ASSESSING PROTON EXCHANGE MEMBRANE HYDROGEN FUEL CELL PERFORMANCE WITH **ALICAT FLOWMETER** TO DETERMINE ITS PRACTICAL EFFICIENCY

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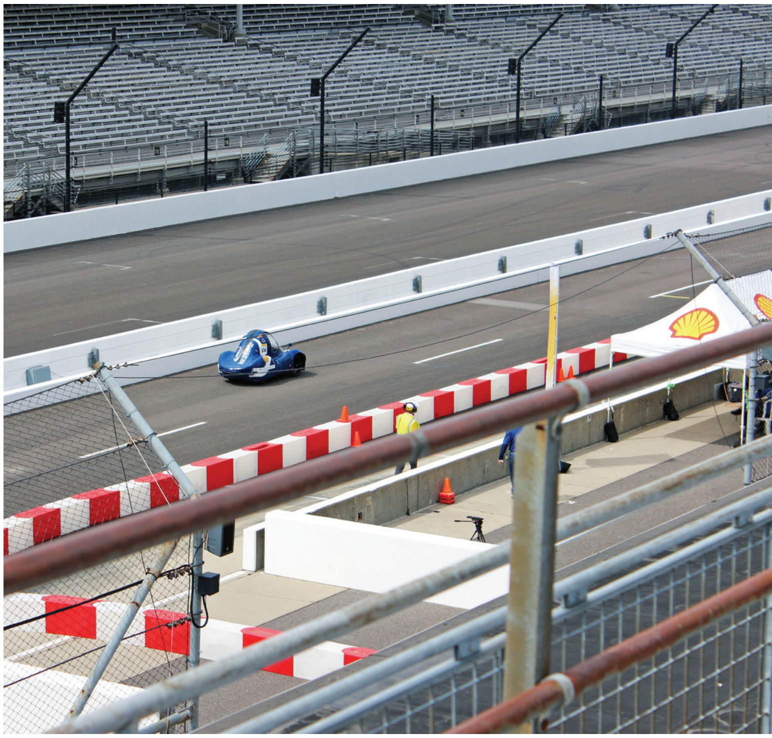
Written by Kalli Alikakos (2025-2026 Powertrain Lead) and Zaki Dawoodally (2025-2026 Technical Director)
Reviewed by Rafael Perez Vicente (2025-2027 Captain)

ABSTRACT

The University of Toronto Supermileage Team develops two hyper-efficient vehicles to compete at the annual Shell Eco-Marathon Americas: Prototype Electric and Urban Concept Hydrogen. The latter, utilizes hydrogen as its source of energy for propulsion, and builds a road-ready vehicle with working lights, horn, wiper, luggage space and a driver cockpit. Pushing the boundaries of efficiency requires rigorous testing. For that, we have used the Alicat flowmeter to assess the performance of our hydrogen fuel cell and compare it to its theoretical performance. Assessing hydrogen consumption at different loads allows us to optimize our racing strategy and the design of our propulsion system.



PROBLEM

Our team uses a proton exchange membrane (PEM) hydrogen fuel cell as our energy source in our vehicle design. The Powertrain Division of the Urban Concept vehicle is responsible for the propulsion, and thus the energy conversion from chemical to mechanical energy to drive the vehicle forward. A large portion of the work throughout the year centers around operating and maintaining optimal performance of the fuel cell. In order to characterize its performance, we need metrics to quantify how efficient our fuel cell is. We compete yearly in the Shell Eco-Marathon Americas, where the vehicle is assessed for how efficiently it can complete 16 km. Therefore the goal of our testing is to determine how efficiently we can convert hydrogen into electrical energy.

In past testing sessions, we measured performance based on the electrical output of the fuel cell and compared that to the power curve given by the fuel cell manufacturer. However, without hydrogen flow data we have a gap in our data collection. We could not accurately track the hydrogen consumption, nor could we track any performance degradation on the fuel cell.

SOLUTION

We have tried to estimate hydrogen consumption from current using Faraday's law, however this poses certain challenges. First, it uses theoretical stoichiometry, not taking into account real world degradation or operational losses; secondly, it does not account for hydrogen lost during purging. Purging is a process where the fuel cell clears the gas products within the cells every 10 seconds during operation. Since water vapour is the only by-product of the hydrogen reaction, water vapour will build up in the cell, taking up space and blocking new hydrogen from flowing into the cell. The purge allows fresh hydrogen to be delivered to the cell, and water vapour to leave. A rotameter would also allow hydrogen to be measured however its accuracy and precision is poor, and it does not allow for digital datalogging.

The team therefore used a mass flow controller provided by Alicat. This device is equipped with realtime flow measurements including a totalizer, average flowrate and live flowrate. It allows our team to also measure and store the data to be analyzed in later trials, and enables our team to assess all the pieces of the puzzles and see the full picture. The totalizer in particular records the cumulative volume of hydrogen delivered over each test step, which forms the basis of our energy and efficiency calculations.

TEST CONDITIONS

The PEM fuel cell was tested with four 150W load banks at constant current mode. The fuel cell was first run at 488W for one hour to allow the fuel cell to warm up and re-hydrate. This rehydration period is necessary as our team is only able to operate the fuel cell once every month due to lab availability. We observe the Open Circuit Voltage (OCV) to increase from 43.5V to 46.1 V after the fuel cell has been adequately rehydrated. Pressure was maintained between 6-9 PSI, and a 2 minute steady state current step was used.

TEST RESULTS

It was observed that the hydrogen flow scaled linearly with stack current. We were also able to quantify our energy consumption at each test point, which was not possible previously from the electrical data alone. The results are shown below in Table 1. It also allows us to compare efficiency between different operation points along the fuel cell curve.

Table 1: *RAW PEM Hydrogen Fuel cell test results*

Current (A)	Voltage (V)	Power (W)	Flow (SLPM)	Vol / 2 min (SL)	Pressure (PSI)	Temp (°C)
5.0	35.0	175.0	2.03	4.15	9.0	32
10.2	32.6	332.5	4.05	8.11	8.5	43
15.3	30.3	463.6	5.90	11.74	7.5	44
18.3	26.5	485.0	6.90	13.85	6.5	44
19.2	26.3	505.0	7.25	14.55	6.0	44
20.21[1]	26.0	525.2	-	-		45

1 Flow data is not reported for the final 20.2 A point, as this operating condition was reached only briedly at the end of the run and a stable 2 minute steady-state average could not be captured

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Efficiency may be calculated by dividing the electrical power output by the hydrogen energy input. Hydrogen contains 11.89 kJ of energy per Standard litre using its higher heating value (HHV) [1]. Thus the hydrogen energy input rate can be computed from the totalized volume measured over the 2 minute multiplied by the HHV basis, and then expressed in watts. The calculated efficiency for each current step is shown below is Table 2.

CALCULATED EFFICIENCY FOR EACH CURRENT STEP

We observe that efficiency decreases from 42.56% to 35.03% as current is increased to 19A. This decline follows the drop in stack voltage from 35.0 V to 26.3 V over the same range, which reflects the increasing activation, ohmic, and concentration losses that occur at higher current densities. In practical terms for the Shell Eco-marathon, this means the fuel cell converts hydrogen most efficiently at the lower end of its operating range. Therefore the most efficient race strategy is to draw the minimum current required to sustain the necessary vehicle speed.

Current (A)	Electrical Power (W)	H2 Energy Output(W)	Efficiency (%)
5.0	175.0	411.0	42.56
10.2	332.5	803.6	41.38
15.3	463.6	1163.2	39.85
18.3	485.0	1372.3	35.34
19.2	505.0	1441.7	35.03

Table 2: *Calculated efficency for each current step*

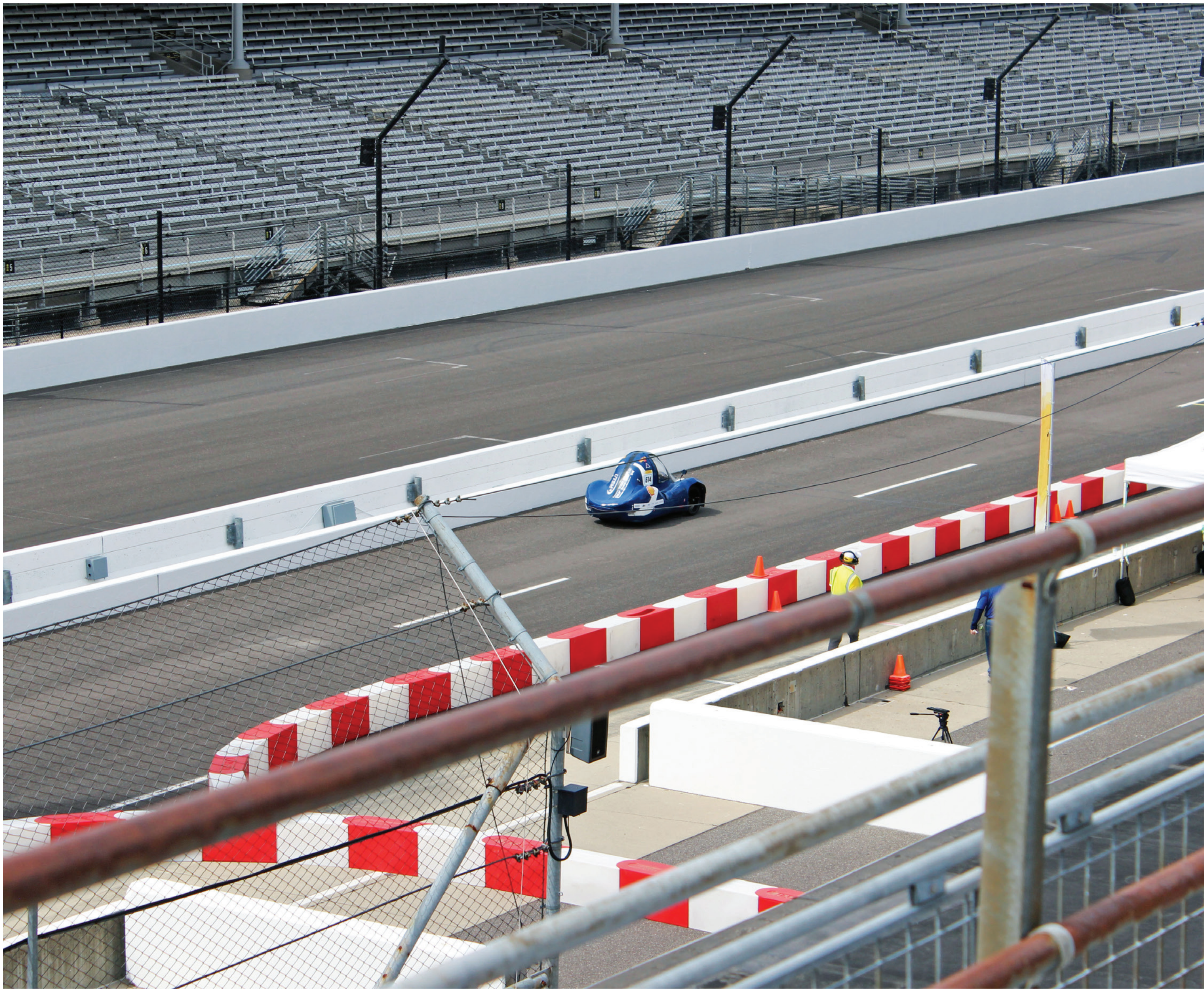
CALCULATED HYDROGEN UTILIZATION RATIO FOR THE HORIZON H-1000

After using Faraday's Law in calculating the effective rate of hydrogen being consumed by our output current and comparing it with the total hydrogen flow, the stack's fuel utilization ratio is approximately 90% at low current and increases to about 97% at higher currents.

Current (A)	Flow (SLPM)	Hydrogen Consumption Rate (SLPM)	Hydrogen Consumption Rate (mol/s)	Effective Hydrogen Consumption Rate (mol/s)	Stack Utilization Ratio (%)
5	2.03	2.03	0.001384	0.001244	89.88%
10.2	4.05	4.05	0.002761	0.002537	91.91%
15.3	5.9	5.9	0.004022	0.003806	94.63%
18.3	6.9	6.9	0.004703	0.004552	96.79%
19.2	7.25	7.25	0.004942	0.004775	96.64%

Table 3: *Calculated Hydrogen Utilization Ratio For the Horizon H-1000*

The Alicat mass flowmeter successfully provided measurable hydrogen flow data our team needed to calculate energy consumption and efficiency during fuel cell testing. Recommended steps for future testing would be to repeat the test with an increased number of loadbanks in order to capture the flow data across a greater power range. Continuous logging may also be implemented in order to capture transient behavior such as purging as opposed to the 2 minute steady state averages used in this test. Additionally the hydrogen flow data will prove useful to allow the team to experiment with "smart-purging" wherein the frequency and duration of purges are tuned to minimize the hydrogen vented during each purge, while still clearing accumulated water vapour.



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[1] Kiwa N.V., "The properties of hydrogen," Kiwa Technology, Apeldoorn, The Netherlands. [Online]. Available: https://www.kiwa.com/globalassets/netherlands/nieuws/documenten/infographic-properties-of-hydrogen.pdf [Accessed: Jun. 10, 2026].