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Abstract

The E158 experiment, currently underway at the Stanford Linear Accelerator Center (SLAC) scatters a high power 45 GeV polarized electron beam off a large liquid hydrogen target. The total volume of liquid hydrogen in the target is 55 liters, which, if detonated, could produce an explosive yield corresponding to more than 10 kg of TNT. This paper describes the requirements, design and performance of the E158 hydrogen target safety system. The methodology of the design and the safety review process is also described. The experience with the E158 target may be valuable for other sizable liquid hydrogen target systems.

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INTRODUCTION

The object of the SLAC E158 experiment is to make precision measurements of the Weak Mixing Angle in Moeller (electron-electron) scattering at a energy of 48 GeV. The measurements will test the Standard Model and allow the search for new phenomena. In the experiment, a 48 GeV electron beam is passed through a 1.5 m long, 76.2 mm diameter tube of liquid hydrogen. The beam can deposit as much as 660 W into the liquid hydrogen. The hydrogen is moved through the tube at flow rates of up to 1.5 kg/s by a axial vane pump. A hydrogen/helium shell in tube heat exchanger removes the heat deposited in the hydrogen. A large helium refrigerator provides the helium coolant. The target loop is inside a cryostat known as the scattering chamber. Figure 1 shows the schematic of the target loop and its associated hydrogen supply and relief system. The target cryogenic system is fully described in reference [1].

THE NATURE OF THE PROBLEM

If the entire volume of liquid hydrogen were released into the air and ignited with only a 10 % yield the energy released would be equivalent to roughly 11 kg of TNT. The flammability range for hydrogen is 4% to 75% by volume and the energy to ignite a flammable hydrogen/air is only 0.02 mJ. Static electricity can easily cause ignition.

Complicating the safety problem, the very high amounts of ionizing radiation created by the experiment requires that the hydrogen target along with the rest of the experiment be inside a very thick concrete shielding enclosure. Thus, any leaking hydrogen would be concentrated inside a relatively small space which would magnify the impact of any fire or explosion. The operation of the experiment required that people enter the shielding enclosure containing the target for short periods of time to adjust equipment. The timing and frequency of these accesses are unpredictable. Since venting and reliquefaction of the target hydrogen required approximately 8 hours, simply banning people from the radiation shielding enclosure during the presence of hydrogen was not an option.

There is another, more subtle, problem. It has been many years since SLAC last conducted an experiment using large amounts of liquid hydrogen and almost all the hydrogen safety experts had retired. Thus, to ensure a truly safe system, external help was required.

THE E158 HYDROGEN SAFETY SYSTEM

Design philosophy

Work began on the safety system design at least 18 months before the first expected use of liquid hydrogen. An initial meeting was held between the E158 collaboration and the SLAC Hazardous Experimental Equipment Committee (HEEC) which has the authority to review the hydrogen system for safety. A group of outside experts on hydrogen safety was brought in to help review the target system. This group consisted of J. Novak (who had recently retired from Los Alamos National Laboratory) T. Lucas from Oak Ridge National Laboratory and J. Mark, a retired SLAC physicist who had built many liquid hydrogen targets during his SLAC career. The external review committee visited SLAC and held a series of meetings with both HEEC and the E158 collaboration. A number of safety measures were considered.

Two possible solutions were rejected as unworkable. The concept of a blast shield around the scattering chamber was dismissed because any credible shield would be too large to be practical and any lesser "shield" would likely just increase the impact of an explosion by adding debris to it. It was also decided not to require all the electrical equipment in the hydrogen area to meet the National Electrical Code Standard for explosion proof wiring (Class 1, Division 2, Group B). The reason for this decision is that the hydrogen area could realistically be considered the entire E158 beam line inside the radiation shielding. The beam line is filled with complicated custom made detectors, diagnostics and actuators most of which could not be made to meet this standard. It is felt that trying to impose this standard, some component would invariably be missed and the result would be a less safe system with a false sense of security. The explosion proof wiring standard is required in the hydrogen storage area which uses standard industrial components.

After much discussion and hard work, the HEEC committee approved a hydrogen safety system based on three basic requirements:

1) Under no credible accident should hydrogen be released into the experimental hall. All venting should be done outside the building, away from any ignition sources
2) As a backup, a Hazardous Atmosphere Detection (HAD) system must be installed to continuously monitor for hydrogen leaks and take appropriate action if hydrogen is detected.
3) The space immediately around the target vessel must be continuously ventilated so that any hydrogen that leaks is rapidly removed from the shielding enclosure and displaced into the much larger experimental hall.

Worst case analysis and venting system design

In order to meet the first requirement above, two worst case accident scenarios are analyzed. In the first, it is assumed that the target is full of liquid hydrogen and the isolation vacuum surrounding the target loop is suddenly brought up to room pressure. The air condensing on the cold target surface will cause the hydrogen to boil off rapidly and raise the pressure in the loop. The target loop and venting system must be designed to withstand the resulting pressure and safely vent the hydrogen out of the building. In the second scenario, it is assumed that the target suddenly breaks dumping its entire hydrogen inventory into the 300 K cryostat where it quickly flashes into vapor. The cryostat venting system must be designed to safely vent the hydrogen.

To analyze the first scenario, the heat load due to the air condensing on the target is taken to be 22 kW/m^2. This heat load results in all the hydrogen in the target boiling away at a rate of 0.11 kg/s in roughly 30 seconds. The target venting system is designed with a 51 mm diameter line connecting the target loop to the gas panel relieving through a 51 mm diameter burst disc (that opens at 273 kPa) into a 102 mm diameter vent line that takes the hydrogen outside the building. See figure 1. A second 51 mm line connected to another 51 mm burst disc (that opens at 584 kPa) provides backup. With this system the maximum pressure reached in the target is 252 kPa. The target is pressure tested to 651 kPa at the start of each experiment. The resulting safety factor for the target is thus 2.6.

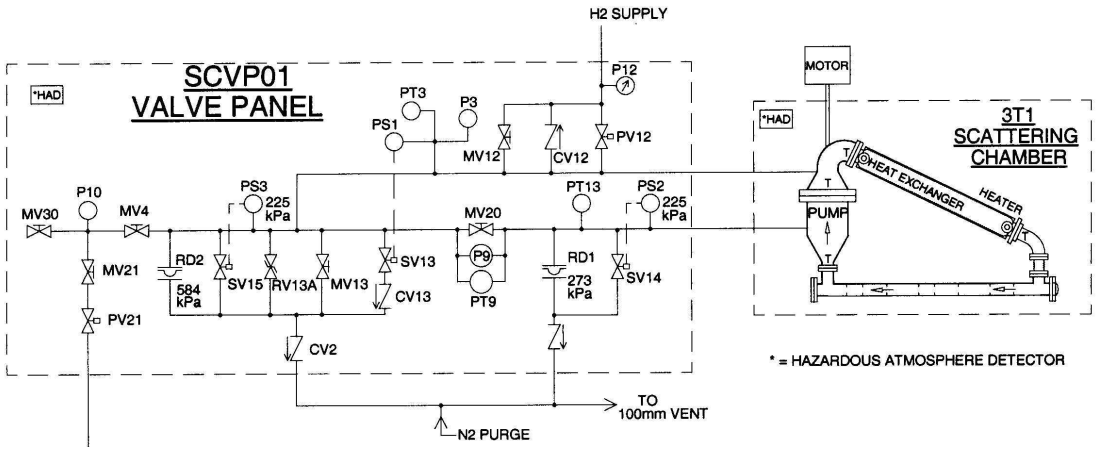

Figure1 Schematic of E158 target venting system

For operational efficiency, 51 mm diameter, high speed pneumatic valves that open at 225 kPa are placed in parallel with the burst discs. These open first and serve to protect the burst discs but are not considered part of the safety system.

In the second scenario, in which the target fails completely, the heat load to the boiling hydrogen in the warm cryostat is taken to be 100 kW/m^2 [2]. The cryostat is vented by a 152 mm diameter burst disc (that opens at 105 kPa) that connects to a 152 mm relief line venting outside. Using this relief system, the maximum pressure reached in the cryostat is 152 kPa. A conservative estimate of the allowable pressure in the cryostat is 227 kPa for safety factor of 1.5.

Another very conservative assumption was made in both the above calculations. The venting hydrogen was assumed to instantly reach room temperature and all fluid properties were taken at 300 K. This means that the maximum pressure calculated in each case is far more then in reality. This was not considered in designing the venting systems. A continuous purge of nitrogen gas is maintained in all vent lines to avoid a potentially flammable hydrogen air mixture during venting.

These worse case analysis were reviewed and meet the requirement that no hydrogen will be released into the experimental hall during any credible accident.

Hazardous atmosphere detection system

As a backup to the hydrogen system design a Hazardous Atmosphere Detection (HAD) system was installed. Monitors for this system were installed above the scattering chamber, above the gas panel, at the end of the experimental beam line and over the hydrogen storage tank and hydrogen tube trailer. The system consists of sensors heads and model 580 detector readout boxes made by General Monitors. Redundant heads are used in each location. The system is calibrated to trigger at 10% of the lower explosive limit for hydrogen.

If the HAD system detects the presence of hydrogen gas in the experimental hall it initiates the following actions automatically:

1) Sounds an evacuation alarm for the experimental hall
2) Notifies the fire department
3) Turns on the experimental hall ventilation fans.
4) Turns off all electrical power to the experimental beam line and the hydrogen gas panel.
5) Closes the main hydrogen supply valves.

Similar actions are taken if hydrogen is detected in the gas storage area. This is a highly reliable completely hardwired system. At the start of each experimental run, the system is tested and certified. Figure 2 is a photo of the hydrogen gas panel showing the HAD heads mounted directly above the panel. To date, the system has been highly reliable with no failures or false alarms.

Additional safety steps

Augmenting the venting system design and the HAD system, administrative steps were taken to ensure safe operation of the hydrogen system. These steps included:

1) No open flames, grinding, welding or forklift use was permitted in ESA while hydrogen was present in the system. Use of the overhead crane was limited (except in rare cases) to areas away from the hydrogen system.
2) Only personnel who had undergone hydrogen safety training that made them aware of the hazard, and taught them what to do in the event of an alarm were permitted into ESA during hydrogen operation.
3) Detailed procedures containing checklists were developed for the operation of the hydrogen gas system. These procedures were reviewed by outside experts and used for all operations. Only specially qualified people were allowed to operate the hydrogen gas system.

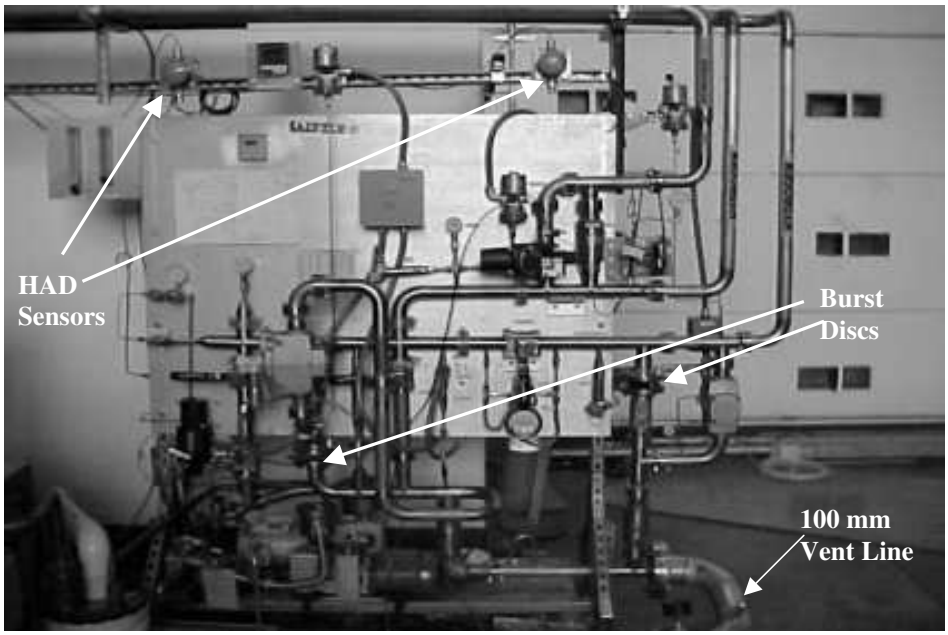

Figure 2 E158 Gas panel showing the HAD sensors, burst discs and 100 mm target vent line.

CONCLUSIONS

The E158 hydrogen target system has safely operated for a total of approximately 8 months over the last two and one half years. While operational problems have led to the venting of hydrogen out the vent system, there has never been a hydrogen release into End Station A and the HAD system has never detected a hydrogen leak.

This experiment illustrated the value of designing safety into the system from the beginning and the use of external experts when required. It also shows that conservative, robust and straightforward safety systems are preferable to more complicated ones that may only give the illusion of safety.

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