HYDROGEN VENTILATION TEST FACILITY FOR UNDERGROUND MINING AND TUNNELING

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ABSTRACT

One of the focus areas in the heavy-duty transport industry globally is de-carbonization of trucks, dozers, shovels, semi-trucks, buses, etc. Hydrogen fuel cells (FCs) technology is one considered solution for the industry due to its zero-emissions, its MW scalability and capacity to store large amounts of energy for long duration continuous power operation. Underground deep mines is another option for deployment and operation of hydrogen FCs. Benefits include lower emissions, improved health, comfort and safety, as well as reduced operating costs. Underground mining trucks, loaders and other machines have power ratings up to 750 kW, which proves difficult for battery and tethered electric energy. Hydrogen FCs have the ability to overcome these power and energy storage limitations. The risks and technologies associated with delivering, storing and using hydrogen underground first need to be investigated and proven safe. This work presents the design, construction and operation of a mining ventilation test facility (VTF) at the North-West University in South Africa that aims to quantify the risk of hydrogen in confined ventilated environments. Initial work has been conducted on measuring concentrations of hydrogen released in the temporary ventilation site and is discussed.

Keywords: hydrogen fuel cell, hydrogen safety, underground mining, HySA, ventilation

1.0 INTRODUCTION

Mining companies are facing significant challenges in their efforts to de-carbonize and not loose on productivity and cost. 2015 data showed that half of worldwide industrial greenhouse gas emissions could be traced back to just 50 companies [3]. Two mining companies were in the top 5, and 20 of the top 100. Conventional powering technologies like diesel and batteries are not simultaneously clean, safe, and productive. Tethered vehicles are power-dense and have no direct emissions. However, the tether introduces additional safety fears, interferes with mobility and productivity, and introduces weaknesses and high strain at the tether interfaces [1]. Diesel internal combustion engine(ICE)-powered equipment are power-dense but more mobile and more productive than tethered, but generate harmful emissions and unwanted heat due to inefficiencies along with wasted heat from torque converters that require expensive additional ventilation and cooling [1]. Because workers are constrained to an underground workplace, mining is one of the most regulated industries. Implementing more strict emissions and noise regulations will further increase vehicle capital and operating costs and lower mine productivity. Changing to electrical drive trains provide significant benefits in the mining environment. A sensitivity analysis of diesel-, battery- and tethered-powered equipment shows that the capital cost benefits are not considerable: battery equipment is 5% more expensive and tethered 2.5% less expensive than the diesel equivalent. Tethered and battery equipment showed a 29.5% lower maintenance cost than diesel. Battery equipment added 6% battery replacement cost but 5.5% more annual tonnage than diesel while tethered resulted in a sizeable 27% less tonnage. Cost differences are more sensitive to electricity prices than to diesel fuel fluctuations [2]. According to cost trends from the energy information agency (EIA), diesel prices will increase significantly while intermittent renewable energy (RE) sources like solar and wind will decrease in price [2]. The drawback of these RE sources is their intermittent nature, requiring short-term to seasonal storage capabilities to support grid stability as well as supply energy when these sources are not abundant due to seasonal changes. Hydrogen has been researched in many industries as an energy storage technology for intermittent sources and is seen as a solution to prevent curtailment of RE, to store this energy and use later when needed. The added benefit for mines, especially remote ones, is the ability to produce their own hydrogen for FC powered equipment. Both RE and electrolysis technologies have experienced capital and operating cost reduction [2], and provides a solution for mines to transition to complete energy independence. The Government of Chile proposed a center for energy transition of mining industries by the adoption of new technologies. Proposed research topics include solar PV and concentrated solar technologies, storage technologies, hydrogen and liquid fuel technologies that can serve the transport and processing activities of the mining sector [5].

Hydrogen powered equipment and their cost benefits have been studied in the past. Bétournay et al. [4] conducted FC vs. diesel cost-benefit analysis for Canadian mines. At the time FC-powered machines, based on expensive metal-hydride technology, showed a cost reduction in both operation and maintenance of equipment as well as overall mine ventilation and cooling requirements. Cost of hydrogen and diesel used in the analysis were estimated at \$3.85/kg (~\$0.12/kWh) and \$0.5/liter (~0.05/kWh) respectively. Efficiency curves of typical PEM FC and diesel ICE given in Fig. 1a, show the FC to be more efficient that the diesel ICE through the entire power range. Fig. 1b provides the usable energy cost comparison between diesel fuel at a 5 year projected price of \$1.43/liter and hydrogen fuel at \$3.00/kg possible with large-scale RE hydrogen production. Cost of electricity is again identified as the dominant cost factor for load-factors above 50% [6]. For typical mines there exists a potential for 24 to 53% reduction in the electrical operating cost of the primary ventilation system for an intake airflow reductions of 9% for operations below 2400 m depth, and intake airflow reductions of 24% for operations between 400 – 800 m depth. Reduction in auxiliary ventilation system operating costs are between 11 and 20%. Reductions in greenhouse gas emissions for the same sites results in 27 to 38% by replacing diesel ICEs with FCs [7].

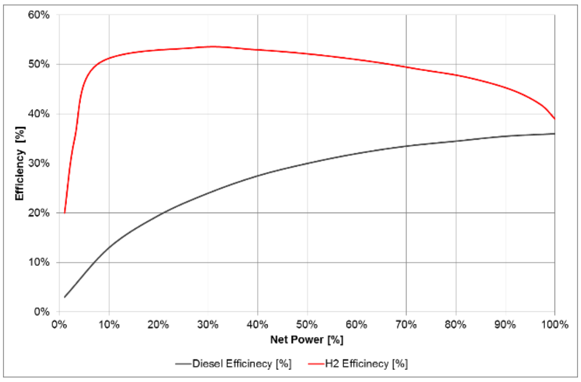

Figure 1a. Diesel ICE vs. FC efficiency.

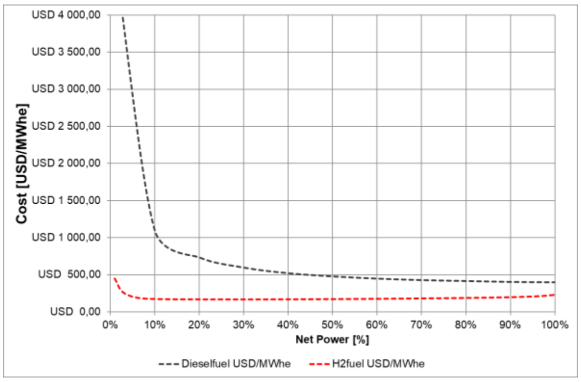

Figure 1b. Diesel vs. hydrogen energy cost.

Although hydrogen FC powered equipment could provide health, comfort and economic benefits, hydrogen safety in underground confined spaces is a major concern. Various components and systems are usually required to measure, alarm, and mitigate when unsafe scenarios arise. Hydrogen in underground confined spaces is however not understood. Several issues have been identified regarding hydrogen in underground mining [7]. One issues is the amount of ventilation required to dilute a possible hydrogen leak that could result from the hydrogen system on-board the FC powered equipment. There are also no codes and standards for hydrogen FC powered equipment underground.

This work describes the development of a hydrogen VTF with the purpose of addressing these issues by evaluating and quantifying the risks associated with the use of hydrogen in ventilated underground mining and tunneling environments. The next section provides background on FCs in mining and gives a history of work done in the past. Next is a section providing design detail of the temporary and main VTF and safety considerations, including specification and safety. Initial results and discussions are also provided. This is followed by a discussion of future work and a conclusion.

2.0 BACKGROUND

The first mention of hydrogen FC application in underground mining dates back 20 years [8]. At the time hydrogen FCs were determined to be economically viable for underground mining. Providing traction power in enclosed highly regulated environments is a challenge and the inadequacies of conventional power are the basis of economic stress in the industries. Clean, safe, and productive FC powered equipment offer cost offsets that are commercially successful. Despite the high capital cost of FCs, cost offsets arising from solving problems associated with enclosed, underground operating environment (emissions, noise, heat, etc.) make FC more cost-competitive than in surface applications. These offsets allow the FC powered equipment to compete strictly on economic merit. The reason FCs have not been more actively pursued for the underground environment, is possibly from the misperception and misrepresentation of safety associated with hydrogen gas, especially with the advanced materials available today. Reference is always made to hydrogen's wide flammability limits and ignition energy. The fact that acetylene cylinders, commonly found in household garages, in every workshop around the world and even in underground mines, posing similar and in many cases more undesirable properties than hydrogen, is unnoticed most probably due to it being a commonly used gas. Hydrogen has an ignition temperature almost double that of acetylene, diesel and gasoline, and higher than Methane. Hydrogen has a low ignition energy but in fact is equal to that of acetylene. Moreover, acetylene has a wider flammability range than hydrogen, and acetylene unlike hydrogen can violently decompose and explode without oxygen, a spark or flame present. Hydrogen has a very low buoyancy and high diffusion coefficient; properties that allow designing safety concepts to get rid of hydrogen effortless. Although hydrogen has these attributes, it is the smallest molecule and therefore could leak much easier.

In September 1999 a consortium of companies lead by the Fuelcell Propulsion Institute (FPI) [9] received funding to develop a FC powered mine locomotive using metal-hydride storage [10]. Underground testing occurred in October 2002 in a gold mine under representative production mine conditions. The locomotive performed flawlessly with zero failures or downtime. The FC-locomotive showed 100% power availability for 8½ hours operation, whereas the battery-powered version revealed a steady performance decrease for around 7 hours of operation. A second project was to develop a FC-hybrid powered mine loader. The project had three goals: develop a FC powered mine loader, develop associated MH storage and refueling systems and demonstrate the FC hybrid loader underground [11]. The working loader was developed and successfully tested aboveground. Following these two successful projects, examining the direct application to underground vehicles, called the Hydrogen Mine Introduction Initiative (HMII), was implemented [15, 16]. The HMII main objective was to develop norms and standards to support mining regulations for technological application in underground vehicles. The HMII was an industry consortium established to develop and test a range of needed operational technology, specifications and best practices for hydrogen power applications in underground mining vehicles in order to consider this technology as replacement to diesel. Two later projects by FPI and funded by Anglo American Platinum Ltd. (AAPL) included a second locomotive and a FC-powered mining dozer [12]. Like all previous demonstrators, both used hydrogen reversible metal-hydride hydrogen storage. AAPL continued the dozer demonstrations, and have recently demonstrated the same dozer using liquid organic hydrogen carrier (LOHC) technology and plans to start testing underground in 2019 [13].

Even with FC power-plant capital costs much higher than comparable diesel power-plants, FCs are still cost-competitive due to other important cost components (recurring costs) besides capital cost that were lower for the FC. Recurring costs considered included fuel, tires, driver and maintenance labor, labor to assure conformance to diesel regulations, e.g., exhaust- gas sampling lost time, consumable parts such as filters, drivetrain maintenance due to breakdown and rebuild, and engine control system (safety system) breakdown and rebuild costs. This is for values conservative towards diesel, assuming that both recurring and capital costs would remain constant over time. Both these cost components would in-fact increase. A FC production vehicle would be more productive than a diesel vehicle for a number of reasons: higher allowed vehicle density, higher availability, substantially higher performance, and lower non-vehicle subsidiary mine operating costs such as ventilation [1]. From literature reviewed, the immediate issues, resulting in the opportunities identified to necessitate the need for an alternative such as hydrogen FCs underground, is summed up:

- De-carbonization of the underground mining industry: Removing diesel emissions and CO_2.
- Health and comfort: FCs offer noise and vehicle heat load reduction.

- Operating Costs: Includes ventilation costs savings in energy bills. Further cost savings related to diesel equipment, maintenance, downtime (improved production), automation and reliability.

More recently, several publications and reports mention hydrogen as a solution for the mining industry. A recent publication by the Rocky Mountain Institute (RMI) mentions the rise of current FC powered vehicles and highlights the similarity in power requirements of a typical mining truck and Alstom's Coradia iLint train and the Nikola One truck [17]. By 2020 hydrogen could already be competitive with US gasoline prices. Hydrogen has other advantages besides cost, which include electrolysis plants to prevent intermittent RE curtailment and grid stability assistance. The Columbia Centre on Sustainable Investment recently published in a report that hydrogen is particularly attractive to the mining sector, as it can provide a storage solution for distributed RE and fuel for trucks and power generation systems [18]. The consequence would be a reduction in logistical and operational costs and give mine operators system redundancy and backup fuel stock, as well as reduction in ventilation requirement and cost. Energy and Mines published an article titled "Hydrogen in mines: the missing piece of the puzzle" [19]. Ten years ago, hydrogen FC focus was on passenger cars. The focus has now shifted to large, heavy-duty vehicles. Heavy vehicles and heavy cycle vehicles require the power density possible with hydrogen. A demonstration at Glencore's Raglan mine in the North of Quebec, utilizes hydrogen in a hybrid system to generate electricity for mining operations. The was commissioned in December 2015. The system consists of a wind turbine, electrolyser and FC with hydrogen tanks, as well as flywheel and battery storage. The storage systems reduced the need for wind curtailment and additionally reduced the need for diesel power and spinning reserves in total [20]. In 2018 CORFO, the Chilean economic development agency awarded two projects specific to the mining industry [21]. The first is for a dual fueled (diesel and hydrogen) mining truck. The project is to convert a surface mining extraction truck and demonstrate the technical and economic viability of running the machine on a duel-fuel; hydrogen and diesel. Recent works on this topic have published promising results [21]. Surface mining extraction trucks that are targeted have power plants ranging from 225 kW to 3 300 kW with payloads between 20 and 500 tons. The second project will focus on FC power for loaders. Underground loaders have typical power plants ranging from 110 kW to 375 kW with payloads between 7 and 20 tons.

Issues identified include hydrogen re-fueling infrastructure and protocols, as well as the costs of metal-hydride storage units [10]. Since the last demonstration projects, hydrogen storage technologies and infrastructure have seen considerable development that results in much lower costs than metal-hydride beds. Further, no safety regulations exist relating to FC and hydrogen in mining applications [11]. Cost of FC stacks is listed as a barrier, but these costs have come down considerably. FC system cost projections for 2020 is below $100/kW for FC based on annual production rates of 100,000 systems/year for medium delivery vehicles having power requirements in the 160kW range. Costs for heavy-duty vehicles could be double due to lower production numbers [22]. Additional issues related operational and safety included:

- Little information on the behavior of hydrogen (release, turbulence) in enclosed spaces and none for mining, with and without ventilation and behavior versus lower flammability levels.
- Design, performance, reliability of available on-board hydrogen storage: safety assessment, hazard analysis.
- Existing Mine Regulations, Hydrogen Codes and Standards
    - No mine regulations (coal, metal) against hydrogen.
    - Hydrogen infrastructure already established for surface vehicles.
    - International hydrogen installation codes and standards can support mine regulations.
    - Comply with prevailing generic standards and codes elsewhere.
    - All hazards should be demonstrated to be "as safe, or safer than".
    - Address mine-specific aspects: planning, ventilation, emergency response, fire suppression, etc.
    - Include special provisions for transportation of hydrogen.
- Lack of dedicated refueling infrastructure.
- Lack of performance and durability data (vehicles, hydrogen infrastructure).

All the issues identified, as well as safety perceptions, have prevented the implementation of hydrogen FC technologies in mining activities, especially underground. To make hydrogen possible in the underground mining environment, the issues identified require research, development and demonstration to fast track the technology to implementation.

3.0 VENTILATION TESTS FACILITY

The limitations as well as numerous benefits mentioned, have motivated the need to develop a research infrastructure platform dedicated to hydrogen safety device testing and validation and qualification of underground risks using hydrogen based fuels in both ventilated and unventilated confined underground mining spaces and due to the nature of the problem, tunneling activities will also benefit.

3.1 Project background

A deliverable of the HMII project was to field-test hydrogen leak behavior in ventilated and confined areas [15, 16]. The project included performing leak tests inside a 20” container and included several hydrogen release and ventilation flow configurations and conditions. Hydrogen leaks considered were typical that would be expected from a metal-hydride bed at low pressure (>20 bar). A similar project was initiated by the Hydrogen South Africa Infrastructure Centre of competence (HySA) at the North-West University in South Africa. The objective was to perform similar tests starting at low pressure and then move to pressures as high as 350 bar, typical pressures of composite on-board tanks. General safety concerns of high-pressure hydrogen in confined spaces was not justified or supported by any results and will be answered by performing tests at these conditions.

Initial tests were performed at the Council for Scientific and Industrial Research (CSIR) Kloppersbos explosion test facility near Pretoria, South Africa. The CSIR typically uses this facility to perform full-scale simulations of underground ventilation systems. The facility represents a full-scale underground coalmine section arranged in a last through road, heading and pillar split configuration. HySA used this facility to perform initial hydrogen release experiments. Hydrogen is released through an orifice to simulate a leak and hydrogen concentration is measure at different locations and ventilation airflow values. A PEM electrolysis unit was transported to the site for onsite hydrogen generation. Logistics of having hydrogen onsite and not knowing how much hydrogen would be required necessitated the need to have onsite generation. Future activities would have included the delivery of high-pressure hydrogen cylinder packs to the site once the experimental setup and characteristics were understood. The maximum pressure available from the hydrogen generation unit was 14 bar. This was sufficient for initial concept validation experiments. The strategy was to determine how and if hydrogen can be measured in the environment. Hydrogen was “leaked” into the tunnel in the direction of ventilation airflow at a fixed height, with hydrogen detectors lined up in front at the release level and one more level above the release level. Two ventilation fans are located at the opposite side of the tunnel. Fig. 6 (a) shows a sensor configuration and the direction of airflow. Fig. 6 (b) shows an experimental setup.

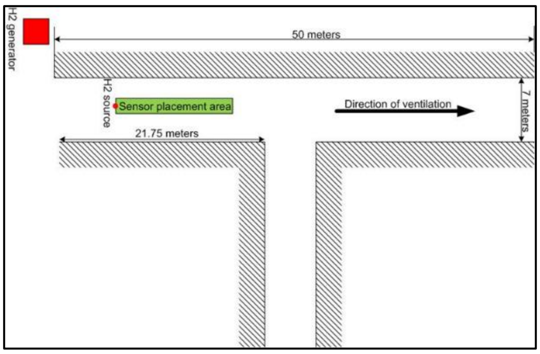

Figure 6 (a). Kloppersbos experimental tunnel and layout.

Figure 6 (b). Sensor configuration inside Kloppersbos tunnel.

Although these initial experiments provide insight into the propagation of hydrogen, their purpose was to prove the concept. Future experimental work will require varying release rates, pressures, direction and orientation in the ventilation flow, and changing the ventilation airflow itself from no-flow up. The Kloppersbos facility however presented some challenges, which included:

- high daily charges for using the facility with several days required for setting,
- the facility was 150 km from HySA's offices. Both transporting hydrogen from the HySA site or having hydrogen delivered was also very costly and time consuming,
- the tunnel had a fixed configuration and it would be expensive to make alterations,
- the ventilation tunnel was for a specific underground coalmine section arrangement which would not represent deep metal mines,
- the existing ventilation fan was old and the airflow control was manual and difficult to tune, and
- the existing ventilation fan maximum airflow rate was low (1.0 m/s max cross-section average), and higher air-flow rates were desired.

Fixing and retrofitting the facility and operating costs for rent, supply of hydrogen and time lost for hydrogen delivery, traveling and accommodation costs was expected to be very high. Exhaustive experimental tests would take several years. Based on these considerations, a decision was made to develop a dedicated VTF with features of deep metal mining and to include on-site production and storage. Additional benefits of such a facility is demonstrating a remote self-sufficient mining site.

3.2 Temporary ventilation test site

The development of a full-scale VTF would require time to identify a location, equipment, complete a design and perform necessary environmental assessments. Validating and testing sensors and concept was performed in parallel at a temporary site consisting of a 40"container, shown in Fig. 7 (a). Hydrogen was supplied from HySA's current production site and supplied to the temporary ventilation site in cylinder packs (200 bar 12 x 50 L). A typical sensor layout used is shown in Fig. 7 (b).

Figure 7 (a). Temporary ventilation test facility.


Figure 7 (b). Sensor layout.

A custom designed low-pressure, high flow ventilation fan was developed with a local South African industry partner. Blades and hub are manufactured from glass reinforced composite materials for spark prevention. A 55kW explosion proof electric motor drives the fan. Air is introduced into the tunnel via the ducting to a couple of meters before the end of the tunnel. Another variable is the distance of the ducting opening from the closed end. A variable speed drive (VSD) controls the ventilation flow and limits the output power to accommodate the available 32A rated supply and small 600 mm ducting.

3.3 Main ventilation test facility

The main VTF consists of a ventilation tunnel, hydrogen production and dispensing system, LOHC hydrogenation unit consisting of process and office containers, bulk storage, ventilation fan, PV system and site office. The ventilation tunnel is 50m long, 5m wide and 3m high sized from consultation with mining experts. The inside of the tunnel is configurable to any size and shape required using temporary construction material, e.g. to introduce roof pockets. Anti-spark ducting found underground is used. The purpose of the VTF is to simulate underground ventilated environments and define the risks and safety considerations needed when using hydrogen FCs in underground mining and tunneling environments. One major concern regarding the use of hydrogen in mining is the amount of ventilation required to dilute hydrogen leaks and regular venting and requires evaluation [23]. Additional safety devices and concepts will be developed and tested, with codes, standards and guidelines to be generated form the data generated. The VTF accommodates the use of various hydrogen storage technologies and hydrogen carriers, such a methanol. The ultimate purpose is developing standards and guidelines providing information on safety distances, process and equipment requirements and configurations, and safe operation of underground-ventilated environments for FC operation.

The VTF includes the production, storage and distribution of hydrogen at pressures of 50 barg, 200 barg and 350 bar. A 4 Nm^3 per hour hydrogen production system is located in a 20" standard ISO shipping container. The production, compression storage and dispensing (CSD) is located in the hydrogen-dispensing container (HDC). Storage at 350 barg (9,47 kg) is integrated in the HDC. Site storage consist of 7800L tube cylinders at 200 barg (110kg). The tube cylinders in-turn supply the on-site 5Nm^3/hr hydrogenation system at 50 barg and the ventilation tunnel at 200 bar. Hydrogenation refers to liquid organic hydrogen carrier (LOHC) which is a safe storage technology for hydrogen and to be researched at the VTF as an alternative hydrogen based fuel. The ventilation tunnel is also be supplied via a dedicated line from the 350 bar onboard the HDC. Fig. 8. shows a block diagram of the sub-system of the VTF. Fig. 9 shows the facility itself. A 50 kW PV system is located off-site on carport roofs 150 meters from the site. The site is connected to the main grid, with all cabling and connections done to

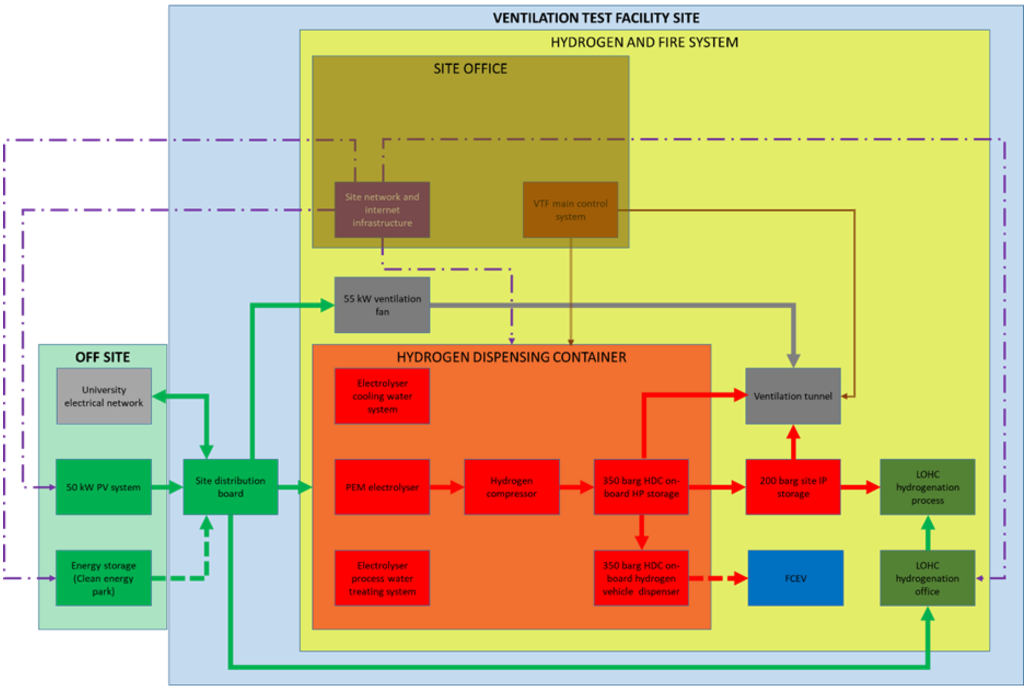

Figure 8. Ventilation test facility, sub-systems block diagram.

switch over to off-grid for times. The HDC contains a water purification system and chiller that feeds the PEM electrolyser. A hydrogen booster boosts the pressure from 15 bar to 350 bar into the composite tanks. From there the HDC feeds the 200 bar storage and ventilation tunnel. The ventilation fan blows air into the tunnel, through 1000 mm diameter ducting that enters the open end of the tunnel up to 10-15 meters before it reaches the closed end. All process equipment is located outside of the tunnel open to atmosphere. A quick opening solenoid valve introduces hydrogen through an orifice into the tunnel. The line between the solenoid valve and the open end is very short.

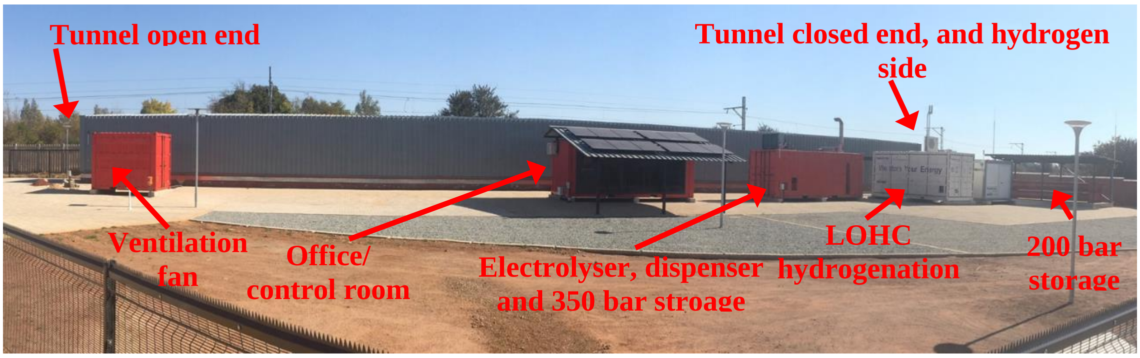

Figure 9. Ventilation test facility.

4.0 SITE SAFETY DESIGN

At the VTF multiple sources of accidental hydrogen are present. During normal operation, there is the additional hydrogen to be leaked inside the ventilation tunnel. The site hydrogen infrastructure is open to atmosphere with the process lines installed 2.5 m above ground level with no other infrastructure (e.g. electrical) close by, and the risk of a hazard environment at these locations is therefore negligible. Further safety principles implemented are described in the sections that follow. Safety systems are all operated from off-grid PV-battery systems preventing loss of grid power to affect operation. In the event of power loss, all systems power down to safe mode, which means valves revert to normal closed positions and hydrogen production is halted.

4.1 Equipment selection, safe distances and removing the risk

Eliminating sources of ignition, maintaining safe distances, placement of equipment, and risk assessment. Potential ignition sources are identified for the site include electrical installations, flames, hot surfaces, static electricity, lightning and mechanically generated sparks. In accordance with the relevant standard [25], pipework is designed to avoid mechanical stresses and damage, protected against corrosion, designed for ease of cleaning and purging and straight and direct to reduce pressure drop. 350 bar rated and certified equipment is used and installed according to accepted standards. Pipes and fittings are Swagelok components, sufficiently rated for the operating pressure. Additionally, manufactured bends are not allowed, with only bent Swagelok tubing used with the number fittings minimized. Regular intervals of pressure testing and maintenance ensure a leak free hydrogen system. Electrical components and wiring are located and routed close to floor level and enclosed inside electrical trunking or inside ventilated electrical enclosures. Hydrogen tubing and equipment are placed high up close to the ceiling or outside at 2.5 meter above ground level ensuring both separation from possible sources, as well as sufficient ventilation. Safety distances according to SANS 10260-1[1] [24] is satisfied for hydrogen installations. Where safety distances could not be satisfied, a 120 min firewall was constructed. Possibility of static discharge is removed through the implementation of earthing (complete earthman) bonding and lightning protection.

1 South African National Standards (SANS) are adopted from ISO standards.

4.2 Hazardous classification

Hazardous area classification for equipment selection. Fig. 10 shows the hazardous area classification. Hazardous classification is determined in accordance with SANS 60079-10-1 [25]. Majority of the site hydrogen installations are open to atmosphere and process equipment elevated above 2.5 m and therefore non-hazardous. The HDC high pressure (HP) compartment is also open to atmosphere but possible low dilution could exist, and due to the high pressures present is decided to be classified as Zone 2. All equipment are suitably selected. Hydrogen is classified [25] as temperature class: T1 (>= 450 ^{o}C) and equipment group IIC. A portion of the ventilation tunnel is indicated as a primary source of release and also considered open to atmosphere due to the size of the tunnel and open end. However, with medium dilution it is determined to be Zone 1. No equipment is located inside the tunnel except for the hydrogen detectors. Operational measures are used to eliminate any risk towards personnel. The site layout is such that access to the gates from the site office is not through any area posing hazards.

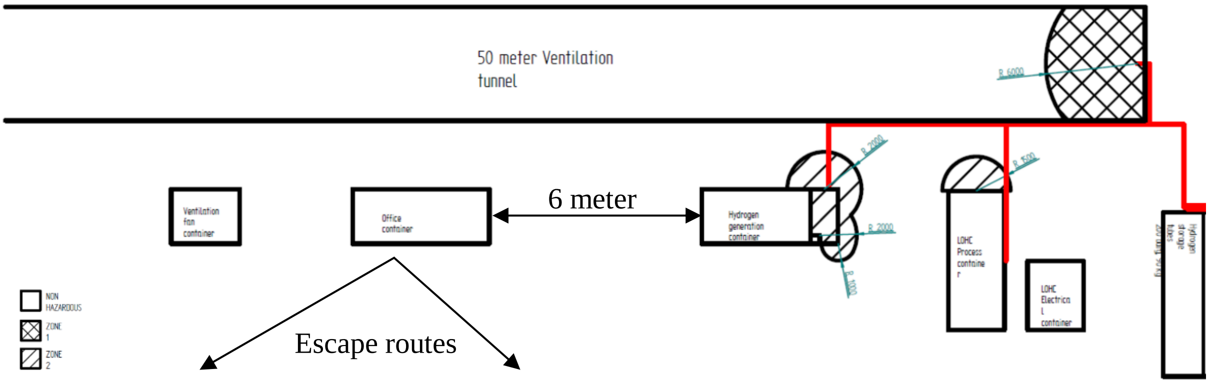

Figure 10. Hazardous classification.

4.3 Emergency shutdown devices

Site wide emergency stop devices (ESD) are located at multiple locations and easily accessible. ESD activation stops the flow off hydrogen everywhere on the entire site, disconnects electrical input to the HDC, activates site visual and audible alarms, and notifies emergency personnel via a GSM system. During ventilation tests the control system forces the automatic gate closed, preventing any persons from entering the site when experiments are conducted. ESD activation will stop the test and force the automatic gates open again. An additional manual gate that can only be opened from the inside is available if the automatic gate fails. Both gates are located far from the risk area.

4.4 Hydrogen leak detection

Two detectors are located in the LOHC container, two inside the HDC container, one at the tube storage and one inside the tube storage vent line. For hydrogen concentrations > 0.4 % (10 % of LEL) at any one of these detectors, a safety sequence initiates that stops tests and shut-down hydrogen production. For hydrogen concentrations > 0.8 % (20 % of LEL), the same sequence of events mentioned for an ESD activation is initiated.

4.5 Smoke detection

One detector is located inside the site office container, one inside the LOHC office container, two inside the LOHC process container, one inside the hydrogen-dispensing container and one inside the ventilation fan container. The same sequence of events as the ESD activation takes place when any of these smoke detectors are activated.

4.6 Organizational measures

Organizational measures implemented for safety include regular training sessions, implementing written instructions and work permits, safety induction and escorts, access control and CCTV monitoring, weekly process parameter recording, safety drills, fire safety and first aid training, housekeeping rules and site maintenance. The site is also not accessible to the general public. All movement on this site is limited to trained and authorized personnel. Materials of construction in the hydrogen impact area are non-flammable. Strict rules are maintained regarding fires, smoking and use of electronic equipment and vehicles inside the perimeter fence.

5.0 RESUTLS AND DISCUSISON

Fig. 11 shows results from the very first experiments conducted at Kloppersbos. Measured data presented is for a specific experimental setup measured at the release level (a) and 1 meter above the release level (b). From these initial simple experiments, the effect of buoyancy is clearly visible and ventilation flow had a noticeable effect on concentration at different levels. Repeated experimental results were consistent.

a b

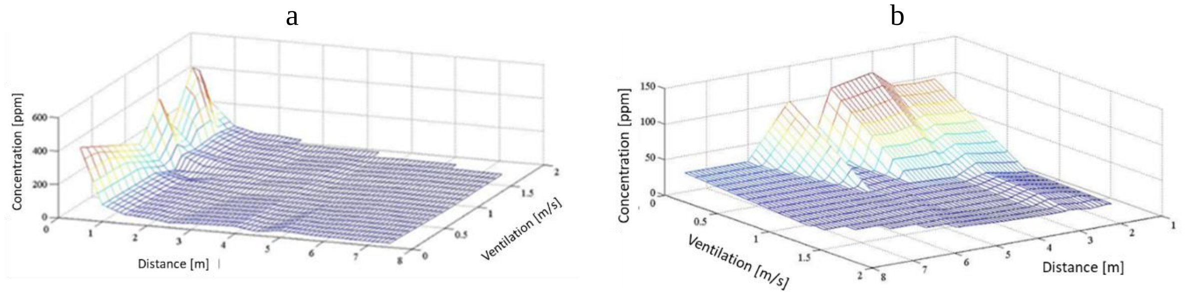

Figure 11. Avg. PPM at relaese level (a) and 1 meter above release level (b).

Hydrogen is released until no further noticeable increase in hydrogen concentration is observed with the maximum values used, resulting in the worst-case scenario in terms of concentration. At the VTF timed releases will be possible. For the Kolppersbos and temporary ventilation test facility, equipment was not available for to achieve this. Hydrogen flow rate for the Kloppersbos experiments was around 5 slpm at 15 bar. Average ventilation flow rates through the tunnel is part of Fig. 11. Initial unknown behavior of hydrogen in the environment motivated to start with low pressure and low flow rates. Fig. 12 and Fig. 13 show results of experiments conducted at the temporary ventilation test facility. Fig. 12 and 13 give results for a 0.8 mm orifice release at 20 bar and 50 bar respectively, measured at (from left to right) 1 m, 2 m, 3 m, 4 m and 5 m distance from the source. Ventilation flow in the temporary tunnel is difficult to determine. As a result, the variable speed drive was set to the same setting for all experiments to ensure that results could be comparable with regards to the ventilation flow parameter. Future work includes ventilation flow measuring devices. Measured data is interpolated in 2D to fill gaps between sensors, resulting in images of cross sections of the temporary experimental tunnel. The top right corner with zero hydrogen (dark blue) is the location of the ventilation ducting blowing into the tunnel. The dark red area (high concentration) to the left bottom in the leftmost image of each figure is the location of the hydrogen release.

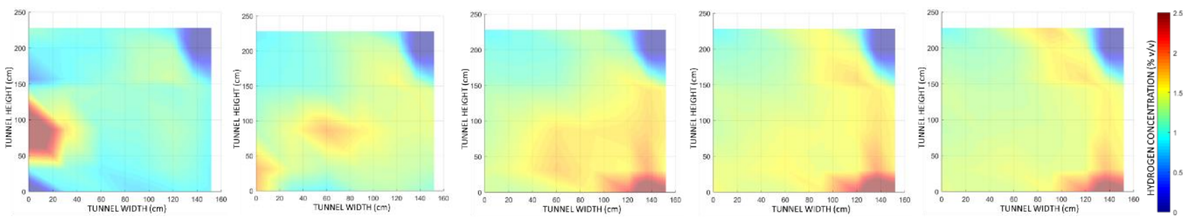

Fig 12. 20 bar, 0.8 mm orifice at 1 m , 2 m, 3 m, 4 m and 5 m.

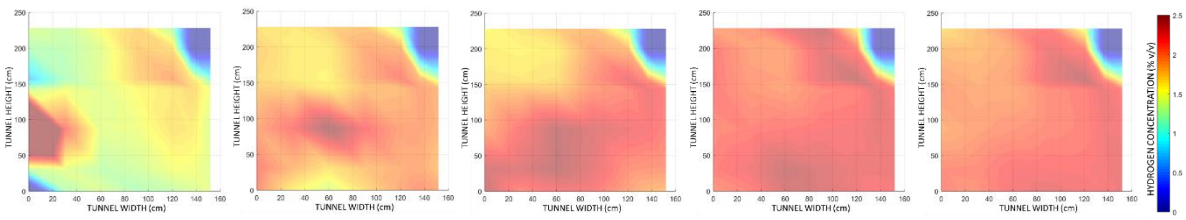

Fig 13. 50 bar, 0.8 mm orifice at 1 m, 2 m, 3 m, 4 m and 5 m.

Kloppersbos experimental setup was primitive although some key findings was possible. The number and type of hydrogen sensors and placement was limited. The temporary test facility allowed multiple sensors with wider measuring ranges and results represented in 3D, which eased visualization and interpretation. Thus far, several experiments were conducted up to 50 bar, with two data sets illustrated in Fig. 12 and 13. Both figures clearly show the movement of hydrogen through the tunnel. The 50 bar release results in higher concentrations and mixing of hydrogen whereas the 20 bar release shows less mixing and lower concentrations. The images show, especially for the 20 bar release, movement of the hydrogen cloud to the bottom right of the tunnel before it exits, with surprisingly high concentrations and implying low diffusion. This effect is a result of the hydrogen velocity and airflow patterns caused by the ventilation in the tunnel. Computational flow dynamics (CFD) work is currently being conducted. The main purpose of the temporary site was to start testing the various sensors available on the market, and familiarize and configure experimental setups, leak scenario orientation, etc. These are still ongoing and majority will be implemented at the VTF.

6.0 CONCLUSIONS AND FUTURE WORK

Hydrogen FC technology has in the past been identified as a viable solution for powering underground mining equipment. Several demonstrators have been developed and successfully operated. These demonstrations showed the benefits of FC underground, with both production and cost improvement. Benefits included health, comfort and savings in operating, ventilation and cooling costs. Hydrogen however has an unfortunate perception that it is unsafe, even with todays advanced technologies to store hydrogen. The biggest risk arises when there is a hydrogen leak from on-board storage. No information exists on the behavior of hydrogen in underground mining environments. Hydrogen is a flammable gas with a wide flammability range and low ignition energy and as a result has a stigma and needs proof that it can safely be introduced underground. This work describes the rationale behind and the development of a VTF specifically designed to perform hydrogen (and other fuels) leak tests into a ventilated tunnel, to generate a database for hydrogen behavior in underground environments. Initial results have indicated that hydrogen leaked can be measured and trends in the data is visible. Higher pressures of hydrogen at various flows are required to match industry hydrogen storage pressures. Pressure will include low pressures expected from for example metal-hydrides and FC venting actions. Higher-pressure (at least 350 bar) experiments are required to quantify the risk of having high pressures in such ventilated tunnel environments. The VTF will add value by providing information regarding hydrogen use in this underground environment. The project has been ongoing since 2014 but the ventilation tests have only started in 2019. Exhaustive experimental work will take several months if not a couple of years to complete the various combinations of flows, pressures, orientations, etc. Future work will include generating data for numerous experimental setups. New experiments and configurations will continuously be required based on previous experimental results. Current and future work includes CFD of the temporary facility and later the VTF.

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REFERENCES

1. Arnold R. Miller, Fuel-cell mine vehicle-development and testing, Proceedings of the 2000 U.S. DOE Hydrogen Program Review, San Ramon, California, May 9-11, 2000.
2. Richard S. Schatz, Antonio Nieto, Serguei N. Lvov, Long-term economic sensitivity analysis of light duty underground mining vehicles by power source, *International Journal of Mining Science and Technology*, Vol. 27, pp. 567-571, 2017.
3. P. Griffin, The Carbon Majors Database, CDP Carbon Majors Report, July 2017.
4. M.C. Bétournay, P. Laliberté, R. Lacroix, C. Kocsis, S. Hardcastle, G. Desrivières, P. Mousset-Jones, and G. Righettini, Fuel cell versus diesel loader operation: Cost-benefit analysis study, Article in CIM Bulletin, May 2005.
5. Nicolas Maennling and Perrine Toledano, The renewable Power of The mine: Accelerating renewable energy integration, Columbia centre on sustainable investment, December 10, 2018.
6. Cédric Philibert, , Renewable Energy for Industry From green energy to green materials and fuels, International Energy Agency (IEA), Insight Series, 2017.

7. Charles Kocsis, Ventilation Benefit Analysis for Canadian Mines Fuelcell Loader Project, CANMET-MMSL report 602422, Report MMSL 03-040(CR), July 21, 2003.
8. Gaibler, D. W., and A. R. Miller, Cost Model for Fuelcell Mine Vehicles: Conservative Analysis of Recurring and Capital Costs. Denver, CO: Fuelcell Propulsion Institute, 1998.
9. Fuel cell Propulsion institute home page: www.fuelcellpropulsion.org/
10. D. Barnes and A. R. Miller, Advanced Underground Vehicle Power and Control: The Locomotive Research Platform, Final Technical Report for the U.S. DoE Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program, Cooperative Agreement: DE-FC36-99GO10458, 2003.
11. Vehicle Projects Inc, Fuelcell-Hybrid Mine Loader (LHD), Final Technical Report for the U.S. DoE Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program, Cooperative Agreement: DE-FC3601GO11095, 2009.
12. A.R. Miller, G. van den Berg, D.L. Barnes, R.I. Eisele, D.M. Tanner, J.M. Vallely, and D.A. Lassiter, Fuel cell technology n underground mining, The Southern African Institute for mining and Metallurgy, 533-546, Platinum 2012.
13. Engineering news article, Fuel cell dozer to make game-changing 2019 debut: http://www.engineeringnews.co.za/article/chris-griffith-2018-04-12
14. Mark Betournay and Brent Rubeli, Hydrogen Power Application to Mining, 18th Annual mine diesel emission council (MDEC) conference, Toronto, 2012.
15. Andrei V. Tchouvelev, Benjamin Angers, Marc Betournay an Gilles LeBlanc, Hydrogen min introduction initiative – Study of hydrogen behavior in underground mine conditions, 23rd Annual mine diesel emission council (MDEC) conference, Toronto, 2017.
16. Christopher Jackson and Patrick Molloy, A renewable hydrogen way forward for the mining industry?, Rocky Mountain Institute, Sunshine for mines: https://www.rmi.org/a-renewable-hydrogen-way-forward-for-the-mining-industry/
17. Columbia Centre on Sustainable Investment, The renewable power of the mine, Accelerating renewable energy integration, Report, December 2018: http://ccsi.columbia.edu/files/2018/12/3418-CCSI-RE-and-mining-report-09-lr-reduced-optmized-07-no-links.pdf
18. Melodie Michel, Hydrogen in mines: The missing piece of the energy puzzle, Energy and Mines, Issue 6, 1 December, 2018
19. Glencore RAGLAN mine renewable electricity smart-grid demonstration, Tugliq energy co., ecoENERGY Innovation initiative demonstration component, Public report, Project: GC 128296
20. Electricidad La revista energetica de ChileDos consorcios probarán en Chile inédita tecnología: construirán motores a hidrógeno para la industria minera, 5 March, 2018: http://www.revistaei.cl/2018/03/05/dos-consorcios-probaran-chile-inedita-tecnologia-construiran-motores-hidrogeno-la-industria-minera/
21. Mohamed El Hannach, Pouria Ahmadi, Laura Guzman, Simon Pickup, and Erik Kjeang, Life cycle assessment of hydrogen and diesel dual-fuel class 8 heavy duty trucks, *International Journal of Hydrogen Energy*, Vol. 44, pp. 8575-8584, 2019.
22. D. Barnes and A. R. Miller, Advanced Underground Vehicle Power and Control: The Locomotive Research Platform, Final Technical Report for the U.S. DoE Office of Energy Efficiency and Renewable Energy, Hydrogen, Fuel Cells and Infrastructure Technologies Program, Cooperative Agreement: DE-FC36-99GO10458, 2003.
23. South African National Standard, SANS 10119:2011, Reduction of explosion hazards presented by electrical equipment – Segregation, ventilation and pressurization
24. South African National Standards, SANS 10260-1:2018, Industrial gas pipelines. Part 1: Design, construction, installation, operation, examination and maintenance (excluding acetylene).
25. South African National Standards, SANS 60079-10-1, Explosive atmospheres Part 10:1: Classification of areas – Explosive gas atmospheres.