A Catalyst Fusible Link for Hydrogen Detection and Activation of Passive Ventilation Systems

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ABSTRACT

This paper presents an experimental study of a hydrogen fusible link developed for use in the detection of hydrogen and in the activation of passive ventilation or other safety systems. Fusible links are commonly used to passively close fire dampers in the event of a fire; they generally consist of two pieces of metal joined together by a low temperature alloy to form a single device. When exposed to fire, the link will heat up and eventually melt the alloy, causing the metal pieces to separate. The same principle has been adopted for the hydrogen fusible link in which hydrogen recombiner catalyst was coated onto small rectangular brass plates. These plates were then soldered together to create prototypes of the hydrogen fusible link. When the resulting link is exposed to a hydrogen-air mixture, an exothermic reaction occurs on the catalyst surface that will heat up the link and melt the solder, separating the two sections of the hydrogen fusible link. A series of experiments was performed to characterize the thermal response of the hydrogen fusible links to various hydrogen-air mixtures. The effect of both hydrogen concentration and its rate of accumulation on the increase of catalyst temperature was examined. This study demonstrated the applicability of the hydrogen fusible link for managing hydrogen risk.

1.0 INTRODUCTION

The hydrogen economy has been proposed as a successor to the hydrocarbon economy, mainly to eliminate the negative environmental impact of using hydrocarbon fuels. This entails the widespread use of hydrogen energy-based vehicles and power generators. Hydrogen safety technology is of major importance to support public acceptance of hydrogen as an energy carrier. One of the most important issues is the use of such systems in confined or semi-confined areas, such as private garages, underground parking, and road tunnels, due to potential accumulation of flammable gas mixtures.

One element of a hydrogen safety system is the use of sensors to detect and monitor unexpected hydrogen releases [1]. The United Nations Economic Commission for Europe Global Technical Regulation (GTR) Number 13 (*Global Technical Regulation on Hydrogen and Fuel Cell Vehicles*) is the defining document regulating the safety requirements for light-duty hydrogen vehicles [2], which has defined several hydrogen monitoring requirements. The use of hydrogen detectors has also been required by the standard developed by the National Fire Protection Association (NFPA 52) for indoor hydrogen-fuelling operations [3]. Indeed, hydrogen sensors are of increasing importance in connection with the development and expanded use of hydrogen gas as an energy carrier [4].

The Canadian Hydrogen Installation Code [5] addresses hydrogen accumulation by requiring all indoor hydrogen installations to be adequately vented to the outdoors with a minimum ventilation rate of 6 air changes per hour or 0.3 m^3/min per square metre of floor space, or other means to prevent the accumulation of hydrogen above 25% of the lower flammability limit (that is, 1% hydrogen in air). Maintaining such a ventilation rate can be expensive for interior hydrogen storage, especially in climates where environmental temperatures deviate significantly from normal indoor room temperatures. One solution is to activate a ventilation system only when a hydrogen leak occurs. This can be accomplished by the use of a commercial hydrogen detector that will trigger an active ventilation system. Although there are numerous hydrogen safety sensors available commercially [6], active systems would require a power source, and battery backup systems are notorious for not being available when called upon during a power outage. Non-traditional hydrogen detection and mitigation technologies will expand the deployment of hydrogen vehicles or appliances to areas or industries, where active ventilation may not

be the most feasible option due to the risk of power outage and the high overall costs associated with its operation. Examples are underground mining, road tunnels, garages, underground parking and warehouses.

A passive ventilation system was examined in this study to mitigate hydrogen risks for indoor hydrogen applications. A key component of the passive hydrogen ventilation system, the "hydrogen fusible link", was developed based on two well-known technologies: (1) passive autocatalytic recombiners (PARs), which has been widely adopted for hydrogen mitigation in nuclear industry [7], and (2) mechanical fusible links, which are commonly used for fire dampers [8]. PAR is designed to use the heat of catalytic oxidation of hydrogen with oxygen (from the air) to form hot steam that drives flow through the PAR unit by natural convection. Its self-start and self-sustained behaviour makes it a passive technology. A mechanical fusible link is a device consisting of two strips of metal soldered together with a fusible alloy that is designed to melt at a specific temperature, thus allowing the two pieces to separate. For fire dampers, the fusible link separates during fires, enabling the spring-loaded weight held by the link to release, allowing for passive shutting of the fire dampers. The same principle has been adopted for the hydrogen fusible link in which hydrogen recombiner catalyst, originally developed by Atomic Energy of Canada Limited, was coated onto small rectangular brass plates. These plates were then soldered together to create prototypes of the hydrogen fusible link. When the resulting link is exposed to a hydrogen-air mixture, an exothermic reaction occurs on the catalyst surface that heats up the link and melts the solder, separating the two sections of the hydrogen fusible link. As demonstrated by Evans and Madrzykowski for fusible-link sprinklers [9], the overall effectiveness of an automatic sprinkler system in suppressing an unwanted fire is dependent on the time it takes to respond to the fire condition. The effectiveness of a passive ventilation system will also depend on the response time of the fusible link in the presence of hydrogen-air mixtures.

A series of hydrogen fusible link experiments was conducted using both catalyst coated commercial fusible links and in-house fusible links in the catalyst activity bench scale (CABS) apparatus and hydrogen safety test facility (HSTF). The purpose was to investigate the feasibility of hydrogen fusible links as a key component for the passive hydrogen ventilation system. This paper presents experimental results to characterize the thermal response of the hydrogen fusible link in the presence of various hydrogen-air mixtures, and to examine the effect of both hydrogen concentration and its rate of accumulation on the increase of solder temperature.

2.0 EXPERIMENTAL METHODS

2.1 Catalyst Activity Bench Scale Apparatus

The CABS apparatus was designed and constructed to conduct bench-scale testing of the hydrogen recombiner catalyst. A schematic representation of the CABS test apparatus is shown in Fig. 1. The main components of the CABS apparatus are a glass reactor vessel (6 L volume, 14.6 cm inner diameter) with a heating jacket, gas supplies, gas analysis equipment (Agilent Technologies Model 6890N gas chromatograph - GC), humidifier, mass flow controllers (MFCs), and data acquisition system. The hydrogen fusible link was suspended in the middle of the glass vessel. When the commercial fusible link was used, a weight was applied at the bottom of the fusible link to simulate a load, such as spring-loaded force, pulling the link downward. The load was not applied for in-house fusible links as the breakage of the links was not the main focus of the tests.

At the beginning of a test, the vessel was purged with dry air at ambient temperature. The vessel pressure was maintained at 9.9 kPa(g). Hydrogen and air were pre-mixed and injected at 0.5 to 5 SLPM (standard liters per minute[1]) into the bottom of the vessel, and gases exited from the top of the vessel. The injection rates of hydrogen and air were controlled separately to achieve 0.5 to 3%[2] hydrogen in the inlet gas. The inlet gas concentration was verified using the GC after the initial volume of air in the vessel was

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[1] The standard condition is defined as a temperature of 0 °C and an absolute pressure of 1 atm.
[2] The gas concentration is always expressed on a volume basis in this paper.

displaced by the injected gas mixture. The outlet gas concentration was measured until the hydrogen concentration reached a steady state (that is, the hydrogen consumption rate due to recombination was equal to the injection rate of the hydrogen-air mixture). The gas temperature inside the vessel and the hydrogen fusible link temperature were recorded every 1 to 5 s during a test. Initially, the gas concentration inside the vessel was not analysed as the GC requires several minutes to process one sample. In the later tests, thermal conductivity hydrogen sensors, developed by Xensor Integration Inc., were placed inside the vessel to measure the hydrogen concentration transients during testing. This setup allowed measurement of the link temperature as a function of hydrogen concentration; its rate increase at the fusible link could also be determined precisely.
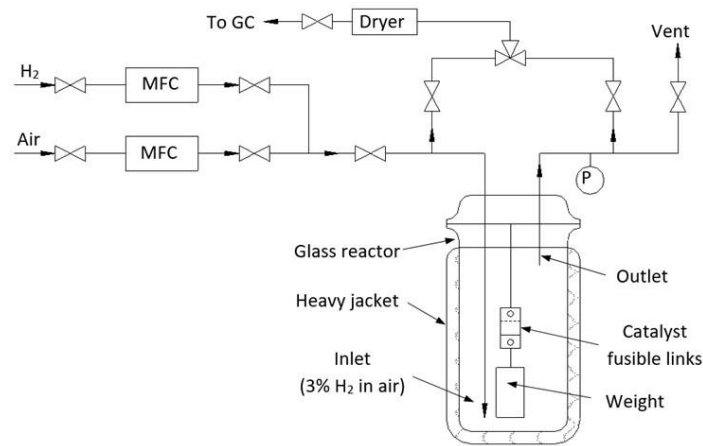

Figure 1. Schematic of main components of catalyst activity bench scale test apparatus

2.2 Hydrogen Safety Test Facility

The HSTF is a structural steel spherical pressure vessel with an internal free volume of 0.25 m^3. A 3 - dimensional rendering of the sphere and locations of the hydrogen sensors, thermocouples and fusible link are shown in Fig. 2. Note that all the instruments are located on the central vertical plane of the sphere. The facility was equipped with vacuum and venting (discharge vessel contents), heating, gas supply (hydrogen and air) and gas mixing (an electrically operated fan).
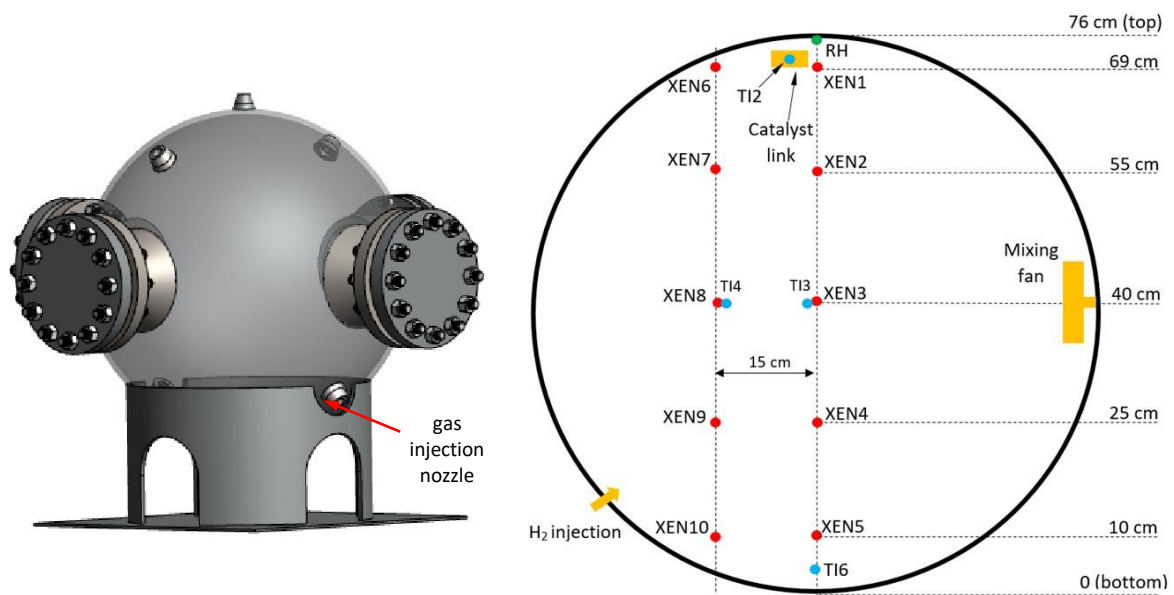

Figure 2. Three dimensional rendering of hydrogen safety test facility (left) and schematics with locations of catalyst coated link and instrumentation (right)

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At the beginning of a test, the vessel was filled with dry air at ~105 kPa (absolute) and 20-25°C. Hydrogen was then injected continuously at a constant rate at an elevation of approximately 15 cm with the mixing fan on or off, resulting in well-mixed or stratified gas mixtures, respectively. The hydrogen flow was regulated by flow controllers for a range of 0 to 5 SLPM. The relative difference between the recorded flow rates and the set values was within ±10%.

The hydrogen concentration was measured by ten XEN-5320 sensors (or "Xensors") installed in the sphere at five elevations on two columns shown in Fig. 2 (right). One of the sensors (XEN1 at 0.7 m height) was placed close to the middle point of the link. The absolute and relative measurement error of the sensors were measured to be ±0.1% hydrogen and ±10%, respectively. One type-K thermocouple (TI2 in Fig. 2 right) was welded in the solder between the two pieces of the link. Three type-K thermocouples (TI3, TI4 and TI6) were placed at the centre and bottom of the sphere. The uncertainty of the thermocouples was ±2°C to a 95% confidence level.

2.3 Fusible Links

To prove the concept of hydrogen fusible link, the earlier tests were conducted using commercial fusible links (J series), purchased from Globe Technologies Corporation, with solder failure temperature ratings of 74 °C and 100 °C. As shown in Fig. 3 (left), the fusible link was sandwiched between two stainless steel sheets of wire mesh, which were coated with hydrogen recombiner catalyst. Each sheet was 2 cm wide, and 3, 4 or 5 cm long. Each mesh was able to completely cover the link surface where the solder was applied. The catalyst mesh sheets were spot welded and particular attention was taken to ensure the gap between the catalyst and the link was as small as possible to minimize thermal contact resistance. Enough room was left to allow a thermocouple to be inserted between the catalyst mesh and link. It was recognized that this configuration did not result in optimal heat transfer from the catalyst coated steel sheets to the commercial fusible link.

To improve the heat transfer from the catalyst material to the solder, the later tests utilized fusible links made in-house, shown in Fig. 3 (right). Hydrogen recombiner catalyst was coated directly onto rectangular brass pieces; each piece was 2.3 cm long, 1.3 cm wide and 0.1 cm thick. To examine the thermal response of the link as a function of a wide range of hydrogen concentration and accumulation rate, a high-temperature solder (rating of 180 °C) was used to connect the brass pieces and no weight was applied during testing to eliminate premature link breakage in these tests. Links with different shapes and dimensions were also examined with different orientations inside the HSTF vessel.
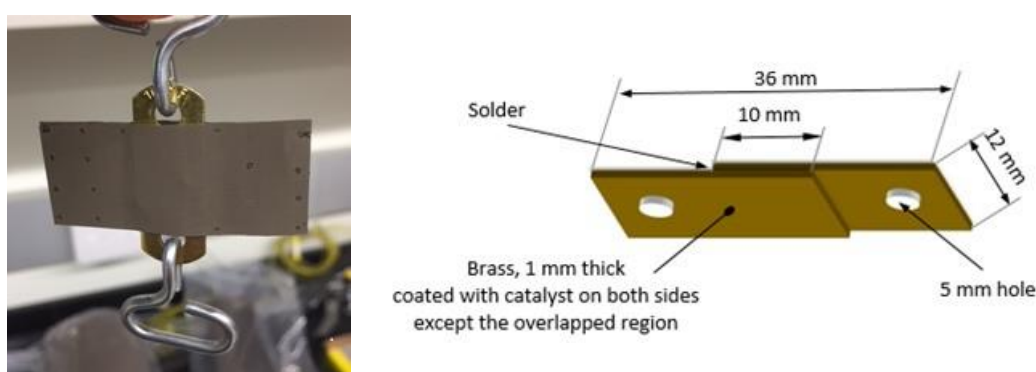

Figure 3. Photo of a commercial fusible link sandwiched with 2×5 cm hydrogen recombiner catalyst mesh (left) and schematic of an in-house hydrogen fusible link (right)

2.4 Test Matrix

Four groups of tests are presented in this paper and their conditions are summarised in Table 1. All these tests were performed under ambient conditions (~1 atm, 20-25 °C and dry air). The Group 1 and 2 tests were performed in the CABS apparatus and the Group 3 and 4 were conducted in the HSTF vessel.

Commercial fusible links wrapped with recombiner catalyst mesh were tested in Group 1 and the in-house fusible links were tested in the other groups. The injection rate was fixed at 3 SLPM and the inlet hydrogen concentration was step-increased from 0.5 to 3% in each Group 1 test, while the inlet hydrogen concentration was fixed at 3%, and the injection rate (0.5 to 5 SLPM) was maintained constant in each Group 2 test. In Groups 3 and 4, pure hydrogen was injected at a constant rate (0.1 to 2.1 SLPM) from the bottom of the HSTF sphere. The mixing fan was turned on in Group 3, leading to well-mixed gas mixtures, but turned off in Group 4, resulting in stratified gas mixtures.

For the Group 1 to 3 tests, the average hydrogen accumulation rates listed in Table 1 were estimated by the ratio of hydrogen injection rate to vessel volume, $H_2\% \times Q/V$, assuming no recombination and pressurization. The average accumulation rate of the Group 4 tests was estimated based on the hydrogen concentrations measured at the link. The hydrogen injection rates used in Groups 3 and 4 were chosen so that the resulting average accumulation rates were similar to Groups 1 and 2.

Table 1. Summary of experimental conditions

| Group | Test Facility | Fusible Link (cm) and Solder Melt Temperature | Catalyst Surface (cm) | Injection Gas | | Average H_2 Accumulation Rate (%/min) |
				Rate (SLPM)	H_2 (%)	
1	CABS (6 L)	Commercial (2.35×1.3×0.1)* 74 & 90 °C	(2×3)* (2×4)* (2×5)*	3	0.5−3	0.25−1.5
2	HSTF (250 L)	In-house (1.3×1.0×0.1) 180 °C	(1.3×1.0)*	0.5−5	3	0.25−2.5
3				0.1−2.1	100 (pure H_2)	0.04−0.84 (uniform)
4						0.04−1.8 (stratified)

*Dimensions of each piece of the link.

3.0 RESULTS AND DISCUSSION

3.1 Group 1: Commercial Fusible Links in CABS

The Group 1 tests were performed to demonstrate that heat generated by the catalytic reaction in the presence of hydrogen-air mixtures could be used to separate the fusible link. Two different types of commercial links with break temperature ratings of 74 °C and 100 °C were utilized and the catalyst mesh sizes of 2 × 3, 2 × 4 and 2 × 5 cm were examined.

The fusible link was connected to both the I-hook of the weight (0.35 kg or 1.47 kg) and that in the vessel lid, causing the weight exerted on the link to be in a downward direction. The gas injection rate for this set of experiments was set at 3 SLPM with a hydrogen concentration ranging from 0.5−3%. The hydrogen concentration was increased incrementally. When it was determined that the temperature increase of the catalysts at the set concentration was beginning to stabilize; the steady-state inlet and outlet hydrogen concentrations were measured. However, the hydrogen concentration at the fusible link was not known.

Fig. 4a shows the catalyst temperature transients of a test performed with 2 × 4 cm catalyst mesh and the solder temperature rating of 74 °C. The steady-state inlet and outlet hydrogen concentrations are also plotted in Fig. 4. In this test, a 350 g weight was applied at the bottom of the link. As observed in Fig. 4a, the catalyst temperature started increasing immediately after the hydrogen-air mixture was injected into the CABS vessel. When the link was exposed to 1% hydrogen, the catalyst temperature increased to 31.6 °C in 10 minutes. Increasing the inlet hydrogen to 1.5%, the catalyst temperature

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stabilized at 62.7 °C in 20 minutes. Further increasing the inlet hydrogen to 1.63%, the catalyst temperature plateaued at 70.3 °C in 15 minutes. The fusible link separated at approximately 74 °C after the inlet hydrogen increased to 1.76% for 8 minutes.

Fig. 4b shows the results of a test performed with 2×5 cm catalyst mesh and the solder temperature rating of 100 °C. A 1.47 kg weight was applied in this test. It is important to note that the manufacture's minimum required weight was 1.36 kg for the link to properly function. It was observed in the initial tests that the link did not separate with the 0.35 kg weight when the catalyst temperature exceeded 133 °C. The link break temperature became consistent with the rating temperature after the 1.47 kg weight was applied. As shown in Fig. 4b, the catalyst temperature plateaued at 97.9 °C at an inlet hydrogen concentration of 2.3%. Further increasing the inlet hydrogen to 2.5%, the catalyst temperature ramped up quickly and the link separated at 107 °C.

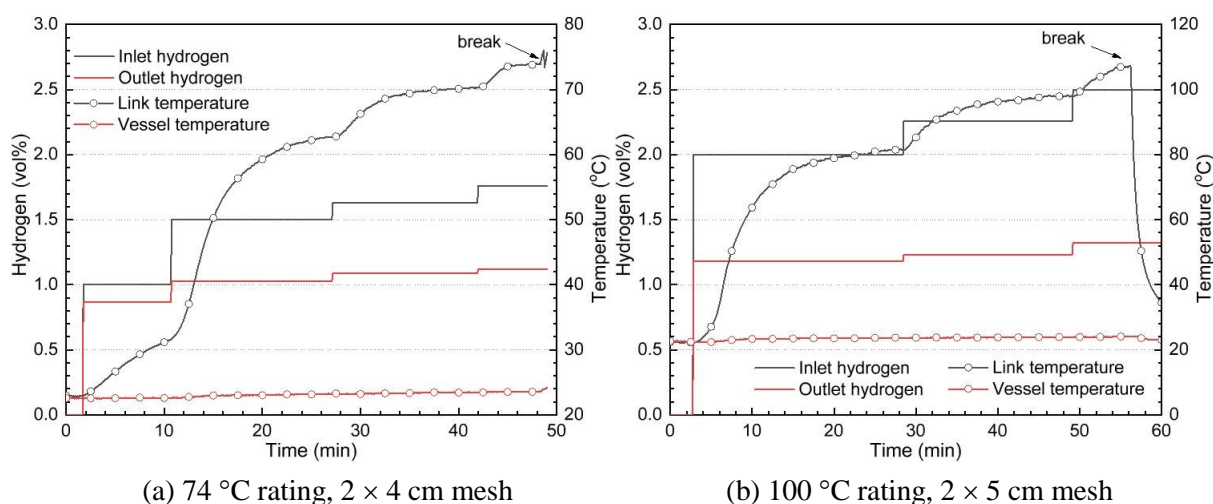(a) 74 °C rating, 2 × 4 cm mesh   (b) 100 °C rating, 2 × 5 cm mesh

Figure 4. Time transients of hydrogen concentrations and link temperature using commercial fusible links wrapped with recombiner catalyst mesh (Group 1)

The tests with different catalyst mesh sizes (not shown) demonstrated that the outlet hydrogen concentration was smaller with a larger catalyst mesh at a given inlet hydrogen concentration, hence the overall hydrogen conversion (heat release) was greater with larger catalyst mesh. However, a higher inlet hydrogen concentration was required for the catalyst to reach the same break temperature with larger catalyst mesh. The results suggest that smaller catalyst mesh were more efficient for heat transfer to the fusible links. Overall, the Group 1 tests demonstrated that the hydrogen recombiner catalyst has the capacity to generate sufficient heat to cause a fusible link to melt in the presence of non-flammable hydrogen-air mixtures.

3.2 Group 2: In-house Fusible Links in CABS

3.2.1 Hydrogen Distribution and Catalyst Temperature Transients

The Group 2 tests were performed to characterize the transient behaviour of the link temperature as a function of hydrogen concentration and its rate increase. In these tests, Xensors were placed inside the vessel at three elevations: bottom (close to the entrance of the gas inflow, ~1 cm above the vessel bottom), middle (close to the link) and top (~1 cm below the lid) slightly off the centre line. The hydrogen concentrations were acquired with a sampling rate of 3.3 Hz. The temperature of the fusible link was acquired at a sampling rate of 1 Hz. Steady-state hydrogen concentrations at the flow inlet and outlet were also measured by the GC.

Fig. 5 plots the time histories of hydrogen concentrations and link temperatures for injection rates of 0.5, 1, 3 and 5 SLPM with 3% hydrogen in air at the inlet. Time zero corresponds to the start of hydrogen injection. The dashed lines represent the time histories of average hydrogen concentrations with no

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recombination. The hydrogen concentrations at the three Xensor measurement locations immediately increased when the hydrogen injection started. The link temperature also started to increase almost immediately, suggesting that the recombination started at very low hydrogen concentration ($< 0.2\%$). However, the effect of recombination was negligibly small initially, so the hydrogen concentration and its rate of increase were primarily affected by the injection rate. After reaching a maximum, the hydrogen concentration started to decrease to approach a steady state while the link temperature increased to reach a plateau, suggesting that the recombination rate also reached a steady state.

The hydrogen concentration in the vessel was always higher at the bottom and lower at the top. Before reaching the maximum hydrogen concentration, the hydrogen was largely stratified for injection rates of less than 1 SLPM (Fig. 5a), slightly stratified for injection rates of close to 1 L/min (Fig. 5 b), and almost well mixed for injection rates of greater than 1.0 SLPM (Fig. 5 c & d), meaning that the hydrogen distribution was buoyancy-driven at lower injection rates, but switched to momentum-driven at higher injection rates. Because hydrogen was injected from the bottom of the vessel, the hydrogen concentration was expected to be well-mixed after a short distance from the nozzle. In addition, the recombination rate increased with an increase in the hydrogen concentration. At the steady state, the hydrogen concentration at the top was significantly smaller than that in the middle due to recombination, but the difference became smaller at higher injection rates due to flow-induced mixing.
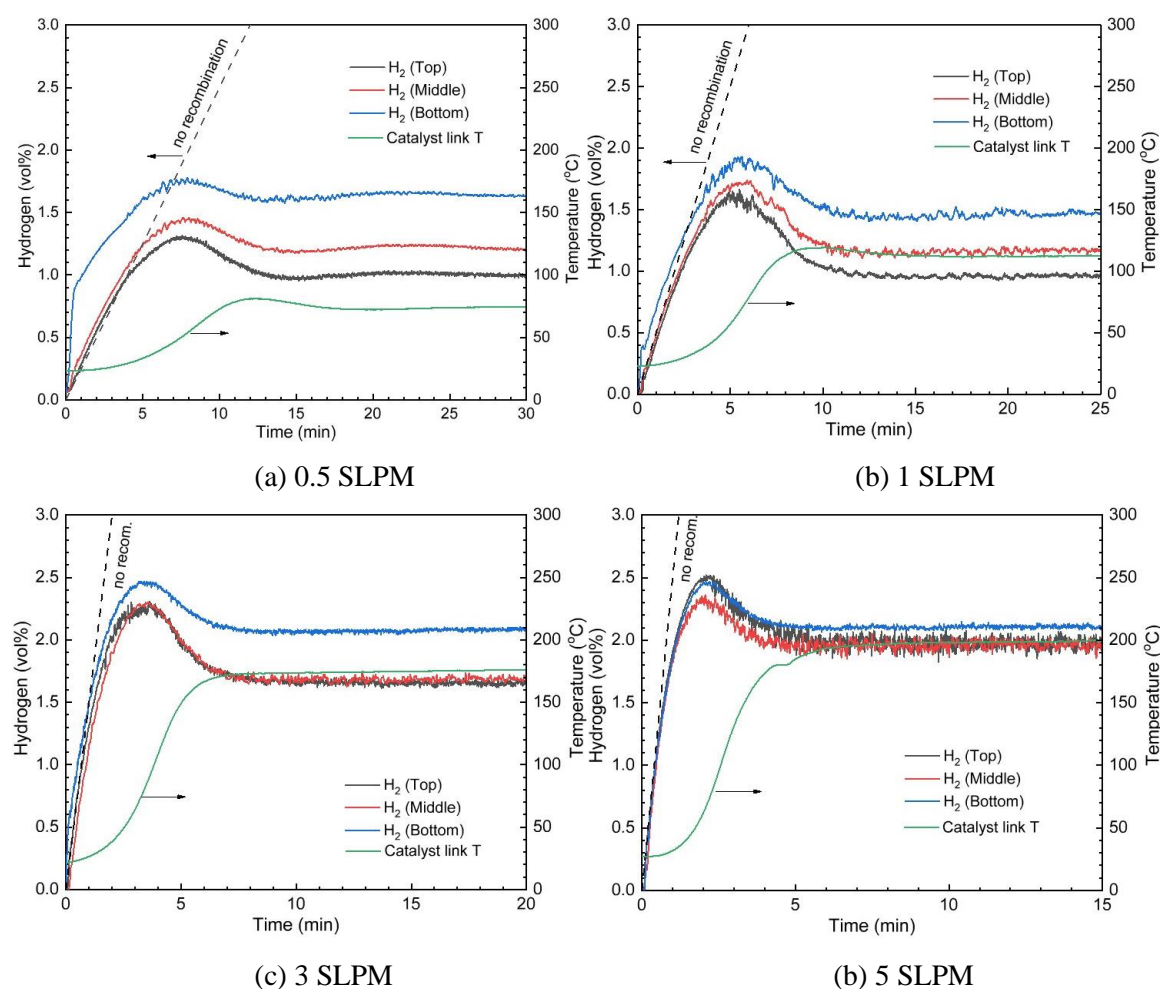

(a) 0.5 SLPM

(b) 1 SLPM

(c) 3 SLPM

(b) 5 SLPM

Figure 5. Time transients of hydrogen concentrations and hydrogen fusible link temperature for injection rates of 0.5 to 5 SLPM at 3% hydrogen (Group 2)

The maximum hydrogen concentration increased and the time to reach the maximum value decreased with increasing injection rate. A higher injection rate would cause several competing effects. The mass diffusion could be higher due to thinner boundary layer, thus increasing the recombination rate, but the

heat dissipation would be faster, thus reducing the catalyst temperature. In addition, a higher inject rate would help to replace the recombination product with "fresh" hydrogen-air mixture fast, but gas mixing would be enhanced to reduce the hydrogen concentration. Overall, a faster inflow resulted in an overall lower recombination efficiency due to competing effects on mass and heat transfer as well as gas mixing.

3.2.2 Catalyst Temperature versus Hydrogen Concentration

Fig. 6 shows the catalyst temperature against the hydrogen concentration measured at the mid-elevation (close to the link) of the Group 2 tests. The catalyst temperature initially increased nearly linearly as a function of hydrogen concentration when it was below 30 °C, but it started to increase exponentially afterward. As shown in Fig. 5, the hydrogen concentration increased faster for higher injection rates, so the catalyst temperature was always higher for lower injection rates at a given hydrogen concentration. To reach a catalyst temperature of 75 °C, the hydrogen concentration spanned from 1.4 to 2.4% (shaded area) when the injection rate was increased from 0.5 to 5 SLPM.

Fig. 7 shows the hydrogen concentration at the link temperature of 75 °C against the injection rate of the Group 2 tests. The dashed line has been added to show the trend of the hydrogen concentration increase as a function of the injection rate (and the accumulation rate). As explained in Section 2.4, the hydrogen accumulation rate in the CABS vessel was close to half of the injection rate, so it was approximately 2.5% hydrogen per minute at 5 SLPM. For injection rates of greater than 3 SLPM, the gradient of the hydrogen concentration versus injection rate curve decreased with increasing injection rate.
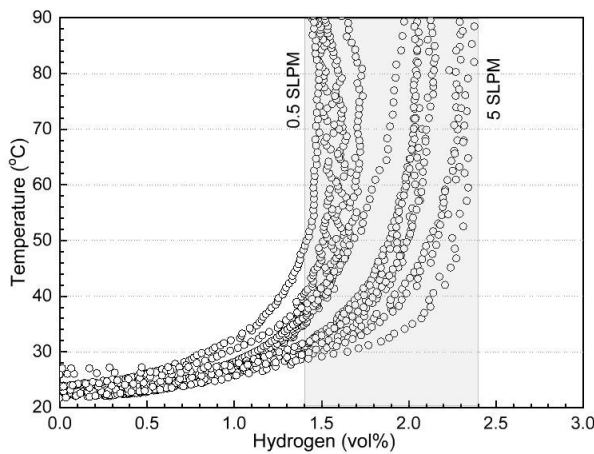

Figure 6. Hydrogen fusible link temperature versus hydrogen concentration for injection rates of 0.5 to 5 SLPM (Group 2)
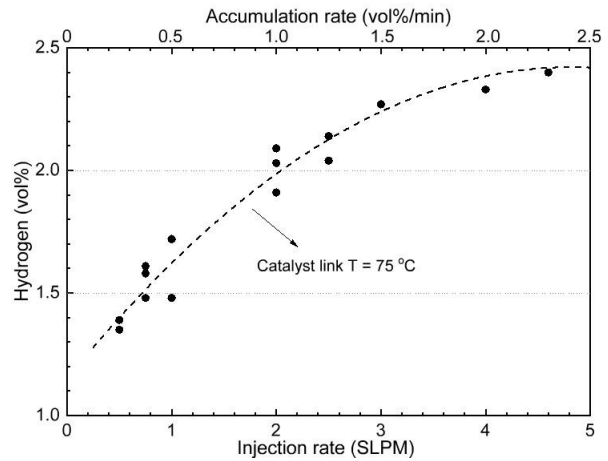
Figure 7. Hydrogen concentration at link to reach 75 °C as a function of injection rate or hydrogen accumulations rate (Group 2)

3.2.3 Steady States

Fig. 8 compares the steady-state outlet hydrogen concentration and recombination efficiency as a function of injection rate of the Group 2 tests. The dashed lines have been added to show the trend of the data. The recombination efficiency was defined as the ratio of the hydrogen concentration difference between the inlet and outlet versus the inlet hydrogen concentration. The inlet flow velocity was calculated by dividing the injection rate with the cross-sectional area of the injection line (diameter of 6.4 mm). For injection rates of less than 1 SLPM, the inflow velocity was less than 0.6 m/s, and the outlet hydrogen concentration was always close to 0.9%. The resulting recombination efficiency was approximately 72%. For injection rates of greater than 1 SLPM, the outlet hydrogen concentration increased linearly as a function of injection rate, whereas the trend for the recombination efficiency was opposite. This relationship is similar to a full-size PAR [10], where the PAR recombination efficiency decreased linearly with an increase in the inflow velocity because a slower inflow would allow the hydrogen mixture to be in contact with the catalyst plates longer to undergo recombination. Overall, the

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recombination efficiency was lower at larger injection rates, but the steady-state hydrogen concentrations and link temperatures were both greater for higher injection rates, suggesting that the overall recombination rate remained larger for faster flows. The recombination rate depends on both the recombination efficiency and inflow velocity, so the decrease in the recombination efficiency was supplemented by the increase in the injection rate.
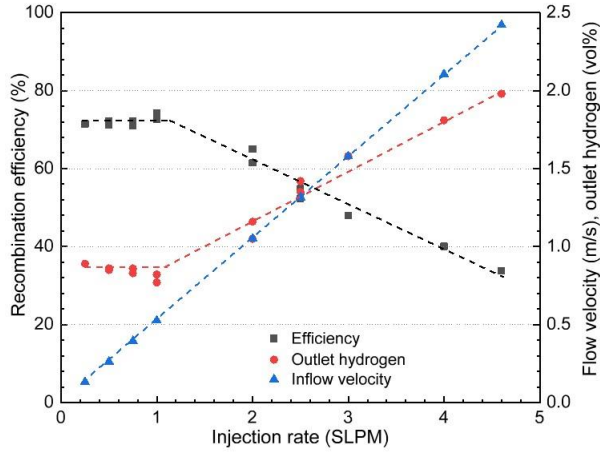

Figure 8. Steady-state outlet hydrogen concentration and recombination rate as a function of injection rate (Group 2)
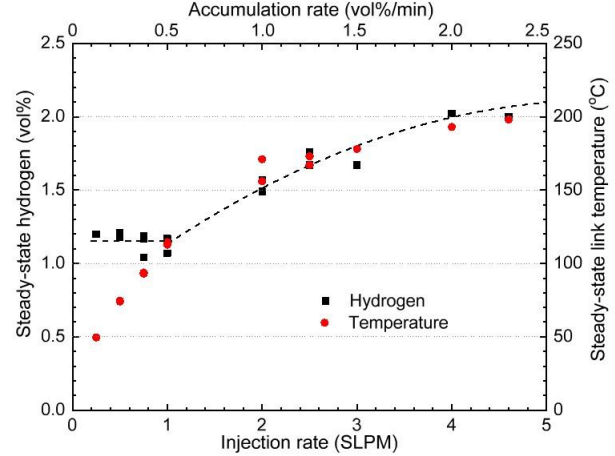
Figure 9. Steady-state link temperature and hydrogen concentration as a function of injection rate (Group 2)

Fig. 9 shows the steady-state catalyst temperature and hydrogen concentration at the link (mid elevation) against the injection rate (and the accumulation rate) of the Group 2 tests. The dashed line has been added to show the trend of the hydrogen concentration increase. For injection rates of less than 1 SLPM, the link temperature increased nearly linearly from 50 to 100 °C as a function of injection rate, but the steady-state hydrogen concentration at the link stayed fairly constant (around 1.3%). For injection rates of greater than 1 SLPM, the steady-state link temperature and hydrogen concentration both increased with an increase in the injection rate. The ratio between the steady-state catalyst temperature and the hydrogen concentration at the link was about 100, which is also similar to the full-size PAR measurements [10].

In summary, the Group 2 results demonstrated that the hydrogen fusible link is able to separate with solder failure temperature of 75 °C before the hydrogen accumulates to a flammable level.

3.3 Groups 3 & 4: In-house Fusible Links in HSTF

The Group 3 & 4 tests were performed in the HSTF to further quantify the thermal response of hydrogen fusible link under typical accident conditions. When hydrogen is released into a confined space, hydrogen tends to be stratified along the height. If the release is a high-momentum jet, the inertia of the jet will drive the mixing of hydrogen with the surrounding air, resulting in a well-mixed system. To simulate these conditions, the mixing fan was turned on in Group 3 and turned off in Group 4, leading to well-mixed or stratified hydrogen-air mixtures, respectively.

3.3.1 Hydrogen Distribution and Catalyst Temperature Transients

Fig. 10 compares the hydrogen concentration and catalyst temperature transients for an injection rate of 0.6 SLPM. As expected, hydrogen was always uniformly distributed in the sphere with fan on (Fig. 10a). Hydrogen was detected at all measurement locations as soon as the injection started, suggesting that hydrogen was mixed instantaneously. The catalyst temperature started to increase at approximately 0.3% hydrogen and grew exponentially with time after an initially slower increase. The hydrogen concentration continued to increase linearly with time during the catalyst recombination. The catalyst

temperature exceeded 75 °C at approximately 1.5% hydrogen and 100 °C at approximately 1.6% hydrogen. The results are consistent with Group 2.

With the fan off (Fig. 10b), hydrogen was highly stratified along the height of the vessel. The hydrogen concentration at the top increased suddenly at 0.2 minutes and it was always the highest during the entire transient. Hydrogen was detected gradually at lower elevations, indicating that hydrogen rose up as a vertical plume, reached the ceiling, then spread to the side and descended downward. Hydrogen accumulated mostly in the upper half of the vessel. The signals at 0.70 m height contained strong oscillations due to gas movement in the ceiling. The increase in the hydrogen concentration at each measurement height was approximately linear and the concentration difference between the top and bottom increased with time. The catalyst temperature increased faster than that with fan on due to higher hydrogen concentration at the link, and it exceeded 75 °C at approximately 1.3% hydrogen and 100 °C at approximately 1.5% hydrogen.

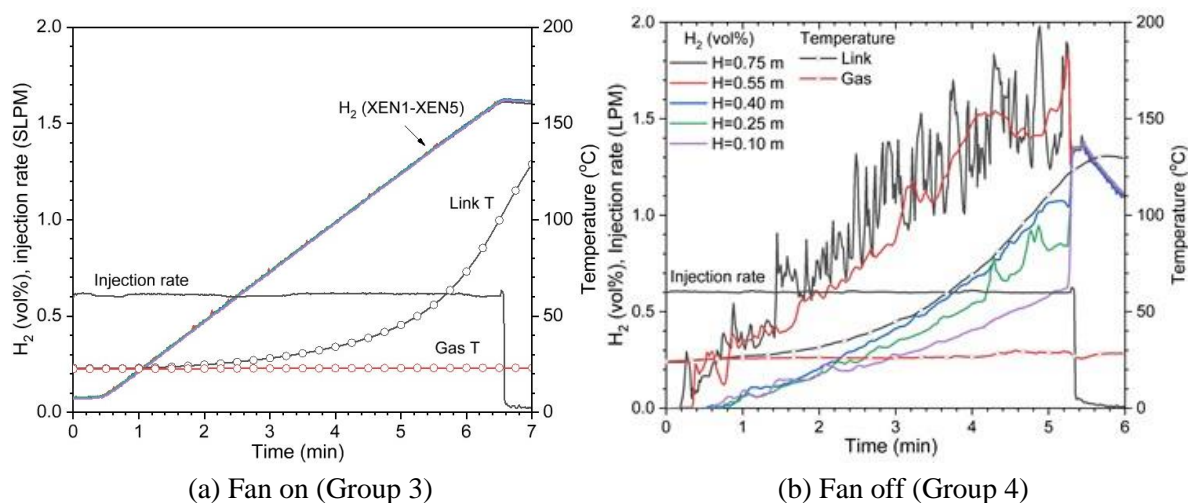(a) Fan on (Group 3) (b) Fan off (Group 4)

Figure 10. Time transients of hydrogen concentrations and catalyst temperatures for injection rate of 0.6 SLPM with hydrogen fusible link (Groups 3 and 4)

Fig. 11 compares the hydrogen concentration transients of four Group 3 (fan on) tests performed with or without the link. As observed in Fig. 10, with fan on, hydrogen was always well mixed in the vessel and the concentration increased linearly with time. At any given time, the hydrogen concentration was greater for higher injection rates. For injection rates of 0.9 to 1.7 SLPM, the hydrogen concentrations of the "with-link" tests overlapped with the "no-link" tests, but they became smaller than the "no-link" tests for injection rates of less than 0.3 SLPM, suggesting that the recombination rate was insignificant as compared to the injection rate at higher injection rates.

3.3.2 Hydrogen Accumulation Rate

Fig. 12 shows the hydrogen accumulation rates at 0.7 m height as a function of injection rate of the Group 3 and 4 tests. The dashed line are a linear fit of the estimated hydrogen accumulation rates. As explained in Section 2.4, the hydrogen accumulation rate was estimated as the ratio of the injection rate and the volume of the vessel. With fan on, the hydrogen accumulation rate increased linearly as a function of the injection rate and the slope was approximately 0.432% hydrogen per liter. With fan off, as shown in Fig. 10b, the hydrogen concentration at the link fluctuated largely, but the increase in the average value was approximately linear. The average hydrogen accumulation rate of the Group 4 tests was determined based on the average slope of the hydrogen concentration transient at 0.7 m height smoothed using a 2 Hz low-pass filter. As seen in Fig. 12, with fan off, the average hydrogen accumulation rate also increased linearly as a function of injection rate, but the slope varied depending on the injection rates. At a given injection rate, the accumulation rate of the tests with fan off was significantly higher than that with fan on. At 2.1 SLPM, the average accumulation rate was

approximately 0.84% hydrogen per minute with fan on, but up to 1.76 % hydrogen per minute with fan off.
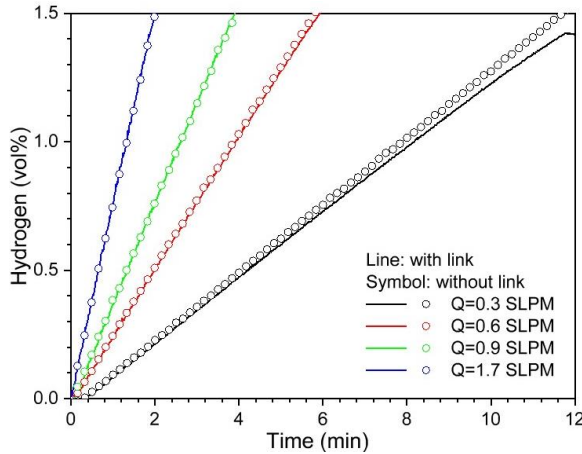

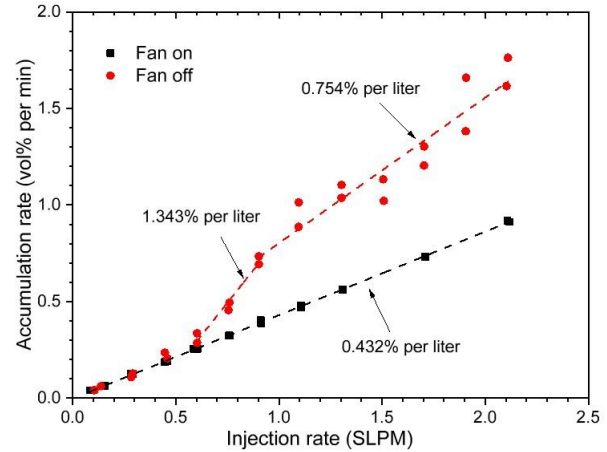Figure 11. Comparison of hydrogen concentration transients w/o link (Group 3)

Figure 12. Hydrogen accumulation rate at link vs. injection rate (Groups 3 & 4)

3.3.3 Catalyst Temperature versus Hydrogen Concentration

The hydrogen fusible link temperature as a function of hydrogen concentration at 0.7 m height of all Group 3 and 4 tests is plotted in Fig. 13. With either fan on or off, the link temperature increased exponentially with an increase in the hydrogen concentration at a given injection rate after the initially linear increase. As observed in Fig. 6 for the Group 2 tests, the hydrogen concentration increased faster for higher injection rates, so the catalyst temperature was always higher for lower injection rates at a given hydrogen concentration. At a given injection rate, hydrogen accumulated faster with fan off, so the hydrogen concentration range was wider to reach the same catalyst temperature. For example, as shown in the shaded area, the link temperature exceed 75°C with approximately 1.1% hydrogen at an injection rate of 0.1 SLPM with either fan on or off, but at an injection rate of 2.1 SLPM, the link temperature exceeded 75°C with approximately 2.2% hydrogen with fan on and 2.9% hydrogen with fan off. Overall, the results are consistent with the Group 2 tests. The Group 3 and 4 measurements further demonstrated that the hydrogen fusible link could separate in the presence of non-flammable hydrogen-air mixtures.
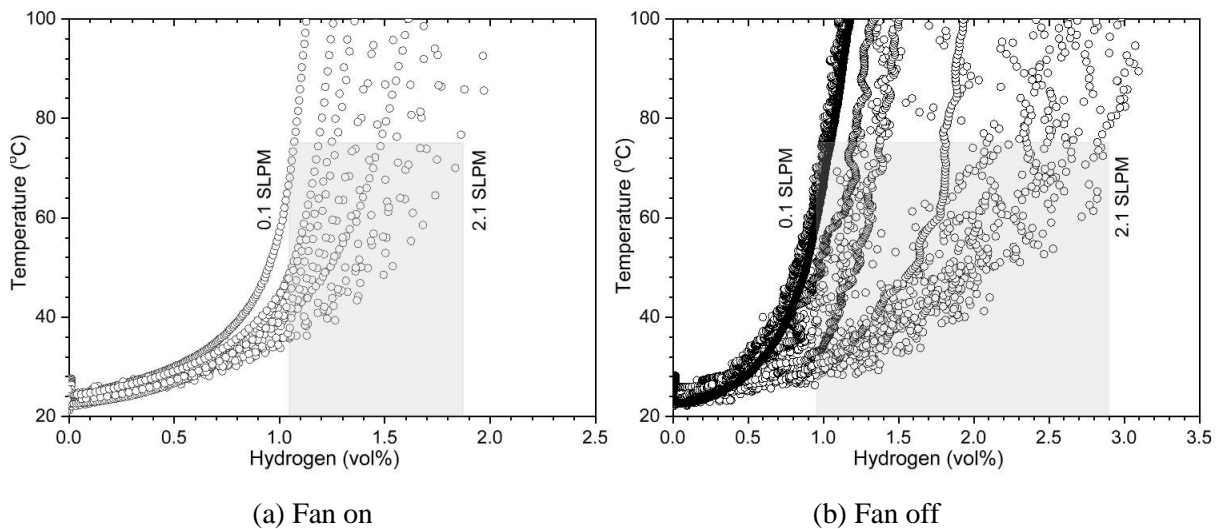

(a) Fan on

(b) Fan off

Figure 13. Hydrogen fusible link temperature versus hydrogen concentration (Groups 3 & 4)

4.0 CONCLUSIONS

This study examined a hydrogen fusible link that can be used for detection of hydrogen and activation of passive ventilation systems or other safety systems. A series of experiments was conducted to characterize the thermal response of the hydrogen fusible link in the presence of various hydrogen-air mixtures using two types of vessels (open vs. closed systems). Commercial fusible links wrapped between two hydrogen recombiner catalyst mesh were tested initially to prove the concept of the design. In-house fusible links were tested later by coating catalyst directly onto rectangular brass pieces (1.3 cm wide and 2.3 cm long) to improve the heat transfer to the solder; each pair of pieces were soldered together using an alloy with a failure temperature rating of 180 °C.

The measurements demonstrated that the catalyst reaction started almost immediately when the link was exposed to low hydrogen-air mixtures (<0.2% hydrogen). The test results showed that AECL's catalyst formulation was able to generate sufficient heat to cause the link to separate at low temperatures (such as 75 °C) in the presence of non-flammable hydrogen-air mixture (<4% hydrogen by volume) with an accumulation rate of up to 1% hydrogen per minute under turbulent conditions (well-mixed mixtures) or with an accumulation rate up to 2% hydrogen per minute under quiescent conditions (stratified mixtures). There is a time delay in the link temperature increase, therefore the hydrogen concentration accumulation rate has to be below a limit to allow the link to reach the activation temperature at the pre-determined hydrogen concentration. This time delay is dependent on the design of the link, such as geometry, body material, bonding material, and catalyst type.

The experimental results suggest that the catalyst coated fusible links have potential for use in passive or active systems for mitigation of hydrogen risks, where active ventilation may not be the most feasible option due to the risk of power outage and the high overall costs associated with its operation. This study has supported a patent application for the hydrogen fusible link.

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