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SAFETY CONTROL SYSTEMS USED IN A HYDROGEN-FUELED MINE VEHICLE

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Abstract

The Spokane Research Laboratory of the National Institute for Occupational Safety and Health has demonstrated a prototype hydrogen-fueled mining vehicle as an alternative to diesel equipment in underground mines. Safety and control systems were added to allow a 70-kW rubber-tired hydrogen vehicle, originally developed by the U. S. Bureau of Mines and Hydrogen Consultants, Inc. (now Hydrogen Components, Inc., of Littleton, CO), to be tested. This work began in late 2000 and culminated with a Mine Safety and Health Administration fire safety review and field tests at the Stillwater Mine in Nye, MT, in 2004.

Introduction

The Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH) prepared an EIMCO 975[*] articulated utility vehicle converted from diesel to hydrogen internal combustion for a demonstra-tion in an underground metal mine. Because of its low pro-duction of noxious emissions, the working prototype was dubbed ZEUS, the Zero Emissions Utility Solution, by the development team at SRL. The goal was to demonstrate the vehicle's potential benefits and the safety systems required to operate alternative-fuel vehicles in underground mining operations.

During tests at the Stillwater Mine, Nye, MT (Woodward et al., 2004), the vehicle was used to transport 3,600-kg loads of raise borer drill rods from the surface shop to an underground work site. These 10-km round trips included a 350-m elevation gain on grades of up to 10%. Vehicle performance successfully matched that of equivalent diesel-powered materials haulers. The nominal operating range of the fuel supply was 3 hours for a climb under full loads and downhill return trips at a nominal speed of 7 km/hr. This was equivalent to diesel fuel consumption at a rate of 8 L/hr. Over level and slightly rolling terrain, the range was approximately 100 km at an average speed of 30 km/hr.

The technology for hydrogen internal combustion engines parallels that for electric fuel cells as to issues surrounding hydrogen fuel storage, safety, leak detection and monitoring, and control system needs (Couts and Thomas, 1998). The conversion of the EIMCO 975 vehicle to hydrogen power involved unique subsystems that required a specific safety evaluation before the vehicle could be used underground (Lynch et al., 1987). Continuing evaluations have resulted in the present configuration, which incorporates sensors and fuel-management controls so that the working vehicle can function safely throughout the total operation.

This paper provides a brief history of vehicle development prior to its being acquired by SRL, followed by an overview of the systems required for its underground operation. The details of the safety features incorporated into each vehicle subsystem are then presented. Results

follow, including a brief discussion of the critical areas of future development required before the use of hydrogen-powered mining vehicles can become feasible.

Background

For underground mining, hydrogen stored in metal hydrides is safer than storage in high-pressure tanks. A compromised high-pressure vessel would release the full volume of its contents, whereas in the case of a catastrophic event, hydrogen stored in a hydride alloy would have a limited release depending on the characteristics of the specific hydride being used. A broken hydride storage vessel would quickly reach equilibrium pressure, limiting release of the full volume of gas from the metal matrix. The van't Hoff curve shows that the log of pressure versus reciprocal temperature is linear with a negative slope, which is related to the heat of reaction. Equilibrium pressure and hydrogen concentration in the alloy are related to temperature (figure 1). As hydrogen is desorbed from the hydride, it cools, requiring additional heat to continue releasing hydrogen.
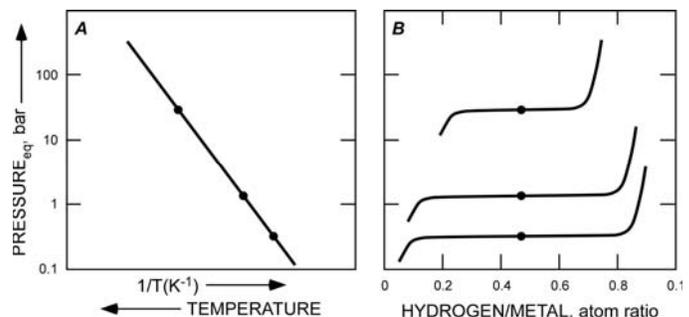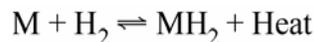

Figure 1 — The equalization dissociation pressure of a hydride alloy (van't Hoff plot) and pressure-concentration-temperature (pcT) plot.

The adsorption of hydrogen releases heat, and heat is required desorb the hydrogen from the metal hydride. The equation shows that a reversible reaction is determined by the supplied or rejected heat.

$$M + H_2 \rightleftharpoons MH_2 + Heat$$

where M = metal hydride and H_2 = gaseous hydrogen.

Starting in 1977, under a research contract between EIMCO Mining Machinery International and the Twin Cities Research Center of the U.S. Bureau of Mines, a normally aspirated diesel Caterpillar 3304 engine was modified to burn hydrogen (Baker and Lynch, 1982, 1983).

Separating hydrogen-laden hydrides into smaller volumes reduces the risk even further than storing it in a single container. By 1980, 14 hydrogen metal hydride heat exchanger modules had replaced the single module originally used. These were constructed using a capsule-and-tube arrangement to allow for hydride expansion and contraction during the adsorption and desorption of hydrogen. Hydride capsules laid end-to-end fill each of seven heat exchanger tubes within the modules (figure 2).

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[*] Mention of specific products or manufacturers does not imply endorsement by NIOSH. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.
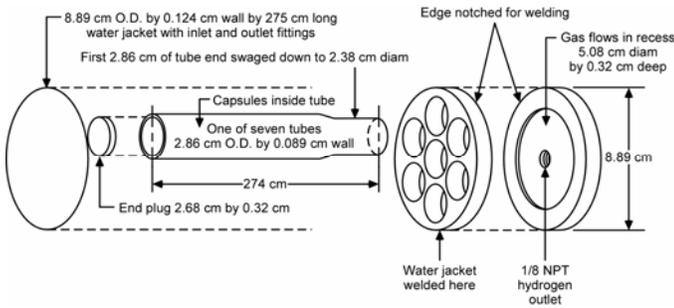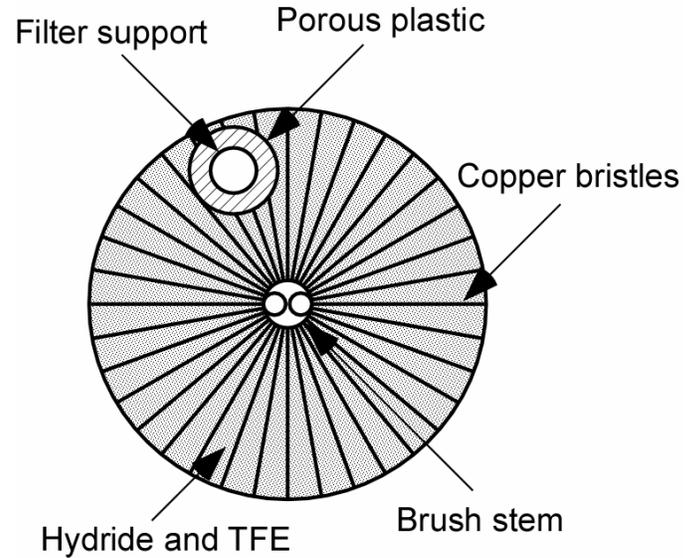
Figure 2 — Internal configuration of early heat exchanger module with tube and hydride capsule placement.

The equilibrium pressure shown by a metal hydride at a given temperature and hydrogen saturation is dependent on the alloy forming the hydride. Two hydride alloys were chosen according to the heat required to release or store hydrogen. Two of the 14 heat exchanger hydride modules, the "cold start" modules, contain the high-pressure rare-earth alloy $MNi_{4.17}Fe_{0.83}^{-H}$. This small volume of hydride is pressurized at 25 °C and supplies hydrogen fuel to start, idle, and warm up the converted engine. However, a larger volume of hydrogen is needed to run the engine during its work period. This volume is stored in a hydride having desorption characteristics that require higher temperatures to build pressures. Thus, when engine coolant temperatures reach 68 °C, a valve opens to route the coolant through the 12 remaining heat exchangers, called the "main bed" (figure 3). These 12 modules contain a sintered metal hydride rare-earth alloy, $MNi_{4.5}Al_{0.5}^{-H}$, as their hydrogen storage medium (Baker and Lynch, 1984).

Figure 3 — Routing of hydrogen, coolant, and ventilation systems on the ZEUS vehicle. PT_x represents pressure transducers.

In 1985, an EIMCO 975 articulated utility truck was outfitted with the converted Caterpillar engine and hydride fuel modules (Baker and Lynch, 1985). The hydride capsule-tube storage design was improved to provide more efficient heat transfer, expansion characteristics, and gas flow. The new hydride module packaging design incorporated seven additional hydride modules, which brought the total storage module count to 21. The seven modules had copper brushes inserted into their heat exchanger tubes to enhance heat transfer from the engine coolant to the hydrides (figure 4). These are referred to as "heat-transfer-enhanced" (HT/E) modules. Since hydride alloy particles expand by up to 25% as hydrogen is absorbed, tetrafluoroethylene resin (TFE) powder is mixed with these hydride alloys to reduce strain on the enclosure during hydrogen absorption. A filtered porous plastic hose extends the length of the tube to facilitate hydrogen gas transfer to the egress point of the module.

Not to scale

Figure 4 — Cross-section of HT/E heat exchanger tube .(Courtesy of F. E. Lynch)

Six of the seven HT/E modules contain a subatmospheric hydride, $LaNi_{4.8}Al_{0.2}^{-H}$ (table 1). This alloy has a characteristic desorption pressure of 0.8 bars at 25 ºC. These modules were termed "mine-safe" in the 1985 report (Baker and Lynch, 1985) because the release of available hydrogen was limited when pressures equalized to ambient levels, as would occur in a system failure. The seventh module was configured as a HT/E cold start module using the same high-pressure rare-earth alloy of $MNi_{4.17}Fe_{0.83}^{-H}$ as the cold start capsule-tube modules. The desorption and absorption isotherms for the three types of hydrides using the two storage methods are shown in figure 5.

The final configuration of the modules installed for fuel storage consisted of three cold start modules containing 1.14 kg of hydrogen and 18 main bed modules with a total capacity of 7.14 kg of hydrogen. The combined hydrogen capacity by weight for the prototype vehicle was 8.24 kg (table 1).

Aboveground field and dynamometer tests were conducted during this phase of the project. The last document that focused specifically on this hydrogen vehicle was a reliability and safety evaluation report published in 1987 (Lynch et al., 1987). After SRL acquired the vehicle in the fall of 1999, work began in late 2000 to address the specific areas of concern outlined in the 1987 study.

Further work was required to introduce the hydrogen technology underground. With renewed interest in alternative fuels and advances in control system technologies, the work was resumed with the intent of addressing the shortcomings of the prototype and developing improved control and safety systems. A lack of accepted hydrogen-related standards and codes for the mining industry was a concern as development guidelines were sought. Safety reports by the U.S. Department Energy (Thomas, 1997) and the U.S. Department of Transportation (Technology and Management Systems, 1998) were reviewed for relevance to mining equipment.
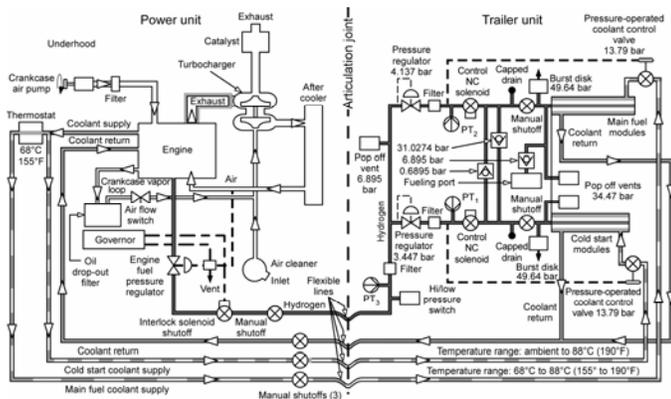
Table 1.—Summary of hydrides and modules on prototype vehicle

Description	Main bed		Cold start	
	Capsule method	HT/E method	Capsule method	HT/E method
No. of modules	12	6	2	1
Diameter, cm	8.89	8.89	8.89	8.89
Length, cm	275	237	275	275
Effective tube surface, m^2	1.7	1.5	1.7	1.7
Hydride alloy	$MNi_{4.5}Al_{0.5}$	$LaNi_{4.8}Al_{0.2}$	$MNi_{4.17}Fe_{0.83}$	$MNi_{4.17}Fe_{0.83}$
25 °C desorption pressure, bars	3.4	0.8	10.4	10.4
Construction material, container				
Stainless steel, kg	20	17	20	20
Aluminum, kg	2.40		2.40	
Construction material, filter				
Stainless steel, kg	0.90	0.23	0.90	0.30
Polypropylene, kg		0.26		0.30
Hydride alloy, kg	33.90	24.60	33.90	26.70
Copper-fiber and stem, kg		3.30		3.50
Tetrafluoroethylene resin, kg		2.70		3.00
Container water in jacket, kg	3.70	3.20	3.70	3.70
Hydrogen capacity:				
Overall weight, kg	0.44	0.31	0.41	0.32
% hydrogen	0.72	0.60	0.66	0.60

HT/E = Heat-transfer-enhanced

Overview of Systems

The ZEUS is based on an early 1980's EIMCO 975 articulated utility mine vehicle designed for underground use (figure 6). The factory-installed Deutz F6L-912W air-cooled engine was replaced with a modified Caterpillar engine (Lynch et al., 1985). Because hydrogen cannot be compression ignited, the internal combustion engine has spark plugs with individual coils and an engine-driven magneto to provide spark and timing (figure 7).

Early research focused on developing a solution to instances of hydrogen predetonation prior to its introduction to the cylinder head combustion chamber (Escher, 1975). Hydrogen Consultants, Inc., solved this problem on the ZEUS vehicle by using a parallel-port fuel intake system (Baker and Lynch, 1982). Fuel and air are maintained in separate paths and are not mixed before they enter the combustion chamber (figure 8). The engine is turbocharged to provide an efficient air-fuel mixture of 0.48 lambda[†] at the engine's normal working range of 1,600 to 1,900 rpm. An aftercooler heat exchanger cools the turbo-compressed air before it enters the intake manifold (figure 3). Both turbocharging and aftercooling increase the mass airflow to the engine by increasing the air

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[†] A lambda value indicates how the actual proportions of oxygen and reducing agents in an exhaust mixture compare to the chemically correct or stoichiometric proportions that would be necessary for the complete reaction of the oxygen with the reducing agents. Lambda is less than 1.0 when the exhaust is rich because of an excess proportion of reducing agents and more than 1.0 when the exhaust is lean with an excess proportion of oxygen.

density of the air-fuel mixture entering the combustion chamber (Lynch et al., 1987).
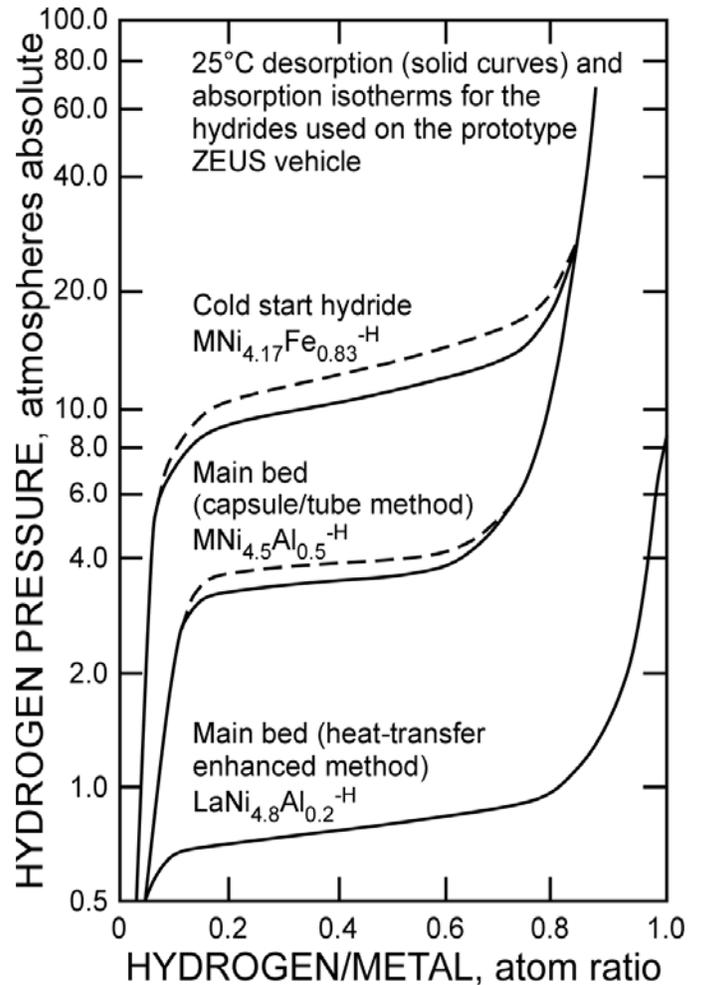

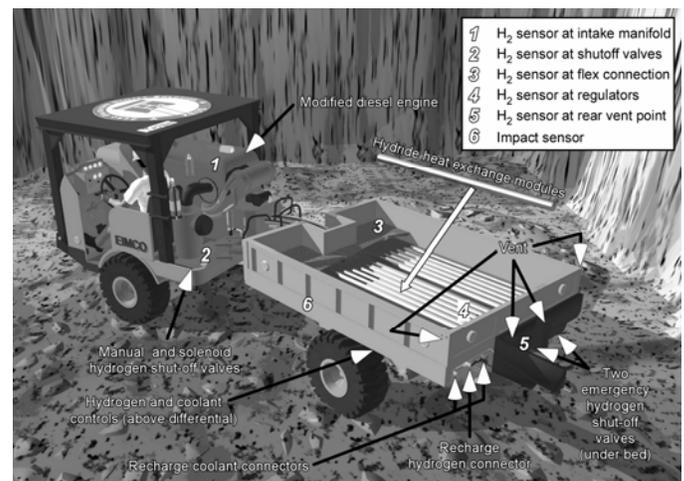**Figure 5 — pcT plot shows isotherms of hydrides used on prototype vehicle. (Courtesy of F. E. Lynch)**

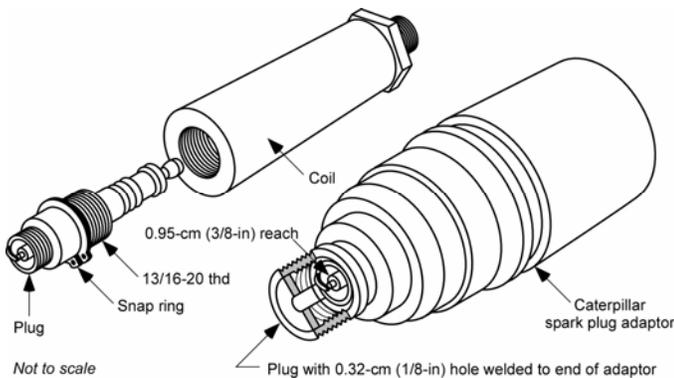**Figure 6 — Graphical representation of the prototype vehicle.**

Figure 7 — Modified spark plug with snap-ring fits a standard Fairbanks Morse coil. A Caterpillar spark plug adaptor with a plug welded to the end forms a shroud chamber around the plug electrodes. (Courtesy of F. E. Lynch)

Hydrogen fuel storage on the ZEUS consists of hydride modules and a regulation system mounted beneath the utility truck's flatbed. During refueling, the adsorption of gaseous hydrogen into the hydride matrix is an exothermic reaction. Excess heat is removed by routing the coolant flow through the external heat exchanger. As the hydride temperature increases, the hydrides' capacity to adsorb additional hydrogen diminishes. During normal operation, coolant fluid warmed by the engine heats the hydrides through the heat exchanger modules, causing the hydride beds to desorb the hydrogen and increase the equilibrium pressure.
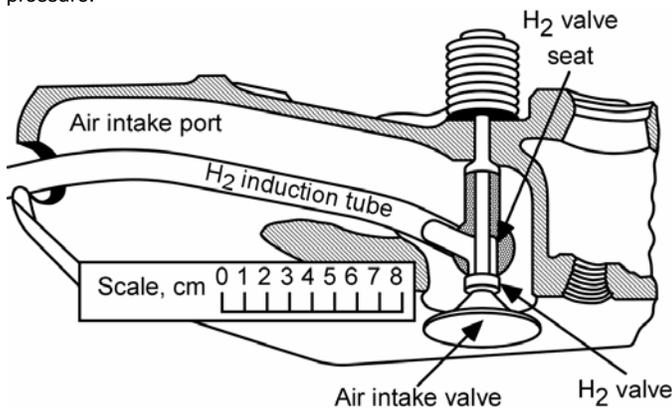

Figure 8 — Section of cylinder head with delayed hydrogen valve, seat, and induction tube exemplifying the parallel port system. (Courtesy of F. E. Lynch)

Over-pressurization of the fuel system is prevented with pressure-actuated flow-control valves that regulate coolant flow through the heat exchangers. Two proportional circulation valves in the trailer control coolant flow around the hydride tubes within the heat-exchanger modules. As hydrogen pressure reaches 14 bars, the coolant flow valves close, restricting fluid flow. This feedback loop prevents unregulated coolant flow around the capsules and limits the hydrogen pressures developed in the hydride modules.

The coolant fluid also serves to chill the beds during the exothermic fueling process. The coolant is routed through an external heat exchanger to transfer excess heat from the hydrides as hydrogen is introduced. The hydrides are charged upon fueling to a nominal pressure of 24 bars. The gaseous hydrogen is adsorbed into the hydride metal matrix until it becomes saturated, after which the gas continues to be introduced until pressure reaches 21 bars. The hydride modules are interconnected by manifold systems to collect, supply, and regulate hydrogen flow and pressure to the engine (figure 3).
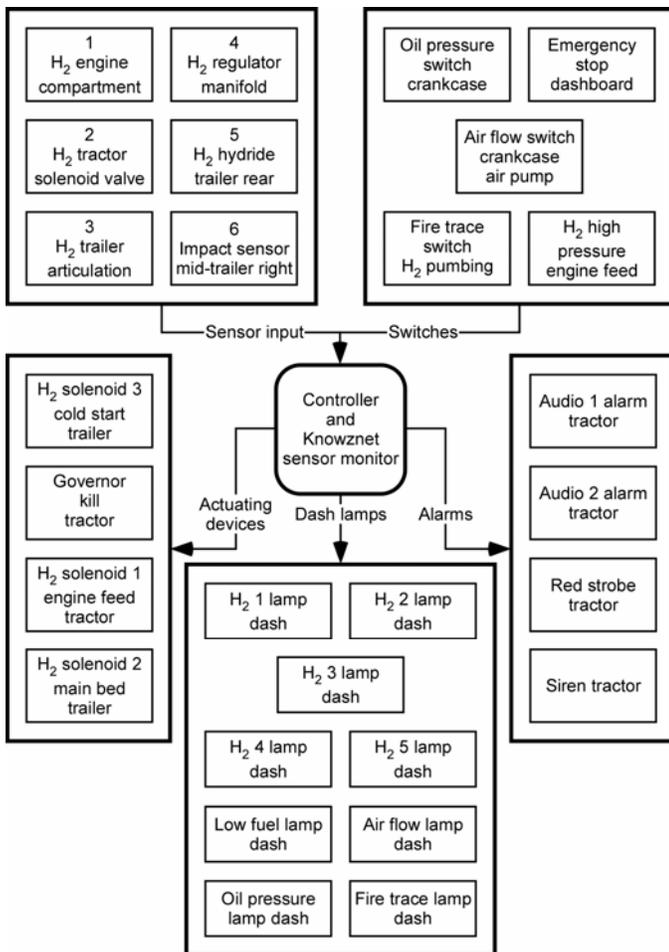
Safety and Management Features

Hydrogen overpressure vents are located on the hydrogen regulator valves and on the hydrogen collection manifolds on the rear of the flatbed (figure 3). Onboard hydrogen sensors can detect hydrogen gas concentrations greater than one-eighth of the lower flammability limit (LFL), which will cause the controller to sound an alarm and/or isolate the fuel supply and shut down the auxiliary power systems. A controller integrated with numerous sensors prevents starting or operation of the vehicle unless vehicle status is within safe operating parameters (figures 9 and 10).

Figure 9 — Lid (left) and controller box (right) on ZEUS. The Knowznet gas sensor monitor is mounted under the lid.

For field tests, common safety features were added to the original 1980's EIMCO test frame, e.g., ROPS (rollover protective structure) and FOPS (falling object protective structure) protection, back-up alarm, lamps, fire extinguisher, and seat belts. Indicator lamps and gauges positioned on the dash, signal gas leaks, coolant temperatures, and gas pressures, and notify the operator in case of fire. Driving the vehicle requires the same skill as driving an unmodified articulated mine truck, but additional training is required to familiarize the operator with the monitoring systems specific to the prototype vehicle.

The vehicle has five sensors to detect gaseous hydrogen at low levels with minimum interference from other gases and compounds. The sensors are positioned along the hydrogen supply path from the engine to the flatbed fueling port (figure 6). Neodym Technologies, Inc., Vancouver, BC, provided an eight-bit Knowznet sensor controller and gas monitors based on TGS821 hydrogen gas sensors from Figaro USA, Inc., Glenview, IL. The gas sensor uses a tin dioxide (SnO_2) semiconductor as its sensing element and can detect hydrogen concentrations as low as 50 ppm and up to 10,000 ppm. The sensor's conductivity increases in the presence of a detectable gas depending on gas concentrations in the air, and this change is translated into an output signal. Because sensor output accuracy depends on humidity and temperature, Neo-dym added temperature-compensating circuitry to each sensor unit. Sensor voltage ranges from 0 to 5 V. The Knowznet sensor controller will interpret a signal of 0 to 0.5 V as a short circuit and a signal of 4.5 to 5 V as an open circuit. Either controller condition will trigger an alarm, whereas the vehicle cannot be started without all the hydrogen sensors installed and functioning.

The alarm system and redundant shutdown methods are actuated at two hydrogen concentration thresholds. If hydrogen is detected at one-eighth the LFL (0.5% hydrogen), a red explosion-proof strobe is activated, and an audible alarm notifies the operator that free hydrogen gas was identified. The dash and controller screen show the zone of the reporting sensor. If the hydrogen concentration detected reaches one-fourth the LFL (1.0 % hydrogen), a more severe audible warning is given to clear the area, battery power is shut down except to the controller, and three solenoid hydrogen supply valves close. With the hydrogen supply isolated at the hydride modules and the magneto kill line grounded, the engine will shut down.

An X-Y axis accelerometer was installed under the trailer bed to signal major impacts to the vehicle. The activation force was set at 9 G's ± 8%, and if triggered, will shut down all systems of the vehicle. To deter the continued operation of the ZEUS after a substantial impact and before systems are inspected for damage, the reset switch is not readily available to the operator. The Neodym gas detection system, fire detection circuit, impact accelerometer, main battery relay, and the emergency shutdown switch are all coupled to an onboard controller.

Figure 10 — Control structure on the ZEUS prototype vehicle

During the starting sequence, a timer controls power to the master battery relay, allowing a 60-s delay for the hydrogen sensors to warm to operating temperature. A safety interlock prevents the magneto from firing and fuel entering the intake manifold until the hydrogen sensors detect safe gas levels, the engine oil pressure builds to 0.3 bars, and the crankcase airflow switch detects the ventilation air stream. This creates a short delay in starting after the ignition switch is turned on. Detecting airflow during this interim assures that no hydrogen has collected in the crankcase prior to ignition.

A fire-detection system rather than a fire-suppression system was considered a more appropriate device for reacting to a pressurized hydrogen-fueled fire (Swain, 2004). In the case of inadequate ventilation, the possibility of free gas escaping and accumulating would create a greater hazard than a single-point fire. A fire-detection system based on a linear pneumatic flame detector from Amerex Corp., Trussville, AL, was integrated into the ZEUS safety design. The system consists of a compressed air canister and tube assembly with a monitoring pressure switch integrated into the vehicle's controller. The fire-detection circuit is a plastic tube with a low melting point of 224 °C. The tube follows the hydrogen line from the engine to the manifold systems in the rear of the trailer. The tube is either bundled with the hydrogen lines or mounted above them. When triggered, the controller will close down hydrogen supply at the rear trailer and tractor, ground the magneto to stop spark, and start the shutdown alarm.

Multiple redundant safety vents were added to the hydrogen tank plumbing circuits to protect the system from being overpressurized and to conserve fuel within the system. The overpressure safety valves can be identified by their placement in the fuel system design (figure 3). On the high-pressure side of the hydrogen system, two emergency burst discs and two relief valves vent to the atmosphere at the rear corners of the trailer. On the low-pressure side of the system, two relief valves on the

regulators and one relief valve on the manifold vent to the atmosphere through the rear of the trailer. For redundancy, if pressure increases beyond designed levels, the vents open at sequentially higher settings. A pressure switch signals an overpressure problem in the engine supply line if values over 7 bars are detected. This could happen if both a regulator and a vent failed.

All plumbing for the hydrogen gas is routed through stainless steel piping with Swagelok-type fittings. The maximum inside diameter of the piping is limited to 12.7 mm or less. This size is smaller than a hydrogen detonation cell and limits the chance of a stable detonation occurring in case of a rupture and ignition (van Wingerden et al., 2005).

The normal range in fuel pressure is 1.4 to 5 bars when the engine is working. Behind the driver's seat, a manual shut-off valve in series with a normally closed solenoid valve controls gas flow to the engine intake manifold. All flexible hydrogen fuel lines within the tank and regulation system are corrugated and wrapped 304 stainless steel.

During fueling, cold water is circulated first through the cold start modules, and then routed through the main bed modules. At the same time, gaseous hydrogen is introduced into the hydrides in reverse order, with the gas entering the main bed before entering the cold start modules. The fuel system includes two internal check valves. One valve was added to ensure that the cold start modules would not have their desorbed hydrogen enter the main bed modules below 31 bars. This configuration assured that a volume of gas is available to start and run the vehicle. The second check valve was installed to shunt excess pressure from the cold start section to the main bed region of the tank (figure 3). This addresses a potential overpressure issue in which the cold start section desorbs hydrogen faster than it can be consumed by the engine. Heat radiating from adjacent modules could continue to warm the cold start modules even if the coolant flow valve closed. Mine Safety and Health Administration-approved foam insulation was applied to the voids between the modules to limit heat radiation. If cold start fuel pressure does exceed the design parameters of 31 bars, the excess desorbed hydrogen is routed to main bed storage. This solution uses the available capacity of main bed hydrides to prevent premature venting of hydrogen to the atmosphere from the cold start modules. If abnormal hydrogen pressure continues to rise in all modules, the vents will open starting at 34 bars. To optimize cold start hydrogen volumes during frequent starts and stops, main bed gas pressure in excess of cold start pressure by 0.7 bars allows a check valve to open and pass hydrogen to the cold start supply.

Results

The Stillwater Mine test demonstrated the first introduction of a mine vehicle powered by a hydrogen internal combustion engine underground in the world. The base technology is sound and, with proper refinements, has great potential for widespread use in the mining industry. The following describes areas where improvements in the prototype are needed.

Hydrogen sensors installed on the ZEUS for the Stillwater Mine test proved to be functional, but more work is needed to make them mineworthy. Temperatures under the engine cowling exceeded the upper operating range of the hydrogen sensor positioned at the engine intake manifold (figure 6). All hydrogen sensors were susceptible to false readings and/or damage by water and mud splashed on them. When the hydrogen sensors were subjected to one or more of these conditions, the Knowznet controller signaled a shutdown of the vehicle, with all designed alarms functioning. Additional work in developing improved physical sensor protection should eliminate the reliability problem.

During the 90-hr run-time at the Stillwater Mine, mine personnel found that the vehicle operated with power equivalent to that of similar diesel-powered vehicles. After becoming familiar with the prototype's safety and operating systems, initial apprehension about using a hydrogen-powered vehicle faded. This was reinforced when the control system efficiently shut down the vehicle and indicated which sensor zone was affected.

The harsh mine environment placed a strain on trailer plumbing systems. Excessive vibration caused a leak in a coolant port on the heat exchanger module. This leak was unnoticed during operations until engine block temperature started to rise. Heat transfer to the hydrides was limited due to the lower coolant flow. By slowing the desorption rate of the hydrogen, less hydrogen was available to the engine, thus

adversely affecting power. Improvements to the heat exchanger design will be needed to address failure caused by vibration.

In conjunction with improved vibration dampening of the fuel system, a new design should include sequencing hydride desorption from module to module. This would limit the amount of releasable free gas available in case of multiple failures of vessel pressure. The 1987 safety report (Lynch et al., 1987) made recommendations to help reduce the potential for a hydrogen leak during underground operation. Limiting the choices for hydride fuel storage to those with a high-temperature desorption rate was proposed. In addition, it was recommended that the fuel management system have sequential controls so that each module could be exhausted prior to the next being warmed.

In the Stillwater Mine test, the approach taken was to examine the maximum amount of hydrogen that could be released from a catastrophic failure of the vehicle storage system and limit the use of the prototype to areas of the mine with ventilation adequate to mitigate the hazard. The Society of Automotive Engineers (SAE) has produced recommendations for hydrogen storage on motor vehicles (2001a, 2001b). One recommendation is that automatic shut-off valves be required on fuel supply cylinders. Adequate ventilation should be considered for the largest release possible from a single valve failure. Released hydrogen quickly diffuses into air under still conditions, but adequate ventilation assures that flammable concentrations will not accumulate. ZEUS has the fuel supply divided into two separate systems isolated by both manual and automatic control valves. The greatest potential for a release is at the fully fueled and pressurized cold start portion of the system in addition to unabsorbed gas in the main bed modules. It would take 1 min to release 1.4 kg of hydrogen, requiring 396 m^3/min of ventilation air to prevent accumulations in excess of the LFL in a worst-case scenario. By further subdividing the system with automatic control valves, the minimum ventilation rate could be further reduced to the 113 m^3/min required to replenish the oxygen consumed by normal engine combustion.

The belt-driven air pump used to clear the crankcase of possible hydrogen collection caused excessive engine oil pressure. During extended running under load, oil was forced into the combustion chamber. The air pump should be replaced with an electric or similar type of pump that would ventilate the engine during the 60-s period prior to start up and then disengage. This modification would maintain the existing safety feature of purging the crankcase air and reduce the probability of spark plug fouling caused by excessive oil blow-by past the piston rings.

The benefit of reducing noxious emissions has been the driving force behind introducing hydrogen-powered equip-ment underground (Schnakenberg, 2004). However, to achieve this goal, additional research and development are needed in hydrogen storage methods, fueling station designs, monitoring systems, and means to reduce hydrogen consumption.

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