**Proton Technologies Canada**

# Hydrogen Extraction Project

**Saskatchewan Petroleum Innovation Incentive (SPII)**

**ER-SPII-1219-003**

**Final Technical Report Submission**

**Date of Submission: March 19, 2024**

# Table of Contents



# Table of Figures/Tables

# 1. Project Background

## 1.1. Introduction

Proton Technologies Canada (Proton) has operations based in Saskatchewan and has a patented hydrogen ($H_2$) production and separation processes which are intended to economically produce and extract $H_2$ from hydrocarbon reservoirs through in-situ oxidation and gasification. Current industrial processes for $H_2$ production primarily involve steam methane reforming (SMR) and electrolysis, which are carbon intensive and costly. The eligible project aimed to use a process known as In-Situ $H_2$ Generation (ISHG), which combines in-situ oxidation and steam injection to produce $H_2$ from uneconomic hydrocarbon reservoirs.

The production of $H_2$ from a hydrocarbon reservoir demonstrates an innovation new to Saskatchewan's oil and gas industry and does not have an equivalent in the Saskatchewan market. Given Saskatchewan's rich endowment of hydrocarbons, Proton's technology has the potential to make Saskatchewan a major $H_2$ producer. This would benefit existing industries in Saskatchewan by supplying domestic hydrogen to upgraders, refineries, ammonia producers, methanol producers, and as a fuel for electricity generation. Increased and stable $H_2$ production could lead to more value-added processing in oil and gas, refining, petrochemicals, and other industries and it provides an energy transition pathway to low carbon energy sources that complements and utilizes the existing energy infrastructure in Saskatchewan. It also provides a mechanism to address well abandonment liabilities as mature oil reservoirs could be repurposed to $H_2$ production.

The project faces a range of technical challenges due to the first-of-its-kind deployment as a field pilot, facility installation, testing, data collection and reservoir optimization.

## 1.2. Project Location

The project is located at Township 33, Range 24, west of the Third Meridian (T33-R24W3) (see Figure 1) in the SK ER E2002 Kerrobert Waseca Toe-to-Heel Air Injection (THAI) Project, operated by Superb Operating Company Ltd. (Superb). The target reservoir already had elevated temperatures of 100 to 150 °C due to historical air injection through THAI and steam injection. The original reservoir temperature was approximately 25 °C. The project also had in-situ oxidation infrastructure due to the previous THAI well architecture and thermal enhanced oil recovery due to the subsequent addition of steam. In short, the reservoir already had in-situ combustion, also known as fire flooding, due to the THAI process.

*Figure 1: Project Location*


## 1.3. Summary Of Technology

The goal of Proton Technologies Canada's patented method is to produce clean energy in the form of $H_2$ from hydrocarbon reservoirs by adapting proven technologies from the in-situ gasification industry with $H_2$ selectivity techniques from the steam methane reforming industry. The concept began with an investigation by Dr. Ian Gates' team at the University of Calgary into the reaction kinetics associated with in-situ hydrocarbon recovery methods involving air and or oxygen ($O_2$) injection. These are commonly referred to as in-situ combustion (ISC), in-situ gasification (ISG), $O_2$/air injection, or fire-flooding. These processes have been applied to light, heavy, and bitumen oil reservoirs, as well as coal.

Research started with the analysis of the Marguerite Lake Cyclic Steam and Air Injection pilot. Historically, most fire flood projects have generated some amounts of $H_2$ due to in-situ steam reforming within the reservoir, dominated by the water gas shift reaction (WGS), and with contributions from gasification reactions. These enhanced oil recovery processes have been applied to reservoirs for decades, but Proton is now trialing the use of the fire-flood method with the primary goal of extracting $H_2$ from uneconomic oil reservoirs.

The Marguerite Lake pilot is considered to have some important outcomes. The key finding was that ISG reactions occurred in the reservoir and, consequently, $H_2$, methane, and carbon oxides were produced in the gas stream to the surface. Thus, the Marguerite Lake pilot serves as proof-of-concept even though the pilot was focused on enhanced oil recovery rather than $H_2$ production. A novel aspect of Proton's field demonstration is to optimize ISC processes for ISHG and to optimize the reservoirs for the commercial production of $H_2$ rather than hydrocarbon production.

In broad terms, the research challenge for Proton is to re-engineer both the existing ISC technologies, the existing hydrocarbon infrastructure, and develop methods for optimizing the reservoir for ISC to maximize $H_2$ production through ISHG. In short, ISHG involves re-engineered ISC to focus on the optimal in-situ generation and production of $H_2$. This involves geotechnical and reservoir simulations, optimized well spacing and placement, varying $O_2$ injection and $H_2$ production cycles, cyclically managing reservoir temperatures, and re-engineering wellbore downhole configuration and metallurgies.

### Proton's Originally Proposed ISHG Method:

I. Heat the reservoir: Air/$O_2$ injection oxidizes and warms residual oil while generating $H_2$. The reservoir is pre-heated by steam to a target of 300+°C. Pre-heating from natural reservoir temperature (~25°C) to above 240°C, including rock grains, gives a higher baseline temperature for endothermic water-gas shift (WGS) and gasification reactions to occur. WGS was expected to be the most important reaction for $H_2$ production ($CO + H2O \rightleftharpoons CO_2 + H_2$). This reaction only occurs efficiently above a minimum localized (pore-throat) temperature at the site of combustion of approximately 300°C. By pre-heating with steam, combustion has a smaller temperature delta to reach the critical water-gas shift reactions.

   The purpose was to use the reservoir as the reaction vessel for $H_2$ production, and to test our hypotheses and reservoir simulations which indicated ISHG has the potential to produce $H_2$ at less than $2.00/kg, it has the potential for a lower carbon intensity compared to blue $H_2$ via SMR (i.e., 9-12 kg $CO_2$/kg $H_2$), and approximately 90% of $H_2$ is released when oxidized, which is a similar efficiency factor compared to SMR.

II. Separate and purify the $H_2$ from the produced gases using proven industrial gas separation techniques at the surface (e.g., cryogenic distillation or pressure swing absorption) and re-injecting the greenhouse gases back into the reservoir.

III. $H_2$ is then stored and shipped to market via tube trailers or through existing or new pipelines (e.g., methane blending).

## 2. Project Description & Results

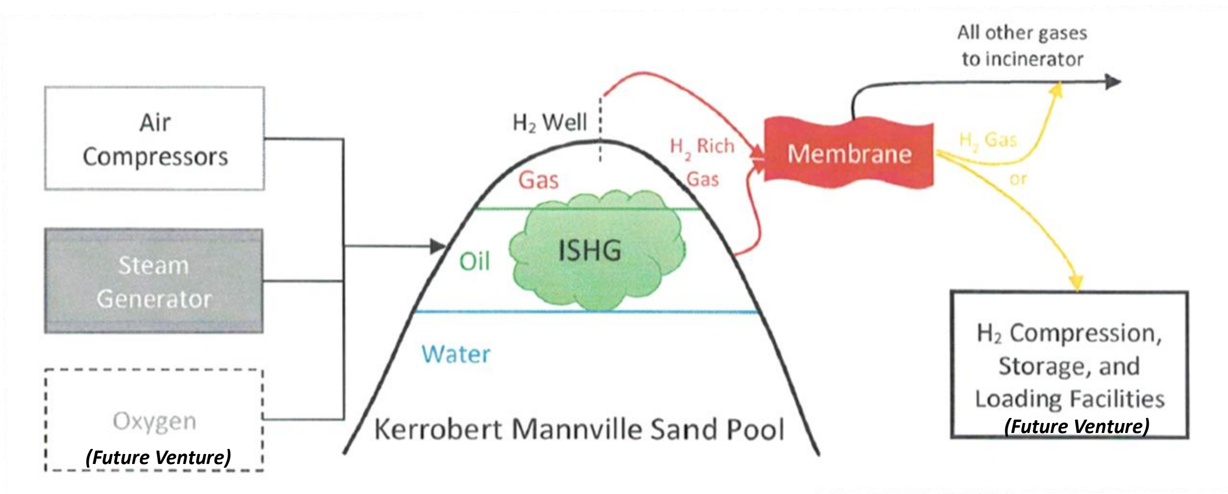
The project schedule start date was January 2020 and concluded in June 2023. The approved SPII project covered the following deliverables:

a) $H_2$ Production Field Experiment on Oil Wells
b) Drilling/Completion/Testing of an $H_2$ Well

c) Micro Scale Surface Membrane Separation Test
d) Design and Construction of $H_2$ Compression, Storage, and Loading Facilities
e) $O_2$ Injection Test

Deliverables d) and e) did not occur and will be a part of Proton's future ventures (see conclusion section for more details). Figure 2, below, is a simplified block flow diagram illustrating the overall flow inputs and outputs from the reservoir representing the scope of Proton's $H_2$ Extraction Project.

*Figure 2: Simplified Block Flow Diagram of Proton's In-Situ Hydrogen Generation (ISHG) Process*




## 2.1. $H_2$ Production Field Experiment on Oil Wells

Proton started a field experiment in the Kerrobert Mannville Sand Pool in 2020 using the existing enhanced oil recovery (EOR) project oil wells from SK ER E2002 to demonstrate the potential to produce commercial quantities of $H_2$. Proton hypothesized that $H_2$ production concentrations could be improved from the 'air injection only'-baseline of 0.5% $H_2$ by injecting both steam and air. The injection of both steam and air was hypothesized to raise reservoir temperatures further and induce WGS reactions ($CO + H_2O \rightleftharpoons CO_2 + H_2$).

The testing concluded in the fall of 2022 and included the following:

- Use existing air compressors and one steam generator to co-inject air and steam near the thickest part of the reservoir pay zone. Existing injection wells will be used to inject air and steam simultaneously and cyclically.
- Air injection adds $O_2$ to the reservoir to oxidize oil (oil + $O_2$ + $H_2O$) and the resulting energy assists in gasification reactions ($C + CO_2 \rightarrow 2\,CO$) and ($C + H_2O \rightarrow H_2 + CO$).
- Steam injection ensures a surplus of steam for the WGS reactions, which produce $H_2$. WGS is highly equilibrium-driven, and slightly exothermic reaction. Extracting $H_2$ thereby drives the reactions in the

system towards more $H_2$ production [$CO + H_2O \rightleftharpoons CO_2 + H_2$]. WGS was expected to be the main source of $H_2$ contributor in Proton's process.

For this portion of the project, all produced gas from the oil wells and $H_2$ well was directed to the existing incinerator at the CPF. The purpose was to measure the concentrations of $H_2$ and gather data based on injection cycles and variations, which will subsequently be used to further refine Proton's analytical and numerical models and operational plans.

The incinerator located at Superb's central processing facility (CPF) is designed and licensed to burn up to 900,000 $m^3$/d of gas. The gas is sent to the CPF through existing flowlines.

*Figure 3: Map of Superb wells in the Kerrobert Mannville Sand Pool in Section 13 and 14-033-24W3.*

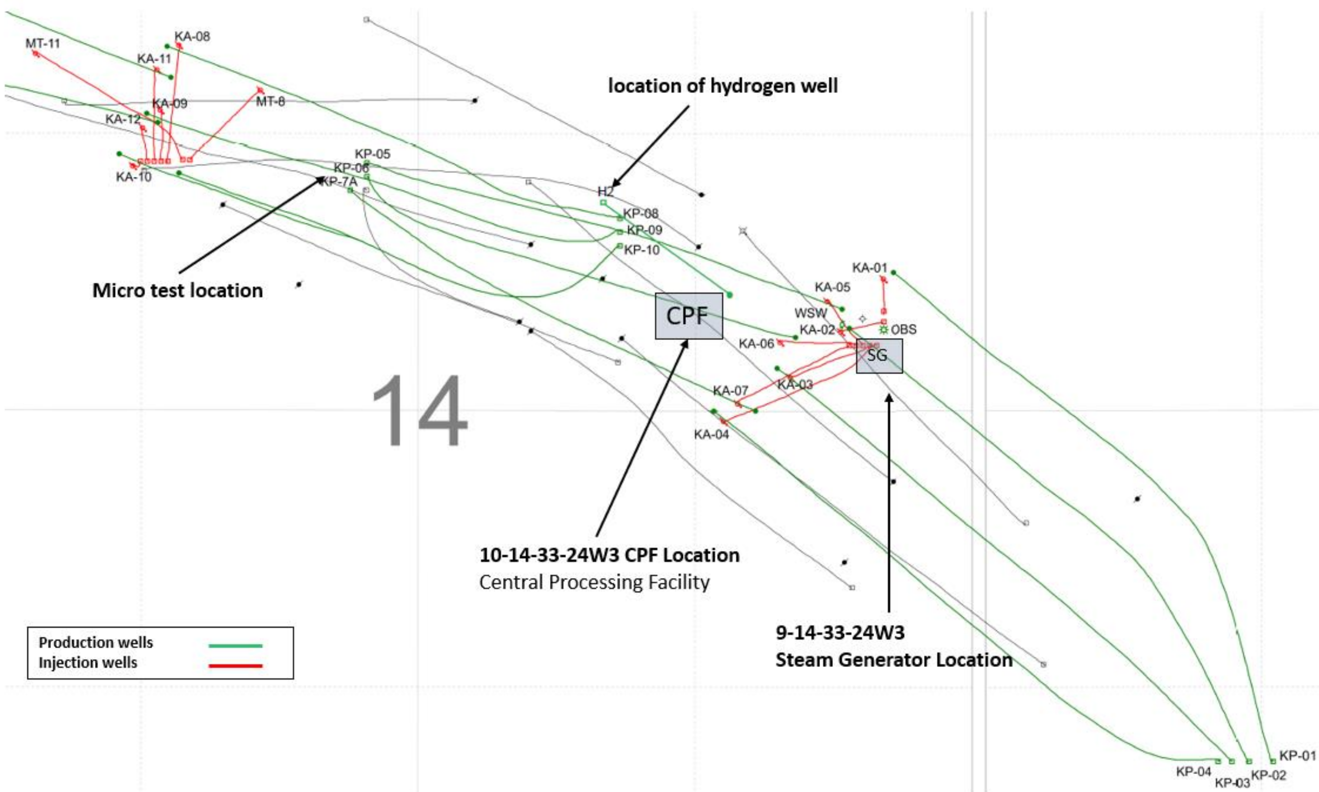



Figure 3 outlines which project wells are used for oil and $H_2$ production, and steam or air injection. All Unique Well Identifiers (UWIs) for the injection wells and production wells in the project area are included in Table 1 and 2.

*Table 1: Project Wells Used for Injection*

| Count | Well | UWIs |
|---|---|---|
| 1 | KA-01 | 196/09-14-033-24W3/00 |
| 2 | KA-02 | 197/09-14-033-24W3/00 |
| 3 | KA-03 | 121/09-14-033-24W3/00 |
| 4 | KA-04 | 193/08-14-033-24W3/00 |
| 5 | KA-05 | 102/09-14-033-24W3/00 |
| 6 | KA-06 | 112/09-14-033-24W3/00 |
| 7 | KA-07 | 113/09-14-033-24W3/00 |
| 8 | KA-08 | 194/14-14-033-24W3/00 |
| 9 | KA-09 | 195/14-14-033-24W3/00 |
| 10 | KA-10 | 141/12-14-033-24W3/00 |
| 11 | MT-8 | 19A/14-14-033-24W3/00 |
| 12 | MT-11 | 191/13-14-033-24W3/00 |

*Table 2: Project Wells Used for Production*

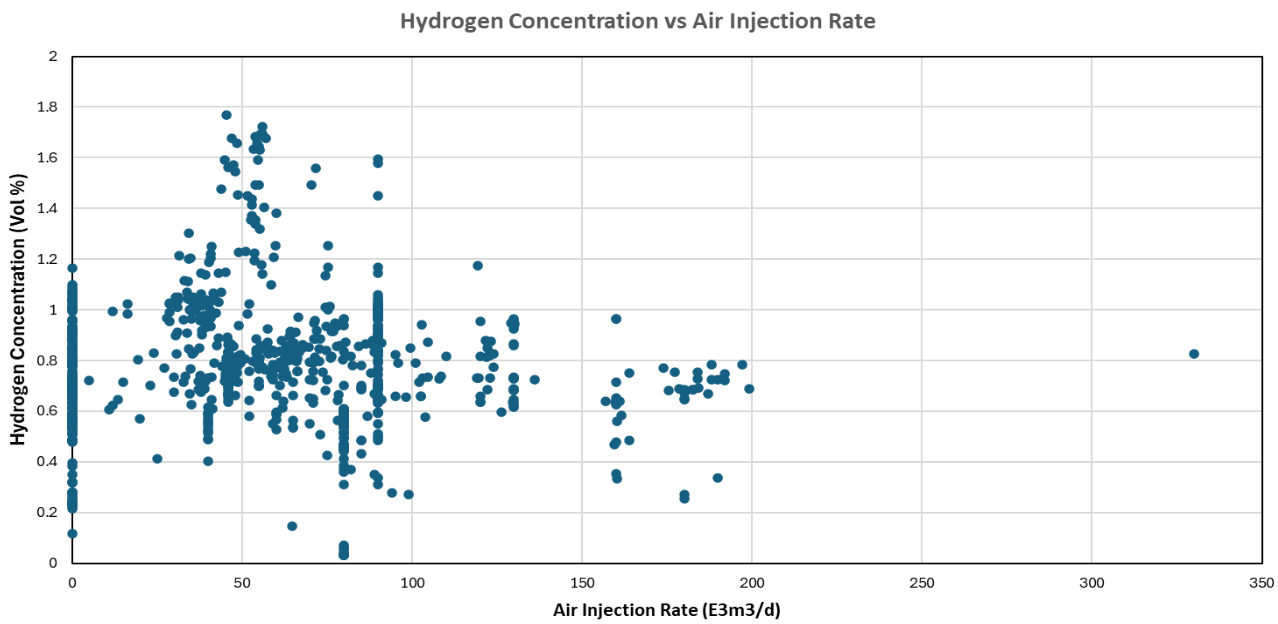
| Count | Well | UWIs |
|---|---|---|
| 1 | KP-02 | 195/09-14-033-24W3/00 |
| 2 | KP-03 | 198/09-14-033-24W3/00 |
| 3 | KP-05 | 19A/09-14-033-24W3/00 |
| 4 | KP-06 | 19B/09-14-033-24W3/00 |
| 5 | KP-07 | 194/08-14-033-24W3/00 |
| 6 | KP-08 | 192/14-14-033-24W3/00 |
| 7 | KP-09 | 193/14-14-033-24W3/00 |
| 8 | KP-10 | 143/12-14-033-24W3/00 |

- $H_2$ hardware used for a surface test in 2018 was re-employed for this project. The micro test was conducted on the surface location of the following producing oil wells: KP-05, KP- 06, KP-7A on legal subdivision 11-14-33-24W3.
- Proton co-injected air and steam into the following wells: KA-01, KA-02, KA- 03, KA-04, KA-08, KA-09, KA-10, KA-11, KA-12 were used for air injection and KA-05, KA-06 and KA-07 were used for steam injection. Gas samples were collected daily from associated production wells while measuring $H_2$ concentrations.
- Proton collected $H_2$ samples from the following wells: KP-02, KP-03, KP-05, KP-06, KP-07, KP-08, KP-09, KP-10
- Wells in the project area that were not used for injection trials: KP-01, MT-8, MT-11, KP-04, KP-11 and KP-12 all had attempted pump change and sand clean out however this was a failed attempt as liner appeared to be damaged and would require additional capital.

## Results

Steam injection rate remained constant at 130 $m^3$/d c.w.e. (cold water equivalent) throughout the trials. Air injection rates were varied during the trial as Proton attempted to test for a relationship (correlation) between air injection rates (~21% $O_2$) with produced $H_2$ concentrations. Gas chromatography/mass spectrometry (GCMS) testing was used on the produced gas mixture from production wells. Figure 4, below, shows the $H_2$ concentration vs. the total air injection.

*Figure 4: H2 concentration vs. Total Air Injection*




Proton found that over the course of the experiment there was no direct relationship between air injection rates and produced $H_2$ concentrations lacked correlation. Despite a lack of correlation between $H_2$ production and air injection, the data indicated there was an increase in the well's temperature (~25°C to 40°C) and a small increase in $H_2$ concentration after steam was injected at full rates. Steam was injected at full rates beginning July 22, 2020, and the $H_2$ concentrations were shown to increase mid-August 2022 once reservoir temperatures were believed to have elevated. Proton expected to be producing 84kg/d $H_2$ when the experiment concluded. Although this was not achieved on a consistent basis due to the reservoir not reaching temperatures for optimal $H_2$ production, Proton did produce at it's maximum 120kg/d and upwards of 90kg/d for four consecutive months. The results from Table 3 shows GCMS data of KP-07 production well and Figure 5 shows KP-07 hydrogen concentrations over time.

*Table 3: KP-07 GCMS data*

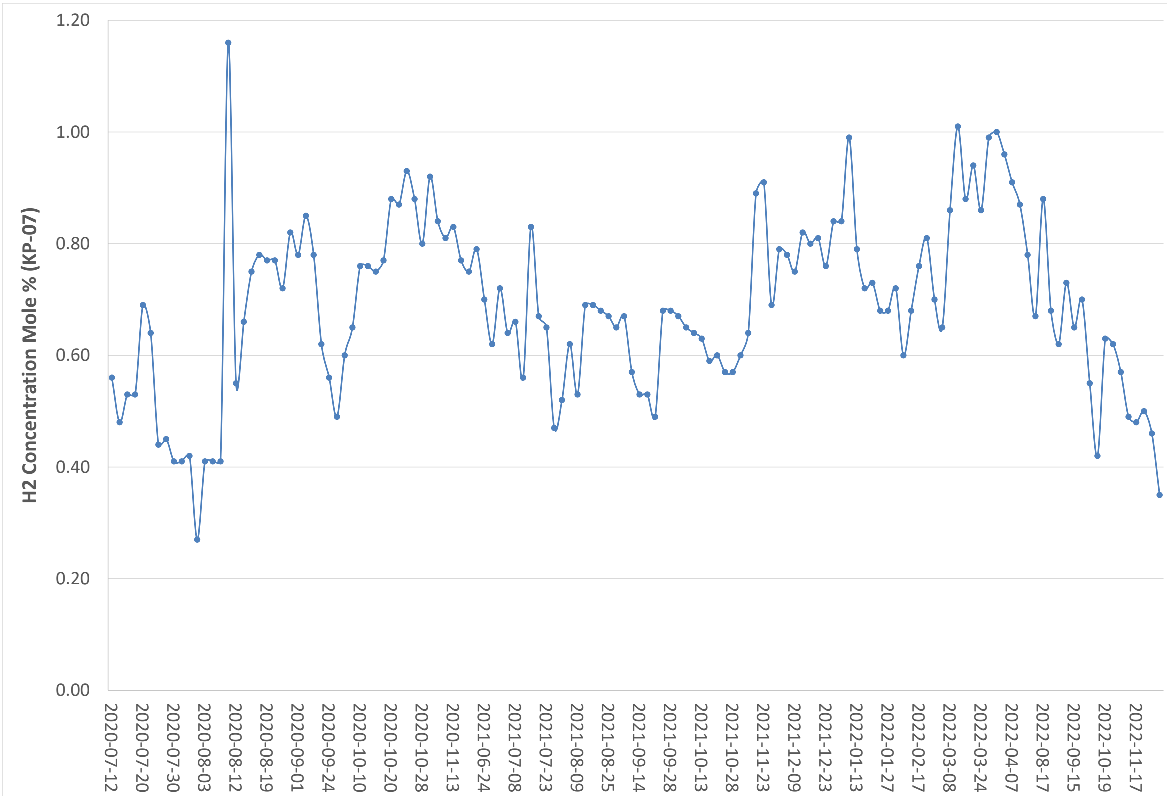
| DATE | Normalized GC Composition - Mole% | | | |
|---|---|---|---|---|
| | H2 | O2 | N2 | CH4 |
| 2020-07-12 | 0.56 | 0.18 | 75.14 | 7.15 |
| 2020-07-14 | 0.48 | 0.57 | 75.08 | 7.22 |
| 2020-07-16 | 0.53 | 0.32 | 75.03 | 7.46 |
| 2020-07-18 | 0.53 | 0.24 | 74.08 | 7.92 |
| 2020-07-20 | 0.69 | 0.39 | 75.86 | 5.57 |
| 2020-07-22 | 0.64 | 0.43 | 77.13 | 5.34 |
| 2020-07-28 | 0.44 | 0.04 | 81.58 | 2.73 |
| 2020-07-29 | 0.45 | 0.03 | 70.15 | 16.90 |

| | | | | |
|---|---|---|---|---|
| 2020-07-30 | 0.41 | 0.04 | 76.77 | 9.19 |
| 2020-07-31 | 0.41 | 0.06 | 81.31 | 2.97 |
| 2020-08-01 | 0.42 | 0.04 | 81.41 | 3.12 |
| 2020-08-02 | 0.27 | 0.11 | 77.90 | 7.19 |
| 2020-08-03 | 0.41 | 0.08 | 78.68 | 6.14 |
| 2020-08-05 | 0.41 | 0.36 | 84.11 | 0.00 |
| 2020-08-06 | 0.41 | 0.06 | 84.43 | 0.00 |
| 2020-08-07 | 1.16 | 0.42 | 55.48 | 0.00 |
| 2020-08-12 | 0.55 | 0.59 | 77.80 | 7.26 |
| 2020-08-16 | 0.66 | 0.22 | 77.84 | 6.43 |
| 2020-08-17 | 0.75 | 0.16 | 79.40 | 3.86 |
| 2020-08-18 | 0.78 | 0.06 | 79.45 | 3.87 |
| 2020-08-19 | 0.77 | 0.35 | 78.61 | 4.40 |
| 2020-08-22 | 0.77 | 0.32 | 77.21 | 6.40 |
| 2020-08-30 | 0.72 | 0.67 | 79.58 | 3.73 |
| 2020-08-31 | 0.82 | 0.18 | 78.17 | 5.76 |
| 2020-09-01 | 0.78 | 0.25 | 76.64 | 6.25 |
| 2020-09-04 | 0.85 | 0.41 | 79.44 | 3.53 |
| 2020-09-10 | 0.78 | 0.45 | 79.68 | 3.70 |
| 2020-09-22 | 0.62 | 0.67 | 72.74 | 10.06 |
| 2020-09-24 | 0.56 | 0.56 | 70.06 | 13.90 |
| 2020-10-04 | 0.49 | 0.22 | 65.86 | 19.08 |
| 2020-10-06 | 0.60 | 0.63 | 65.41 | 19.81 |
| 2020-10-07 | 0.65 | 0.78 | 66.07 | 18.39 |
| 2020-10-10 | 0.76 | 1.10 | 76.22 | 6.98 |
| 2020-10-12 | 0.76 | 0.32 | 76.17 | 6.97 |
| 2020-10-14 | 0.75 | 0.71 | 78.25 | 4.68 |
| 2020-10-16 | 0.77 | 0.79 | 76.67 | 6.28 |
| 2020-10-20 | 0.88 | 0.20 | 76.44 | 6.15 |
| 2020-10-22 | 0.87 | 0.36 | 76.42 | 5.94 |
| 2020-10-24 | 0.93 | 0.18 | 75.66 | 6.22 |
| 2020-10-26 | 0.88 | 0.89 | 76.12 | 5.79 |
| 2020-10-28 | 0.80 | 0.88 | 76.72 | 5.03 |
| 2020-11-06 | 0.92 | 0.28 | 76.14 | 5.11 |
| 2020-11-09 | 0.84 | 0.72 | 76.38 | 5.21 |
| 2020-11-11 | 0.81 | 1.35 | 74.36 | 7.56 |
| 2020-11-13 | 0.83 | 1.14 | 75.53 | 6.27 |
| 2021-05-04 | 0.77 | 0.12 | 78.59 | 4.86 |
| 2021-06-09 | 0.75 | 0.11 | 70.89 | 13.54 |
| 2021-06-17 | 0.79 | 0.41 | 75.20 | 7.60 |
| 2021-06-24 | 0.70 | 0.26 | 77.62 | 5.37 |
| 2021-06-28 | 0.62 | 0.18 | 77.62 | 5.23 |
| 2021-06-30 | 0.72 | 0.19 | 76.27 | 6.84 |
| 2021-07-06 | 0.64 | 0.22 | 76.63 | 6.96 |

| | | | | |
|---|---|---|---|---|
| 2021-07-08 | 0.66 | 0.23 | 76.47 | 6.92 |
| 2021-07-13 | 0.56 | 0.12 | 77.31 | 6.22 |
| 2021-07-15 | 0.83 | 0.20 | 76.51 | 6.60 |
| 2021-07-19 | 0.67 | 0.15 | 76.44 | 7.47 |
| 2021-07-23 | 0.65 | 0.06 | 77.47 | 6.20 |
| 2021-07-28 | 0.47 | 0.06 | 73.82 | 11.53 |
| 2021-08-03 | 0.52 | 0.21 | 77.93 | 5.96 |
| 2021-08-05 | 0.62 | 0.29 | 77.85 | 6.14 |
| 2021-08-09 | 0.53 | 0.22 | 77.67 | 6.25 |
| 2021-08-17 | 0.69 | 0.26 | 77.49 | 5.83 |
| 2021-08-19 | 0.69 | 0.15 | 77.50 | 5.98 |
| 2021-08-24 | 0.68 | 0.22 | 77.04 | 6.56 |
| 2021-08-25 | 0.67 | 0.07 | 77.23 | 6.39 |
| 2021-08-31 | 0.65 | 0.50 | 78.85 | 4.71 |
| 2021-09-02 | 0.67 | 0.49 | 79.28 | 4.97 |
| 2021-09-08 | 0.57 | 0.18 | 75.48 | 8.76 |
| 2021-09-14 | 0.53 | 0.40 | 75.41 | 8.54 |
| 2021-09-15 | 0.53 | 0.33 | 76.47 | 7.52 |
| 2021-09-21 | 0.49 | 0.15 | 76.16 | 7.76 |
| 2021-09-23 | 0.68 | 0.06 | 75.50 | 7.89 |
| 2021-09-28 | 0.68 | 0.09 | 75.01 | 8.48 |
| 2021-09-30 | 0.67 | 0.04 | 74.78 | 8.64 |
| 2021-10-05 | 0.65 | 0.06 | 74.39 | 8.79 |
| 2021-10-07 | 0.64 | 0.28 | 74.46 | 8.34 |
| 2021-10-13 | 0.63 | 0.13 | 72.71 | 9.56 |
| 2021-10-19 | 0.59 | 0.24 | 72.68 | 9.31 |
| 2021-10-20 | 0.60 | 0.11 | 72.35 | 9.71 |
| 2021-10-26 | 0.57 | 0.25 | 72.72 | 8.54 |
| 2021-10-28 | 0.57 | 0.14 | 72.56 | 8.31 |
| 2021-11-03 | 0.60 | 0.17 | 75.85 | 4.14 |
| 2021-11-09 | 0.64 | 0.03 | 77.35 | 3.88 |
| 2021-11-16 | 0.89 | 0.03 | 78.63 | 3.24 |
| 2021-11-23 | 0.91 | 0.11 | 77.57 | 4.90 |
| 2021-11-30 | 0.69 | 0.13 | 79.26 | 4.27 |
| 2021-12-02 | 0.79 | 0.20 | 77.61 | 5.05 |
| 2021-12-07 | 0.78 | 0.09 | 76.50 | 5.87 |
| 2021-12-09 | 0.75 | 0.09 | 77.38 | 5.53 |
| 2021-12-14 | 0.82 | 0.10 | 76.49 | 5.95 |
| 2021-12-16 | 0.80 | 0.19 | 77.08 | 5.57 |
| 2021-12-21 | 0.81 | 0.24 | 76.00 | 6.20 |
| 2021-12-23 | 0.76 | 0.07 | 76.64 | 6.57 |
| 2021-12-29 | 0.84 | 0.27 | 75.20 | 6.79 |
| 2022-01-04 | 0.84 | 0.28 | 77.05 | 5.52 |
| 2022-01-11 | 0.99 | 0.25 | 69.70 | 12.24 |

| | | | | |
|---|---|---|---|---|
| 2022-01-13 | 0.79 | 0.19 | 76.46 | 5.98 |
| 2022-01-18 | 0.72 | 0.20 | 76.88 | 5.76 |
| 2022-01-20 | 0.73 | 0.49 | 76.87 | 6.01 |
| 2022-01-25 | 0.68 | 0.36 | 77.13 | 6.10 |
| 2022-01-27 | 0.68 | 0.27 | 77.27 | 5.39 |
| 2022-02-02 | 0.72 | 0.24 | 77.27 | 5.13 |
| 2022-02-05 | 0.60 | 0.00 | 76.92 | 7.62 |
| 2022-02-15 | 0.68 | 0.30 | 77.07 | 5.73 |
| 2022-02-17 | 0.76 | 0.19 | 77.19 | 5.79 |
| 2022-02-23 | 0.81 | 0.19 | 75.05 | 7.27 |
| 2022-03-01 | 0.70 | 0.36 | 76.11 | 6.60 |
| 2022-03-03 | 0.65 | 0.35 | 76.47 | 6.31 |
| 2022-03-08 | 0.86 | 0.25 | 77.60 | 5.01 |
| 2022-03-10 | 1.01 | 0.29 | 77.61 | 4.60 |
| 2022-03-15 | 0.88 | 0.48 | 77.16 | 5.30 |
| 2022-03-17 | 0.94 | 0.25 | 75.96 | 7.01 |
| 2022-03-24 | 0.86 | 0.18 | 75.01 | 8.38 |
| 2022-03-28 | 0.99 | 0.18 | 71.38 | 10.42 |
| 2022-03-30 | 1.00 | 0.13 | 71.62 | 10.31 |
| 2022-04-05 | 0.96 | 0.28 | 72.02 | 10.42 |
| 2022-04-07 | 0.91 | 0.24 | 71.58 | 11.41 |
| 2022-04-12 | 0.87 | 0.09 | 73.86 | 9.28 |
| 2022-04-14 | 0.78 | 0.23 | 76.28 | 7.02 |
| 2022-08-11 | 0.67 | 0.32 | 76.80 | 6.14 |
| 2022-08-17 | 0.88 | 0.03 | 75.84 | 6.21 |
| 2022-08-25 | 0.68 | 0.11 | 75.78 | 7.91 |
| 2022-08-31 | 0.62 | 0.15 | 76.03 | 7.76 |
| 2022-09-07 | 0.73 | 0.13 | 71.83 | 9.13 |
| 2022-09-15 | 0.65 | 0.08 | 73.04 | 9.81 |
| 2022-09-20 | 0.70 | 0.05 | 71.55 | 10.58 |
| 2022-10-05 | 0.55 | 0.13 | 68.19 | 13.88 |
| 2022-10-12 | 0.42 | 0.13 | 72.74 | 12.62 |
| 2022-10-19 | 0.63 | 0.20 | 68.94 | 12.86 |
| 2022-10-25 | 0.62 | 0.20 | 68.28 | 13.59 |
| 2022-10-27 | 0.57 | 0.44 | 66.59 | 14.13 |
| 2022-11-15 | 0.49 | 0.25 | 67.33 | 17.76 |
| 2022-11-17 | 0.48 | 0.05 | 67.46 | 17.93 |
| 2022-12-08 | 0.50 | 0.00 | 67.64 | 17.84 |
| 2022-12-13 | 0.46 | 0.24 | 63.51 | 22.68 |
| 2022-12-15 | 0.35 | 0.19 | 60.36 | 27.22 |

*Figure 5: Hydrogen concentration of KP-07*




Proton's reservoir modelling suggests that improved $H_2$ production could be achieved through the injection of $O_2$-enriched air or pure $O_2$ at higher pressures instead of atmospheric air. This is primarily due to the higher partial pressure of $O_2$ injected into the reservoir. Increasing the $O_2$ concentrations and partial pressures, is expected to result in higher reservoir temperatures, increased combustion and oxidization, improved reservoir kinetics, and the displacement/reduction of $N_2$ present in the reservoir. Due to the inert nature of $N_2$, it is hypothesized to limit the combustion reactions in the reservoir leading to an overall cooling effect. The increased temperatures expected to result from the injection of enriched air, or pure $O_2$, are hypothesized to result in more complex reactions across a wider range of temperatures resulting in the production of more $H_2$.

Further analysis led Proton to conclude that the processes required for $H_2$ production are non-linear and cyclical in nature, and the reservoir would require a range of temperatures to create the kinetics and chemical reactions necessary to maximize $H_2$ production. These reactions include the following:

1) Low Temperature Reactions primarily aqua thermolysis (<300°C)
    a. Maltenes and asphaltenes to $H_2$, $CH_4$, CO, $CO_2$, $H_2S$
2) Medium Temperature Reactions (300-500°C)
    a. Thermolysis (>300°C)
    b. Pyrolysis
    c. WGS
3) High Temperature Reactions (500-900°C)
    a. High Temperature Oxidization
    b. Coke Gasification

Proton further hypothesized that reservoir temperatures could not remain at low temperatures ranges (<350°C) for sustained periods of time which result in increased methanation reactions, nor could the temperatures ranges be too high which result in the combustion and cannibalization of $H_2$.

## 2.2. Drilling/Completion/Testing of a $H_2$ well

A vertical $H_2$ production well at the apex of the reservoir was drilled, completed, and tested.

### Results

One $H_2$ production well (apex well), 103/09-14-033-24W3/00, was drilled in September 2020, and perforated in the highest part of the Waseca formation just below the caprock where Proton hypothesized the highest concentrations of $H_2$ should accumulate due to density stratification. The apex well began production in November 2020 and was tested with regular sample analysis to measure $H_2$ concentration and volume from the structural high of the formation. Gas flow rate for the test period was on average 40m$^3$/day, with a total gas volume of approximately 3370m$^3$. Preliminary analyses of produced gases from the $H_2$ well revealed greater methane quantities than expected (~5%), suggesting that undesired methanation reactions could be occurring in the reservoir. Initial data suggested that $H_2$ stratification was not occurring to the extent hypothesized, however a boiler failure in Q1 2021 interrupted steam injection trials. As a result of the boiler failure, the data collected was insufficient to prove or disprove the methanation and $H_2$- stratification hypotheses. These hypotheses will be tested in the future. The well saw higher than expected gas rates that lead to two pump failures in May and June of 2021. The well also needed a sand cleanout in September 2021. It was at this time that steam injection trials were paused, the apex measurement well was shut in, with plans to recomplete the well for gas measurements during future $O_2$ injection trials. It was also observed that the temperature in the reservoir was not hot enough to reach the temperatures required to produce optimal levels of $H_2$.

To date, samples from this well indicate $H_2$ concentrations between 0.5-2%. Table 4, below, shows GCMS data during production test period of the apex well.

*Table 4: H2 production well GCMS data*

| **DATE** | **GC Normalized Composition Mole%** | |
|---|---|---|
| | **$H_2$** | **$CH_4$** |
| 2020-10-29 | 0.47 | 4.32 |
| 2020-10-30 | 0.48 | 4.66 |
| 2020-10-31 | 0.49 | 5.56 |
| 2020-11-01 | 0.51 | 5.68 |
| 2020-11-02 | 0.48 | 6.21 |
| 2020-11-03 | 0.52 | 5.84 |

| | | |
|---|---|---|
| 2020-11-18 | 0.60 | 5.54 |
| 2020-11-19 | 0.60 | 5.56 |
| 2020-11-20 | 0.50 | 4.82 |
| 2020-11-21 | 0.48 | 4.80 |
| 2020-11-23 | 0.48 | 4.63 |
| 2020-11-24 | 0.54 | 4.77 |
| 2020-11-25 | 0.54 | 4.76 |
| 2020-11-27 | 0.50 | 4.24 |
| 2020-11-29 | 0.48 | 3.91 |
| 2020-11-30 | 0.50 | 3.98 |
| 2020-12-01 | 0.50 | 3.94 |
| 2020-12-05 | 0.50 | 3.55 |
| 2020-12-06 | 0.52 | 3.69 |

The $H_2$ production well is expected to be reused in future ISHG tests involving the injection of enriched air, or pure $O_2$. Proton's hypothesis is that the apex well should produce gases with much higher concentrations of $H_2$ (up to 20%) by volume because of the injection of $O_2$ above ambient air levels (~21% $O_2$). Proton further expects the process to be optimized by cyclically controlling the temperatures within the reservoir to maximize $H_2$ production.

## 2.3. Micro Scale Surface Membrane Separation Test

Determining $H_2$ flux rates and recovery rates and membrane run-time through the membrane was another goal for this project. The expectation was that 99.9% of $H_2$ would be separated out of the gas stream. This was to be accomplished through field testing of the palladium alloy membrane on a continuous stream of gas produced from the apex $H_2$ well and other project wells.

### Results

Proton started testing the membrane in Q1 2021. Produced gas from the reservoir was run through the membrane, and outlet gas compositions were measured with GCMS. Initial tests resulted in membrane failure and outlet $H_2$ concentration being equal to inlet concentration (1-2%). It was hypothesized that membrane performance would increase with higher partial pressure of $H_2$ in the inlet gas. Since $H_2$ concentration in the reservoir was fixed, the total inlet gas pressure was raised by increasing the wellhead 7" casing pressure. However, outlet $H_2$ concentrations remained the same as inlet, even after reaching pressures high enough to create liquid carryover from the wells. Membrane cracking was also observed, and a few hypotheses were advanced: 1) pressure fluctuations, 2) $H_2S$ contamination, and 3) temperature-induced membrane phase transition.

Follow-up membrane tests were conducted using the produced gas. Pressure regulators were installed ahead of the membrane inlet to mitigate pressure transients, and iron- oxide (FeO) scrubbers were used to reduce inlet $H_2S$ concentrations. $H_2$ make-up gas sourced from Air Liquide was added to the inlet stream. Each cylinder had 45 liters of gas at 2000 psi. The make-up gas was to permit testing at desired $H_2$ concentrations, which were not yet available in the reservoir. Despite achieving higher $H_2$ concentrations in the outlet gas and performing much better than in previous tests, the membrane still failed, as the palladium layer was damaged and then peeled off; this was thought to be attributed to either sulphur poisoning or temperature fluctuations.

The metallurgy of membranes proved too sensitive to the syngas produced from the reservoir resulting in cracking and damages. Therefore, the initial goal of determining flux rates, recovery rates, and run times through the originally proposed membrane was not achieved. Proton concluded that different a membrane species is required.

In the future, additional field tests will be conducted by third-party manufacturers using different membrane species including ceramics and polymers. Information derived from these tests will be required for the design basis for future H2 separation and purification.

# 3. Project Costs

The total cost for this project was $16,129,957.38. Please see Table 5, below, for a summary of project costs, and please see Appendix A for further details.

*Table 5: Summary of project costs.*

| Cost Category | Jan 1 2018- Mar 31 2020 | Apr 1 2020- Sept 30 2020 | Oct 1 2020- Oct 31 2021 | Nov 1 2021 - Mar 15 2022 | Mar 16 2022 - Sept 30 2022 | Oct 1 2022 - June 30 2023 |
|---|---|---|---|---|---|---|
| OPEX | $ 2,273,895.48 | $ 1,159,775.00 | $ 3,698,801.34 | $ 825,506.60 | | |
| H2 Test | $ 117,097.04 | $ 364,441.00 | $ 335,606.58 | $ 73,136.18 | $ 77,791.24 | $ 43,881.76 |
| Steam(Asset & Startup Costs) | $ 961,652.34 | $ 119,495.00 | $ 159,802.76 | | | |
| 04-13 Air Compressor | $ 36,128.07 | $ 9,714.00 | $ 13,332.46 | | $ 4,936.32 | |
| H2 well drill | | $ 421,760.00 | $ 414,900.92 | | | |
| Well Workovers | | | $ 1,343,809.44 | $ 763,508.40 | $ 354,016.39 | $ 7,394.87 |
| Oxygen Injection | | | $ 452,130.19 | $ 369,618.95 | $ 153,905.43 | $ 21,678.25 |
| Contractors, Salaries & fees | | | $ 320,966.86 | $ 370,062.65 | $ 536,525.50 | $ 324,686.36 |
| **Total Accrued** | **$ 3,388,772.93** | **$ 2,075,185.00** | **$ 6,739,350.55** | **$ 2,401,832.78** | **$ 1,127,174.88** | **$ 397,641.24** |
| **Final** | **$ 16,129,957.38** | | | | | |

# 4. Project Conclusions

Proton's $H_2$ Extraction Project began in 2020 by demonstrating a field experiment in the Kerrobert Mannville Sand Pool using the existing oil recovery (EOR) project oil wells from SK ER E2002 to demonstrate the potential to produce significant quantities of $H_2$. Co-injection of air and steam in existing injection wells was performed and observational data was collected from produced gas stream from oil wells via GCMS. Proton attempted to correlate injection rates to the $H_2$ concentration. The initial data did indicate an increase in reservoir temperature and small increase in $H_2$ concentration when steam was first introduced. However, it was observed through data and reservoir simulations that temperatures needed to produce greater than 4% $H_2$ were not achievable using air injection at 20% $O_2$ concentrations. It is hypothesized that improved $H_2$ production would be achieved by injecting enriched air or pure $O_2$ to increase reservoir temperatures to the ranges necessary for optimal $H_2$ production.

Proton expected to be producing 84kg/d $H_2$ when the experiment concluded. Although this was not achieved on a consistent basis due to the reservoir not reaching temperatures for optimal $H_2$ production, Proton did produce at it's maximum 120kg/d and upwards of 90kg/d for four consecutive months.

Another hypothesis was that of density stratification in the reservoir with greatest concentration of $H_2$ accumulating at the highest point of the formation. Proton drilled and completed an apex $H_2$ well to confirm this hypothesis in Q3 2020. Well logs indicated large gas cap accumulation due to continuous air injection in the reservoir from the previous THAI project. Initial data did not suggest higher concentrations of $H_2$ from the gas cap however, due to a boiler failure that interrupted the steam trials, the data collected was not sufficient to prove or disprove density stratification. Proton's hypothesis is that $H_2$ concentrations via density stratification at apex well may improve when higher concentrations of $O_2$ are injected.

Proton also started testing palladium alloy membranes for $H_2$ separation in Q1 2020. Initial results revealed inadequate $H_2$ concentrations of outlet gas where concentration of $H_2$ remained equal to inlet gas. It was hypothesized that membrane performance would increase with higher partial pressure of $H_2$ in the inlet gas. During testing outlet $H_2$ concentrations remained equal to inlet concentration and membrane cracking was also observed. A few hypotheses were advanced for the membrane failure: a) pressure fluctuations, b) $H_2S$ poisoning, and c) temperature-induced membrane phase transition. Ongoing tests will be conducted using different membrane species. Proton intends to engage a third-party membrane manufacturer to test different membranes at the field site. The results of these tests may allow testing to be scaled up to surface separation of the $H_2$ well at higher gas rates. Produced $H_2$ may be further compressed, stored on-site, and trucked in gaseous form for sale.

Proton did not complete two deliverables from the original project proposal. These include 1) $H_2$ Compression, Storage and Loading and 2) the O2 injection tests as outlined below. The scope of these deliverables has since changed and revised projects are part of the company's future testing plans for ISHG.

## 4.1. Design and Construction of $H_2$ Compression, Storage, and Loading Facilities

This deliverable was planned to allow for the scaled-up palladium alloy membrane test of separating $H_2$ at flow rates, compressing the separated $H_2$, and storage in tanks or tube trailers for truck loading to sales.

This deliverable was planned to include the following main components:

a) Three-stage Waukesha Pre-compression.
b) H2Sweet Sulfur Removal.
c) H2SITE Palladium membrane.
d) Two-stage PDC Machines H2 Compressor.
e) Blending facility.

Proton was planning to design this portion of the facility for the capacity to produce, process, and store 80-100 kilograms (kg) of $H_2$ per day.

### Results

The design phase began in Q4 2021, involving process engineering and contracting an engineering, procurement, and construction (EPC) firm. The project was then put on hold due to delays in $O_2$ injection project and unexpected prolonged troubleshooting of palladium alloy membrane cracking.

Future $H_2$ compression, storage, and loading facilities will be designed and constructed based on $O_2$ injection tests, surface separation technology development, and available markets for hydrogen sale.

## 4.2. Oxygen Injection Test

This deliverable involved the purchase of liquid $O_2$ and trucking to the injection facility. The $O_2$ was planned to be gasified and blended with the air and steam injection through a variety of test for optimal production of $H_2$. The purpose of the planned test was to prove that the production commercial concentrations of $H_2$ from an oil reservoir was achievable via in-situ oxidation.

### Results

Proton encountered equipment failures at the CPF, delays with funding for the project, and it had to re-evaluate the injection program to optimize for $H_2$ production. The re-evaluation of the injection program involved the need to address equipment failures by performing a comprehensive operational readiness review, Hazard and Operational Studies (HAZOP). It also involves the need to improve our numerical and analytical models to simulate and analyze the reservoir kinetics and full range of chemical reactions to maximize $H_2$ production. Lastly, the revaluation identified the need to model the optimal well configuration, production processes, and redesign the surface process engineering and facilities necessary to commercially produce $H_2$.

Early-stage reservoir simulation models were developed using both homogenous and heterogenous reservoir characteristics to investigate the effect of different $O_2$ concentrations on $H_2$ generation using different reservoir conditions (e.g., reservoir pressures, temperatures, oil and water saturation, and different perforation intervals). The results indicate that $H_2$ production increases with higher concentrations of $O_{2,}$ and it varies between 1.5% to 45% (mole fraction) for air injection (21% $O_2$) to pure $O_2$ injection (100% $O_2$), respectively. Depending on the $O_2$ concentration, the expected production rate of $H_2$ was modelled in the range of 35 kg/d to 450 kg/d in the case of steam/air/enriched air cycles across multiple well scheme, and 38 kg/d to 400 kg/d in the case of single well steam/air/enriched air injection and production scheme.

Although the $O_2$ injection has been delayed, the predicted outcomes and conclusions from the completed tests remain. As the injection rate (partial pressure) of $O_2$ into the reservoir increases, higher concentrations of $H_2$ are expected to be produced. The process is cyclical, and the reservoir needs to be maintained within the optimal temperature bands to maximize $H_2$ production.

Additional $O_2$ injection tests are planned in 2024 using a cyclic injection and production methods using enriched air (or pure $O_2$), steam, water, and/or diluent. The test parameters are based on additional reservoir simulations and analysis that have been completed in-house led by Dr. Ian Gates and Dr. Jacky Wang from the University of Calgary. The expected test schedule will be over a 12–18-month period.

Future $O_2$ injection tests are critical for next development phase of the project. These tests will be required to support commercial viability of industrial scale $H_2$ production, and the additional investment required for commercial scale $O_2$ production, large scale gas separation, $H_2$ purification, compression, storage, and transportation.

APPENDIX A: COST SUMMARY

**Proton Technologies Canda Inc.**
**Schedule of Eligible Project Costs**
**Project ER-SPII-1219-003**
**(Costs incurred by Superb Operating Company Ltd.,**
**a wholly-owned subsidiary of Proton Technologies Canada Inc.)**
**For the period from January 1, 2018 to March 31, 2020**

| **Cost Category** | | |
|---|---|---|
| Operating Expenses | $ | 2,273,895.48 |
| Hydrogen Test | | 117,097.04 |
| Steam Asset Costs | | 490,454.96 |
| Steam Startup Costs | | 471,197.38 |
| 04-13 Air Compressor | | 36,128.07 |
| Total expenses incurred | **$** | **3,388,772.94** |

**Proton Technologies Canada Inc.**
**Schedule of Eligible Project Cost**
**Project ER-SPII-1219-003**
**(Costs incurred by Superb Operating Company Ltd., a wholly-owned subsidiary of Proton Technologies Canada Inc.)**
**For April 2020**

| **Cost Category** | | |
|---|---|---|
| OPEX | $ | 244,651 |
| 2020 Hydrogen Test Preparation | | 227,866 |
| Steam(Asset & Startup Costs) | | 33,369 |
| 04-13 Air Compressor | | 9,714 |
| Total costs incurred | $ | 515,599 |

**Proton Technologies Canada Inc.**
**Schedule of Eligible Project Cost**
**Project ER-SPII-1219-003**
**(Costs incurred by Superb Operating Company Ltd., a wholly-owned subsidiary of Proton Technologies Canada Inc.)**
**May 1, 2020 to Sep 30 2020**

| **Cost Category** | | |
|---|---|---|
| OPEX | $ | 915,124 |
| Hydrogen well drill | | 421,760 |
| 2020 Hydrogen Test Preparation | | 136,575 |
| Steam(Asset & Startup Costs) | | 86,126 |
| Total costs incurred | $ | 1,559,585 |

**Proton Technologies Canada Inc.**
**Schedule of Eligible Project Cost**
**Project ER-SPII-1219-003**
**(Costs incurred by Superb Operating Company Ltd., a wholly-owned subsidiary of Proton Technologies Canada Inc.)**
*(Amended and restated information, see note 2)*

**October 1, 2020 to October 31, 2021**

| **Project** | | |
|---|---|---|
| Operating Expenses | $ | 3,698,801.34 |
| H2 Micro Surface Test | | 335,606.58 |
| Salaries | | 320,966.86 |
| Oxygen Injection - Downhole | | 319,305.03 |
| H2 Equip | | 245,552.00 |
| KP4 Jet Pump | | 225,218.56 |
| KP11 Workover | | 223,003.74 |
| KP7A Workover | | 199,422.71 |
| H2 Well Workover | | 191,449.31 |
| Steam(OTSG and Startup Costs) | | 159,802.76 |
| Oxygen Injection - Surface | | 132,825.16 |
| KP4 Jet Lift | | 113,957.94 |
| KP1 Workover | | 89,702.60 |
| H2 Completion | | 87,501.12 |
| H2 Well Drill | | 81,847.80 |
| KP12 Workover | | 81,277.42 |
| KP2 Workover | | 64,984.79 |
| KP4 Workover | | 57,303.44 |
| KP6 Workover | | 17,473.92 |
| KA5 Workover | | 16,155.20 |
| KA7 Workover | | 15,191.21 |
| 4-13 Air Compressors | | 13,332.46 |
| KA6 Workover | | 12,917.45 |
| KP5 Workover | | 12,326.50 |
| KA12 Workover | | 8,474.63 |
| KA11 Workover | | 5,223.75 |
| KA1 Workover | | 4,550.15 |
| KA10 Workover | | 2,848.75 |
| KP3 Workover | | 1,450.37 |
| KA9 Workover | | 877.00 |
| Total expenses incurred | $ | 6,739,350.55 |

**Proton Technologies Canada Inc.**
**Schedule of Eligible Project Costs**
**Project ER-SPII-1219-003**
**(Costs incurred by Superb Operating Company Ltd., a wholly-owned subsidiary of Proton Technologies Canada Inc.**
**November 1, 2021 to March 15, 2022**

| Project | | |
|---|---|---|
| Operating Expenses | $ | 825,506.60 |
| Contractors - Project Managers | | 280,357.50 |
| KP7A Workover | | 247,803.20 |
| Oxygen Injection - Downhole | | 190,683.86 |
| KP2 Workover | | 142,944.86 |
| KP1 Workover | | 122,558.67 |
| H2 Well Workover | | 119,813.25 |
| KP12 Workover | | 115,446.25 |
| KA2 Oxygen Injection | | 95,206.90 |
| Salaries | | 89,705.15 |
| H2 Micro Surface Test | | 73,136.18 |
| HMI Upgrade | | 67,644.40 |
| Oxygen Injection - Surface | | 16,083.79 |
| KP2 Workover | | 10,256.67 |
| KP7A Workover | | 2,150.50 |
| KP3 Workover | | 1,575.00 |
| KP5 Workover | | 960.00 |
| Total expenses incurred | | 2,401,832.79 |
| Adjustments, see note 2 | | (97,193.87) |
| Net eligible cost claim | $ | 2,304,638.92 |

**Proton Technologies Canada Inc.**
**Schedule of Eligible Project Costs**
**Project ER-SPII-1219-003**
**(Costs incurred by Superb Operating Company Ltd., a wholly-owned subsidiary of Proton Technologies Canada Inc.**
**March 16, 2022 to September 30, 2022**

| **Project** | |
|---|---|
| Contractors - Project Managers (note 2) | 456,348.93 |
| H2 Well Workover | 287,251.11 |
| Oxygen Injection - Surface | 153,905.43 |
| H2 Micro Surface Test | 77,791.24 |
| Salaries | 70,176.57 |
| KP4 Acid Job | 35,544.40 |
| KP7A Workover | 27,645.88 |
| Audit fees | 10,000.00 |
| Air Compressor Liquid Knockout | 4,184.51 |
| KA2 Oxygen Injection | 3,575.00 |
| 4-13 Air Compressors | 751.81 |
| Total expenses incurred | 1,127,174.88 |

**Proton Technologies Canada Inc.**

**Schedule of Eligible Project Costs**

**Project ER-SPII-1219-003**
**Costs incurred by Superb Operating Company Ltd.,**
**a whollyowned subsidiary of**
**Proton Technologies Canada Inc.**
**October 1, 2022 to June 30, 2023**

| **Project ER-SPII-1219-003** | |
|---|---|
| Contractors - Project Managers | 199,179.96 |
| Salaries | 123,506.40 |
| H2 Micro Surface Test | 43,881.76 |
| Oxygen Injection - Surface | 21,678.25 |
| KP7A Workover | 6,899.87 |
| Audit fees | 2,000.00 |
| H2 Well Workover | 495.00 |
| | 397,641.24 |