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Robert Sanders

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

Henryk Piekarz

Florida State University
Tallahassee, Florida 32306

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CRYOGENIC DESIGN CONSIDERATIONS OF SOLID ARGON CALORIMETERS AND PERFORMANCE OF A SOLID ARGON TEST CELL*

Robert Sanders

Fermi National Accelerator Laboratory
Batavia, IL 60510

Henryk Piekarz

Florida State University
Tallahassee, FL 32306

ABSTRACT

This paper presents the cryogenic design and discusses the operation of a small test cell with a 20.6 L cryostat, built to demonstrate the feasibility of Solid Argon Calorimeters (SAC) for possible use in high energy physics experiments. In addition, design considerations for a large SAC are described. The test cell froze argon in a solid block around the particle detector assembly reaching temperatures more than 6 K below the argon freezing temperature. Aspects of the test cell design can be used for a large SAC including the use of two liquid nitrogen cooling circuits: one for condensing argon gas and controlling the argon pressure, another for freezing the argon around the detector assembly with gravity fed liquid nitrogen at 77 K. An insulated open-top box surrounding the detector assembly separated the solid argon from warmer liquid argon restricting the growth of the solid argon. A generalized look is taken at the heat transfer problems of a SAC.

INTRODUCTION

Solid argon calorimeters are similar to liquid argon calorimeters (LAC) in their design and application. Both can be applied in high energy physics experiments to measure the energy of particle beams. The technology for the design and operation of a LAC is well established and in fairly common use[1,2]. A SAC differs from a LAC in that solid argon instead of liquid argon fills narrow gaps in the detector module. Previous attempts to use solid argon in calorimeters [3,4] experienced problems with cracks developing in the solid argon because of large thermal gradients generated by the use of liquid helium as the coolant. These earlier experiments had no direct contact between the heat exchanger and the detector assembly. The approach presented in this paper is fundamentally different from the earlier work. Here it is proposed that liquid nitrogen be the coolant with the coolant tubes attached directly to the outer edges of the metal plates of the detector module. These plates are an integral part of a LAC or SAC detector module and would serve, for a SAC, the additional role as cooling fins for the solid argon.

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Table 1. Argon and Nitrogen Properties

argon fusion temperature @ 101 kPa (0 psig)	84 K
nitrogen saturation temperature @ 101 kPa (0 psig)	77.3 K
nitrogen saturation temperature @ 239 kPa (20 psig)	85.4 K
argon vapor temperature @ 101 kPa (0 psig)	87.29 K
argon vapor temperature @ 122 kPa (3 psig)	89.07 K
argon triple point pressure	68.8 kPa (.6785 atm)
argon triple point temperature	83.8 K
argon solid density @ 84 K	1630 kg/m^3
argon liquid density @ 84 K	1390 kg/m^3

In 1990 small scale tests completed at Fermilab[5] indicated the feasibility of using liquid nitrogen as the coolant. The initial test had a small .05 m X .05 m X .05 m mockup of a detector module with an attached copper cooling coil that was immersed into an open glass dewar containing liquid argon. Flowing liquid nitrogen in the cooling coil caused the argon to solidify, completely covering the detector module. The solid argon was very clear and free of cracks with the detector module visible through it. Later tests done in this and another small dewar confirmed the importance of the direct attachment of the cooling coils to the module and use of the metal detector plates as paths for heat transfer. After these encouraging experiments, a preliminary design and proposal[6,7] were submitted for a solid argon test cryostat to be installed in a Fermilab beam line. Work also commenced on the solid argon test cell, a working solid argon detector[7] that would measure cosmic rays and radiation from alpha and beta sources. Both the proposed test cryostat and the test cell are described below.

Table 1 contains some physical properties of nitrogen and argon pertinent to the design and operation of a SAC. The pressure of the liquid nitrogen coolant must be near atmospheric pressure in order to get its temperature well below the 84 K argon fusion temperature. Also, it is desirable to keep the argon pressure in the SAC above atmospheric pressure to keep out contamination. This requires that the 84 K surface of the solid argon must be covered with warmer ~88 K liquid argon to keep the pressure above atmospheric pressure. As well, the density of solid argon is 17% greater than for liquid argon. The consequences of the contraction of solidifying argon and expansion of melting argon must be considered in the design of a SAC.

PROPOSED SOLID ARGON TEST CRYOSTAT

Details from the design for the proposed solid argon test cryostat[6] will serve as an example of a large SAC. Figure 1 shows a cross section through the test cryostat. The vacuum jacketed 3.1 m outside length and 1.7 m outside diameter cryostat would contain liquid argon. Beneath the liquid argon level is the detector module, a laminar assembly of .0085 m lead plates, .005 m sheets of G-10 and .001 m gaps filled with solid argon. The detector module has a .5 m X .5 m cross section and a 1.8 m length. The path of the particle beam would be perpendicular to the layers of G-10 and lead. Insulation, possibly G-10 or Teflon would separate the sides of the detector module from the bulk of the liquid argon. The top of the detector would be open to the liquid argon. Liquid nitrogen would be in the cooling tubes attached directly to the lead plates. A top view of a representative section of the laminar structure of the detector module is in Figure 2. The unit cell shown in Fig. 2 is repeated 94 times along the length of the detector. The mechanical design details and electrical connections of the test cryostat proposal are not shown in Figures 1 and 2.

Referring to Fig. 2, the measurement process can be described. The layers of G-10 on each side of the argon were copper clad so that a voltage differential (~30 kV/cm) could be applied across the argon filled gaps using the copper clad G-10 layers on each side as electrodes. When particles in the beam have collisions in the lead plates they result in showers of secondary particles that ionize the argon medium in the gaps. In a time shorter than 5 nsec, the ionization electrons are thermalized to energies in the 1 eV range. Then under the electrical field in the gap they drift to the positively charged electrode. The

charge accumulation on the positive electrode is measured by a charge sensitive amplifier mounted on the detector and is proportional to the particle energy deposited in the detector gap. The generated electrons have a three to four times faster drift velocity for solid argon that is below 80 K[8, 9, 10] compared to liquid argon, resulting in a much faster detector response. It is not practical to operate an argon calorimeter between 80 K to 88 K because of the dramatic changes in electron drift velocity in that temperature range; a small change in temperature would cause a very large change in the calorimeter timing response making it difficult to interpret the calorimeter measurements.

SOLID ARGON TEST CELL DESCRIPTION

The solid argon test cell has been built, successfully operated and used to make measurements. The test cell was operated as both a SAC and a LAC and comparisons of signals were made from both modes of operation.

Figure 3 is a simplified schematic of the cryogenic system of the solid argon test cell. The central feature of the system is the foam insulated 20.6 L cryostat, with a .19 m inside diameter and .91 m internal depth. Inside the cryostat are two separate cooling circuits; one for condensing the argon gas, located in the vapor space and another, the freezing heat exchanger attached to the detector module. The condenser heat exchanger is a coil of .0095 m diameter copper tubing. The detector module is in the G-10 box beneath the argon liquid level. The .12 m X .14 m X .15 m G-10 box was sealed on its .013 m thick sides and bottom while open at the top. The box insulated the solid argon from the surrounding warmer liquid argon. Liquid nitrogen was supplied from 160 L dewars to the freezing heat exchanger attached directly to the detector plates. Two freezing heat exchangers were tried. The first consisted of an inverted U-shaped stainless steel tube filled with pool boiling liquid nitrogen. It was later replaced by an all copper heat exchanger that held more liquid nitrogen and had more surface area. The liquid nitrogen in the heat exchanger was essentially a pool boiling bath.

Features not shown in Fig. 3 include a batch mixing system to mix small amounts of allene or methane to the argon to determine the benefits of the additives. Temperatures at various points inside the cryostat and phase separator were measured by platinum RTDs and diodes. A Moore 352E controller was used to automate the system and a data logger recorded the RTD temperatures and cryostat pressure. Type K thermocouples measured temperatures of nitrogen inlets and outlets to monitor system performance.

The test cell underwent changes in the course of its operation. Temporarily, the G-10 box was replaced with a Rohacell foam enclosure until it was suspected that outgassing from the foam may have contaminated the argon. The detector plates in the G-10 box in Fig. 3 were part of the original installation. The copper plates were slanted nearly horizontal for the study of cosmic rays. A later and more compact detector module had .001 m gaps between the plates, the same as the solid argon test cryostat.

During the cool-down of the cryostat only the condenser heat exchanger was used. High purity argon (less than 1 PPM oxygen) was supplied from a high pressure gas cylinder. The pressure regulator, PRV-746 controlled the argon gas flow as it was cooled and condensed in the cryostat. The control valve EV-700 regulated the flow of liquid nitrogen through the condenser heat exchanger from one of the 160 L liquid nitrogen dewars. The cryostat pressure was monitored by the pressure transducer PT-712, which sent a signal to the controller. A PID control loop in the controller manipulated the position of the control valve EV-700 to maintain a constant cryostat pressure of 122 kPa (3 psig) The set point of the controller was lower than the set point of the argon regulator.

The pressure in the argon gas supply cylinder was monitored to determine the amount of argon inside the cryostat. The approximate liquid level in the cryostat was confirmed with a platinum RTD. Usually about 7 L of argon was condensed into the cryostat. Once a sufficient amount of argon was in the cryostat, the argon gas supply cylinder was isolated from the cryostat and the process of freezing argon in the detector module could begin. The cryostat could be cooled down and filled with liquid argon in a few hours.

To solidify the argon in the detector module gaps a constant flow rate of liquid nitrogen was maintained through the freezing heat exchanger. The required flow rate was determined by experience. The flow rate was measured by a differential pressure transmitter DPT-748 that monitored the pressure drop of exhausting nitrogen gas passing through a flow orifice. Using the pressure measurement the controller calculated the flow

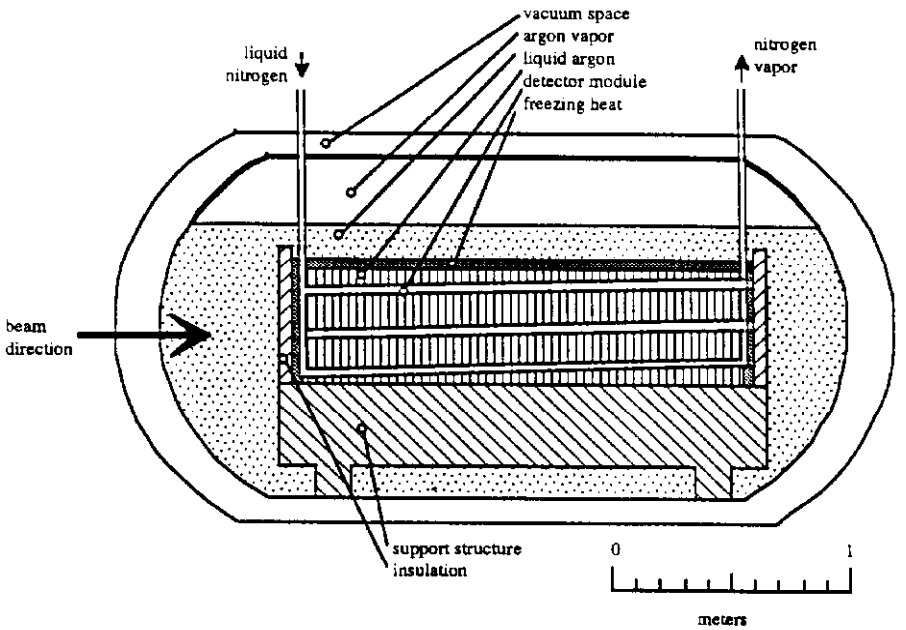

Fig. 1. Cross section of cryostat for solid argon test cryostat proposal showing detector assembly. The condensing heat exchanger in the ullage space is not shown.

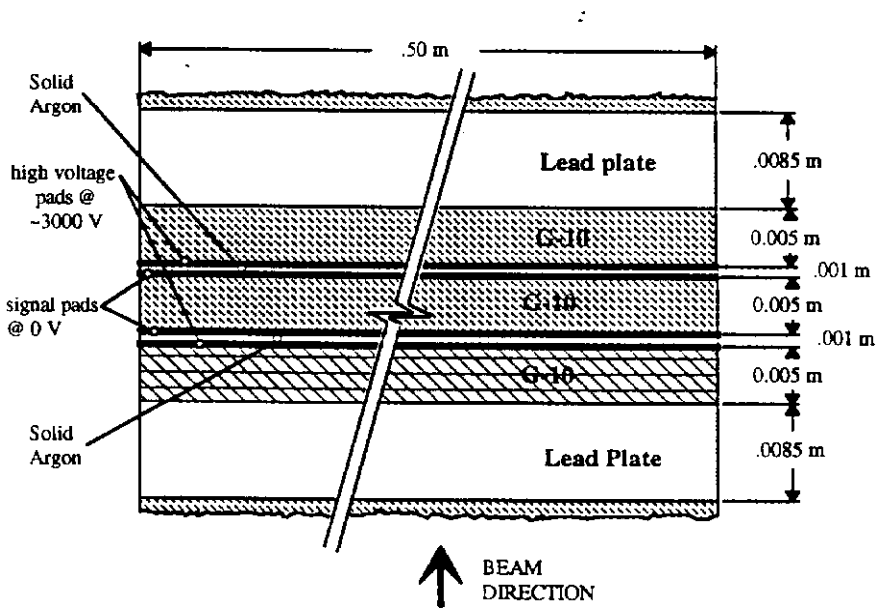

Fig. 2. Top view of a detector module section of the proposed solid argon test cryostat.

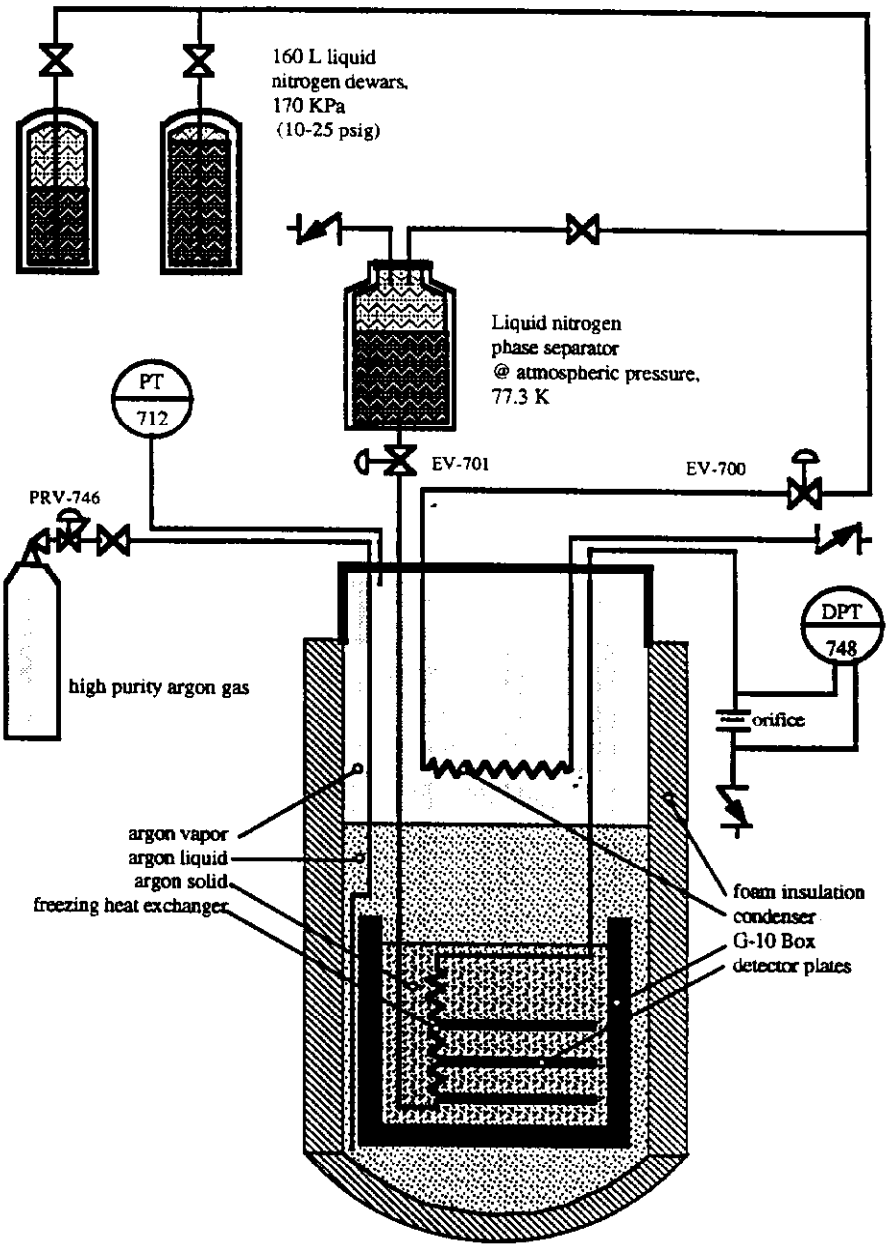

Fig. 3. A simplified flow schematic of the cryogenic system for the solid argon test cell.

rate and maintained a constant rate by manipulating control valve EV-701. This valve throttled the flow of liquid nitrogen from the 25 L phase separator physically located .3 m above the cryostat. The phase separator was manually filled at 12 hour intervals through a manual valve from the 160 L liquid nitrogen supply dewars. The phase separator was vented to the atmosphere through a spring loaded check valve set at 3.4 kPa over

atmospheric pressure (.5 psig); it reduced the liquid nitrogen temperature and expelled vapor resulting from piping heat leaks and depressurization. The original installation of the test cell did not have the phase separator; it was found to dramatically improve the performance of the freezing heat exchanger.

PERFORMANCE OF SOLID ARGON TEST CELL

Once the initial problems were solved the test cell was easy to cool down and operate. The cool-down and freezing the argon was automated as was most of the operation except for the switching of the 160 L nitrogen dewars and filling the phase separator. Most of the heat load on the system was on the foam insulated liquid nitrogen transfer line from the nitrogen dewars. The test cell has been cooled down, to date, twelve times, with periods of continuous operation for as long as five days. Temperatures below 78 K were achieved on the detector plates, practically identical to the coolant temperature. During operations, the test cell provided good signals. The response time of the signal while using solid argon was found to be a substantial improvement over using liquid argon. Further tests are in progress to accurately quantify the relative speed of the faster response.

It was discovered that it is extremely important to well insulate the nitrogen lines inside the cryostat that went to and from the freezing heat exchanger. Ideally these lines should be vacuum insulated. The tubing connected to the freezing heat exchanger inside the test cell cryostat had only layers of Teflon wrapped tightly around them, which proved to be barely adequate. The poor insulation had the undesirable effect of vaporizing the liquid nitrogen coolant and adversely affecting the freezing heat exchanger performance. These poorly insulated lines, as well, condensed argon gas in the cryostat (just as the condenser heat exchanger does) and could cause the cryostat argon pressure to fall and even create a vacuum in the cryostat. A vacuum is very undesirable because any atmospheric oxygen pulled into the cryostat is an unacceptable contaminate that degrades the measured signal from the detector.

GENERAL DESIGN CONSIDERATIONS

It is worthwhile to compare techniques for solidifying argon to metal casting technology. Molten metal can hold a considerable amount of dissolved gases. The solubility decreases upon solidification of the metal. If not allowed to escape from a mold, the gas can form undesirable bubbles creating voids in the metal castings. Molds are designed to have molten metal fed into them by gravity through vertical risers. The released gases can escape from the mold into the risers and are replaced by more molten metal. By design the solidification front moves from the remotest sections of the mold toward the points of feeding. A SAC can be designed with the same principles in mind. Argon contracts about 15% in volume as it solidifies. If the detector module is cooled from the sides and bottom then the solidification front moves inwards and upwards. Liquid argon above the detector module keeps the solid argon "casting" fed so that voids do not form.

In the proposal for the solid argon test cryostat, heat transfer calculations were presented[6] for the case of natural convection in a bath of liquid argon at 88.9 K next to a vertical surface of solid argon at its fusion temperature of 84 K. The heat transfer rate to the test cryostat detector module was calculated to be 4000 W, which is a very high heat load. This implies that it would be difficult to maintain a block of 84 K solid argon in a bath of liquid argon at 88.9 K. For this reason, in both the test cryostat proposal and the test cell, an insulated box separated the sides and bottom of the detector module from the bulk of the liquid argon. This insulation restricts the growth of the solid argon into the cryostat and reduces the cooling load on the freezing heat exchanger. Natural convection heat transfer in the liquid argon around the freezing heat exchanger would explain an observed phenomenon during the operation of the test cell. Very soon after the initiation of nitrogen flow through the freezing heat exchanger, the entire contents of the G-10 insulation box, including an RTD on the inside of the box not connected to the detector module, would fairly quickly and uniformly drop from ~ 88K to the 84 K fusion temperature. It appears that the natural convection currents kept the temperatures in the G-10 box uniform as it cools until the fusion temperature is reached.

An important factor in the design of a SAC is the time required for solidifying the argon. Because of natural convection heat transfer in the liquid argon, the temperature of the entire detector module should reach the fusion temperature, of about 84 K almost uniformly and comparatively quickly. Once the freezing starts it can be assumed that the entire detector module is near the fusion temperature of 84 K. However, calculations presented in the proposal for the solid argon test cryostat[6] did not make this assumption and yet very conservatively demonstrated that the .5 m X .5m X 1.83 m detector module could be completely filled with solid argon within 9 to 18 hours using cooling tubes attached at discrete locations to the side of the detector module. In these heat transfer calculations the detector module was modeled as a two dimensional heat conduction problem. The G-10 and argon layers in the detector are so thin, in comparison to the height and width of the detector module, that their temperature profile at any time would closely match the temperature profile of the lead plates. The only mode of heat transfer considered was heat conduction in the lead plates. The latent and sensible heat capacities of the G-10 and lead plates were added to the sensible heat capacity of the lead plates combining the thermal masses, but only the thermal conductivity of the lead was used in the calculations.

In the test cell, pool boiling heat transfer was used in the freezing heat exchanger with transport of the nitrogen in the heat exchanger caused solely by thermal effects. This scheme has the advantage of being inherently safe in that only cold liquid nitrogen is sent to the heat exchanger. Any failure of equipment, controls or mistakes by operating personnel cannot force warm nitrogen through the cooling tubes causing inadvertent melting of the solid argon. Alternate cooling schemes using the forced flow of liquid nitrogen through the heat exchanger achieve considerably higher heat transfer rates as found in the earlier tests at Fermilab[5].

If melting solid argon is confined, high pressures can be generated. In a worse case a SAC could be damaged by melting argon if it were not properly designed. To prevent this, the detector module must have no internal sources of heat and the argon must be able to expand as it melts. A pool boiling cooling system cannot become an internal source of heat. No special procedures were followed in melting the solid argon in the test cell and after numerous freeze-thaw cycles there was never any damage.

There is considerable experience with heat exchangers in liquid helium refrigeration systems that all too often become completely plugged with frozen nitrogen. Usually the nitrogen appears as a contaminant in the helium. Solid nitrogen expands when it melts. Special precautions are not usually taken in the design of liquid helium refrigeration systems to prevent the melting nitrogen from causing damage. If it were inherently dangerous to thaw out frozen cryogens there would be a history of catastrophic failures to liquid helium refrigerators due to such occurrences. As long as reasonable prudence is taken in the design of a SAC to eliminate internal sources of heat within the detector module, the solid argon will melt without causing damage.

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