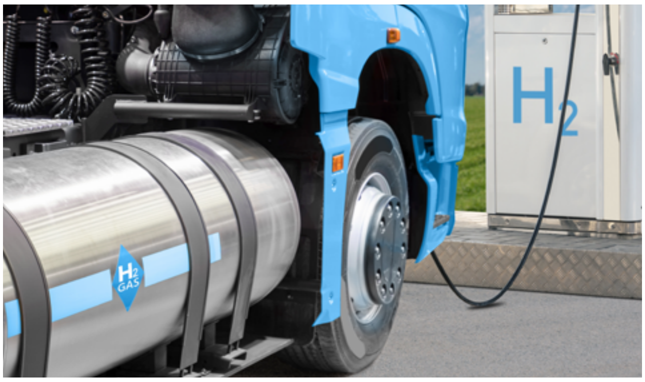
Hydrogen can store more energy in less weight, making it suitable for high-volume shipping. A fuel cell stack's power can be boosted by adding extra fuel cells at a marginal additional weight gain, further increasing the payload capability for commercial hydrogen-powered fleets. Hydrogen trucks have demonstrated competitive range and even faster refueling times than traditional combustion engines.

With predictable commercial routes, hydrogen refueling station (HRS) operators could recover their initial investment by using a 'hub-and-spokes' model to service fuel cell HDVs in continuous operation.

What are the challenges for fuel cell stack makers in this market?

High initial vehicle cost and insufficient material durability already present significant barriers to fuel cell vehicle (FCV) commercialization in the light-duty vehicle (LDV) sector – and these concerns become even more critical for HDVs.

The different drive cycles, operating conditions, and significantly longer lifetimes of HDVs will challenge the current durability limitations and failure mechanisms of PEM fuel cell components. The US Department of Energy (DOE) recently released targets for hydrogen Class 8 long-haul trucks which highlight the leap in performance criteria for HDVs compared to LDVs; a nearly fourfold increase in system lifetime to 12 years and over 1 million miles in operation.



These longer lifetimes and increased efficiency demands require new technical and integration strategies to meet them, especially under operating conditions that have not yet been assessed with LDVs.

From a material perspective, the design and durability of the membrane electrode assembly (MEA) at the core of the fuel cell stack itself is critical to overcoming these challenges and delivering reliable high-performance fuel cell HDVs.

How is the MEA vulnerable to damage?

The MEA is where the electrochemical reaction of hydrogen and oxygen takes place at the core of the fuel cell stack. It can be a harsh operating environment - nowhere more so than in long-haul, heavy duty applications. As the critical component inside the MEA, a PEM's chemical-mechanical stability becomes even more critical to ensure sustained performance over a longer lifetime.

The MEA is subject to physical and chemical damage during operation. Dynamic drive cycles cause voltage changes that lead to material degradation, such as carbon carrier corrosion or PEM thinning, and ultimately a deterioration in performance. Air pressure fluctuation and humidity and temperature cycling (hygro-thermal stress) causes mechanical degradation and can cause cracks and tears that lead to early PEM failure.

The extended HDV lifetime also raises the concern of contaminant exposure over a longer period of time, which may accelerate degradation pathways (such as iron ions acting as Fenton's reagents). Contaminants can be introduced through the fuel stream, air stream, or other components in the fuel cell stack, so ensuring a PEM's chemical durability is a high priority. Plus of course, minimizing hydrogen-gas crossover means greater energy efficiencies for longer – exactly what we're looking for in HDV applications.

How does the design of an MEA overcome these challenges?

To meet the increased voltage and temperature requirements for higher efficiencies, fuel cell stack manufacturers need a more dedicated focus on reducing kinetic losses and mixed potentials due to gas crossover, and localized issues due to catalyst/ionomer reactions in the MEA.

The MEA itself consists of three regions (Figure 2):

- the 'function' area, which generates the electric power for the cell;
- the 'structure' area, which provides chemical-mechanical durability for the MEA;
- and the 'transition region', composed of both function area and structure area components.

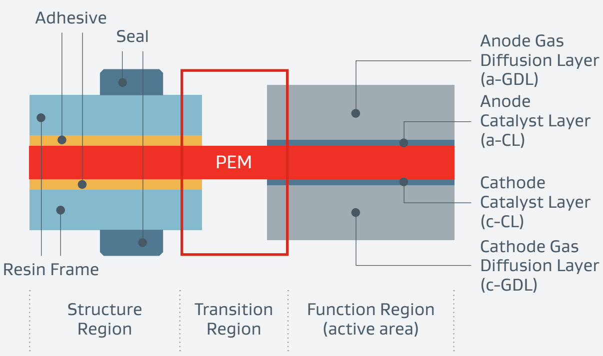
The transition region is directly exposed to physical damage and chemical contamination. The transition region contains catalyst and gas diffusion layers which determine power density and energy efficiency, and adhesives, frames and sealants that determine the structural integrity of the MEA. Prudent design with sufficiently robust materials is essential to producing reliable MEA that can maintain high output in tough operating conditions.

The transition region is subject to clamping forces, hygro-thermal stress, and gas pressure fluctuations during fuel cell operation. Improper design will lead to cracks along the PEM, leading to loss of efficiency, decreased power density, and increased gas crossover - and eventually, a catastrophic failure of the fuel cell stack.

Structural frames and protective layers can add mechanical durability, while gaskets and robust sealing can manage external gas leakage or internal crossover between the cathode and the anode, reducing the rate of chemical contamination.

Figure 2.

Schematic diagram of the primary structure of an MEA



A Review of the Transition Region of Membrane Electrode Assembly of Proton Exchange Membrane Fuel Cells: Design, Degradation, and Mitigation, Membranes (Basel), 2022, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8952641

To eliminate development trade-offs, such as sacrificing PEM durability for power density, components in the MEA transition region should be integrated as much as possible to achieve design, performance, and cost targets. For example, sealing components can be bonded onto separator plates or integrated into the MEA itself to provide greater protection against electrochemical damage. Polyfunctional components help engineers and designers produce compact and reliable MEA structures.

How can MEA manufacturers benefit from using GORE-SELECT® Membranes?

Gore entered the fuel cell industry almost three decades ago, and our technology has been proved in thousands of transportation applications worldwide. We're one of the only PEM manufacturers integrated into commercialized fuel cell electric vehicle production in the world!

Our extensive experience and materials science expertise have opened a new design space for PEM with the latest generations of GORE-SELECT® Membranes. We can decrease either membrane resistance or permeance by up to 50% without compromising other attributes – a colossal step forward for fuel cell stack designers trying to eliminate development trade-offs.

These membranes are reinforced with our proprietary expanded polytetrafluoroethylene (ePTFE) membrane, allowing for thinner design without compromising durability or performance. Low thickness enables low proton resistance, which results in higher power. Thinner membranes also have higher water transport, which results in higher performance, especially at low relative humidity (RH).

GORE-SELECT® Membranes have been rigorously tested to maintain long-lasting current outputs even under extreme conditions. For example, our membranes offer greater resistance to hygro-thermal stress, proven to exceed 1x - 3x of the US DOE target in RH cycling mechanical durability testing.

Gore's advanced additive technology compensates for chemical contamination and enables a long service life in harsh operating environments, such as long-haul trucking. This provides the superior ability to compensate for Fenton metal contamination and reduces fluoride release rates. Our reinforced membranes have a lower gas permeation rate than non-reinforced membranes, reducing the damage caused by gas crossover.

In a highly competitive industry, managing and reducing total cost of ownership (TCO) is a high priority. With our material expertise, supply security and quality consistency, and culture of continuous innovation, Gore is well positioned to help its customers lower their TCO by delivering greater PEM performance over a longer service life.

W. L. Gore & Associates

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INTERNATIONAL CONTACTS

Australia	+61 2 9473 6800	**Japan**	+81 3 6746 2570	**South America**	+55 11 5502 7800
China	+86 21 5172 8299	**Korea**	+82 2 393 3411	**Taiwan**	+886 2 2173 7799
EMEA	+49 89 4612 2211	**Mexico**	+52 81 8288 1283	**USA**	+1 410 506 7812
India	+91 22 6768 7000	**Singapore**	+65 6733 2882		

W. L. Gore & Associates, Inc.
201 Airport Road, Elkton, MD 21922
T +1 800 523 4673 **F** +1 410 506 8585 **E** performancesolutions@wlgore.com
gore.com/alt-energy

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