Hydrogen Explosion Due to Inadequate Maintenance

Summary

A hydrogen explosion occurred at a plant, damaging a wall adjacent to the hydrogen storage assembly. The investigation revealed that the explosion was the consequence of deficiencies in components integral to the hydrogen storage assembly, and that this assembly belonged to a supplier contracted to provide hydrogen to the plant. The analysis revealed that had the supplier properly installed and maintained this equipment, this incident would have been prevented. By receiving assurance, on an ongoing basis, that the supplier was properly maintaining this equipment, the company could have also reduced the chance of occurrence of this incident.

Introduction

The explosion damaged a wall adjacent to the hydrogen storage assembly (see Figure 1 below). The investigation revealed that the explosion was the consequence of deficiencies in components integral to the hydrogen storage assembly – a vent cap failed, allowing water to accumulate in the vent pipe. The water froze and damaged the burst disc, ultimately allowing the hydrogen to escape containment. The pipe through which the hydrogen was vented was improperly installed. This promoted the formation and ignition of an explosive mixture of air and hydrogen.

Figure 1. Blast damage sustained by the turbine house transite wall. The arrow points to the approximate location of the worker nearest to the hydrogen assembly when the explosion occurred.

The hydrogen supplier was under contract to supply hydrogen to the facility, as well as to supply an on-site hydrogen storage facility, and the hydrogen was being used to cool the generators at the site. This incident was the result of the failure of this supplier's equipment. This report hereby acknowledges the accountabilities held by the supplier, but focuses on root causes linked to the plant's role in this incident. It is understood that root causes related to the hydrogen supplier's role in this incident will be identified by this company and detailed in their investigative report.

Background

A hydrogen supplier was awarded a contract in 1990 to supply the plant with hydrogen as well as to provide on-site hydrogen storage. At that time, six hydrogen tubes, each about 23 feet in length and having a diameter of 24 inches, were installed at the northwest corner of the turbine house. They were arranged in two rows of three tubes each, stacked two high. For the purpose of this report, the tubes occupying the top row were numbered one through three, from north to south. The tubes on the bottom row were similarly numbered four through six. Tubes 1, 2, 4, and 5 were used to supply hydrogen to the station. Tubes 3 and 6 served as reserve storage and were isolated from the four supply vessels.

A valve and piping arrangement was fitted to the east end of the tube six-pack. It included two pressure relief valves: one plumbed into the four supply tubes and the other being shared by the two reserve tubes. Burst discs were fitted to each of the storage tubes at the west end of the six-pack. Vent pipes rose from each burst disc to an elevation of about 10 feet above grade. Five of the six vent pipes were plumbed straight and near vertical, and were each secured to the tube frame by two U-clamps. The vent pipe fitted to the No. 6 hydrogen tube was not straight; rather it contained two 90° bends, and it was secured to the tube frame by only one U-clamp (see Figure 2). Concrete-filled steel bollards, located at 6-ft centers, surrounded the hydrogen storage assembly.

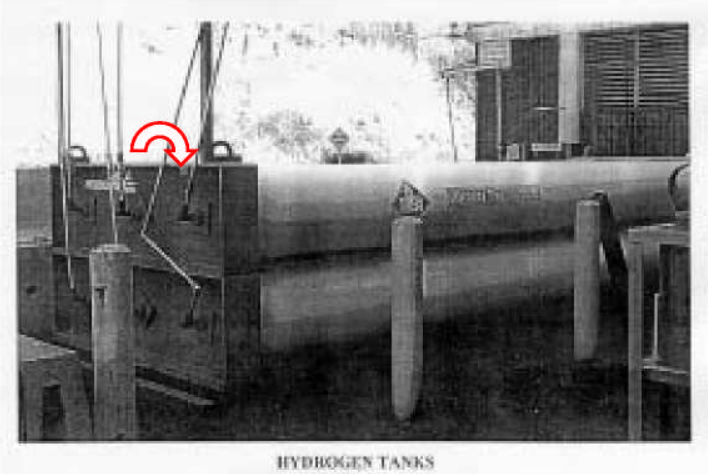

Figure 2. A photograph of the hydrogen storage tubes taken prior to the date of the subject incident. Note the No. 6 vent pipe contains two 90° bends, unlike the other five vent pipes. Also, this vent pipe is secured to the tube frame by only one of the available two U-clamps (the arrow points to the second U-clamp available, but not used, to secure the No. 6 vent pipe to the tube frame).

Figure 3. A burn pattern on the hydrogen tube six pack west frame. Note the vent pipe is missing from tube No. 6.

The hydrogen storage assembly had operated largely without incident until the date of the subject explosion. In February 1997, ice was found in the vent for the pressure relief valve coupled to the four hydrogen supply tubes. At this time, the hydrogen supplier changed out the damaged pressure relief valve.

The hydrogen system was upgraded in 1999. This project involved a broad spectrum of modifications to the hydrogen handling system, including the installation of LEL meters, hydrogen flame detectors, and hydrogen emergency vent valves on the generators. The Maintenance & Operating Instructions Manual that accompanied this project contained a four-page table entitled "Recommended Maintenance Intervals for Mechanical and Electrical Components". One entry in this table recommended that the burst discs fitted to the hydrogen storage vessels be inspected upon each fill or every three months, and specifically to "check for corrosion, discharge obstructions, leakage, rain cap on vent pipe; Replace on a regular schedule based on manufacturer's recommendations and operating experience [Note: Plant to check with equipment supplier]".

Incident Details

On 28 January 2002 at approximately 13:10 hours, hydrogen escaped from containment in the hydrogen storage area. An explosive mixture of hydrogen and air formed before ignition occurred. Damage caused by the resulting explosion is shown in Figure 1 above. The explosion occurred in an area through which workers walk. A worker had exited the door at the northwest corner of the turbine house (the door located beneath the damaged wall in Figure 1) and walked west for no more than about 10 seconds, reaching the location of the arrow shown in Figure 1, when the explosion occurred. The explosion's pressure wave jarred this worker, but did not knock him down.

Emergency response was immediately initiated. The local fire department was called and the onsite fire response team was assembled. Plant personnel gathered at the two master stations and were subsequently moved to the east end of the site. They were instructed to leave via a plant access road after the all-clear siren was sounded.

Hydrogen continued to escape from the storage tubes and burn. The two fire crews cooled the hydrogen tubes and adjacent gas storage cylinders. The fire burned out at approximately 14:58 hours. The plant's senior management was advised of the incident before the all-clear siren was sounded at 15:25 hours. The incident scene was secured and roped-off. A crew was assigned to clean up the asbestos-containing transite wall cladding that had fallen to the snow-covered ground within the blast zone. This crew worked for several days, double-bagging the large pieces of transite, then wet-wiping the entire debris zone. The site was inspected and declared free of asbestos before the investigation team examined it in detail for evidence of the cause of the explosion.

Findings

The burst disc fitted to the No. 6 hydrogen storage tube had ruptured, allowing 14,500 cubic feet of hydrogen stored in the two reserve tubes to release to atmosphere. This burst disc was rated at 3,300 to 3,700 psi. However, the tank pressure at the time of the failure was only 2,100 psi. A pressure relief valve, set at 2,450 psi, was available to respond to any over-pressure condition. There was no known cause for, or evidence of, an over-pressure condition being reached. Therefore, the burst disc must have ruptured prematurely.

The remains of the burst disc were retrieved and submitted to a local engineering firm for examination of its fracture surface using a scanning electron microscope. This examination revealed that the burst disc failed from an initial overload imposed on the atmospheric side of the disc. The only known mechanism by which the burst disc could have been loaded in this manner is by the expansion of water as it freezes to ice while in direct contact with the burst disc. Temperature profiles are consistent with the formation of ice (tank temperatures were recorded to be 0° C for 48 hours preceding the incident, and ambient temperatures recorded at a nearby weather station dropped to -6° C on the evening preceding the incident).

Water could only access the burst disc after passing the vent pipe cap and a plastic weather membrane integral to the burst disc valve body. Caps were found on only two of the six burst disc vent pipes (on the pipes venting the No. 1 and 4 hydrogen tubes). Two additional caps were found on the ground under the tube six-pack. The four recovered caps were constructed of rubber and all were markedly degraded; each cap contained large cracks on their side surfaces (the two caps found on the ground are shown in Figure 4 below). Two coats of paint, red over brown, covered the black rubber caps; brown paint was present on the crack surfaces – indicating both coats of paint were applied to the caps after the cracks had formed! The

degraded state of these caps would have readily allowed water to enter the vent pipes.

Figure 4. Two vent caps, typical of the four vent caps found at the site.

The plastic weather membrane for the No. 6 burst disc valve body had been consumed by the heat of the fire. Examination of the remaining five membranes revealed each to be markedly degraded. If their condition represented that of the weather membrane for the No. 6 burst disc valve body, then water could readily by-pass No. 6 burst disc weather membrane.

The vent pipe originally fitted to the No. 6 hydrogen tube was found leaning against the barricade about 8 feet north of the No. 6 hydrogen tube. All three sections of tubing comprising this vent pipe were bent. Analysis of this pipe configuration revealed that hydrogen must have initially briefly flowed through this vent pipe to cause the pipe to separate from the burst disc valve body. The tendency for this vent pipe to separate from the valve body was enhanced by this pipe assembly being fixed to the tube frame by only one of the available two clamps (Figure 2 above) - two clamps being the standard configuration used to secure all other vent pipes to the frame.

Further analysis revealed that if the vent pipe were designed and installed to withstand the reaction forces generated by the flow of hydrogen, as per the requirements of the Boiler and Pressure Vessel Act (1987, ASME B31 .3, Part 322.6.2), then it would not have separated from valve body in response to the hydrogen release. Furthermore, if the hydrogen had vented through the pipe, then it is likely that it would have simply vented to atmosphere and dissipated in air, or ignited and burned at the top of the vent pipe. Instead, the hydrogen released from the valve body directly to atmosphere once the vent pipe parted from the assembly. This release mode likely increased the chance of the explosion occurring, compared to the chance of an explosion occurring when hydrogen releases, as designed, vertically through a vent pipe.

Conclusions

The uncontrolled release of hydrogen occurred as a result of the premature rupture of the No. 6 hydrogen storage tube's burst disc. This disc failed in response to being overloaded by mechanical stresses developed as water expanded and formed ice while in direct contact with the burst disc. It was the degraded condition of the vent cap that enabled water to access the burst disc.

The vent pipe's configuration (two 90° bends) led to reaction forces being generated, in response to the flow of hydrogen that exceeded the ability of the single U-clamp to secure the pipe to the tube frame. This force imbalance caused the vent pipe to separate from the burst disc valve. The hydrogen released from the valve body directly to atmosphere once the vent pipe parted from the assembly. This release mode likely increased the chance of the explosion occurring, compared to the chance of an explosion occurring when hydrogen releases through a vent pipe.

The hydrogen supplier was required under the Workers Compensation Act to ensure that the hydrogen storage assembly was safe and in compliance with the regulations. Applicable regulations require the container of a hazardous substance to be designed, constructed, and maintained in good condition to securely contain the substance. The two components that permitted the explosion to take place, the degraded (or missing) vent cap and the non-compliant vent pipe, were both integral parts of the hydrogen storage equipment belonging to the hydrogen supplier.

Lessons Learned

1. The uncontrolled release of hydrogen occurred as a result of the rupture of the No. 6 hydrogen storage tube's burst disc. This disc failed in response to being overloaded by mechanical stresses developed as water expanded and formed ice while in direct contact with the burst disc. **It was the degraded condition of the vent cap (defective equipment) that enabled water to access the burst disc.**
    a. As a corrective action, eliminate burst discs from hydrogen storage assembly. Redesign venting system for the pressure relief valves to prevent or inhibit moisture build up and allow moisture drainage.

2. The practice of acting on information that is of relevance to the plant's operations needs improvement. For example, the plant's Hydrogen Handling System (1999) Upgrade Maintenance and Instruction Manual includes the following recommendation pertaining to burst discs: "check for corrosion, discharge obstructions, leakage, rain cap on vent pipe." Had the hydrogen supply company's management confirmed with the supplier that the supplier was carrying out this checking activity, then the chance of the incident occurring would have been reduced.
    a. As a corrective action, when plant management becomes aware of information that both impacts the installation, operation, or maintenance of supplier-

owned equipment, then they will ensure, and document that the supplier is made aware of such information.

b. Reports that have already been commissioned and received by the plant's management, that have a reasonable potential to contain information of the class described in item 1 above, shall be reviewed for such information.

3. The investigation uncovered two instances where the supplier was in possession of information ("safety data") that, if successfully conveyed to plant management and subsequently acted upon, would have prevented or reduced the chance of occurrence of the subject incident. Specifically, the hydrogen supplier found ice in a vent pipe, and was aware that the vent caps were cracked (recall the cracks were painted). Had a requirement existed for this information to be communicated to the plant, then plant management would have had the opportunity to evaluate and potentially influence the supplier's maintenance and operations program.
   a. As a corrective action, contract documents for the hydrogen and nitrogen supplies will be modified to stipulate the following:
      i. Suppliers of potentially hazardous equipment will provide plant management, for acceptance purposes, with written documentation describing the supplier's preventive maintenance program.
      ii. The supplier shall provide the plant representative with a copy of a preventive maintenance report upon the completion of each PM check performed by the supplier. The supplier shall expeditiously rectify any identified deficiency.
      iii. Plant management will recommend to the Manager of Corporate Safety and Health that the above contract document modifications are implemented corporate wide.

4. The vent pipe separated from the burst disc valve body (it was not secured to the tube frame), causing the hydrogen to release directly from the valve body rather than through the vent pipe. This non-compliant mode of release increased the likelihood of an explosion.
   a. As a corrective action, eliminate the burst discs and their associated vent pipes from the hydrogen storage assembly.

5. During the installation and ongoing service life of the hydrogen storage tubes, plant management relied on the hydrogen supplier to ensure that the hydrogen storage assembly met applicable codes, standards, and regulations. Plant management, however, did not examine the methods by which the hydrogen supplier intended to discharge this responsibility. Such an examination could have led to the supplier reviewing the entire hydrogen storage assembly, possibly identifying the substandard vent tube installation, and consequently could have prevented, or reduced the chance of occurrence of the hydrogen explosion.
   a. As a corrective action, contract documentation for the hydrogen and nitrogen supplies will be altered to stipulate the following:
      i. Suppliers of on-site inherently potentially hazardous equipment shall provide the plant with documentation, certified by a Professional

Engineer, stating that such equipment has been designed and installed in accordance with current applicable codes and standards.

ii. Plant management will recommend to the Manager of Corporate Safety and Health that the above contract document modification is implemented corporate wide.