Cryogenic targets within streamer chambers and supply of cryogenic fluids to targets

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This review discusses the operation of cryogenic targets inside streamer chambers. Various means of supplying the cryogenic fluids to the target are discussed, and their advantages and disadvantages are given.

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1. CRYOGENIC TARGETS FOR STREAMER CHAMBERS

In 1963, several papers were published by Soviet authors[1–5] in which it was reported that a spark chamber with a large gap between the electrodes and anisotropy in the formation of luminous tracks of traversing particles could be transformed into a physical instrument with isotropic sensitive volume. For this, a voltage of order 20–30 km/cm must be applied to one of the electrodes for 20–30 nsec. At the positions traversed by the particle, streamers form—centers that initiate development of discharges that disappear when the voltage is taken off without developing to spark breakdown. To study the interaction of incident particles with protons, it is necessary to introduce a liquid hydrogen target into the streamer chamber. Then the streamer chamber can compete with a hydrogen bubble chamber and in some cases, for example, in the search for rare processes, have the advantage. Therefore, alongside the improvement of the streamer chambers, work was begun on the development of liquid hydrogen targets. The problem was complicated by the fact that the target must operate in a pulsed electric field, and therefore only dielectric materials can be used to prepare it. The danger of electric discharge in the potentially explosive hydrogen imposed particular requirements on the construction of the target.

From November 1963 the development of streamer chambers was pursued very intensively at Stanford University in the United States. And already in March 1967 the first tests of a two-meter streamer chamber were made in a photon beam. The target was gaseous hydrogen in a 12.5-mm diameter Dacron tube under a pressure of 6 atm.

The target developed at DESY

The first streamer chamber with a liquid-hydrogen target was developed in 1968 at DESY (in the German Federal Republic).[7–9] It was set up in a γ-ray beam and designed to investigate photoproduction of hadrons (Fig. 1). The electrodes are arranged vertically in the streamer chamber. The potential electrode 5 is in the center, and the grounded electrode 7 surrounds it. The electrodes are isolated from one another by the chamber walls 2, which are made of glass. The sensitive region of the chamber is filled with a 75% neon and 25% helium gas mixture, and the region measures 1000 $\times 600 \times (2 \times 160)$ mm. In the photographing region, the electrodes are made of the wires 6, and the sensitive region is separated from the surrounding medium by a Mylar film. The streamer chamber is mounted in the vacuum jacket of a 84-cm bubble chamber (not shown in Fig. 1) and set up inside a 22-kOe dc magnet. A 350-kV pulsed voltage (22 kV/cm) is applied to the chamber electrode. The pulse duration is 10 nsec.

The liquid-hydrogen target (Fig. 2) consists of an inner container 7 and the vacuum jacket 6. The inner container of the target has diameter 25 mm and length 40 mm. It, like the tube 1 along which the hydrogen is poured into the target, is made of 125-μ thick Kapton. The inner container with the hydrogen is parallel to the potential electrode 8 of the chamber at a distance 25 mm from it. The vacuum jacket containing the inner container of the target is made in the form of a beaker with elliptical bottom. The container has diameter 50 mm and is 160-mm long. It is made of black Perspex plastic 1-mm thick and its axis is perpendicular to the electrodes 3 and 8. At its open end, outside the sensitive region of the chamber, it is connected to the metal adapter 2. For detection of the particles that pass through the target, the cylindrical scintillation counter 5 is fitted onto the vacuum jacket, this being shielded from the light of the streamers by a thin light-shielding film 4.

In the immediate proximity of the streamer chamber, within the yoke of the magnet 4 (see Fig. 1) there is

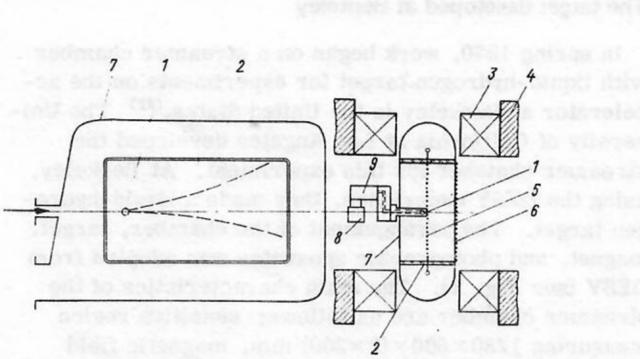

FIG. 1. General arrangement of streamer chamber with liquid-hydrogen target at DESY. 1) Liquid hydrogen target; 2) walls of streamer chamber; 3) windings of magnet; 4) yoke of magnet; 5) potential electrode of chamber made of wires; 6) grounded electrode made of wires; 7) continuous grounded electrode; 8) diffusion pump; 9) refrigerator.

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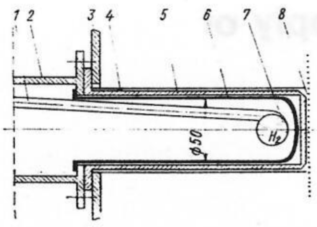

FIG. 2. Liquid hydrogen target. 1) Tube for filling the target with hydrogen; 2) metallic adapter; 3) grounded electrode; 4) light-shielding film; 5) scintillation counter; 6) vacuum jacket; 7) inner container of target; 8) potential electrode.

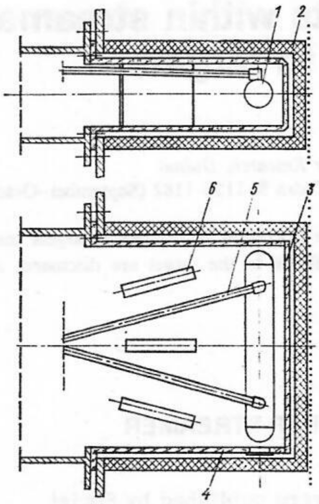

FIG. 3. Arrangement of target developed at Berkeley. 1) Inner container of target; 2) shielding jacket; 3) vacuum jacket; 4) front wall of vacuum jacket; 5) tubes for filling the target with hydrogen; 6) supports.

Joule–Thomson refrigerator 9, which supplies the liquid hydrogen to the target. The power of the refrigerator is 5 W and the heat influx to the target 1 W.

Before experiments were begun in the streamer chamber with the liquid hydrogen target, three technical trials were carried out, during which certain problems were noted and eliminated. One of the serious problems encountered during the first technical trial was electrical breakdown in the sensitive region of the chamber near the black light-shielding film. As was explained in Ref. 7, these breakdowns were initiated by a soft discharge along the inner surface of the vacuum jacket. A very simple way of preventing the breakdown was found: The inner surface of the jacket was covered with a thin film of electrically insulating silicone-base grease having a partial vapor pressure $5 \cdot 10^{-6}$ mm · Hg. The grease does get pumped from the surface of the vacuum jacket by the cryogenic surface of the target, and it must therefore be replaced after a few days of operation. During 12 months of operation, one million photographs were taken of the streamer chamber with the liquid hydrogen target and one in every eight of these showed production of hadrons on hydrogen.[10]

This work at DESY showed that the difficulties associated with introducing a liquid hydrogen target into the sensitive region of a streamer chamber can be overcome. The streamer chamber had become a worthy tool for investigating high energy particles.

The target developed at Berkeley

In spring 1970, work began on a streamer chamber with liquid-hydrogen target for experiments on the accelerator at Berkeley in the United States.[11] The University of California at Los Angeles developed the streamer chamber for this experiment. At Berkeley, using the DESY experience, they made a liquid-hydrogen target. The arrangement of the chamber, target, magnet, and photographic apparatus was adopted from DESY (see Fig. 1). The main characteristics of the streamer chamber are as follows: sensitive region measuring $1280 \times 600 \times (2 \times 200)$ mm, magnetic field 13.2 kOe, voltage 700 kV (3 kV/cm) applied to the electrode, pulse duration 7–15 nsec. The chamber is filled with a mixture of 90% helium, 10% neon, and 10^{-5}% Elegas. The liquid-hydrogen chamber is constructed like the one developed at DESY, differing from it in dimensions. The inner container of the target 1 (Fig. 3) is 294-mm long and has diameter 25.4 mm. The cylindrical part of the vessel is made of Mylar 75-μ thick, and the ends are 50-μ thick. Two tubes 5 carry the hydrogen from the refrigerators to the target and take the gas back again. The vessel is fixed to these tubes inside the vacuum jacket 3. The rectangular vacuum jacket of the target serves simultaneously as a scintillation counter. It measures $320 \times 200 \times 60$ mm. The thickness of the jacket is 6 mm. The front wall 4 is an independent counter and has an opening of diameter 22 mm, covered by a film, to let in the particles. After the first unsuccessful experiments, the vacuum jacket was made of a different material—Nuplex-3. Within the jacket, three supports 6 stop the flat walls from bending. In contrast to the DESY chamber, a foam polyurethane shielding jacket 2 is placed around the vacuum jacket within the streamer chamber. It shields the scintillation counter from the light of the streamers and also makes it possible to extract the target without destroying the hermetic sealing of the chamber. The targets are supplied with hydrogen by two 10-W refrigerators working in parallel.

The first technical trials of the streamer chamber with liquid-hydrogen target showed that the main difficulty comes from electrical discharges that arise within the vacuum jacket of the target: First, they destroy the hermetic sealing within the container and, second, initiate discharges in the sensitive region of the chamber and illuminate the film. Although not all causes of the discharges were known, the unwanted illumination was stopped by various measures: 1) As in the DESY target, the inner surface of the vacuum jacket was covered with a thin film of Krylon 1329 grease; 2) a mechanical filter was fitted into the liquid-hydrogen supply tube to prevent a fine "hardly visible gas" of metallic shavings entering the inner container. After these measures had been taken, the streamer chamber with the liquid-hydrogen target worked well, except for dielectric breakdowns, which occurred on the average once in 600 cycles. This was probably due to the penetration of moisture into the gap between the vacuum and shielding jackets.

The first experimental trials were made in Spring

1972, and by the middle of the summer 300 000 photographs had been obtained, 60 000 of these with the events being studied.

The target developed at the Argonne National Laboratory

In Spring 1969, a combined group of the University of Illinois and the Argonne National Laboratory turned to the development of a streamer chamber with liquid-hydrogen target. This chamber was designed for carrying out two experiments on the Argonne accelerator: study of mesons emitted backward in the reaction $\pi^- p \to p\bar{X}$ and study of the interaction $\pi^- d \to p_s p X^{--}$. The chamber was developed at the University of Illinois, and the target for the chamber at the Argonne Laboratory.[12,13]

The chamber, magnet, target, and photographic system were arranged in the same way as the installations at DESY and Berkeley.[8] The streamer chamber, which measured 1500×1000×(2×300) mm, was placed in the 15-kOe magnet of a 500-liter bubble chamber. Foam polyurethane, covered with plastic on the side of the sensitive region, was used as the electrically insulating material separating the chamber electrodes. A 10-nsec pulsed voltage of 700 kV (23 kV/cm) was applied to the central electrode.

Three liquid-hydrogen target constructions were developed at the Argonne National Laboratory. The targets constructed at DESY and Berkeley had a strong influence on the first of these: The vacuum jacket was made of Plexiglas and was rectangular in shape. The inner container was 300-mm long with diameter 25 mm. The heat inflow into this target was too large, at 20 W, and the temperature of the vacuum jacket during operation with hydrogen was reduced by 25 °C. At that time, the causes of breakdown in the targets were not fully investigated and were the main unsolved problem in that construction. It was not established how one could obtain a vacuum appropriate to prevent breakdowns within the vacuum jacket of the target. In addition, after the cooling of the target, the inner container of the target was displaced from the beam because of the thermal deformations of its parts. No solution was found to the problem of determining and, if necessary, adjusting the position of the inner container within the vacuum

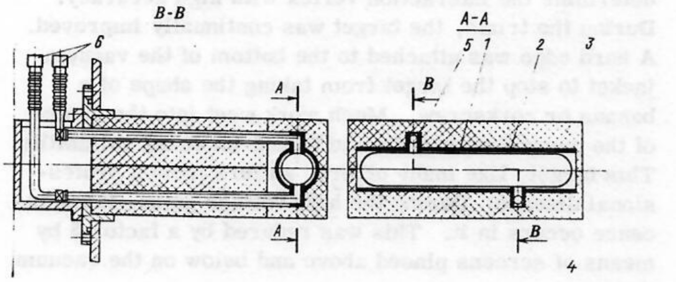

FIG. 4. Arrangement of the target at the Argonne National Laboratory. 1) Inner container; 2) support tube; 3) foam plastic vacuum jacket; 4) tube for filling the target with liquid hydrogen; 5) tube for discharge of gaseous hydrogen from the target; 6) sylphon bellows.

jacket. All this led to an attempt to develop a new target construction.

The following factors were foremost in the development of the new construction: 1) The width of the vacuum gap between the inner container and the jacket must be as small as possible in order to facilitate a high vacuum; 2) the vacuum space parallel to the electric field must be minimal in order to avoid breakdown across the vacuum; 3) to avoid distortions of the electrical field and prevent large mechanical stresses in the material due to thermal deformations, the construction of the target should avoid as far as possible the use of different materials; 4) the position of the inner container must be firmly fixed to prevent its changing when the target is cooled.

The new target was developed in the light of these criteria and the shortcomings of the previous construction. Its main difference from the preceding construction was in the use of foam plastic for the vacuum jacket of the target. One of the main disadvantages of the majority of foam plastics with closed pores is their inability to withstand low temperatures and vacuum. An exception is the PVC foam plastic used to insulate cryogenic containers.[14] A PVC foam plastic of density 0.033 g/cm^3 was used to make the vacuum jacket. Suggestions that foam plastic should be used for vacuum jackets of liquid-hydrogen targets had also been made elsewhere.[15,16] The inner container of this target 1 (Fig. 4) is made of a Mylar film of type D of thickness 76 μ with diameter 3.4 mm and length 266.7 mm. The container is fixed within a nylon support tube 2 of diameter 38.1 mm and wall 4.2-mm thick, which, in its turn, is fixed in the foam-plastic vacuum jacket 3. Two nylon tubes enter the inner container at opposite ends: the one 4, below, with diameter 6.3 mm, fills the container with liquid hydrogen; the other, 5, at the top, carries away the evaporated gas. To compensate thermal deformations stainless steel sylphon bellows are attached outside the chamber to the tubes. Two openings are made in the jacket, through which the tubes are joined to the target. The annular gaps between the tubes and openings serve as channels for evacuating the vacuum space around the inner container of the target. The inner and outer surface of the foam-plastic jacket are covered with two thin films of epoxy glue. The heat inflow to the target is 7 W. The mean coefficient of thermal conductivity of the foam plastic, deduced from the heat inflow to the target, is 0.01 W·cm^{-1}·°K^{-1}. The target with the foam-plastic jacket worked much more reliably than the one with the plexiglass jacket, although the inner surface was not covered with grease. Thus, the PVC vacuum jacket has good electrical and heat insulating properties.

The next target was made on a somewhat larger scale, and its construction was simplified. The diameter was increased to 30 mm and the length to 305 mm. The target does not have the supporting nylon ring. Both tubes for supplying and evacuating the hydrogen are joined to the end of the target at which the beam enters. In contrast to the preceding target, in which the vacuum jacket was made of two sheets of foam plastic and was

125-mm thick, the final target is made of a single sheet 75-mm thick. The heat inflow to the target is 12 W. The target is served by a 50-W refrigerator.

The first trials of the streamer chamber with the liquid-hydrogen target in the accelerator beam were made in the beginning of 1972, and in March and April two physics experiments were made. During the first, a total 113 000 $\pi^- p \to p \pi^-$ events were obtained; in the second, the target was filled with deuterium and 54 000 photographs were obtained.

Stanford target

In the period from 1967 to 1972, three experiments were made with streamer chambers at Stanford University: photoproduction, K^0 decay, and a search for hyperons in the $K^- p$ reaction. Photoproduction experiments were made in the gas hydrogen target of Fig. 5 (Refs. 17 and 18). The electrodes of the chamber were arranged horizontally. The photographs were taken from above. The chamber measured 1000×1000×(2 ×200) mm. Polyurethane was used to construct the frame of the chamber. The gas target 5 was inside the sensitive region of the chamber 2, near the potential electrode 3. It was joined at its ends to opposite walls of the chamber 4. The target was made of a Mylar tube of diameter 12.5 mm and had a 2000-mm length. The hydrogen in it was at the temperature of the surrounding medium and a pressure of 8 atm.

A liquid-hydrogen target (see Fig. 5b) was used for the first time at Stanford in a streamer chamber in the search for hyperons in the $K^- p$ reaction. The experiment was a collaboration with the universities at Berkeley and Riverside. The streamer chamber in this experiment, like the majority of chambers used at Stanford, had horizontal electrodes and was photographed from above. The chamber measured 2000×800×(2 ×300) mm, and was placed in a 16-kOe magnet. A pulsed voltage of 600 kV (20 kV/cm) was applied to the chamber electrode.

The liquid-hydrogen target developed at Stanford differs appreciably from the targets of other laboratories. The construction of the target was influenced by the

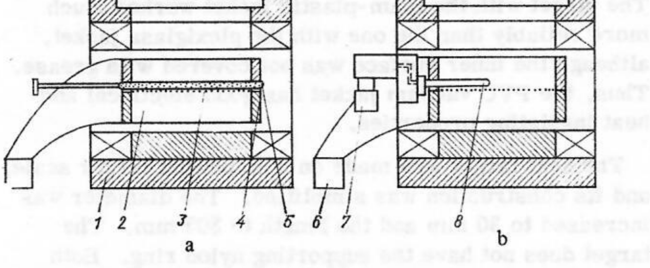

FIG. 5. Streamer chambers with hydrogen targets: a) gas, b) liquid. 1) Magnet; 2) streamer chamber; 3) potential electrode; 4) walls of chamber; 5) gaseous hydrogen target; 6) system of pulsed electrical supply; 7) system for sypplying liquid hydrogen; 8) liquid hydrogen target; 9) photographic apparatus.

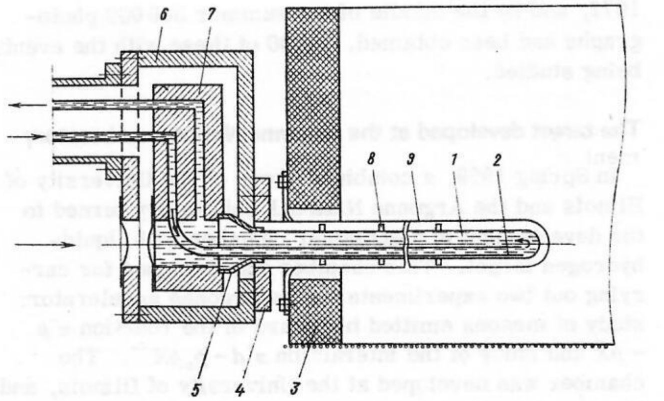

FIG. 6. Construction of target. 1) Inner container; 2) inner tube; 3) side wall of streamer chamber; 4) flange; 5) adapter ring; 6) adapter vacuum box; 7) base plate; 8) nylon supports; 9) vacuum jacket.

horizontal arrangement of the chamber electrodes as well as by the desire to have the interaction vertex of the particles close the sensitive region.[19–21] The target is 460-mm long. The inner container 1 of the target (Fig. 6) is made of a Mylar tube 125-μ thick with diameter 10 mm. The tube is connected through the adapter ring 5 to the base plate 7, in which there is a large opening for the beam and two small openings for the hydrogen to be supplied and evacuated. The vacuum jacket 9 is also made from a Mylar tube. Its diameter is 13 mm and its thickness 300 μ. The jacket is joined by means of the flange 4 to the transitional vacuum box 6, which contains the base plate. Between the inner container and the vacuum jacket there are three nylon supports 8, each of which touches the vacuum jacket at three points. A forced circulation system is chosen to supply the hydrogen to a target with such a small diameter. Supercooled liquid hydrogen under pressure produced by a pump passes through the entire target along the inner tube 2 or diameter 2 mm and thickness 50 μ, arrives then at the pump and, having passed through the heat exchanger, returns to the target. The pump and heat exchanger are in a container with liquid hydrogen boiling at atmospheric pressure. The heat inflow to the target is 10–15 W. The thin part of the target is introduced into the sensitive region through an opening in the side wall of the chamber 3. One of the advantages of the target is its geometry, which makes it possible to determine the interaction vertex with high accuracy. During the trials, the target was continually improved. A hard edge was attached to the bottom of the vacuum jacket to stop the target from taking the shape of a banana or corkscrew. Much work went into the choice of the pump construction and to guarantee its reliability. This target, like many others, suffers from a professional disease: During the high voltage pulse, luminescence occurs in it. This was reduced by a factor 5 by means of screens placed above and below on the vacuum jacket.

In August 1972, the collection of statistics for the $K^- p$-hyperon experiment was completed. A total of 2.3 million photographs were obtained, and in these 600 000 cases of hyperon production were identified.

Features in the construction of cryogenic targets

In view of the requirements of physics experiments, the specific conditions of operation of streamer chambers, and also the experience gained from the development of liquid-hydrogen targets, the following points should be made:

1) the distance between the working material of the target and the sensitive region of the chamber must be minimal in order to determine as accurately as possible the vertex of the interaction of the incident particle with the hydrogen;

2) the target should be placed in the sensitive region of the chamber in such a way that the tracks of the incident particles are visible;

3) the material intended for construction of the target, which is in an electric field, must be a good dielectric. For example, one cannot use aluminized Dacron for heat insulation;

4) the pressure in the insulated space must be not greater than $5 \cdot 10^{-6}$ mm Hg to prevent vacuum breakdown;

5) the walls of the target must not be dirty since inhomogeneous materials can initiate surface breakdown;

6) to avoid distortion of the electric field, it is inadvisable to construct the target with materials having different dielectric constants, and if possible materials of a different kind should not be placed in the gap between the electrodes. For example, it is better if the vacuum jacket of the target fills the space between the electrodes without a gap;

7) for the design of the facility, it is necessary to arrange the streamer chamber and the magnet, and also the target and system for supplying it with fluid, with due regard to the cryogenic conditions;

8) because the target walls must have as little material as possible, i.e., be thin, be made of a nonmetal, and be in an electric field, in which electrical breakdown and destruction of the target are possible, the amount of hydrogen (deuterium) in the system must, for reasons of safety, be minimal (in the limit equal to the volume of the target), i.e., the reserve storage of hydrogen in the system must be reduced to a minimum.

2. METHODS FOR SUPPLYING TARGETS WITH CRYOGENIC FLUIDS

Replenishment of targets from reserves of cryogenic fluid in containers

Replinishment from a gravity flow

Because of the heat inflow to the target from the surrounding medium or the energy deposited by particles, the liquid evaporates. The target can be continuously replenished with cryogenic liquid from an intermediate container. The advantage of this method is its simplicity and reliability. Liquid hydrogen from a Dewar is first poured into the intermediate container, which is placed above the target, and then flows by gravity into the target. The intermediate container and the target can be in the same vacuum jacket and have a common insulation vacuum.[22] They can also be separate containers with an independent vacuum.[23] The advantage of the second construction is, first, rapid exchange of the target without loss of hermetic sealing of the containers and, second, if there is a failure of the vacuum in, for example, the target, the heat flow to the intermediate container is not increased. One of the main disadvantages of replenishing the target with hydrogen from the intermediate container is the large amount of hydrogen in the system. There are, for example, installations in which there are several tens of times more hydrogen in the intermediate container than in the target itself. Bearing in mind that

TABLE I. List of first liquid hydrogen targets within streamer chambers.

Laboratory, date experiment completed	Streamer chamber: Experiment, number of events	Streamer chamber: Position of electrodes; dimensions, mm	Streamer chamber: Electric field, kV/cm, magnetic field, kOe	Target: Dimensions, mm: Internal container	Target: Dimensions, mm: Vacuum jacket	Target: Heat inflow, W	Hydrogen supply system, refrigerator power
DESY, West Germany, September, 1968	Photoproduction of hadrons, 40 000	Vertical 1000 × 600 × (2 × 160)	22; 22	$d=25$, $l=40$ Kapton, 0.125	$d=50$ $l=160$ Perspex; 1	1	Joule–Thomson refrigerator; 5 W
Berkeley, USA, July, 1972	$\pi^- p \to x^0$ 60 000	Vertical 1280 × 600 × (2 × 200)	35; 13.2	$d=25.4$, $l=294$; Mylar 0.075; 0.050	320 × 200 × 60 Nuplex −3; 6	—	Two 10-W refrigerators
Argonne, USA, April, 1972	$\pi^- p \to p x^0$ (180°) 70 000	Vertical 1500 × 1000 × (2 × 300)	23; 15	$d=23.4$, $l=266.7$ Mylar; 0.076	356 × 300 × 127 foam plastic; 50 PC	7	Two 10-W refrigerators
Stanford, USA, August, 1972	$K^- p \to$ hyperon, 600 000	Horizontal 2000 × 800 × (2 × 300)	20; 16	$d=10$, $l=460$ Mylar; 0.125	$d=13$, $l=470$ Mylar; 0.300	10–15	Forced circulation of liquid hydrogen

the target, as a rule, has thin Dacron windows, which can easily be damaged, the presence of the large amount of hydrogen in the system becomes extremely dangerous.

Condensation of hydrogen by helium

In the cases when the target has small dimensions and the room containing the facility with the liquid-hydrogen target is not adapted to working with hydrogen, it is advisable for safety reasons to condense the hydrogen by means of liquid helium. This method of liquefying hydrogen is not economically advantageous, but it is sometimes the only one possible if the hydrogen target operates under especially dangerous conditions, i.e., inside a streamer chamber in which one can have electrical breakdown capable of destroying the target. In this case, one must have as little hydrogen in the system as possible, in the limit equal to the volume of the target itself. There are several ways of liquefying hydrogen by helium and keeping the target in a working state.

At the Los Alamos laboratory of the University of California, gaseous helium is used as a heat-transmitting medium between liquid helium and the hydrogen in the target.[24] The apparatus with the target (Fig. 7) consists of a helium container 1, the intermediate container 2, and the target 5. The target is connected to the reservoir 8, which contains gaseous hydrogen. After the container 1 has been filled with liquid helium, gaseous helium is supplied to the intermediate container 2. The helium pressure is chosen to ensure the necessary heat transfer to the hydrogen. The thermocouple 3 measures the temperature difference between the helium container and the hydrogen target. If it is necessary to raise the temperature of the liquid hydrogen in the target, the heater 4 is switched on. This system makes it possible to keep the hydrogen in the target in the nonboiling, supercooled state. It has a serious shortcoming resulting from the fact that only the heat of evaporation of the liquid helium is used to condense the hydrogen.

At CERN, hydrogen was condensed by means of the cooling effect of the vaporized gaseous helium.[25] The arrangement is shown in Fig. 8. The helium which vaporizes in the container 1, passes through the coil 2

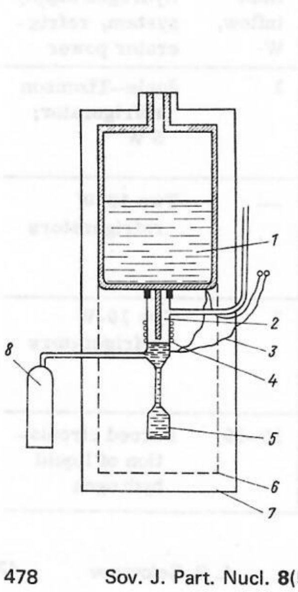

FIG. 7. Condensation of hydrogen through heat of evaporation of helium. 1) Helium container; 2) intermediate container; 3) thermocouples; 4) heater; 5) target; 6) heat shield; 7) vacuum jacket; 8) reservoir with gaseous hydrogen.

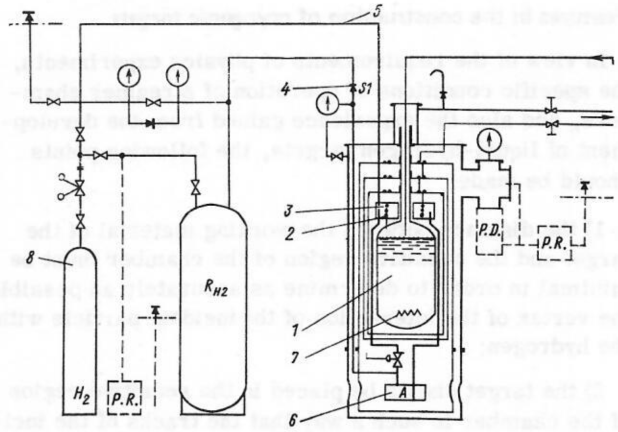

FIG. 8. Condensation of hydrogen through cooling by helium vapor. 1) Container with helium; 2) coil; 3) condenser; 4) check valve; 5) line for filling target with hydrogen; 6) target; 7) heater; 8) cylinder with hydrogen.

placed inside the condenser 3. The hydrogen vapor condenses on the walls of the coil and flows off it into the target 6. The system is originally filled with hydrogen from the cylinder 8 through the line 5. A feature of this system is that the helium coming from the condenser is used to cool the heat shields of the container. To increase the amount of vaporizing helium when necessary, the heater 7, which is inside the container, is turned on.

At the Erevan Physics Institute, a liquid-hydrogen target has been developed[26] in which the hydrogen condenses as a result of cooling by helium vapor. A feature of the target is the separation of the insulation space of the target and the helium container and their placement in a single vacuum jacket. The experimental data show that the amount of liquid helium needed to condense 1 liter of hydrogen agrees well with the calculated value and is 2.6 liters.

At the Joint Institute for Nuclear Research at Dubna, they have developed a hydrogen condenser which uses not only the heat capacity of the vapor but also the heat of evaporation of the liquid helium. The equipment automatically maintains the pressure in the target filled with liquid hydrogen to within ± 100 mm H_2O. The condenser and the automatic arrangement ensure normal operation of the target with heat flow to the target up to 50 W. The arrangement of the automatic control of the pressure in the target is shown in Fig. 9. To fill the target, gaseous hydrogen from a cylinder is passed through the heat exchanger 5 and is cooled in it to 21 °K. Then, having passed through the condenser 2, the hydrogen flows into the target 3. Liquid helium from the container 1 reaches the condenser, and then the heat exchanger and the gas collection system. After the target has been filled with liquid hydrogen, the helium from the condenser is passed through the regulating device 6 for automatic maintenance of the target in the working state. If the pressure increases in the target, a pneumatic signal reaches the measuring block 7 of the differential manometer DMPK-100, in which it is amplified and used to open the regulating device. This increases the

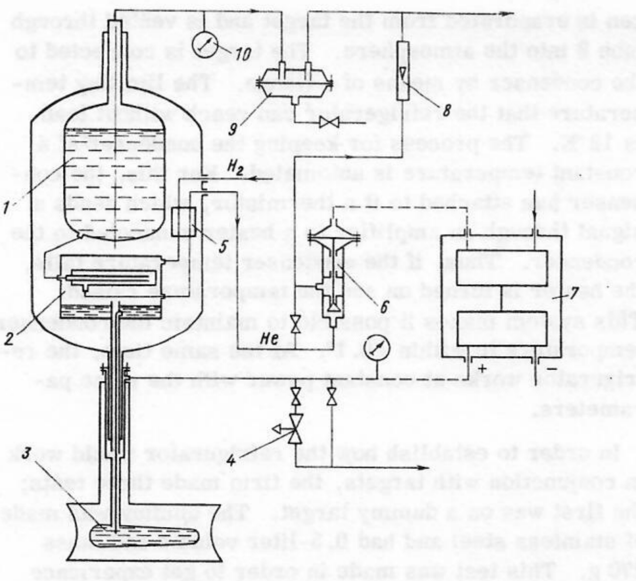

FIG. 9. Automatic control in the liquid hydrogen target. 1) Container with helium; 2) hydrogen condenser; 3) target; 4) precooler valve; 5) heat exchanger; 6) regulating device; 7) measuring block with pneumatic relay; 8) flowmeter; 9) regulator of pressure above liquid helium; 10) manometer.

amount of helium passing through the condenser, and as a result of condensation of the hydrogen the pressure in the target falls. This fall in the pressure leads, in its turn, to the closing of the regulating device. The operation of the condenser is controlled by means of the manometer 10 and the flowmeter 8. If there is a sudden increase in the hydrogen pressure in the target, the safety valve 4 comes into operation and the hydrogen escapes into the venting line.

Use of refrigerators to maintain cryogenic targets in the working state

The operation of the Joule–Thomson refrigerator and the target at DESY

A refrigerator as cooling source for a cryogenic target was first used at DESY in 1965 (Ref. 27). The cold source was a low-power refrigerator designed to cool detectors of infrared radiation. It was suitable as regards its cold production and temperature and was convenient in that the target could be directly fitted onto its cold part. For cooling the target, there were at that time two suitable types of refrigerators: the 10-W Cryodyne (at $T=20\,^\circ K$) made by the firm A. D. Little and the 5.8-W Cryo-Tip of Air Products and Chemicals. The second model was chosen, being cheaper and simpler. In this refrigerator, the ordinary Joule-Thomson cycle is used with nitrogen cooling. Hydrogen is the refrigerant. The refrigerator operates in the open-loop scheme without compressor: High-pressure hydrogen is supplied from cylinders and the low-pressure hydrogen that comes out of the refrigerator is vented into the atmosphere. The installation with refrigerator and target contains two systems: first, a cooling system (open-loop), by means of which the condenser is cooled and the other, which is the target filling system (closed-loop), which ensures the supply of hydrogen for condensation and filling the target. Figure 10 shows the arrangement of the refrigerator and the target.

Cooling system. Hydrogen from the cylinders 1 reaches the refrigerator 10 through the pressure reducer 15. Then, having passed through the hot-zone heat exchanger, the nitrogen heat exchanger, and the cold-zone heat exchanger, it reaches the capillary tube in which the Joule-Thomson effect takes place. The liquid hydrogen flows into the condenser 8. Having evaporated and passed through the heat exchanger and flowmeter 14, it is discharged into the atmosphere. If desired, the condenser temperature can be lowered by evacuating hydrogen backward by the pump 2. The output of the refrigerator is controlled by the hydrogen pressure: During a run while the target is being filled, the pressure is maintained at about 100 atm; in a stationary regime, at 30 atm. The liquid nitrogen is supplied to the refrigerator bath from the Dewar 6. The nitrogen level is replenished automatically. A vacuum of 10^{-5} mm Hg is maintained within the jacket by means of the diffusion pump 5.

System for filling the target. The gaseous hydrogen (or deuterium) intended for condensation and filling of the target is kept in the container 3. Before being filled into the container, the hydrogen is purified by passing it through a small nitrogen-cooled adsorber. The volume and pressure of the gas in the container is chosen in such a way that the hydrogen can be condensed at pressure not more than 0.6 atm. Gas from the container, having being first cooled in the coil 9 soldered to a nitrogen screen, reaches the condenser, is liquefied, and then flows into the target 4, which is fastened to the condenser by means of a flange and indium seal. The condenser is made of copper. The working surface of the condenser is 1250 mm². At $\Delta T=1°$, it makes it possible to transmit about 2 W. This refrigerator can work with a target for which the heat inflow is not more than

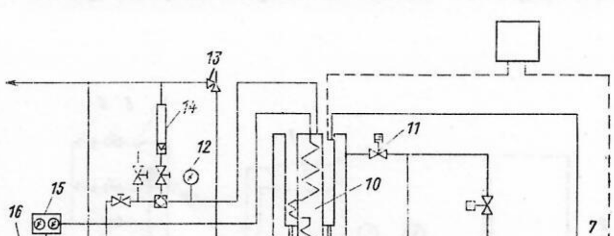

FIG. 10. Operation of refrigerator and target without compression. 1) High-pressure H_2 cylinder; 2) fore vacuum pump; 3) gas storage container; 4) target; 5) diffusion pump; 6) N_2 Dewar; 7) solenoid valve 220 V AC; 8) condenser; 9) coil for cooling hydrogen before condensation; 10) refrigerator; 11) solenoid valve 60 V DC; 12) manometer; 13) precooler valve; 14) flowmeter; 15) pressure reducer; 16) shutoff valve.

4 W. This value corresponds, for example, to the heat inflow from a noninsulated surface of area 85 cm^2 or a surface of area 300 cm^2 insulated by multilayer insulation. The arrangement does not foresee a system of rapid removal of the liquid hydrogen from the target for background measurements. If it is necessary to remove the liquid, the supply of high-pressure hydrogen to the refrigerator is stopped, and the liquid in the target evaporates because of the heat inflow from the surrounding medium. Such removal and subsequent refilling takes about 20–40 min.

The target and refrigerator operated successfully during tests for about 100 hours. The defects of the cooling system include the following: the open cooling loop, the use of hydrogen as a refrigerant, the liquid nitrogen in the cycle, and the absence of automation and a system of rapid removal of the hydrogen from the target for background measurements. These shortcomings were eliminated in the later designs.

Investigation of the operation of refrigerators supplied by the firm "500 Incorporated" with targets

This firm, which manufactures refrigerators with power 2–3 W at $T=20\,°K$ for cooling microwave devices in terrestrial satellite-tracking stations, decided to adapt their refrigerators for cooling and condensing hydrogen used in targets.[28] For this, the power of the refrigerator was increased to 5–7 W by increasing the working pressure. The refrigerator operates in a closed loop with two gas-expansion machines with helium circulation. The compressors, the refrigerator, and the panel are connected by flexible tubes. The system for supplying the hydrogen to the target is shown in Fig. 11. The hydrogen is supplied by the cylinder 1 through the pressure reduces 2, passes through the purifying system 14, and then is cooled in the heat exchanger 12 of the first stage of the gas-expansion machine to $T=65\,°K$. The hydrogen then reaches the condenser 11, is cooled in the second stage of the gas-expansion machine, and at $T=20\,°K$ condenses and flows into the target 10. At the end of operation, the hydrogen is evaporated from the target and is vented through tube 8 into the atmosphere. The target is connected to the condenser by means of a flange. The limiting temperature that the refrigerator can reach without load is 12 °K. The process for keeping the condenser at a constant temperature is automated. For this, the condenser has attached to it a thermistor, which sends a signal through an amplifier to a heater connected to the condenser. Thus, if the condenser temperature falls, the heater is turned on and the temperature raised. This system makes it possible to maintain the condenser temperature to within ±0.1°. At the same time, the refrigerator works at constant power with the same parameters.

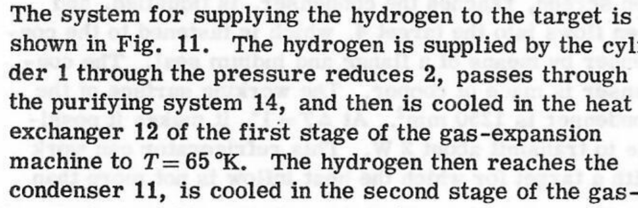

FIG. 11. Arrangement of hydrogen supply to target. 1) Hydrogen cylinder; 2) pressure reducer; 3) compressor; 4) warmup coil; 5) hand valve; 6) check valve; 7) 4 psig relief valve; 8) primary vent; 9) vacuum jacket of refrigerator and target; 10) target; 11) condenser; 12) first-stage heat exchanger; 13) refrigerator; 14) hydrogen purifying system.

In order to establish how the refrigerator would work in conjunction with targets, the firm made three tests; the first was on a dummy target. The dummy was made of stainless steel and had 0.5-liter volume and mass 270 g. This test was made in order to get experience in working with hydrogen, which the firm had not hitherto had, and to find out the problems presented by combined operation of the refrigerator and a target. During the tests, two unexpected problems arose: 1) a low cooling rate; to increase the cooling rate, it was proposed to connect the condenser to the target by a copper strap. This measure was effective only for targets with large mass; 2) oscillations in the venting line during the discharge of the liquid hydrogen from the condenser into the atmosphere when the liquid hydrogen reached the hot zone. The oscillations ceased when the gaseous hydrogen was removed from the upper part of the condenser.

Testing of the DESY *target.* The second test was made on one of the working targets at DESY, which was supplied to the firm. The target of capacity 0.5 liter had diameter 80 mm and length 100 mm. The ends were made of stainless steel and the cylindrical part out of a Kapton film 0.125-mm thick. The mass of the target was 60 g, and it was insulated by two layers of metallized Mylar. The heat inflow was about 0.3 W. The combined tests of the target and the refrigerator showed that the cooldown time of the refrigerator was 50 min and that of the target 20 min. Hydrogen was liquefied at 0.25 liter/h. Tests were made with preliminary cooling of hydrogen in a nitrogen bath. The liquefaction rate was then increased slightly to 0.30 liter/h. The cooldown graph of the refrigerator and the target is shown in Fig. 12a, and the characteristic of their combined operation in Fig. 13.

Testing of the Cambridge target. For comparison, a target of large mass 680 g and volume 0.2 liter was tested. The target was made of stainless steel and the window of Mylar. The target was insulated by two films of metallized Mylar, and it had a heat inflow of 1.3 W. To shorten the cooldown time, the target was connected to the condenser by a copper strap. It took 1 hour to cool the refrigerator to 20 °K. The cooldown of the target after the condenser cooldown was 2.2 hours. The cooldown graph is shown in Fig. 12b.

After comprehensive tests of the refrigerator had

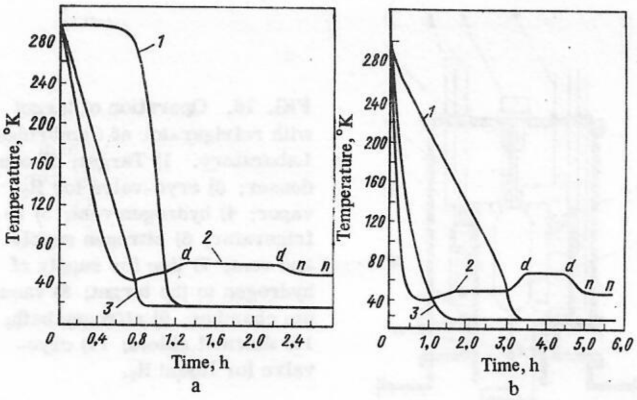

FIG. 12. Target cooldown by refrigerator. a) DESY without thermal strap; target volume 0.5 liter; mass 60 g; heat inflow 0.3 W; rate of liquefaction without preliminary cooling 0.25 liter/h and with preliminary cooling 0.3 liter/h. b) CEA with thermal strap; volume of target 0.2 liter; mass 680 g; heat inflow 1.3 W; rate of liquefaction without preliminary cooling 0.23 liter/h and with preliminary cooling 0.29 liter/h; 1) target; 2) first stage of refrigerator; 3) second stage of refrigerator; *d–d* is the filling of the target with hydrogen; *n–n* is the steady regime of recondensation.

been made with different targets and modifications introduced, the firm produced two new models: one is the Cryodyne Model 342, a 5-W hydrogen condenser–recondenser, and the other is the Cryodyne Model 1022, which has 10-W power at $T = 20$ °K. The characteristics of this second model are shown in Fig. 14.

Use of refrigerators at the Argonne National Laboratory

At the Argonne National Laboratory, the targets were originally replenished by hydrogen from 30-liter reservoirs. This system operated automatically. Besides the large on-site hydrogen inventory, this method suffered from a complicated pneumatic system and electronic automation system and also frequency replenishment of the hydrogen reservoir.

A first 5-W refrigerator was used at the Argonne National Laboratory in the beginning of 1967 (Ref. 29). A refrigerator of this power can operate only with a small target of capacity 20 cm³. The target had diameter 38 mm and length 20 mm. It was connected to the condenser by means of a glass-reinforced plastic tube. The cooldown of the refrigerator itself required 40 min; the cooldown of the entire system and filling of the target with hydrogen, 150 min. The target and its connecting tube were made of a material with low thermal conductivity, so that the cooldown took a very long time, being done solely by the thermal conductivity of the gas

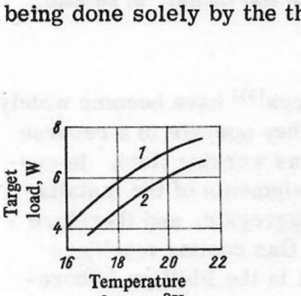

FIG. 13. Characteristics of refrigerator in combined operation with targets: 1) DESY; 2) CEA.

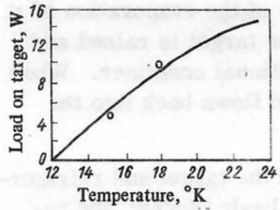

FIG. 14. Characteristics of Cryodyne Model 1022 refrigerator with 35-W load on the first stage.

and convective heat exchange. The limiting temperature to which the target could be cooled without filling it with gas was 12.2 °K.

After tests of this refrigerator and accumulation of experience in operation with such systems, a program was developed for constructing a complex of reliable standard systems for supplying liquid hydrogen to targets by means of refrigerators.[30] The arrangement of the joint operation of target and refrigerator is shown in Fig. 15. The hydrogen is supplied from the cylinder 1, passes through the purifying system, and reaches the first-stage heat exchanger, where it is cooled to 70 °K. It is then passed to the condenser 6. The condensed liquid flows first to the additional container 8, and then from it into the inner container of the target 11. Two tubes are connected to the container: The liquid tube 9 connects the bottom of the target to the container 8, while the gas tube 14 joins the upper part of the target to the condenser. On the gas tube near the condenser there is a sylphon valve 15 with pneumatic drive. The target has its own vacuum jacket 12, which is connected through an adapter ring to the jacket of the refrigerator. The target and refrigerator have a common vacuum chamber, which is evacuated by the fore pump and diffusion pump 19. The precooler membrane 7 is on the vacuum jacket. The system consisting of the condenser, the additional container, and the target makes it possible to remove hydrogen from the target during the time of background measurements. For this,

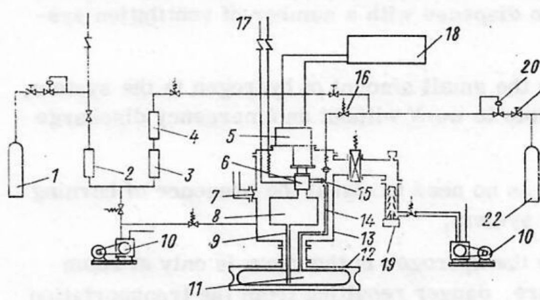

FIG. 15. Arrangement of target and refrigerator at the Argonne National Laboratory. 1) Hydrogen gas bottle; 2) and 4) driers; 3) catalyzer; 5) refrigerator; 6) condenser; 7) precooling membrane; 8) additional container; 9) liquid supply tube; 10) fore pump; 11) internal container of target; 12) vacuum jacket of target; 13) vacuum jacket of refrigerator; 14) tube for gas to escape from target; 15) valve for raising pressure in the target; 16) valve with drive from solenoid; 17) check valve; 18) compressor; 19) diffusion pump; 20) pressure self-regulator; 21) valve with manual control; 22) helium cylinder.

the valve 15 is closed. Because of the evaporation of the hydrogen, the pressure in the target is raised and the liquid is pushed into the additional container. When the value 15 is opened, the liquid flows back into the target.

The complete installation with the target and refrigerator is made in the form of five basic blocks: the refrigerator, compressor, fore pump with system of valves, the control panel, and the target.

Two models supplied by the firm 500 Incorporated are used as refrigerators: the 5-W Cryodyne Model 342 and the Cryodyne Model 1022 of power 10 W at 20 °K. The compressors for these refrigerators were also supplied by the same firm. All the remaining elements were developed at the Argonne National Laboratory. The fore-pump block, which is placed on a small carriage, includes pump, electricity supply panel, control valves, and the hydrogen purifying system. The control panel, which includes a system of control, blocking, and signaling, makes it possible to measure the temperature and pressure in the target, control the temperature in the condenser to within ±0.1 °K, and also measure the vacuum and determine the presence of hydrogen at upper and lower points of the target. The target block includes the vacuum jacket, the precooling membranes, the diffusion pump, and also everything inside the jacket: the condenser, and additional container, the target, and so forth. All systems are standardized and replaceable. By the middle of 1969, six installations were ready for operation with the Argonne accelerator.

Operation with refrigerator-cooled targets has many advantages:

1) the supply of hydrogen to the targets is more reliable;

2) the on-site hydrogen inventory is greatly reduced, which increases the safety factor during the experiments;

3) operation with hydrogen in a closed loop makes it possible to dispense with a number of ventilation systems;

4) given the small amount of hydrogen in the system, it is possible to work without an emergency discharge tube;

5) there is no need to signal the presence of burning gas in the system;

6) since the hydrogen in the room is only at room temperature, danger resulting from the transportation of Dewars, spilling of liquid hydrogen, etc., is completely eliminated;

7) the automatic system of filling the target with hydrogen and the control of the state of the equipment reduces the number of service personnel;

8) the new system for supplying the targets with hydrogen makes it possible to carry out 12–15 experiments in a year with simultaneous work on up to six targets;

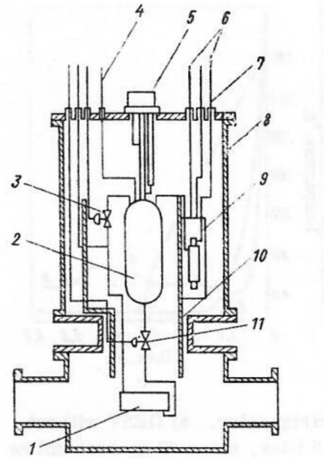

FIG. 16. Operation of target with refrigerator at Cambridge Laboratory. 1) Target; 2) condenser; 3) cryo-valve for H_2 vapor; 4) hydrogen vent; 5) refrigerator; 6) nitrogen supply and vent; 7) line for supply of hydrogen to the target; 8) vacuum chamber; 9) nitrogen bath; 10) thermal shield; 11) cryo-valve for liquid H_2.

9) although the original expenditure on the development and construction of the complex was large, the average cost per target is appreciably lower than it was before refrigerators were used;

10) operation with hydrogen and deuterium in a single session is simplified.

Operation of refrigerator with target at the Cambridge Laboratory (United States)

The targets of the Cambridge electron accelerator were originally kept in the working state by means of liquid helium supplied to the targets in Dewars.[31] The shortcomings of this method were the frequent removal of the accelerator beam when the Dewars were changed, and the high helium consumption. For a six-liter target in steady-state regime, the liquid helium consumption was 10–12 liter/h.

In February 1968, two refrigerators were acquired: one from the firm Cryomech Incorporated, the other by 500-Incorporated; this last, the Cryodyne Model 1020, can operate for 2000 hours. The Cambridge targets are operated in a particular way with refrigerators.[32] The arrangement of the combined operation of the target and the refrigerator is shown in Fig. 16. The hydrogen is cooled before condensation by liquid nitrogen. The condenser is in a separate strong container. It is connected to the target by two valves. This system makes it possible to remove the hydrogen to measure the background or in the case of dangerous operations involving work with personnel near the target. The pressure at which the safety valves on the condenser operate is 1.6 atm; for those on the target, 0.28 atm.

Gas cooling machines

Recently, gas cooling machines[33] have become widely used as Cryogenic sources. They operate in a reverse Stirling cycle, and use helium as working fluid. In contrast to refrigerators, all the elements of the installation are combined in a single aggregate, and therefore the machine is very compact. Gas cooling machines were first developed in Holland in the Phillips Laboratories, and they are frequently simply called Phillips machines. These machines are now sold by Phillips in Holland, the United States, and also in the Soviet Union. For combined operation with cryogenic targets, the most suitable are two of the foreign types: PPH-110 and PGH-105.

The gas cooling machine PPH-110 *(Ref. 34)*

The gas cooling machine consists of two main parts: a single-cylinder two-stage cryogenerator and head recondenser (Fig. 17). The cryogenerator includes a piston 1 to compress the gas and a two-stage expeller 4, a water cooler 2 and regenerators 3 and 13. The recondenser consists of two cold heat exchangers 12 and 14, a radiation screen 9, and connecting tube 5 for connecting the recondenser to the hydrogen system. The intermediate cold heat exchanger 12 is used to cool the radiation screen and for original liquefaction of a small amount of hydrogen or neon for their preliminary cooling. The upper cold heat exchanger 14 is designed to withstand a pressure up to 20 atm and liquefy cold gas or supersaturated vapor. The condenser and the connecting tubes are within the vacuum jacket 10, which is evacuated through the connecting pipes 15 by the diffusion pump 17 in the version with precautions against explosion. The vacuum is measured by the vacuum meter 18. The recondensation occurs as follows. The evaporating hydrogen, for example, from the target, passes through the tubes 5 and 8. The gas is cooled in the upper cold heat exchanger 14, and the liquid is returned to the target through the tubes 7 and 5. The maximal pressure in the liquefaction system is not more than 20 atm.

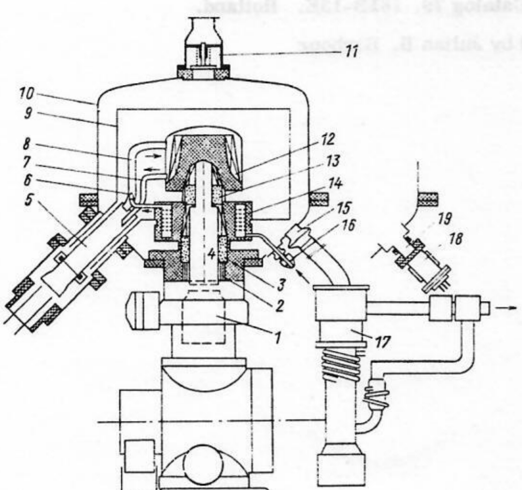

FIG. 17. General layout of the gas cooling machine PPH-110 for condensing hydrogen or neon. 1) Compressor piston; 2) water cooler; 3) and 13) regenerators; 4) two-stage expeller; 5) tube connecting condenser to target; 6) tube for transporting cooled hydrogen from the heat exchanger to the condenser; 7) tube for pouring hydrogen out of the condenser; 8) tube leading to upper heat exchanger; 9) radiation screen; 10) vacuum jacket; 11) precooler valve; 12) and 14) heat exchangers; 15) connection tubes to diffusion pump; 16) connecting pipe for filling the system with gaseous hydrogen; 17) diffusion pump; 18) vacuum meter; 19) connecting pipe to vacuum meter.

Although this cooling machine was not designed to cool hydrogen, it can be used for the original filling of the target with hydrogen. In this case, the gas reaches the central cold heat exchanger 12 through the tubes 16, in which it is cooled, while impurities such as water or carbon dioxide are frozen and depositied on a metallic grid. The cooled gas then passes along the tubes 6 and 8 to the condenser, where it is liquefied. To avoid clogging of the heat exchanger 12, not more than 5 liters of hydrogen containing a standard amount of impurities is admitted for liquefaction.

The gas cooling machine PPH-110 has the following technical data:

1) the rate of condensation of saturated hydrogen vapor is 10 liter/h;

2) power required by the electric motor, 9 kW;

3) consumption of cooling water: 0.75 m^3/h;

4) pressure of the cooling water: 1.7 kg/cm^2;

5) duration of the startup period: 35 min;

6) working pressure of cryogenerator: 30 kg/cm^2;

7) amount of working gas in the system: 30 g helium;

8) mass of target: 340 kg;

9) overall dimensions: 950×500×1550 mm.

It is clear from the construction of the machine that the PPH-110 can operate with targets from which more than 10 liter/h of hydrogen evaporates. The target or cryostat must be in the immediate proximity of the machine and arranged in such a way that the hydrogen can flow into the target under gravity. Cooling machines are also manufactured in which the cryogenic production is much faster, for example, the PPH-440. The machine is capable of condensing 40 liter/h hydrogen or 18 liter/h neon.

The gas cooling machines PGH-105 *(Ref. 34)*

The machine PGH-105 differs from the machine PPH-110 in that its construction foresees transmission of the cold over a distance up to 50 m. This means that the target can be situated within a radius of 50 m of the machine. The cold is transmitted by means of circulating gaseous helium at the two temperature levels 20 and 80 °K through two independent loops. The siphon through which the helium circulates consists of four 8×0.5 mm stainless tubes enclosed in a vacuum jacket of an armoured flexible hose. Cold helium passes along the two tubes to the target: along one at $T = 20$ °K and along the other at 80 °K, and back along two others. The tubes are insulated by 50 layers of Mylar and shielded by a screen at temperature 80 °K. The calculated heat flow to the tubes with $T = 80$ °K is 1.5 W/m and to the tubes with $T = 20$ °K it is 0.06 W/m. The tube can withstand 30 bends with radius 0.75 m. The helium is circulated by means of fast circulating turbines at pressure 20 atm. The turbines are set up inside the vacuum jacket of the machine. Another important feature is the automatic control of the second-stage temperature.

When the target is filled with hydrogen, the temperature can be kept at 20 °K by means of a regulator; in the case of deuterium, at 23 °K. The temperature can be kept automatically at a value in the range from 17 to 80 °K. The cryogenic capacity of this machine is 60 W at $T = 20$ °K and 300 W at $T = 77$ °K. The machine with two low-temperature loops is economical and convenient in that the cold of one loop can condense the hydrogen evaporating from the target, and the cold of the other loop can be used to cool the screen and reduce the heat flow to the liquid hydrogen.

As a rule, such cooling machines are used as the cryogenic source for liquid hydrogen and deuterium targets in the large accelerators in the world: at Serpukhov, Geneva, Batavia, and so on.

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