Fermi National Accelerator Laboratory

FERMILAB-Conf-91/184

Design and Performance of Liquid Hydrogen Target Systems for the Fermilab Fixed Target Program

D. Allspach, J. Danes, J. Peifer and R. Stanek

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

July 1991

* Presented at the *Cryogenic Engineering Conference*, June 11-14, 1991, University of Alabama, Huntsville, Alabama.

DESIGN AND PERFORMANCE OF LIQUID HYDROGEN TARGET SYSTEMS FOR THE FERMILAB FIXED TARGET PROGRAM[*]

D. H. Allspach, J. F. Danes, J. A. Peifer and R. P. Stanek

Fermi National Accelerator Laboratory
Batavia, Illinois

ABSTRACT

The Fermilab 1990-1991 Fixed Target Program featured six experiments utilizing liquid hydrogen or liquid deuterium targets as part of their apparatus. Each design was optimized to the criteria of the experiment, resulting in variations of material selection, methods of refrigeration and secondary containment. Collectively, the targets were run for a total of 14,184 hours with an average operational efficiency of 97.6%. The safe and reliable operation of these targets was complemented by an increased degree of documentation and component testing. This operation was also aided by several key upgrades. All the systems were designed and fabricated under a set of written guidelines that blend analytical calculations and empirical guidance drawn from over twenty years of target fabrication experience.

INTRODUCTION

Fermilab, the world's highest energy accelerator, has been in operation since 1974. During that time, the accelerator has transformed from 400 GeV fixed target operation to 800 GeV fixed target operation and finally to 900 GeV collider operation. It currently cycles between the latter two modes.[1] Hydrogen targets have played a key role in the fixed target program since its inception. In all, approximately 50 target systems have been installed, with sizes ranging from 0.2 L to 300 L and diameters up to 10 cm. Although the majority of targets have used hydrogen, deuterium targets have also shared the work load. The physics objectives have been quite varied, as witnessed by the experiment titles for the 1990 run (see Table 1); however, the requirements for a tightly controlled, safe and reliable target system have been very consistent.[2]

The general design criteria has been to provide a "clean" interaction region of either hydrogen or deuterium with as little additional material surrounding the fluid as possible. This translates to fabricating the cryogenic and vacuum vessels from low Z materials, such as Mylar, beryllium or Rohacell,[†] a closed cell polymethacrylimide. All support equipment including the refrigeration system must be kept out of the particle trajectories to avoid unnecessary irradiation and halo effects. Controlling the target density to a few tenths of a percent is essential for experiments trying to measure their interaction cross sections.

---

[*] This work is sponsored by the Universities Research Association, under contract with the U.S. Department of Energy.

[†] Registered trademark of Rohm Tech, Inc., Malden, Massachusetts.

Table 1. Target Operating Data

EXPERIMENT	EXPERIMENT TITLE	OPERATIONAL EFFICIENCY	TOTAL OPERATING TIME (hrs.)	STATIC HEAT LOAD (W)
665-Deuterium	Muon Scattering with Hadron Detection	99.90%	2736	4
665-Hydrogen	Muon Scattering with Hadron Detection	93.60%	3360	3
683	Photoproduction of High Pt Jets	First Run Pending	0	5
687	Photoproduction of Charm and B	95.40%	4608	6
690	Study of Charm and Bottom Production	99.96%	1248	3
704	Experiments with the Polarized Beam Facility	99.20%	2232	4
706	A Comprehensive Study of Direct Photon Production in Hadron Induced Collisions	First Run Pending	0	4

TARGET SYSTEM COMPONENTS

A generalized schematic of the target system components is shown in Figure 1. The target flask material chosen for a particular system varies with the expected amount of radiation energy absorbed by the target from the beam. The flask is designed for a maximum allowable working pressure of at least 172.3 kPa differential, while taking into account pressure, liquid head and cooldown loadings. The flask, along with the rest of the hydrogen circuit, is protected with a safety relief valve set at the maximum allowable working pressure.

A vacuum jacket surrounds the flask as well as the refrigeration unit(s). The vacuum volume is sized to contain the liquid hydrogen in the target flask as cold vapor at atmospheric pressure. This reduces the chance of subsequently damaging the vacuum jacket in the case of a target flask failure. The vacuum system is supplied with relief devices set to relieve slightly above atmospheric pressure. The evacuation system consists of a roughing pump and a diffusion pump which is in series with a fore pump. Cryostat vacuum pressure after cooldown of the target is approximately 7.0×10^{-8} Pa. Continuous pumping of the vacuum space is required due to the permeability of gases through Mylar. The roughing pump is used to prepump the cryostat vacuum jacket and evacuate the hydrogen circuit during the pump and purge cycles.

Refrigeration is supplied to a plate in contact with the hydrogen vapor space in the condensing pot. Hydrogen circulates in the system using a thermal siphon effect. The liquid from the condensing pot passes through the reservoir and into a tube connected to the bottom of the flask. The hydrogen vaporizing in the flask, bubbles out the top of the flask through a tube to the top of the condensing pot and then recondenses back into the reservoir. The rate at which the liquid condenses is controlled by a heater to maintain a constant pressure in the hydrogen circuit, such that the liquid hydrogen density varies less than 0.2%. The hydrogen pressure, in most cases, is controlled at 103.4 kPa. Hydrogen is supplied during a target fill from high pressure cylinders. In the event that a recovery system is installed for deuterium use, the deuterium is supplied from recovery tanks rather than from cylinders. Refrigeration, when supplied by a mechanical cryocooler incorporates an APD Cryogenics Inc. Gifford-McMahon unit. Fermilab targets use both 10 W and 50 W models. Actual cooling capacity has been measured for the "10 W" unit at 12 W and for the "50 W" unit at 36 W for optimum conditions. Multiple refrigeration units are used at some target locations to provide adequate cooling capacity. In each case a heater is attached to the condensing plate which regulates the excess refrigeration.

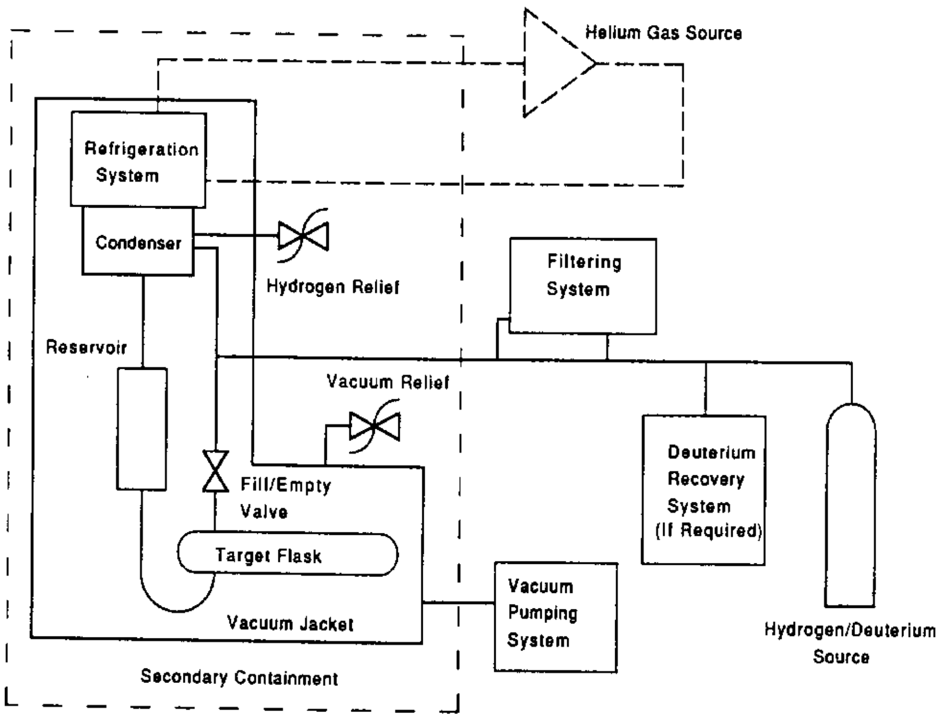

Figure 1. General Target System Components

The compressor used to supply high pressure helium to the 10 W APD refrigeration unit is the APD model HC-8. The compressor discharge pressure is 2306 kPa and the suction pressure is 514.8 kPa. The helium flowrate is approximately 3.2 g/sec for each 10 W unit. The 50 W units are supplied with helium from a high pressure header maintained at 1962 kPa. Suction pressure for this unit is at 108.2 kPa. The suction and discharge headers also service other helium systems at Fermilab. The helium flow through a 50 W unit is approximately 11.1 g/sec.

The liquid hydrogen target systems each have some form of secondary hydrogen containment. Its purpose is to contain and control the release of hydrogen gas from the hydrogen target system in the event of a failure. In some cases this secondary containment is in the form of a tent constructed with flame retardant materials. However, when the experimental apparatus dictates a more compact design, a vacuum buffer volume is used. It is sized to create a total vacuum volume large enough to contain the equivalent amount of gas generated by the liquid at room temperature and subatmospheric pressure.

DESCRIPTION OF 1990-1991 TARGET SYSTEMS

Design Parameters

The following paragraphs describe the design criteria and solutions for each of the liquid hydrogen targets built for use in the 1990-1991 Fermilab Fixed Target Run. Six different experiments requested liquid hydrogen targets for this run (see Table 2).

Experiment 665 - This experiment consists of one 8 L liquid hydrogen target and one 8 L liquid deuterium target. The two targets are independent so far as insulating vacuum and refrigeration are concerned. Each of these targets is cooled with a 50 W APD refrigerator. The target flask is 10.0 cm in diameter and made with 0.254 mm thick Mylar. The target vacuum shell is constructed of 2.54 cm thick Rohacell foam with a 0.127 mm thick layer of Mylar covering it. The liquid hydrogen target insulating vacuum space is common with an evacuated Mylar target adjacent to it, in order to provide experimenters with a method of running a calibration with an "empty target". These targets, along with a solid target wheel capable of holding seven types of solid targets, are supported on a moveable table. The table movement is computer controlled so as to position a different target in the beam for each spill, thus reducing the systematic error of the experiment. All of these targets are included inside the secondary containment volume. Secondary containment is provided in the form of a tent with dimensions of 4.9 m height, 3.7 m width and 1.4 m depth. The tent material is Herculite,* an antistatic and flame retardant material. It is used on all but one side of the tent. The fourth side of the tent is covered with Lexan polycarbonate sheet. This is a transparent material which has been included on the tent as a means to assure that no personnel are left inside the tent when interlocking the radiation area. The top of the tent is a sheet metal hood which attaches to ducting leading outdoors. In the case of a hydrogen release into the tent, a hydrogen detector triggers an exhaust fan which vents hydrogen outdoors through the ducting. Intake air is supplied at the base of the tent. The deuterium target includes a recovery system to minimize losses. The 8 L of liquid deuterium when warmed to room temperature is contained in four 3785 L tanks at a pressure below the primary deuterium circuit safety relief device set pressure. When refilling the target, the deuterium is routed through the filtering system before it re-enters the target for reliquefaction.

Experiment 683 - The target flask built for this experiment has a volume of 2.2 L. The experiment will run with liquid hydrogen in the target flask during some portions of the Fixed Target Run and with liquid deuterium during the remaining periods. The flask is constructed of 0.254 mm thick Mylar. The target vacuum shell is made from aluminum type 6061-T6 with Mylar beam windows. The upstream beam window diameter is 8.26 cm and uses 0.178 mm thick Mylar. The downstream window has a 22.9 cm diameter and uses 0.381 mm thick Mylar. The target is cooled with two 10 W APD refrigerators which provide a shorter cooldown time and redundancy during operation. It is supported on a moveable table which is again, computer controlled. A solid target wheel is directly adjacent to the hydrogen target which is capable of holding eight types of solid targets. All of the targets are located inside of a tent having dimensions of 4.3 m height, 3.4 m width and 1.4 m depth. The construction is similar to that of the tent used at experiment 665.

Table 2. Target Design Parameters.

EXPERIMENT	FLUID	TARGET VOLUME (L)	TARGET DIAMETER (cm)	TARGET LENGTH (cm)
665	Hydrogen	8	10	100
	Deuterium	8	10	100
683	Hydrogen or Deuterium	2.2	7.62	50.8
687	Deuterium	7	5.08	340
	Hydrogen	8	Annular, 7.62 o.d., 5.08 i.d.	330.2
690	Hydrogen	0.2	3.81	14.27
704	Hydrogen	2.9	6	100.1
706	Hydrogen	0.5	6.35	15.24

---

*Registered trademark of Herculite Products, Inc., New York, New York.

Experiment 687 - This target is different in concept than any of the others built for the current fixed target run. Beam travels through a flask containing approximately 7 L of subcooled liquid deuterium. The flask containing the liquid deuterium is fabricated from aluminum type 6061-T6 and has a diameter of 5.04 cm. The deuterium flask is surrounded by 8 L of liquid hydrogen in the annular space between the outer wall of the deuterium vessel and another aluminum tube with a 7.62 cm diameter. The hydrogen is cooled by three 10 W APD refrigerators. The liquid hydrogen in turn subcools the deuterium which has a higher saturation temperature at our chosen operating pressures. The deuterium pressure is maintained at 322.0 kPa, while the hydrogen pressure is maintained at 103.4 kPa. The system operating temperature is 20.3 K resulting in 8.0 K of subcooling to the deuterium. A recovery system is used to minimize deuterium losses. The liquid deuterium when warmed to room temperature is contained in one 3785 L tank at a pressure below the primary deuterium circuit safety relief device set pressure of 827 kPa. The vacuum jacket material used for this target is stainless steel type 304 with aluminum type 6061-T6 beam windows of 0.762 mm thickness. Using stainless steel and aluminum as target materials results in higher maximum allowable working pressures, and thus, higher safety relief device set pressures for this target as compared to others built for this fixed target run. The hydrogen circuit is relieved at 274 kPa while the vacuum circuit relieves at 205 kPa. The target system uses no tent or vacuum buffer volume. It is located inside a beam enclosure and is very well protected with concrete blocks positioned primarily for radiation shielding purposes. The exhausts of all safety relief devices for each circuit (deuterium, hydrogen and vacuum) are vented outdoors. A hydrogen detector is located in the enclosure which triggers an exhaust fan in the case of a release of either the hydrogen or deuterium. The gas is then safely vented outdoors. Special procedures are also in effect for accessing the enclosure in which this target is located. The main reason for using a metallic target flask is that this system is located in a beam position which receives 4 x 10^{12} protons per pulse at primary (800 GeV) energy. This results in a radiation exposure which prohibits the use of Mylar material. The cooling method chosen assures a subcooled deuterium target even under peak beam loading. Other target systems have solved this problem by utilizing a forced flow concept coupled with direct heat exchange to the target fluid.[3]

Experiment 690 - The target flask in use at this experiment, holding on the order of 0.2 L of liquid hydrogen, is the smallest flask built for any experiment at Fermilab. The flask material is Mylar at a thickness of 0.127 mm. The beam enters the target insulating vacuum space through a 0.178 mm thick Mylar window. The vacuum shell surrounding the target flask was constructed with 5.1 mm Rohacell wrapped with 0.076 mm thick woven fiber glass cloth saturated with epoxy, thus bonding it to the Rohacell vacuum jacket. The target is located inside a helium purged gas chamber which is part of a series of helium and flammable gas chambers. The hydrogen for this target is cooled with one 10 W APD refrigerator. The target support stand may be manually moved upstream of its operating position allowing experimenters to access experimental apparatus otherwise difficult to reach. Secondary containment is in the form of a vacuum buffer volume. Safety relief valves on both the hydrogen and the vacuum circuits vent through ducting to the outdoors.

Experiment 704 - The target flask has a 2.9 L volume. The flask has a 6.0 cm diameter with a 100.1 cm length. It is fabricated with Mylar of thickness 0.178 mm. The target vacuum shell is made with 1.91 cm Rohacell with 0.127 mm Mylar fixed on its outer surface. The upstream vacuum window is a 0.127 mm Mylar window with a diameter of 6.99 cm. The target is cooled with two 10 W APD refrigerators. The target support stand may be moved manually such that other fixed target experiments may be moved into the beamline. The target uses a standard design tent as secondary containment. Its dimensions are 4.0 m in height, 1.6 m in width and 1.1 m in depth.

Experiment 706 - This is a small target holding approximately 0.5 L of liquid hydrogen. The flask is built of 0.178 mm thick Mylar. Its diameter is 6.35 cm and its length is 15.24 cm. The vacuum shell is made of stainless steel and is cylindrical in shape. The beam windows for the vacuum jacket are made of beryllium plate and are secured using circular stainless steel flanges. The upstream beryllium beam window is 6.35 cm in diameter and the downstream window is 7.62 cm in diameter. Both windows are approximately 0.254 cm thick. The target is supported inside a box as are silicon strip detectors positioned directly adjacent to the target on both its upstream and downstream ends. The box is located on a table which may be manually moved out of the beam line. It is critical for this experiment that the silicon strip detectors sense no vibrations; therefore, an alternative hydrogen refrigeration system was chosen. Helium is transferred from commercial liquid helium dewars through a vacuum insulated transfer line to a heat exchanger that cools the hydrogen. After the helium passes through the heat exchanger a portion of the remaining cooling capacity is used to intercept the heat load by connecting the tube to a radiation shield inside the vacuum can. The helium is then vented outdoors. The secondary containment and hydrogen venting system are similar to that used for experiment 690.

Operational Data

The targets that were operated during the first portion of the 1990-1991 Fixed Target Run totaled over 14,000 hours of running time. Operating efficiencies of these targets ranged from 93.6% to 99.96%. The static heat load of each target was measured and ranges from 3 W to 6 W. See Table 1 for individual target operating data. The major cause for downtime during the first portion of this fixed target run was refrigerator related problems. In each case refrigerator efficiency was sufficiently reduced, thereby failing to provide the cooling capacity required to maintain a stable target. Approximately 220 hours of downtime were accumulated due to this problem. This represents 1.6% of the total operating time for all the targets. See Table 3 for other major causes of downtime during the first portion of this fixed target run.

SYSTEM UPGRADES

The years of experience associated with the target systems operated at Fermilab has led to some key component upgrades which have increased reliability and decreased the need for operator intervention.

Refrigeration System

The compressors used with the 10 W refrigerators have been upgraded to APD model HC-8, rotary type which has proven to be much more reliable than the previously used reciprocating machines. An interesting by-product of this compressor upgrade was that the new compression system with associated filtration had an extremely low oil carryover. The intake/exhaust valve of the Gifford McMahon refrigerator was left with no lubrication and started to fail prematurely. As a result, the graphite filled Teflon valve was replaced with a valve made from molybdenum

Table 3. Major Causes of Down-Time.

PROBLEM	TYPE	DOWN-TIME (hrs.)
Refrigerator	Loss of Refrigeration	220
Relief Valve	Damaged O-rings	130
Compressor Systems	Various Trips	50
Fill/Empty Valve	Control Instability	25
Heater Controller	Controller Malfunctions	19

disulfide filled Vespel. This material is self lubricating and has a lifetime of over 2000 hours. Instrumentation used in analyzing the performance of the refrigerator includes a Hastings mass flowmeter on the helium circuit and a transducer made by PCB Piezotronics, Inc. installed on the first stage of the refrigeration unit. The transducer allows monitoring of the pressure change during a refrigeration cycle in the first stage of the refrigeration unit. The refrigerator may be tuned to optimize its performance with the pressure curve of the refrigeration cycle as an indicator.

Target System

The hydrogen circuit of each target system includes two safety relief valves. The primary safety relief has been upgraded to an Anderson Greenwood Series 80 valve. This valve is fully open within 110% of set pressure and does not exhibit a problem with "sticking" as did the previously used modulating valves. The safety relief device used on the cryostat vacuum space has also been changed. A parallel plate relief device designed at Fermilab has replaced the Kapton rupture disc.

TARGET GUIDELINES

Over the many years of fabrication and operation of hydrogen targets, several standard practices have been developed. These have been compiled with some detailed rules for safety analysis in a document entitled, "Guidelines for the Design, Fabrication, Testing, Installation and Operation of LH_2 Targets." These rules are intended to complement the official Fermilab Safety Standards and will eventually be incorporated into the Safety Manual. An abbreviated table of contents is shown in Table 4.

The guidelines prohibit the use of hydrogen batch filling of the target flask and require that all targets be refrigerated either by mechanical cryocoolers or direct heat exchange with liquid helium. Recommended materials for the target flask are polyester film (Mylar), polyimide film (Kapton) and metals, such as stainless steel type 304 or aluminum type 6061-T6. All target flasks are designed, tested and relieved for a maximum allowable working pressure of at least 172.3 kPa differential. Allowable stresses are set at 63% of yield strength for plastic films and the lesser of 66% of yield or 25% of ultimate strength for metals. If available, the ASME code allowable stresses are referenced. Because of concerns with polyester film degradation, strict controls are placed on initial and periodic testing of material samples. A total radiation exposure limit of 10^8 rads of absorbed energy is imposed for Mylar flasks. High radiation exposure targets are fabricated with an acceptable metal.

Table 4. Table of Contents for LH_2 Guidelines

I. Scope
II. Design Fabrication and Testing:
    Refrigeration System
    H_2 Reservoir
    Target Flask
    Instrumentation and Control System
    Vacuum Vessel
    Secondary Containment
III. System Testing and Installation
IV. Safety Analysis and Review
V. Operation
VI. Target Safety Review Documentation

The successful fabrication of Mylar target flasks has developed over time to a point where both materials and techniques can be standardized. All joints are designed to place the epoxy bond in shear when the flask is pressurized. Dimensions for joint overlaps, surface preparation, the epoxy curing procedures and clean up are all carefully controlled. The recommended adhesives are Shell Epon 838 or 815 with a curing agent of V40 or V25. To decrease flask distortion during cooldown, longer targets incorporate artificial seams to compensate for material added due to joints. Connections to the hydrogen supply and vent tubes are made using a Vespel ring, which also joins the two parts of the cylindrical flask. Plastic flasks are relieved at 170.2 kPa by a dual relief system that is sized for the worst case air condensation heat flux.

The guidelines also set requirements for the secondary containment system that contains and safely vents any release of hydrogen gas from the target system due to failure. Controlling the environment of the target has proven crucial for the safe operation of these systems. By definition, these targets are part of an experimental apparatus, and are therefore in close proximity to equipment requiring personnel access. Each target vacuum box is sized to allow for the initial release of the entire liquid hydrogen volume. As the hydrogen warms, the gas is vented to a position that will not endanger personnel or equipment.

Rigorous testing of target system components is required by the guidelines. In all cases where applicable, the ASME code pressure testing procedures are referenced. Operating and emergency procedures, valve lists and failure mode analyses are developed for each system. The process of authorizing target cooldown requires a written permit signed by the safety panel chairperson and the respective division head.

CONCLUSIONS

Although the criteria for each experiment varied, we were successful in building target systems that met the expectations of both the experimenters and the target guidelines. The liquid hydrogen targets proved to be both safe and reliable during the first period of the 1990-1991 Fixed Target Run.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of J. R. Kilmer in the design and upgrades of these systems. We would also like to acknowledge the mechanical and electrical technicians led by J. A. Peifer for the construction and installation of each system.

REFERENCES

1. J. C. Theilacker, Current operating experience and upgrade plans of the Tevatron cryogenic system, in: "Advances in Cryogenic Engineering," Vol. 35B, Plenum Press, New York (1990), p. 917.
2. R. Rubinstein, "1990 Fermilab Research Program Workbook," internal publication (1990).
3. J. W. Mark, A 650 mm long liquid hydrogen target for use in a high intensity electron beam, in: "Advances in Cryogenic Engineering," Vol. 29, Plenum Press, New York (1984), p. 1033.