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Grant Strem
CEO, Iconoil and Director, Proton Technologies

Dear Grant:

We have conducted the first experiment on the Proton physical model apparatus. The results exceeded our expectations and demonstrated that the Proton membrane apparatus works effectively at separating and producing hydrogen from a gas mixture. The enclosed report summarizes the results of the experiment.

We will be following up on the next steps.

If there are any questions, please call at 403-220-5752 or email me at ian.gates@ucalgary.ca (preferred) to discuss further.

Sincerely,

Ian D. Gates, Ph.D., P.Eng.

Project Report

Laboratory Evaluation of Hydrogen Flow through Proton Technology Membrane System

Submitted to
Proton Technologies Project Team

Prepared by:

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Table of Contents

Executive Summary

The Proton technology for production of hydrogen from petroleum reservoirs relies on in situ gasification of the hydrocarbons within the reservoir. One of the key uncertainties of the process is that the Proton membrane apparatus can effectively separate and produce pure hydrogen from the mixture of gases that are created from gasification of the petroleum within the reservoir. The experiment described here has answered this uncertainty – the results show that even at relatively low pressure and temperature, the Proton membrane apparatus can separate and produce commercial amounts of hydrogen. It is anticipated that at higher pressure and temperature that the hydrogen flux through the membrane apparatus will improve significantly. Future work will be done to optimize the operating pressure and temperature of the membrane apparatus as well as provide the design basis for the in-well device for testing in the field.

1.0 Introduction

With carbon emission limitations being imposed on fossil fuel products, there is a need to find other means to extract energy from petroleum resources that yield small or no carbon emissions. The key issue faced by oil and natural gas-based fuels is that no matter the energy and emissions intensity of the extraction, at the end of the supply chain, the fuel is combusted yielding carbon dioxide to the atmosphere. There is a need for energy generating processes from petroleum where not only is the extraction of the energy from the in situ resource is emissions neutral (or negative) but so too is the utilization of the fuel. One potential option that meets these requirements is hydrogen sourced from petroleum reservoirs. If hydrogen can be extracted cleanly from petroleum reservoirs, then when it is combusted

The hydrogen-to-carbon ratio of heavy oil and bitumen (extra heavy oil) is equal to roughly 1.45 mol/mol on average. With over 1.7 trillion barrels of bitumen in the Athabasca, Cold Lake, and Peace River oil sands deposits, the amount of hydrogen hosted in these reservoir is immense. This is because the hydrogen is not only hosted in the oil but also in the water within the formation (as well as top and bottom water zones). Thus, the energy content of these oil deposits with respect to the total hydrogen content is significant. If all global conventional and heavy oil resources plus associated water were considered for hydrogen production, the amount of hydrogen we could access would last for hundreds of years at current global energy demand.

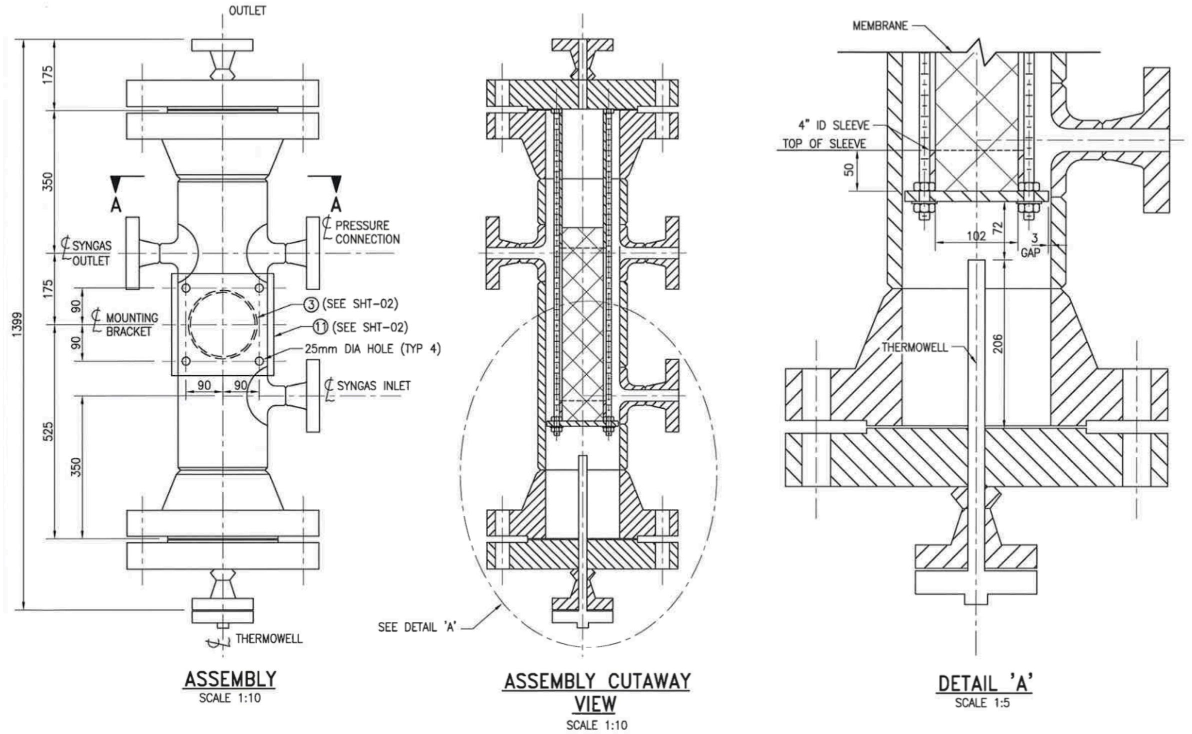
The combined motivation to a) improve hydrogen generation and b) increase energy recovery with lower emission to atmosphere and c) lower water consumption, has driven us to study in situ gasification (ISG) of heavy oil and bitumen. The methods are readily generalizable to natural gas and conventional oil systems. The design of a process for in situ hydrogen generation by oil gasification requires construction of the reaction scheme together with associated kinetic parameters. Since bitumen, oxygen, and water coexist in the presence of heat during bitumen gasification, the reaction system should consider pyrolysis (thermolysis, thermal cracking), aquathermolysis, gasification, and combustion (oxidation) reaction mechanisms.

The Proton technology consists of the use of in situ gasification as well as the use of an in situ membrane completion for the production wells that enable production of hydrogen only to the surface. The Proton technology allows for pure clean energy, in the form of hydrogen, from petroleum (natural gas, oil, heavy oil) reservoirs. The technology is particularly well suited for reservoirs with high water content since the hydrogen is sourced from both the hydrocarbons as well as the water. The key uncertainties that need to be resolved are control of in situ gasification within the reservoir and the ability of the Proton membrane system to produce hydrogen at reasonable rates from the gas mixture that would exist in the reservoir.

In this report, we describe the results of preliminary experimental testing of the proprietary hydrogen membrane cartridge. This unit is the key technological component of the recovery process. The hypothesis of the project is that hydrogen will be transported through the membrane apparatus.

2.0 Experimental Setup

Schematics of the physical model apparatus, referred to as the Proton apparatus, are displayed in Figure 1. The main component of the apparatus consists of a 8 inch diameter pipe constructed of ASTM A335 Pipe (ASME S/A335, iron-chrome-molybdenum); this is a ferritic alloy-Steel pipe rated for high temperature service in the presence of hydrogen. All of the fittings and end plates (ASTM A82 F22 iron-chrome-molybdenum allow) were constructed from materials designed to be operated at high temperatures and pressures in the presence of hydrogen. As shown in Figure 1, the main pipe has three inlet/outlets on the main body. One of these ports is used as a gas inlet and the other is for the outlet and the remaining one is for the pressure connection. The temperature within the apparatus is measured by using a thermocouple (Thermowell Aircom) that is mounted into one of the end plates. The membrane assembly is attached to one of the endplates. The membrane has been designed with a one end sealed and the other inserted into the endplate opposite the one containing the thermocouple; the membrane is held within the Proton apparatus in a cantilever arrangement. The sealing system used in the apparatus is proprietary and a patent is being filed on the configuration that was used.



ASSEMBLY
SCALE 1:10

ASSEMBLY CUTAWAY VIEW
SCALE 1:10

DETAIL 'A'
SCALE 1:5

Figure 1: Proton physical model apparatus.

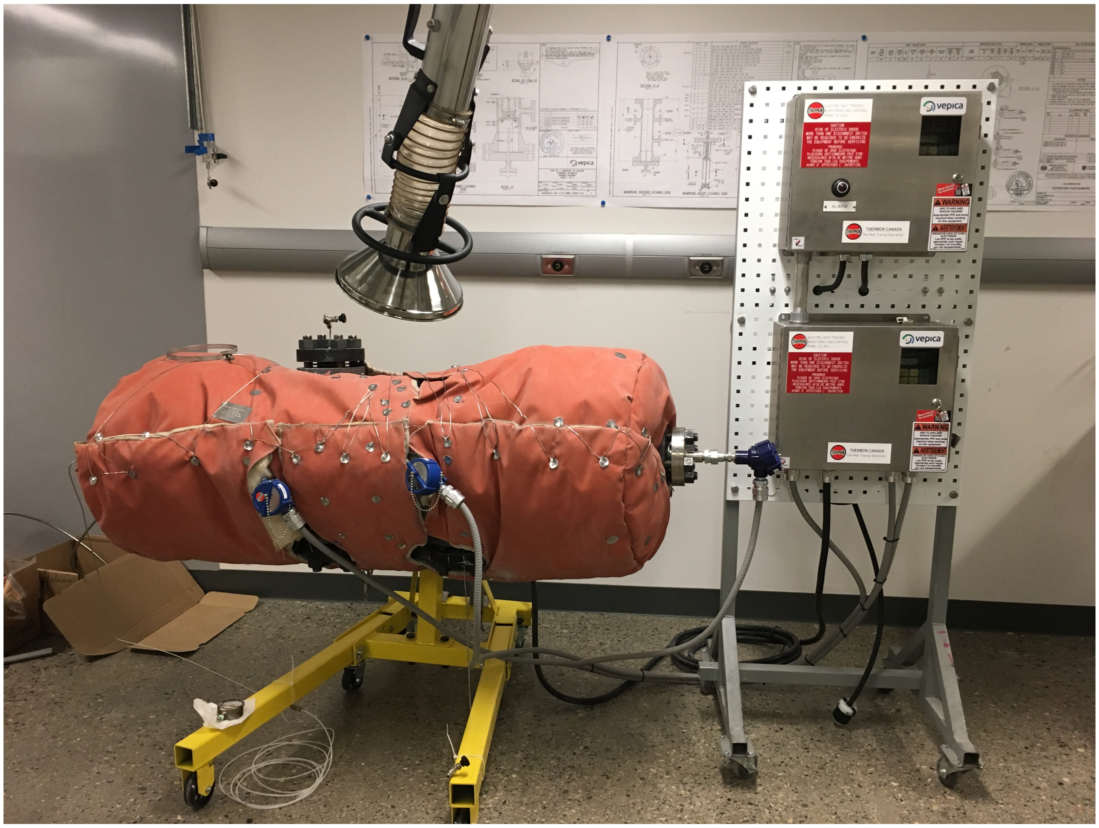
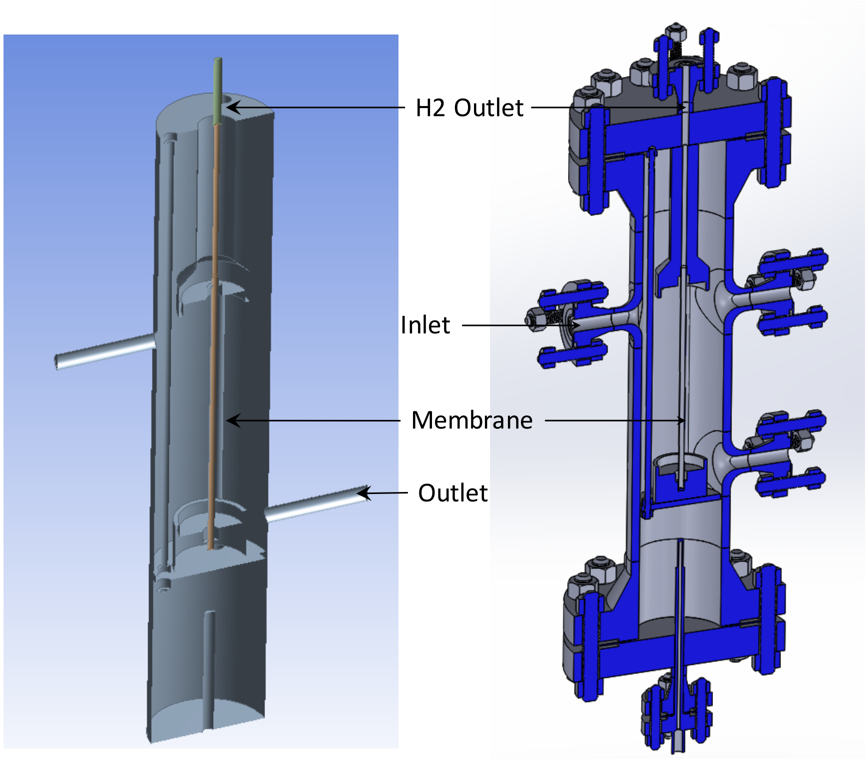


Figure 2: Photographs of the Proton physical model apparatus (top) and membrane cartridge (bottom).

Figure 3 displays the computational fluid dynamics (CFD) model that was constructed for determining flow rates for the experiments. The geometry corresponds to that of the Proton apparatus with the membrane clearly visible at the centre of the device. The conditions of the model are as follows:

- Geometry Length: 1.06 m
- Mixture inlet/outlet dia (ID): .028 m (1.1 in)
- H2 outlet dia (ID): .015 m (0.6 in)
- Membrane length and thickness: 0.406 (16 in) and 10 microns
- Permeability: 10 mD
- Inlet mixture (CO_2+H_2):
- Inlet flow rate: 3.5e-4 kg/sec (velocity 0.5 m/s)
- H_2 volume fraction: 5%
- Mixture and H2 Outlet Gauge Pressure: 0 kPa



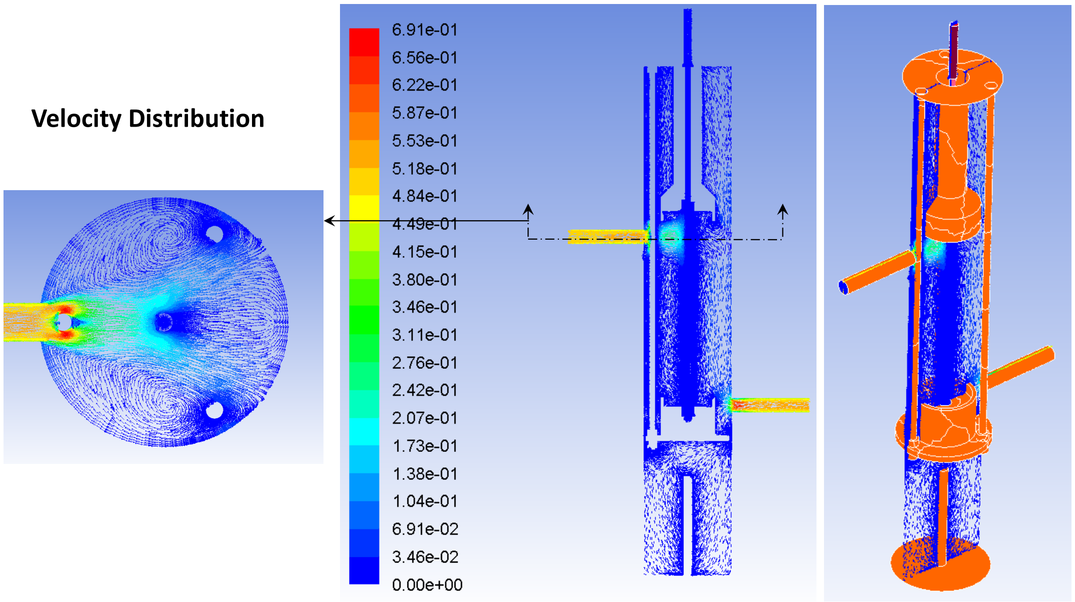
Simulated domain (Section)

Actual Geometry (Section)

Figure 3: Computational fluid dynamics model.

For the CFD simulation, the Navier-Stokes equations are solved together with a realizable K-ε turbulence model with scalable wall function for dealing with turbulence near solid walls. The diffusion equation governs mass transport across the membrane.

The results of the CFD computations are displayed in Figure 3. The results demonstrate that at the flow rates through the Proton apparatus, the membrane will be effective at separating the hydrogen. The results show that the membrane is effective at separating the hydrogen from the carbon dioxide plus hydrogen mixture.



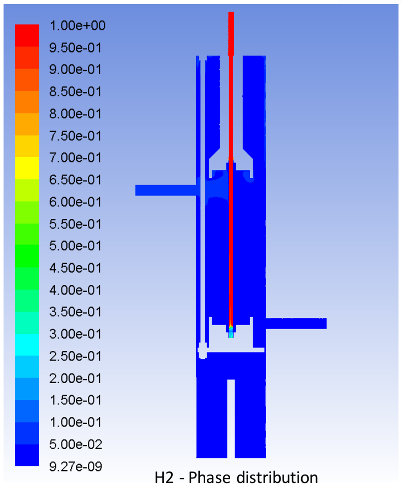


Figure 4: CFD results.

2.1.1 Procedure

The results of the CFD simulations were used to guide the inlet flow rate for the first experiment although one change was made to the operating conditions. In the first experiment, the outlet flow rate was zero – that is, gas was charged to the apparatus, but after the target pressure was reached, gas was only allowed to exit the apparatus through the membrane. The temperature of the experiment was equal to 280°C and total pressure was 1 MPa. The gas rate through the membrane was measured by using a Bronkhorst EL-FLOW Model F-110C gas flow meter with 10% of the gas injected the Proton apparatus being hydrogen and the remainder being carbon dioxide.

3.0 Results

During the experiment, the gas flow that exited the Proton apparatus achieved a steady-state gas flux rate equal to 0.979 $cm^3/cm^2/min$. The product hydrogen gas was combusted and is shown in Figure 5. This is lower than published flux rates (tend to be between 2 to 3 $cm^3/cm^2/min$ obtained at >350°C) but this is due to the temperature of the experiment which was relatively low at 280°C as well as the low total pressure that was used in the experiment. In practice, the pressures that would be used in the field will be equal to about 4 MPa. In this experiment it was equal to 1 MPa and thus, it would be anticipated that the flux rate of hydrogen will be several times that of the rate obtained in this experiment. Furthermore, at elevated temperature, the rates are anticipated to increase.

For a field operation with 1000 m wells, with a 7-membrane cartridge, from 20 wells, the predicted rate would be equal to about 2.85 million scf/day. This is similar to the results from reservoir simulations which after evaluation through an economic model has proven that this process can be economic (with hydrogen cost equal to about US$1/kg). Thus, the experimental results confirm the rates found from the field simulation results. Note, however, that the rates from the membranes are not yet optimized and at higher temperature and pressure, it is anticipated that the flux rates from the experiments will be greater by several times.

Figure 5 displays the blue flame obtained from the hydrogen that was transported across the membrane. A continuous blue flame was obtained for the entire experiment (about 15 minutes). The flame was constant in height throughout the experiment which demonstrates that despite the depletion of hydrogen from within the Proton apparatus (both the total pressure and the mole fraction of hydrogen drops as the experiment proceeds within the main chamber of the apparatus which would both lead to a reduction of the partial pressure of hydrogen within the main chamber), the hydrogen transport rate remains constant.

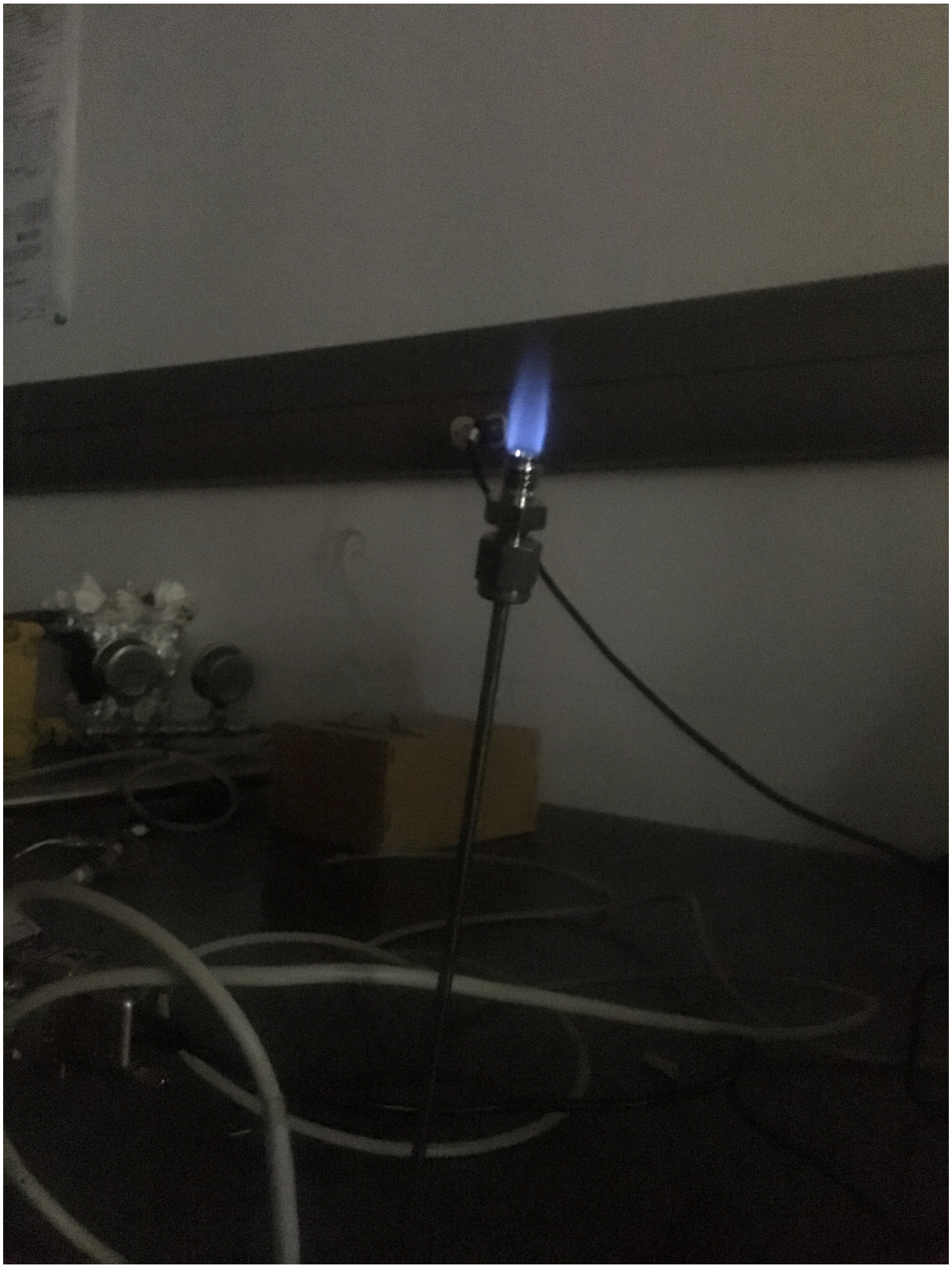


Figure 5. Blue flame from produced hydrogen.

4.0 Implications

The experimental results reveal that meaningful amounts of hydrogen can be transported across the palladium membranes. The results also demonstrate that the Proton apparatus is fully operational and can be used for rapid testing of membranes and membrane configurations. Furthermore, the results show that the Proton membrane cartridges are sealed and will be able to operate at reservoir conditions (with higher pressure and temperature, the flux rate should improve). The key implication from the results that hydrogen can be transported and thus that in a well within a reservoir, the membrane cartridge will be able to transport hydrogen from a reservoir that has a mixture of gas components within it (from in situ gasification) and will do so at rates that would be commercial.

5.0 Next Steps

The next steps are as follows:

1. Conduct experiments at various total pressures and temperatures to determine optimum hydrogen flux rates.
2. Revise the CFD simulation according to the results of these experiments and one planned.
3. Provide design basis for the in-well Proton membrane apparatus for the field trial.