Attachment 1 – Additional Details and Post-Incident Findings

Investigation

1. The investigation focused on finding the source of the hydrogen leak/emission that presumably caused the fire and explosions. Hydrogen is a very flammable material and can be easily ignited by any one of a wide variety of sources. The source of ignition was, therefore, a secondary issue in the investigation. The investigation centered on several pieces of equipment.

    a. Pressure switch
        i. The pressure switch functioned as the high-pressure shutdown on the system and had a set pressure of 3,000 psi. There was a small fire seen at the inlet connection of the switch. It is unclear if this hydrogen leak resulted from the incident or had been present for some time.

    b. Liquid hydrogen pump shaft seal
        i. The pump was removed from service and disassembled shortly after the incident by a technician. The initial examination performed on site showed an excess amount of movement in the shaft where it is sealed on the warm end of the pump. The cold end hat seals were disassembled and no significant amount of wear was observed, but some carbon-like material was observed in the seal area.
        ii. The pump was also shipped to the pump manufacturer and thoroughly examined by them. They concluded that there was most likely a leak at the shaft of the pump due to the excessive shaft movement.

    c. Distance piece nitrogen purge
        i. The distance piece showed evidence of carbon residue from the incident. This shaft seal is fed by a 1/4" nitrogen purge to protect the system from small leaks through the shaft seals. The nitrogen purge line was observed to be broken off the pump shaft seal shroud, possibly as a result of the incident.
        ii. The system is reviewed periodically by the operator and no mention was made of this component being broken prior to the incident. It is possible that a significant leak to the hat seals on the shaft allowed liquid hydrogen to leak in the area and resulted in an explosion in the nitrogen shroud that protects the shaft.

2. The pressure on the hydrogen tank was 130 psig at the beginning of the day. A separate gas compressor takes gas from the tank and lowers the tank pressure. On the day of the incident, the compressor was operated for three hours prior to turning on the pump to lower the tank pressure for pump operation. The hydrogen pump was started up to fill a tube trailer that was at 1,500 psi, and the intended fill was 2,400 psi. The operator visually checked the system after start up and reported that he did not hear/see anything unusual. The pump was in

operation for about 30 minutes when the incident occurred. The pressure on the trailer was about 1,800 psi at the time of the incident.

3. The operator heard a loud bang from the hydrogen fill area. The operator looked at the hydrogen fill area and saw flames and the ripples from the heat generation. The operator hit the emergency shutdown, which closed the feed valves to the hydrogen pump and shut down the hydrogen pump. After the system was shut down, three smaller explosions were heard. There was also the sound of gas releasing from a safety relief valve at this time.

Discussion

1. The fire itself was thought to have originated from the ignition of very cold gas or liquid. The density of very cold hydrogen gas would be near that of air. Operators report that they saw the fire near the ground inside the area enclosed by the firewall. Hydrogen gas would have risen and dissipated relatively quickly, but in this case, the fire propagated at ground level, indicating that the gas was cold.

2. The leak at the pressure switch was one of the first components to be evaluated and was thought to be an important part of the incident, but it was determined that the switch played a minor role in the accident. The small fire observed at the switch was indicative of a small leak at the inlet connection to the switch. It is unlikely that the small leak released enough hydrogen to cause the fire and explosions observed. In addition, this was a gas leak that would not likely have accumulated at ground level. It is possible the fire at the pressure switch acted as an ignition source for the small subsequent explosions.

3. The examination by the pump manufacturer provides conclusive information that the pump was the source of the hydrogen leak. This explanation is consistent with the other data obtained.

4. The maintenance system data on the pump indicates that the necessary maintenance on the pump was performed. However, based on the examination by the supplier, the maintenance procedures used during the preventative maintenance performed appear to be incorrect. Improper maintenance of the pump can lead to excessive wear of the crosshead piston, which can then cause the cold end to leak liquid hydrogen. The pump leak was most likely the source of the hydrogen that caught fire and exploded.

5. The nitrogen purge on the pump distance piece was apparently broken off due to vibration prior to the incident. It initially appeared that the purge line had been blown off the distance piece, but the distance piece did not exhibit any other signs (bulging, other cracks) of having been through an explosion.

6. The controls on the hydrogen pump were very basic. The controls for the pumping system were manually operated, and the only automated control protecting the pump was a high-pressure shutdown. There was no cavitation, low-temperature, or nitrogen purge flow sensors on the pump. There was a low-temperature shutdown after the vaporizers to prevent damage downstream of the pumping system, but this is of no value in protecting the pump.

7. The emergency shutdown system operated as designed and prevented the accident from becoming much worse. The air-actuated valves on the hydrogen feed lines (vapor, liquid) were critical safety components in the system. These valves, when manually actuated during the emergency shutdown procedures, prevented additional hydrogen from escaping from the tank and causing substantially more damage or injury.