National Renewable Energy Laboratory

Environment, Safety, Health & Quality (ESH&Q) Event Investigation Report

INSTRUCTIONS
Environment, Safety, Health, and Quality (ESH&Q) Office Event Investigation Team Lead: Complete the report and approval within 30 calendar days of the event.

1. RECORDKEEPING	
Event Number (from EtQ)	E-00503
Event Subject (from EtQ)	Pressure transducer fails on hydrogen compressor
Significance Level	☐ 1 - Catastrophic ☐ 2 - Critical ☒ 3 - Marginal
Report Number. If Occurrence Reporting and Processing System (ORPS) reportable, identify the ORPS report number.	n/a
Investigation Team. Identify the ESH&Q Office event investigation team leader and the names and job titles of the event investigation team members. Add additional team members as appropriate.	**Names have been redacted for external distribution.** Investigation Team Lead ESIF Research Operations Director ESH Point of Contact ESIF Facility Quality Manager Transportation & Hydrogen Systems Group Manager Pressure Safety Subject Matter Expert ESH&Q Field Support Manager Area Work Supervisor ESIF Research Operations Manager Hydrogen Systems Engineer Hydrogen Systems Researcher

2. EVENT INFORMATION	
Date of Event	1/15/2019
Time of Event	1:42 PM
Organization Number	5B00
Location. Identify the building, room, and location within the room, if relevant.	Energy Storage Outdoor Test Area (ESOTA)
Primary Parties Involved. Identify the individuals involved with the event, and their designations used in this report. For example, Technician #1 = Joe Smith, Site Operations Office.	Researcher #1 ESH Point of Contact
Work Authorization. Select all that apply to the work discussed in this investigation report. Identify specific documents as applicable.	☐ Work Permit: ☐ Work Order: ☒ Readiness Verification: ☐ Other (describe in report)
Worker Authorization. Select all that apply to the workers discussed in this investigation report. Identify specific documents as applicable.	☐ Undocumented Line Manager Assignment ☐ Safe Work Permit: ☒ Safe Operating Procedure: ☐ Other (Describe in report)

3. IMMEDIATE ACTIONS. Identify the immediate actions taken to control, contain, and stabilize the situation after the event.
The leaking hydrogen line was locked and tagged out, and the area restricted until the leak had stopped. After that, the failed pressure transducer was removed and inspected.

4. **DETAILS.** Describe the timeline of events, conditions, or activities leading up to and surrounding the event or near miss. Describe the facts identified during the investigation process. **Include, as appropriate, discussion of the following:** environmental factors; equipment and materials; hazards and controls; and management system elements, such as training and qualifications, work authorization, requirements flowdown, and supervision. Avoid using worker names or personally identifiable information.

Event Discovery and Response:

At 1:42 PM on January 15, 2019, the discharge pressure transducer (PT) on a hydrogen compressor unexpectedly failed, releasing approximately 0.1 kilograms hydrogen to atmosphere from the line. The compressor (Photo 1) is located in the Energy Storage Outdoor Test Area (ESOTA) Hydrogen Pad north of the Energy Systems Integration Facility (ESIF).

Four contractors were present installing insulation and heat tracers on the nearby SoCal biomethanation reactor while the HydroPac and another (PDC) hydrogen compressor were operating. The contractors later reported hearing atypical noises from the HydroPac compressor throughout the day (starting and stopping, loud hissing, chirping indicative of a pressure relief valve lifting). At 1:42 PM, there was a loud pop and disturbance of dust as the PT failed and released hydrogen downwards towards the ground. No workers were immediately near the compressor when the event happened.

One of the contract workers walked to the Energy Systems Integration Laboratory (ESIL) Control Room to report the noise to NREL Hydrogen System research staff. Simultaneous to the device rupture, researchers were alerted by an alarm on the ESIL supervisory control and data acquisition (SCADA) control system of a PT "wire break." Researcher #1 walked outside to the ESOTA with the contractor and found the damaged PT and hydrogen leaking out. Researcher #1 isolated the leak by closing the upstream and downstream hand valves. The Environment, Safety and Health Point of Contact (ESH POC) was notified and responded, as did other research and engineering staff. Access to the ESOTA was restricted until the line was locked and tagged out and no hydrogen hissing could be heard. The failed component, the high-pressure PT originally supplied and installed by the manufacturer (Photo 2), was removed and inspected. Inspection revealed that the stainless steel diaphragm and electrical potting were damaged and off-center (Photo 3).

Equipment History:

The hydrogen gas compressor is a HydroPac model C14-40-12250LX/SS (S/N P14-2089-1) with maximum discharge pressure capabilities up to 14,000 pounds per square inch (psi). The compressor (hereafter referred to as CNH-371) is a single stage hydraulically driven piston compressor. It was purchased in March 2015 and installed in Spring 2016. Startup and shakedown testing occurred in May 2016. A readiness verification was completed and authorization to operate was granted on July 26, 2016.

CNH-371 has been in use since authorization to operate was granted. CNH-371 is used to compress hydrogen, fed from medium-pressure storage tanks (operating pressure 5000-6000 psi), which is then stored in high pressure storage tanks. The high-pressure storage vessels have nominal operating pressures of 13,000 psi and are configured as four individual storage vessels all with dedicated valves, instrumentation and pressure safety valves (PSVs). Hydrogen compression is described and authorized in Safe Operating Procedure #1016, ESIF Hydrogen System. Control of the high-pressure hydrogen compression and storage system is managed through the research SCADA system in the ESIL control room.

The discharge PT that failed was manufactured with a 17-4PH stainless steel diaphragm (Ashcroft Model K1, pressure rated up to 20,000). 17-4PH is a precipitation-hardened martensitic stainless steel manufactured for its strength and corrosion and temperature resistance. This type of stainless steel, while an industry standard for high pressure resistance with other materials, is known in industry to be incompatible with hydrogen. In 2008, Sandia National Laboratory published a technical reference on the compatibility of hydrogen with stainless steels. The document concludes that "precipitation-strengthened martensitic stainless steels are very sensitive to hydrogen-assisted fracture," and that, "this family of alloys is not recommended for service in hydrogen environments." Ashcroft does not currently offer a transducer pressure rated higher than 7,500 psi that can be used with hydrogen.

HydroPac's brochures, instruction manuals, and bill of materials do not identify the specific materials of internal components such as PT diaphragms. The Readiness Verification included functionality testing of PTs but did not include review of individual components' specification sheets. The manufacturer's instruction manual for the purchased compressor states, "All Hydro-Pac compressors are manufactured of materials suitable to resist the affects [sic] of hydrogen embrittlement at the expected operating conditions." After the failure, communications between ESIF Research and Engineering staff and HydroPac representatives have revealed that HydroPac did not intend to supply 17-4PH material in its compressor components; the diaphragm material was overlooked by HydroPac.

In July 2018, the high pressure to medium pressure (HP2MP) crossover system was installed to provide a path to recirculate hydrogen, using a fixed pressure regulator and double-block-and-bleed valve system, with pressure transducer alarming and pressure hardware switches. The HP2MP was designed to enable safe backflow of hydrogen from the high-pressure system to the medium-pressure system. This work was performed in accordance with ESIF change control processes. The system has operated for approximately 200 hours successfully since the changes were implemented.

Events Leading Up to Component Failure:

The morning of the event, operation of CNH-371 began at 10:00 AM. CNH-371 was operating in a recirculation loop using a single high-pressure tank (HP 2) and the HP2MP crossover. The custom-programmed test protocol had the HP2MP operating between the nominal bounds of 12,000 psi and 11,500 psi. Above 12,000 psi, the HP2MP crossover opened. Below 11,500 psi, it closed. There were no other "off-normal" parameters programmed into the test protocol to shut down the program if something went wrong. The protocol was only interlocked to stop in case of faults.

The compressor operated, compressing hydrogen in HP 2 to 12,000 psi. The HP2MP crossover opened, which normally allows hydrogen to flow into the medium-pressure tank until the pressure in HP 2 drops back down to 11,500. Normally, once that lower bound is reached, the HP2MP closes, allowing hydrogen to go into HP 2 once again. However, on this morning, the flow of hydrogen into the medium pressure tank was slower than usual. The medium pressure tank had been filled by a vendor the previous day to "full" (~5,800 psi) rather than the typical ~5,400 psi, and the increased pressure within the tank resulted in reduced flow into the tank. The consequence of this condition was that hydrogen was continuing to be compressed and flowing into HP 2. The pressure in HP 2 exceeded the fill setpoint of 12,700 psi, triggering the soft stop of CNH-371 and the closure of HP 2 as designed. The medium-pressure tank remained open and HP2MP remained open. Without the compressor actively filling HP 2, HP2MP was able to slowly backflow into medium pressure tanks. HP 2 dropped below the fill setpoint, releasing the compressor's internal soft stop and allowing the test protocol "RUN" command to continue being transmitted to the compressor. CNH-371 started compressing again, filling HP 2 above the 12,700 psi setpoint.

Over the course of three hours, the cycle described above repeated several times. During this time as well, pressure within the CNH-371 discharge line approached or exceeded 14,000 psi several times. Contractors working in the ESOTA reported hearing sounds indicative of a PSV lifting. The PSV located on the discharge line (PSV-372) has a threshold of 15,400 psi, with activation at 90% (13,860 psi). The PSV rating of 15,400 psi is well within the discharge PT's pressure limit of 20,000 psi.

Eventually, CNH-371 started automatically one last time. When it did, the diaphragm on the PT ruptured and ejected the electrical potting. The loss of signal from the PT caused a system fault. Upon the fault, both CNH-371 and HP 2 immediately shut down. There was no significant mass lost (~0.1 kg), so tank mass alarms were not activated. The amount of hydrogen released was limited to line volume.

Compressed Hydrogen Operating Parameters	Pressure (psi)
High Pressure Storage Tanks Maximum Operating Pressure (MOP)	13,000
High Pressure Storage Tanks Maximum Allowable Working Pressure (MAWP)	13,500
Maximum discharge pressure for CNH-371	14,000
Current programmed 'soft stop' value for CNH-371	12,700
Pressure Safety Valve on discharge line (PSV-372)	15,400

5. EXTENT OF CONDITION. Document the team's evaluation of this event for whether an extent of condition (EoC) review is warranted. If an informal EoC review is conducted as part of the investigation, document the results here.

The ESIF is the only place where high-pressure hydrogen is stored and used at NREL. Corrective action 4 in this report will address extent of condition of hydrogen compatible wetted parts on the ESIF hydrogen system. This event and hydrogen compatibility issues with Ashcroft K1 pressure transducers will be shared with health and safety field support staff to enable discussions with research staff and individual evaluations (as appropriate) of any lower-pressure hydrogen systems that may use this model pressure transducer.

6. LESSONS LEARNED. Identify lessons learned resulting from the event, if applicable.

It is critical that component parts be appropriately rated for the materials, pressures, temperatures, and other conditions experienced during operation of the system in which they are a part. Don't rely solely on a manufacturer to provide appropriately rated materials and components. Verify components and their specifications as early in the design or procurement process as possible. Manufacturer-provided literature (brochures, instruction manuals, bills of materials, etc.) may not always identify the specific materials for each component, so verification may require Internet research or contacting the manufacturer to obtain the necessary information.

7. **CAUSE ANALYSIS METHOD.** Indicate the level of cause analysis performed and the method(s) used to analyze this event.

Analysis Performed	☐ Root cause	☒ Apparent cause			
Methodology(ies) Used	☐ 5 Whys	☐ Change analysis	☐ Barrier analysis	☒ Events and causal factor charting	☒ Cause mapping

Additional description of cause analysis methods (optional):	Events and causal factors charting was the primary method. A draft cause map was also developed, which supported the findings in the ECF chart.

8. CAUSAL FACTORS. Identify the direct, contributing, and apparent or root causal factors in the table below. Number each causal factor so they can be referenced in the Corrective Actions section. Apply the U.S. Department of Energy (DOE) cause codes to each causal factor. (See DOE O 232.2A and DOE G 231.1-2 for details).

Cause #	**Cause Type** (Direct, apparent, contributing, or root)	**DOE Cause Code** (not required for direct cause)	**Description of Cause**

1	Direct	-	Contact with hydrogen resulted in embrittlement of stainless steel diaphragm on pressure transducer
2	Apparent	A1B2C07 - Error in equipment or material selection	The manufacturer of the compressor installed a pressure transducer not rated for high pressure hydrogen use.
3	Apparent	A4B2C08 - Means not provided for assuring adequate equipment quality, reliability, or operability	NREL relied on the manufacturer of the compressor to provide appropriately rated materials; as a result, NREL's commissioning activities did not specifically check component parts for rating material compatibility.

9. CORRECTIVE ACTIONS. Identify corrective actions developed to address the causal factor(s) identified above. Identify the specific person responsible for each action and provide the date that the corrective action was implemented or an estimated date of completion. Corrective actions are assigned and must be closed out within the Corrective Action/Preventive Action (CAPA) module of EtQ Reliance.

Action Item #	**Addresses Cause #** (See Section 8 above)	**Description of Corrective Action**	**Anticipated Deliverable** (i.e., expected outcome)	**Due Date**	**Assigned Person and Center #**	**Comments** (If completed, enter completion date here).
1	1, 2	Replace pressure transducers on Hydropac hydrogen compressor (CNH-371) with appropriately rated components.	Confirmation from Hydrogen System Owner that new PTs have been installed	April 15, 2019		
2	2	Revalidate process hazard analysis of Hydropac compressor (CNH-371), including a review of material compatibility. Identify any necessary system modifications to be completed prior to re-start.	Documented Process Hazard Analysis	March 15, 2019		
3	1, 2	Complete a re-start Readiness Verification for the Hydropac hydrogen compressor, to include validation of new pressure transducers any system modifications made as a result of the process hazard analysis.	Signed readiness verification	May 1, 2019		
4	2	Verify that wetted components on the ESIF hydrogen system are adequately rated for the materials and pressures encountered on the system.	Documented conclusions of the review and any repair or replacement activities that occurred	May 30, 2019		
5	3	Develop a process for verifying material compatibility for intended use as part of the procurement process for ESIF hydrogen system equipment.	Process description	June 30, 2019		

10. Photographs (Optional). Insert images below. Include labels and captions for each image.

Photo 1. CNH-371 hydrogen compressor.

Photo 2. Failed discharge pressure transducer.

Photo 3. Failed discharge pressure transducer.