LESSONS LEARNED FROM A HYDROGEN EXPLOSION
AT A PHOTOVOLTAIC RESEARCH FACILITY

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Abstract

At the Institute of Energy Conversion (IEC), University of Delaware, a hydrogen explosion occurred on September 1, 1992. A formal investigation was conducted. Suggestions provided by the Accident Investigation Team formed the basis for a complete review and upgrade of the compressed gas handling systems and procedures. In this paper, the causes of the explosion are discussed along with resulting modifications made to the gas handling system, facility, and procedures to prevent a recurrence of this type of incident and to improve the safety of this facility. Lessons learned from this incident and the resulting investigation and response are highlighted, including the need to regularly review both hardware and procedures to ensure that all aspects of the research program and facilities are up-to-date.

Introduction

Hazardous compressed gases, including some that are toxic, explosive, pyrophoric or flammable, are used in photovoltaic module research and manufacturing facilities. The hazards to life and property presented by these gases demand that safety always be given a high priority. At the Institute of Energy Conversion, University of Delaware, hydrogen gas is used in research reactors to deposit amorphous silicon thin-films. On September 1, 1992, an explosion in this facility occurred due to an accidental release of hydrogen. A formal investigation was conducted. Suggestions provided by the Accident Investigation Team formed the basis for a complete review and upgrade of the compressed gas handling systems and procedures. In this paper, the causes of the explosion are discussed along with resulting modifications made to the gas handling system, facility, and procedures to prevent a recurrence of this type of incident and to improve the safety of this facility. Lessons learned from this incident and the resulting investigation and response are highlighted. In particular, there is a need to regularly review both hardware and procedures to ensure that all aspects of the research program and facilities are up-to-date.

Description of the Incident

An explosion occurred during the replacement of a hydrogen cylinder which was stored in a ventilated and sprinklered gas cabinet. This and other hazardous gases flowed to an enclosed reactor in an adjacent room. The gas handling system in use at the time of the accident is shown in schematic format in Fig. 1. During a cylinder change-out, a quantity of high pressure hydrogen gas was accidentally released through a line used for vacuum purging. The explosion occurred when a vacuum bellows burst releasing the gas into the reactor enclosure. The Plexiglas walls of the reactor enclosure blew outward causing extensive damage to the laboratory. Fortunately, no one was in the room at the time of the incident and no one was injured.

The Accident Investigation

A formal accident investigation was conducted, at the request of the Director of the IEC, by an Accident Investigation Team comprised of P. Moskowitz, H. Schulman, and C. Scott from Brookhaven National Laboratory and W. Griffing from the National Renewable Energy Laboratory. The investigation was conducted following Department of Energy accident investigation protocols. In this investigation, the Team's findings centered around facts developed from the following sources:

- Physical inspection of the site
- Physical disassembly and inspection of selected piping/gas distribution components (i.e., excess flow valve, pneumatic valve, and single stage regulator)
- Review of incident reports
- Review of documents, photographs, manuals, etc.
- Interviews with personnel

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Presented below are summaries of the Team's findings divided into three separate sections: Root cause, contributing factors and direct causes.

Root cause

The basic underlying reason for a transient to occur is called the root cause. Root causes may relate to failures in administrative procedures, engineering devices, or in personal protective equipment. Root cause is defined as, "the most basic cause(s) of an event that, when eliminated or compensated for, will prevent accident recurrence." The intent of a root cause analysis is not to place blame, but to determine how to classify responsibilities and reduce errors. In this accident, the root cause was related to the absence of a formal policy for the systematic oversight of gas handling and safety systems.

Contributing factors

Contributing factors are defined to include those factors that did not necessarily directly result in the incident, but presented an environment for an incident to occur. In this incident, several contributing factors were identified including the presence of at least one poorly operating component; the excess flow valve in the gas handling train; the absence of written procedures or checklists for purging, cylinder changing, startup or shutdown of gas system or reactor; and, the lack of formal training and testing programs for gas system operators.

Direct cause

The direct cause arises from the failure of the final protective barrier which isolates the worker from the biologically or physically harmful agent. In this accident the direct cause resulted from an operator error in opening a valve in the wrong sequence resulting in the discharge of hydrogen at pressure >1100 psi through an open valve into a vacuum system not rated for this amount of pressure. Overpressure resulted in the bursting of a vacuum bellows releasing ~0.5 m³ of hydrogen gas into the reactor enclosure. The resulting overpressure of the enclosure, either due to mechanical pressure or chemically induced explosion, caused a blow-out of the enclosure Plexiglas panels, exhaust ductwork and room ceiling tiles.

Safety Modifications

The Accident Investigation Team developed a list of suggestions to prevent a similar event from

occurring in the future and to improve the safety of the hazardous gas operations. A representative sample of these suggestions is shown in Table 1.

Table 1. Suggested Modifications to the IEC Compressed Gas Safety Program.

Engineering
Move gas cabinet panel vacuum pump out from the high pressure to the low pressure side of the regulator.
Install isolation valve on the high pressure side of the regulator in the gas purge panel.
Provide monitoring points for flammable gases in cabinets, cabinet rooms, and reactors. Interface these detectors to the alarm system.
Administrative
Develop written check-lists for all compressed gas systems change-outs, purging, running and shut-down.
Establish training and authorization requirements for all gas system operators.
Personnel
Develop/update training proficiency testing for all gas system operators.
Develop/update training requirements for all "first responders" to emergency incidents.

In the aftermath of this incident, a number of modifications were made to the gas handling system as a follow-up to the accident. The modifications were based on suggestions of the Accident Investigation Team supplemented by information compiled by the IEC staff from discussions with researchers at other laboratories and review of assorted documents, especially the "Safety Analysis Report For the Use of Hazardous Production Materials in Photovoltaic Applications at the National Renewable Energy Laboratory." Fig. 2 displays a schematic of the modified gas handling system. Some key engineering aspects of the upgraded gas handling system include:

- Flow restricting orifices are required for all gas cylinders. The sizes and pressures of the cylinders are limited to ensure that the low pressure line and all components are able to withstand the pressure in the case of a catastrophic regulator failure, provided the excess flow valve functions properly.
- New tied-seat regulators were installed. These regulators allow the cylinders to be purged through the regulator so that vacuum purge res

could be moved to the low pressure side of the regulator.

- Isolation valves were installed on the high pressure side of the regulator.
- Each hazard class of gas is stored in separate gas cabinets with dedicated purge cylinders.

Many facility improvements were made. Two critical features, largely in place before the accident, were upgraded:

- Interlock of the building fire alarm system and automatic gas flow shut off circuits with on-line monitoring for hydride gases and hydrogen in the laboratories, gas cabinets, and reactor enclosures.
- Interlock circuits to ensure that all hazardous gas flows shut off automatically in the event of a loss of ventilation, gas detection, power loss, emergency shut-off buttons, or other alarms in the building.

Finally, written safe operating procedures were developed for cylinder change-out, system start-up, shut-down, operation, maintenance, and emergency response. Each of the procedures was reviewed and approved by the IEC Safety and Chemical Hygiene Committee.

Discussion and Conclusions

Many of the factors which contributed to this accident could potentially have been averted with a formal and regular review of the administrative, engineering and personnel programs associated with the compressed gas systems in place at the IEC. Perhaps most important is the establishment of policies to ensure the continuing surveillance of maintenance operations and review of the condition of all components in the gas handling train. In addition, routine reevaluation of the equipment and procedures should be conducted in light of the latest advances in administrative, engineering and personnel programs. For example, at the time the original system was constructed, the standard and recommended placement of the vacuum purge line was on the high pressure side of the regulator to enable complete purging of the line up to the cylinder valve. Since that time, new tied-seat regulators which enable complete purging through the regulator have become available, so the purge line should now be moved to the low pressure side of the regulator.

Finally, it is useful to visit other facilities and talk with other researchers using similar materials and equipment. Both formal and informal programs to share critical safety information must be encouraged. The costs associated with these efforts and the necessary maintenance and upkeep can be significant, particularly for small laboratories with limited resources such as university-based laboratories. These must be factored into all research and manufacturing programs. Clearly, a failure to accommodate these priorities can be costly.

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Fig. 1. Schematic of the gas handling system in use at the time of the explosion.

Fig. 2. Schematic of the gas handling system in use after the explosion.

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