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CRYOGENIC ENCLOSURE FOR A
COOLABLE INTERFEROMETER

James L. Pritchard

ADB024965

Idealab, Inc. ✓
Franklin, Massachusetts 02038

Final Report
July 1975 - October 1977

October 15, 1977

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INTRODUCTION

This report details the design of the liquid nitrogen dewar to be used as a cryogenic enclosure for a cryogenic interferometer. The total package, including the cryogenic enclosure and the interferometer, will be balloon borne to an altitude of approximately 80,000 feet. Thus the system must be designed and built to withstand the rigors of launch and the changing environment resulting from ascent and descent. This would primarily include changes in temperature and atmospheric pressure. When the system reaches altitude the interferometer will take data in the 4 to 14 micron region. This data will be telemetered to ground for future analysis. Other experiments are also anticipated such as determining certain atmospheric constituents as a function of altitude.

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TECHNICAL REPORT SUMMARY

After reviewing the available literature and trade journals, we arrived at the conclusion that we would have to design and fabricate our own cryogenic enclosure in order to fulfill the requirements imposed by its predetermined use. This dewar is intended for the special application of providing a liquid nitrogen temperature environment for an interferometer. Integral within the dewar a platform must also be provided on which the interferometer can be mounted and the entire mechanical structure must be strong enough to withstand a 10 G load.

The optical platform structure had to be designed rigid enough to be able to maintain optical alignment, and the outer cylindrical structure had to support in excess of one atmosphere of pressure. The chamber itself was designed to maintain a vacuum of approximately 10^{-4} torr. In order to be efficient the cryogenic enclosure has been equipped with a cold shield and a radiation shield. Access to both the front and rear sides of the dewar are available by means of bolt-on covers attached to large flanges and sealed by o-rings.

PRELIMINARY RESEARCH AND INVESTIGATION

A careful research of the available literature and of several textbooks on cryogenic enclosure design and theory show that most available dewars are cylindrical in geometry and are built to stand upright. That is, the cylindrical axis is vertical. The exception to this rule appears to be confined to dewars that are used to transport liquid nitrogen or liquid helium or other liquified gases. However, this type of dewar is used exclusively for transportation and is not used in general for experimental purposes.

The design concepts involved in the construction of cryogenic enclosures are not particularly difficult to understand. Essentially one is attempting to construct an enclosure which is extremely well insulated. Incorporated within this structure will be a container which will be filled with L/N or some other liquified gas. The system is initially cooled down to the L/N temperature by means of L/N external to the system. When the whole system has been brought to the required temperature the storage tank containing the L/N within the system should be of sufficient capacity

to maintain the required temperature within the dewar for the specified period of time. The system should be efficient, that is to say, the heat transmitted from the external world into the cryogenic enclosure should be kept at a minimum. The problem then, in so far as cooling is concerned, is primarily, first, of determining on the one hand the amount of L/N needed to accomplish the hold time specified and second, of doing this efficiently. The procedures for doing this are relatively standard and impose more in the way of ingenuity on the part of the designer than they do in the way of theoretical investigation.

There are essentially three ways that heat can be introduced into the cryogenic enclosure. They are; one, by conduction; two, by convection; and three, by radiation. Since the enclosure is going to be capable of supporting a reasonably stiff vacuum, the loss by heat convection into the enclosure can be neglected as being a minimal factor. Radiational inputs are for the most part taken care of by an adequately designed radiation shield using commer-

cially available materials. With this information as a background, the designer is then left with an iterative process of determining on a first cut basis what he presumes will be the losses into the system as a function of conductivity paths for a given preliminary mechanical design structure and by performing indicated modifications, one eventually hopes to reach an acceptable design configuration. This we have succeeded in doing.

MECHANICAL CONSIDERATIONS

The first thing that we had to determine in connection with the mechanical design was the minimal allowable size which we could use to accommodate the interferometer configuration and its associated hardware. We then had to see if there was a stainless steel tubing size having a wall thick enough for our dimensional needs. A 29 inch I. D. Diameter tube 46 inches long and made of stainless steel was available and appeared to be adequate. The wall thickness of the tubing was also adequate to sustain an excess of one atmosphere of differential pressure. With this basic geometry to work with we next proceeded to determine a viable support configuration for the optical platform on which the interferometer would be located. We also decided that it would be a convenient procedure to incorporate the liquid nitrogen tank as part of the design of the optical platform. There were essentially two reasons for doing this. They were that we would be able to realize an excellent thermal conductivity path to the interferometer while at the same time increasing the rigidity of the optical platform on

which the interferometer would be located. From this point on it became a question of determining the support method that we would use to hold the optical support platform in place on the inside of the tubing. At this point we were confronted with the necessity for a materials investigations. We wished to find what materials were available for supporting the optical platform which would do so in such a manner as to provide adequate rigidity, adequate strength, while not introducing an intolerably high heat input from the outside of the cryogenic enclosure to the inside through thermal conductivity. Many materials were investigated and as it turned out the two materials having a high factor of merit were stainless steel and fiberglass. We should at this point define what we conceive to be a high factor of merit. It was simply the ratio of strength of the material (usually tensile) divided by the thermal conductivity of the material. Having decided upon the materials that we intended to use, we were then confronted with determining the best geometrical configuration which would satisfy the needs for rigidity and strength and at the same time provide us with a relatively low heat input by thermal conductivity. What

we desired was as long a path from the outside of the cryogenic enclosure through the support members to the optical platform as possible. The way that this was accomplished was by designing stainless steel clamps used to clamp the cylindrical fiberglass tubes which we intended to use. These clamps were welded to the inside of the cylindrical cryogenic enclosure in such a manner as to bring their upper portion to the outsides of the support structure. In addition they were connected to it by bolts in such a way as to render the cylindrical cryogenic enclosure essentially stress free as a result of any inertial loading which might occur because of the mass of the interferometer, liquid nitrogen tank and optical base. The support clamps were fitted into the fiberglass tubes which are approximately 22 inches long. At the bottom of the fiberglass tubes which extend well below the optical base, were fitted threaded stainless steel tubing which would be co-axial to the fiberglass tubing and have clamping means at their extreme bottom ends for clamping the fiberglass supports at their bottom. These stainless steel supports extend upwards and a threaded portion fits into four slots appropriately located on the optical base. The stainless steel support clamps were threaded in such a manner as

to make it reasonably easy to adjust the height of the optical platform to make for ease in optical alignment. In designing this total configuration care was taken to insure that considering the complexity of the structure the various components could be assembled and disassembled in a reasonably convenient fashion. In order to insure this, flanges were welded to both the front and the rear of the 29.5 inch diameter tubing. These flanges were machined to accommodate o-rings in order that a proper vacuum seal could be achieved. The stainless steel cover plate which would be used on the rear of the enclosure and would be bolted to the o-ring flange was equipped with an additional o-ring cover port centrally located. This would be of help in assembling the entire cryogenic enclosure. On the front o-ring cover a large opening was machined in order to be able to mount the various optical fixtures that would be needed as optical entrance ports for accomplishing the experiments.

At this point we should mention that the final dimensions of the fiberglass tube support elements were arrived at by a study of their structural strength and of their thermal properties. Various computer programs were accomplished to facilitate this procedure.

What we did in essence was to determine what the maximum elongation of the fiberglass rods would be under the maximum loading that the system would experience. More importantly we also investigated the fiberglass supports as cantilever structures and determined what the deflection would be under the maximum G loading condition. This kind of analysis of the support structure is certainly a worst case analysis. After several iterations of this process, that is, determining maximum flexure and then determining heat loss, we were able to arrive at what we thought was a reasonable compromise in terms of these two conflicting demands. Since the G loading on such a mechanical structure is never known with great precision, we also incorporated into our design a system of bumpers which will provide the total package with considerable design safety margins. This non linear system design of bumpers consisted of eight fixtures, two of which were located at each corner of the optical platform. These fixtures consisted of an adjustable conically shaped nylon bumper adjusted in such a manner as to be approximately 30 thousandths of an inch away from the optical platform. As a consequence of the separation

no thermal conductivity path resulted. However, in the event of a very large G load, the bumpers would take up the excess force as a compressive load and would therefore considerably increase the maximum G load that the system could sustain without doing damage to it.

THERMODYNAMIC CONSIDERATIONS

We have already indicated that in the process of designing the mechanical structure for supporting the optical platform on which the interferometer would be placed, we have had to consider the heat losses that would be necessitated by such a mechanical structure. In order to do this with any degree of accuracy it is necessary to establish an average thermal conductivity for each material used. This means that one needs to have graphical or tabular data of the thermal conductivity of the material in question as a function of temperature over the region of interest. With this data one can integrate over the temperature region in question to determine the area under the thermal conductivity curve versus temperature. With this data in hand, one then determines an average thermal conductivity. The average thermal conductivity figure can be used in the following equation.

$$W = (T_1 - T_2) (YA/L)$$

Where:

W	=	Watts
T ₁	=	High Temperature °K
T ₂	=	Low Temperature °K
Y	=	Avg. Thermal Conductivity (Watts/cm °K)
A	=	Cross Sectional Area (cm ²)
L	=	Length (cm)

A list of the thermal conductivity paths is then made up. This list would include all support members connecting the outside of the cryogenic enclosure to the optical support bench, all input and output electrical wiring, the input and output liquid nitrogen piping and finally the laser fiberglass input optical system. The total wattage due to all of the thermal conductivity of these input means are given in Appendix One of this report.

Heat conduction by residual gas - This process is usually referred to as convection heating and is a particularly complicated matter at high pressures. However, the process becomes more easily understandable at around 10 microns of pressure. We have at two parallel surfaces, separated by a certain distance, the phenomenon of molecules bouncing back and forth between a hot surface and a cold surface. Very little interaction will take place between the molecules themselves. Under these circumstances it can be shown that the amount of heat transferred is independent of the separation between the two surfaces. This fact established a useful design criterion in that it implies there is nothing to be gained by

having a large space between the outer shell of the cryogenic enclosure and the radiation shield adjacent to the cold shield. In any event it is extremely difficult to determine precisely what the heat losses will be as a result of residual gas. This, however, is generally not a serious matter. The general rule is to insure, usually by mechanical pumping, and later on by cryogenic pumping, that the residual gas left in the cryogenic enclosure is of such a low pressure as to make losses due to this phenomenon of academic interest only.

Radiational Heating - The Stefan-Boltzmann equation,

$$W = \sigma e A T^4$$

where e is the emissivity at temperature T , ($^{\circ}\text{K}$)

A is the area, and

σ is the constant 5.67×10^{-12} watt cm^{-2} (degrees Kelvin) $^{-4}$

gives the watts of radiant power emitted as a function of the given parameters. The exchange of radiant energy between two surfaces is given by the expression $W = \sigma A E (T_2^4 - T_1^4)$ where T_1 and T_2 are the temperatures of the two surfaces respectively. This equation shows that exchange of temperature between the outside wall of the dewar, approximately 296 degrees Kelvin, and the in-

side of the container at approximately 70 degrees Kelvin, would be a linear function of the total area A and the emissivity e of the materials. It is obvious upon inspection of the equation that if T_1 and T_2 are at the same temperature or very nearly the same temperature there is no heat exchanged. The knowledge of this fact justified the use of the so-called cold shield. The cold shield in our case consists of a cylindrical aluminum sheet wrapped with evenly spaced 1/4" diameter aluminum tubing. On the front and back of the cryogenic enclosure there are also fitted 2 circular plates onto which 1/4" aluminum tubing has been fastened. This entire configuration is piped so that liquid nitrogen from the storage tank first passes through the front circular cold shield, then to the cylindrical cold shield, and finally out through the rear circular cold shield. This entire arrangement provides the interferometer with a temperature shroud having a small temperature differential from that of the instrument itself from all points of view except for the necessary optical input ports.

Radiation Shields - In the equation $W = \sigma EA(T_2^4 - T_1^4)$ giving the net exchange of radiant energy between two surfaces, the value of E is of considerable significance. It is immediately obvious that if the value of E could be made to be equal to 0, the heat exchange between the 2 surfaces would also be 0. The value of E is of course a function of the emissivities of the two surfaces that are coaxial to each other in all configurations. It can be shown that if the emissivities of either of these two surfaces is equal to 0, then again the net heat flow from one surface to the other will be 0. A great deal of work on materials has been done in an attempt to approach this ideal condition. The net result has been that certain materials have been developed which produce exceptionally good results. Such a material is commercially known as Dimplar and consists of a mylar base coated with a highly reflective aluminum coating. It has been shown that a 16 layer combination of flat and dimpled material produces about the best compromise of total volume versus effectiveness in this type of material as a radiation shield.

This information has been arrived at by experimentation, consequently we have incorporated this criterion into our design and have applied 16 twin layers of Dimplar onto the two circular cold shields and also onto the cylindrical shield. Finally, it should be pointed out that the application of this material to the cold shields greatly increases the necessary pump-down time in order to produce the required vacuum. It is also helpful to know that in order to speed up the pump-down time, it is sometimes convenient to heat the entire enclosure using infrared lamps. We have also incorporated into the system two heaters for heating the inside of the cryogenic enclosure. These heaters may be used at pump-down time to also accelerate the process. Complete pumping down of the system to approximately 1 to 10 M Torr should take place before any attempt is made to fill the liquid nitrogen system. It should be pointed out also that the cold shields in the system perform another very valuable function aside from their normal use, and that is as a cryogenic pumping means. As a pumping mechanism the cold shields are extremely effective.

LIQUID NITROGEN TANK

The liquid nitrogen tank is a 25 inch long, half-moon shaped configuration welded to the bottom of the optical bench. In addition to the two half-moon ends on the tank which are used to complete the enclosure, there are three additional half-moon plates welded, equally spaced, onto the optical platform and extending down symmetrically but not touching the half cylindrical part of the liquid nitrogen tank. These three half-moon plates serve two purposes, to provide additional rigidity to the optical platform, and to provide a thermal conductivity path from the liquid nitrogen to the optical platform. These three plates have had holes bored through them to allow the liquid nitrogen to flow freely inside the tank. In addition to providing a low thermal conductivity path to the optical platform, these plates also make the unit's cooling efficiency as the liquid nitrogen level goes down more nearly constant. The tank's capacity is approximately 20.85 liters. The heat of vaporization of L/N is 47.6 cal. per gram and there are 808 grams per liter.

Thus:

$$(20.85 \times 808) \times (47.6) = 801907.68 \text{ cal.}$$

Since 1 watt hr = 860.04 cal. we then have:

$$\frac{801907.68}{860.04} = 932.4 \text{ Watt-Hrs.}$$

JOULE HEAT INPUT

This source of heat input is a result of energy input to the various electrical sensors and the linear drive motor associated with interferometer. The motor current will account for about 95% of the total energy input resulting from this source.

The resistance of the motor coil is approximately 6 ohms at room temperature and the average current is not expected to exceed 0.1 amperes. The heat input is then given by:

$$W = i^2 R$$

$$W = .060 \text{ watts (worst case condition)}$$

RECAPITULATION OF HEAT INPUTS

SUPPORT COLUMNS	1.194	Watts
STAINLESS STEEL TUBING	.05	Watts
STAINLESS STEEL TUBING	.042	Watts
STAINLESS STEEL LIGHT PIPE	.0176	Watts
ELECTRICAL WIRES	.11245	Watts
JOULE HEATING	.060	Watts
RADIATIONAL HEATING	3.9	Watts *
TOTAL	5.4	Watts

Since the L/N storage tank has a heat input capacity of 932.4 watt-hours cooling time due only to heat of vaporization, (that is completely neglecting the cooling capacity of the gas phase), there should be no problem in exceeding the 8 hour hold time.

* See Appendix 1

APPENDIX 1

THERMAL CONDUCTIVITY

HEAT INPUT

1.

Four support columns

G2 Fiberglass

Thermal Conductivity (avg.) 4.25×10^{-3} watts/cm °K

Dimensions

OD = 5.08 cm

ID = 2.54 cm

L = 48.26 cm (LENGTH)

$$A = 15.2 \text{ cm}^2$$

$$4A = 60.80 \text{ cm}^2$$

$$W = Y \frac{A}{L} (T_1 - T_2)$$

$$W = 1.194 \text{ watts}$$

2.

Stainless Steel Tube

Thermal Conductivity (avg.) .1825 Watts/cm °K

Dimensions

OD = .635 cm

ID = .47625 cm

L = 2.9 cm

W = .05 watts

Stainless Steel Tube

Dimensions same as above except

L = 280 cm

W = .042 watts

3.

Stainless Steel Light Pipe

Dimensions

OD = .15875 cm

ID = .000

L = 45.72

W = .0176 watts

TOTAL SURFACE AREA

$$A_1 + 2A_2 = A_t$$

$$A = 2\pi RL = \pi \times 30 \times 47 = 4429.65 \text{ in}^2$$

$$4429.65 \text{ in}^2 = 9.82 \text{ FT}^2$$

$$A_t = 30.76 + 9.82 = 40.58 \text{ FT}^2$$

For a wrap system of 16 flat and 15 Dimpled such as we used,
the manufacturer gives a figure of heat flux input of
.327 BTU/HR-FT²

$$\frac{.327 \text{ BTU}}{\text{HRFT}^2} \times 40.58 \text{ FT}^2 = \frac{13,358 \text{ BTU}}{\text{HR}}$$

$$\text{Since } 1 \text{ WATT} = \frac{3,413 \text{ BTU}}{\text{HR}}$$

the radiational losses are:

$$\frac{13,358}{3,413} = 3.9 \text{ WATTS (Radiational Input)}$$

The following persons contributed to the research reported on in the document:

James L. Pritchard, Senior Scientist
Robert R. Trottier, Electronic Engineer
George J. Hromnak, Research Associate
Elaine Pritchard, Research Associate

This contract was related to contract #F19628-73-C-0175, previously completed, under which the interferometer to operate in this Dewar was developed, and under which final report number AFGL-TR-76-0311 was published.

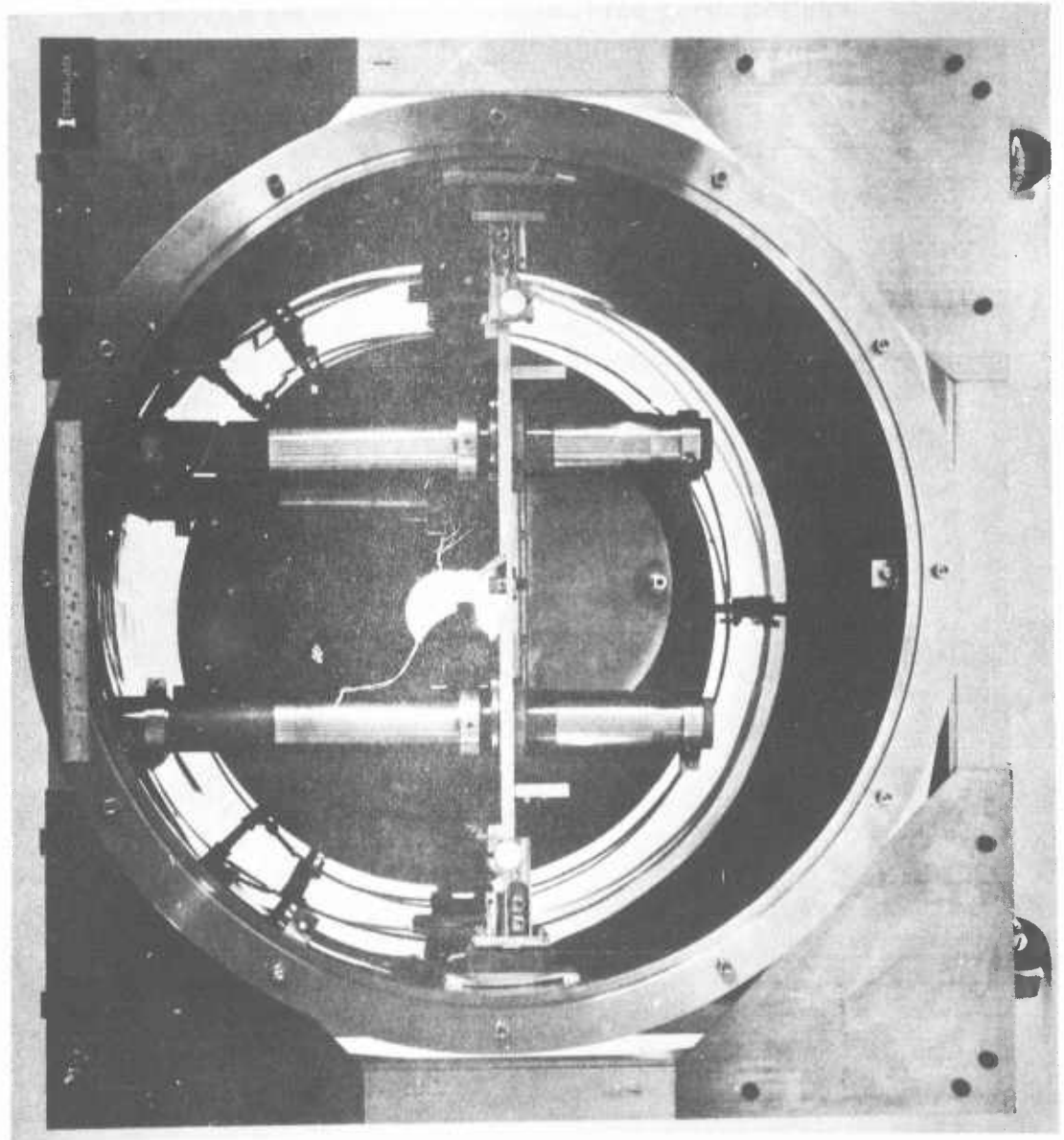


Figure 1 - Cryostat

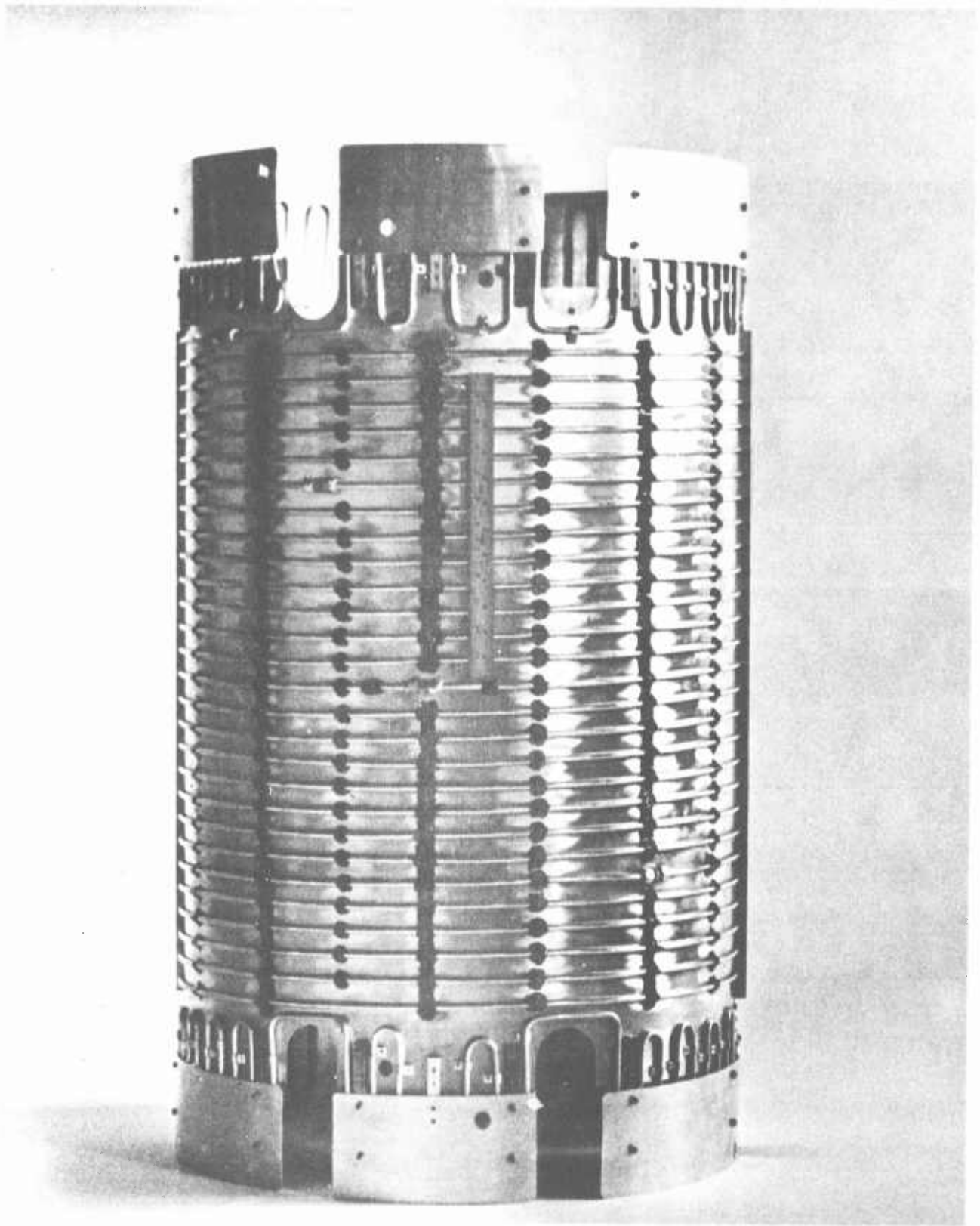


Figure 2 - Cold Shield

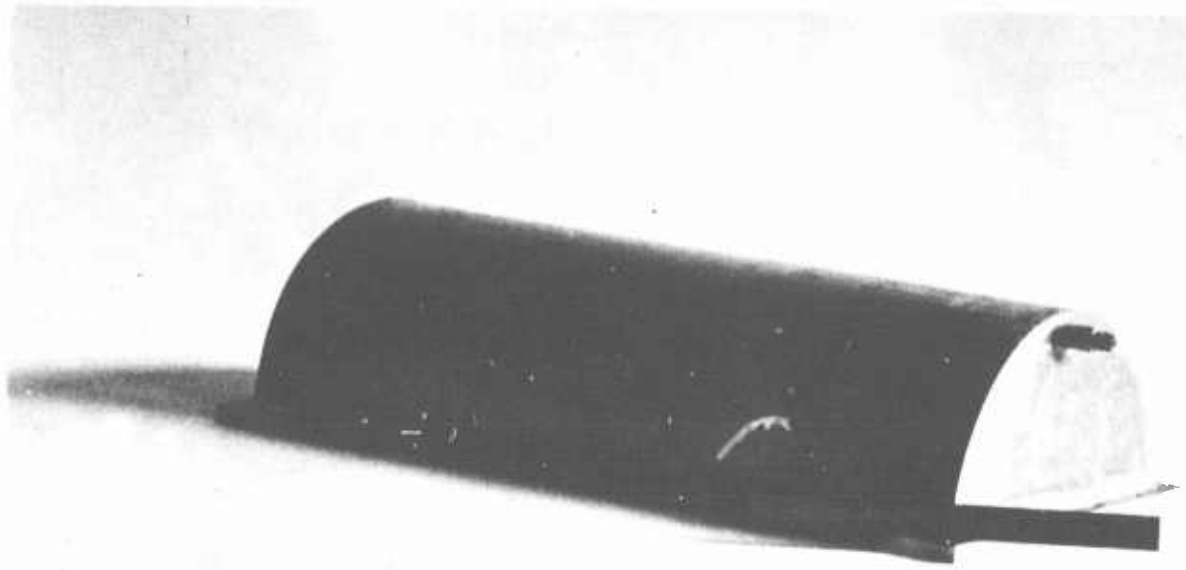


Figure 3 - Liquid Nitrogen
Container

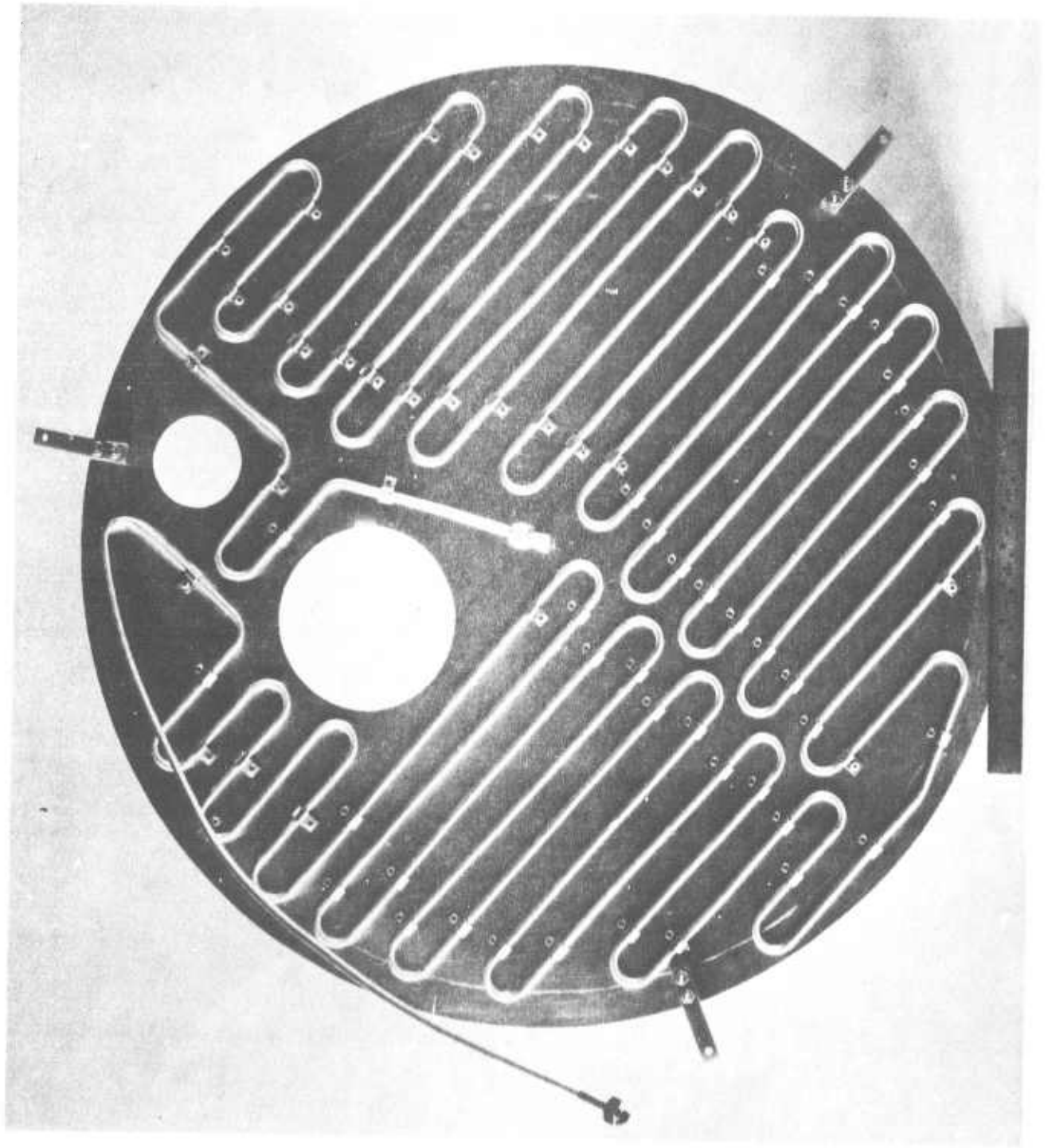


Figure 4 - Front Cold Shield

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