A Cryocooler for Applications Requiring Low Magnetic and Mechanical Interference*

J. E. Zimmerman, D. E. Daney, and D. B. Sullivan
National Bureau of Standards
Electromagnetic Technology Division
Boulder, CO 80303

ABSTRACT

A very low-power, low-interference Stirling cryocooler is being developed based on principles and techniques described in several previous publications over the last four years. It differs in several important details from those built previously. It uses a tapered displacer based upon an analytical optimization procedure. The displacer is driven by an auxiliary piston and cylinder (rather than by mechanical linkage) using some of the working fluid itself to provide the driving force. This provides smooth, vibration-free motion, and, more importantly, allows complete mechanical and spatial separation of the cryostat from the pressure-wave generator. Either of two different pressure-wave generators can be used. One is a non-contaminating, unlubricated ceramic piston and cylinder. The other is a compressed-air-operated rubber diaphragm with motor-driven valves to cycle the pressure between appropriate limits.

INTRODUCTION

For several years we have been investigating new variations on the well-known split Stirling mechanism for cooling very low-power cryoelectronic devices [1, 2, 3, 4]. The variations have included (1) the use of plastic and composite materials for the low-temperature stationary and moving parts and for the regenerator, (2) optimizing the geometry and other parameters to minimize the input power required, (3) electronic stabilization of the low temperature end, (4) simple construction which permits considerable design flexibility at moderate cost, (5) as many as five stages of refrigeration, (6) operation at sub-atmospheric pressures to enhance regenerator efficiency and permit operation at temperatures approaching 3 K. As part of these investigations we have demonstrated operation of a SQUID at 8.2 K in a four-stage cryocooler and a SQUID gradiometer at 7 K in a five-stage cryocooler.

* This work has been supported primarily by the Office of Naval Research.

This paper covers what may be regarded as the final phase of this line of development, including (1) use of a compressed-air-actuated neoprene diaphragm pressure-wave generator which permits removing the electric-motor drive and accompanying interference from the vicinity of the cryocooler, (2) an unlubricated alumina piston and cylinder for a long-life non-contaminating pressure-wave generator, (3) preliminary results on manufacturing an epoxy- glass-composite tapered displacer and sleeve incorporating a titanium-foil diffusion barrier, (4) a low-vibration gas drive for the displacer, in which part of the working fluid itself is conducted through a phase-shift mechanism to an auxiliary piston connected to the displacer. A fifth item on this list, the computer derivation of the optimum distribution of refrigeration, is described in the accompanying paper [4].

The first two items on the preceding list represent alternate mechanisms for producing a pressure wave in the working fluid, as required by the thermodynamic cycle. There are several reasons why one or the other of these mechanisms might be preferred for a particular application. For example, the diaphragm pressure-wave generator is relatively very cheap to manufacture, but outgassing of the rubber and helium diffusion through it may cause problems where long-term continuous operation is required.

The present developments are aimed toward the production of a low-interference cryocooler for highly critical applications such as SQUID-based instruments, which at the same time offers reasonable reliability, portability, ease of operation, and moderate cost.

THE CONCEPT OF A LOW-INTERFERENCE CRYOCOOLER

The essential elements (to be described in the following sections) of a low-interference cryocooler are shown in figure 1. The principle element which qualifies it as "low interference" is the gas-drive mechanism for the displacer. The mechanism has only one moving part with only one degree of freedom, and the gas drive is inherently "soft". Thus, vibrational interference associated with the displacer motion should be greatly reduced compared to that produced by the rotary-reciprocating mechanical drive used previously. In addition, since there is no mechanical connection to the pressure-wave generator, the latter can be placed an arbitrary distance from the cryostat, subject only to the requirement that it have the capacity to handle the extra volume of a long gas line. This physical separation of the two sections of the cryocooler essentially eliminates the pressure-wave generator and its drive mechanism as a source of magnetic interference or vibration, and it also makes the system flexible in that different generators may be interchanged depending upon the requirements of different applications. Two different types of generators have been built. One is electric-motor driven and uses an unlubricated close-fitting alumina (Al_2O_3) piston and cylinder for long-term continuous operation without gaseous contamination. The other is a neoprene diaphragm driven by compressed air alternately applied to the back side of the diaphragm and released to the atmosphere by a pair of cam-operated valves. A third possible way to generate the pressure wave is to use a commercial helium compressor and purification system, alternately admitting high-pressure helium directly to the refrigerator and releasing it to the compressor input with cam-operated valves. A small commercial helium compressor should have the capacity to simultaneously operate several refrigerators of the size we are studying.

The tapered displacer and sleeve (with gap regenerator) was envisioned as a configuration that could be easily manufactured, with whatever profile would provide the optimum distribution of refrigeration as derived by the optimization procedure described in the accompanying paper. The sleeve incorporates a thin metal-foil barrier to block helium diffusion into the vacuum space. Lacking such a barrier, our earlier cryocoolers would not maintain a low temperature for more than a few minutes without continuous pumping. The bottom end of the sleeve also has molded into it an aluminum thermal link between the expansion space and the device chamber.

The system as sketched in figure 1 has been assembled and operated, but with only partial success. In particular, problems have been encountered in fabricating a leak-tight displacer sleeve. Current tests are being run using the five-stage displacer and sleeve described previously, in which a temperature below 7 K was maintained. It should be emphasized that nearly every component of the system represents a significant departure from previous practice, and so some practical difficulties might have been anticipated. On a positive note, none of the defects appear to be conceptual or fundamental, and the remedies are fairly obvious.

The following paragraphs describe the design and tests of the various components.

AIR-DRIVEN DIAPHRAGM PRESSURE-WAVE GENERATOR

Figure 2 shows a cross-section of a neoprene rubber diaphragm, 1.5 mm thick, clamped between circular aluminum plates with smoothly machined surfaces. The surfaces were given a sinusoidal contour so that the rubber is not sharply bent at any point when pressed against either surface (whether or not a sinusoidal contour is optimum for this purpose has not been determined). Several narrow, 1/2 by 1/2 mm, radial grooves were cut in each surface to prevent gas being trapped in case the center of the diaphragm should contact the surface first and block the port. Each port consisted of several small holes rather than one large hole, again for the purpose of preventing stresses on the diaphragm due to sharp bends.

The air-control system, shown schematically in figure 2, consists of a pair of "miniature" bellows-sealed valves, operated by cams to alternately admit high-pressure air ($\sim$ 0.6 MPa) to the diaphragm and release it to the atmosphere, at a rate adjustable around one cycle per second.

PRESSURE-WAVE GENERATOR USING CERAMIC PISTON AND CYLINDER

For some applications (as when compressed air is not available) a conventional generator using a motor-driven piston and cylinder is more convenient. The idea of using hard, unlubricated (or gas-lubricated) sliding surfaces to avoid contamination of the cryostat by liquid lubricants is fairly well known. An alumina (Al_2O_3) piston and cylinder has been operated at 1 cps for over 7000 hours without significant increase of leakage after the first 1000 hours [1]. The leakage rate ("blowby") amount to less than one percent of the total gas leaking past the piston during each compression and expansion cycle. This evidence indicates that the unit should be good for several years of continuous operation at pressures in the neighborhood of a few atmospheres and a speed of 1 Hz.

The pushrod seal is a potential source of contamination both from condensable gases in the grease and, perhaps, from air which might be trapped in the grease and dragged past the O-ring. A double seal was used in an attempt to greatly reduce the contamination. Two O-rings were separated a distance equal to the piston stroke, so that air trapped in the grease would not be dragged all the way from the outside atmosphere into the cylinder in each stroke. Air that is dragged into the intermediate space was diluted by being vented into a small auxiliary helium reservoir. An extra benefit of this arrangement is that grease applied to the pushrod between the O-rings will be pushed into a circumferential ridge which alternately contacts each O-ring at the limits of the stroke - in effect, the O-rings act as grease retainers for each other.

TAPERED DISPLACER AND SLEEVE WITH DIFFUSION BARRIER

The accompanying paper [4] describes the analytical procedure for optimizing the distribution of refrigeration vs. temperature through the use of a tapered displacer and matching sleeve (here we have chosen the term "sleeve", since "cylinder" obviously is not appropriate). A conical glass-epoxy displacer and sleeve, with which a temperature of 9 K was achieved, has been constructed by Myrtle et al [5], showing that the concept is viable. We have attempted to add several features to the concept. Our experimental units are filament-wound except at the small end, a technique which should give better structural homogeneity than cloth layers, and may be more suitable for commercial production (even better might be injection molding, a technique that has not been tried). An aluminum thermal link, molded into the bottom end of the sleeve, is an important feature (figure 3). It should increase the refrigeration efficiency by providing a low-resistance connection between the expansion space and the thermal load, resulting in more nearly isothermal expansion. An essential feature is a 30 μm titanium-foil diffusion barrier laminated into the sleeve about a millimeter from the inner surface, and extending from the top down about three-quarters of the total length. It was considered too difficult to extend the foil all the way to the bottom, but this should not be necessary since diffusion should be negligible at the cold end.

The manufacturing process, which was done by a commercial firm, consisted of filament-winding a thick layer of glass thread and epoxy over a stainless-steel conical form, the small end of which was held in a steady-rest made of 9 mm rod. After curing and removing the form and rod, the 9 mm hole in the small end was filled with a mixture of chopped fibers and epoxy and cured again. This constituted the "blank" for the displacer, which was then machined on a lathe to the desired tapered shape and wall thickness. The displacer itself was used as the form for the sleeve, which was fabricated by exactly the same process. The diffusion barrier was incorporated during filament winding, and the aluminum thermal link was put in place in the small end along with the mixture of chopped fibers and epoxy. The sleeve was then machined to the appropriate external shape.

Filament-winding has been highly successful for construction of cryogenic pressure and vacuum vessels of various shapes. However, our requirements posed some unique problems. The first sleeve that was built appeared not to have a good bond between the titanium foil and the epoxy, and also leaked along the aluminum thermal link. The latter was corrected, after a number of unsuccessful attempts by other methods, by pressing an aluminum cup with epoxy sealant over the bottom end so as to completely enclose the external part of the thermal link. In a second displacer and sleeve that has just been built, but not yet tested, the titanium foil was rough-etched with dilute hyroflouric acid to improve the bonding to the epoxy.

DISPLACER DRIVE

The most significant and unusual feature of the present cryocooler system is a displacer drive which uses some of the helium gas from the pressure wave generator, acting on a small auxiliary piston, to move the displacer (figure 3). The correct amplitude and phase relation between the pressure wave and the displacer motion are obtained by a pair of metering (needle) valves and a small adjustable auxiliary volume, as shown schematically in figure 1. In the absence of friction, no force should be required to move the displacer, and so, ideally, a single metering valve between the helium line and the auxiliary piston should provide $\pi/2$ phase shift. In an electronic system, the valve is analagous to a resistance and the movable piston is analagous to an infinite capacitance. The auxiliary volume and second valve, analogous to a second capacitance and resistance, provides additional phase shift, at the expense of requiring more helium gas (the analog of electric charge). Friction between the moving and stationary parts reduces the available phase shift, and requires more helium gas for a given phase shift. Since friction is difficult to predict and may vary with time, the auxiliary piston was made considerably larger than was estimated to be necessary in order to reduce the relative effects of friction and of gas leakage past the piston. Owing to this and other uncertainties, it is also difficult to predict the amount of gas, and the concomitant extra pressure-wave generator capacity, needed to operate the displacer drive.

The auxiliary cylinder was made of aluminum tubing with a thin stainless-steel inner liner, precisely ground to a uniform bore. The piston was made from a cylindrical cup-shaped aluminum piece with an outer nylon sleeve to rub against the stainless steel cylinder liner, with a radial clearance of perhaps 20 μm. The pushrod seal is a double O-ring arrangement with the same grease-retaining feature as the one described above in connection with the ceramic piston and cylinder.

The dead volume above the auxiliary piston acts as a nearly constant-pressure ballast reservoir, at a pressure slightly less than the average pressure below the piston, owing to the weight of the piston and displacer. In operation, the weight causes the displacer to rest briefly at the bottom of its stroke during each cycle - a very useful feature since it insures minimal dead volume in the expansion space (in zero gravity, this function could be provided by a lightweight spring). Another desirable feature of this type of displacer drive is that, although it is properly characterized as "soft", it is relatively stiff at the bottom of the stroke, owing to the nearly zero volume beneath the auxiliary piston. That is, the gas entering the zero volume will immediately provide a large force if the displacer does not immediately start moving upwards. Since any friction or viscous drag between a tapered displacer and sleeve should occur mainly at the bottom of the stroke (where the two surfaces nominally come into contact) the gas drive is relatively stiff precisely where stiffness is needed and not during the rest of the stroke. In normal operation, the displacer has not been observed to stick appreciably except when impurities have been frozen into the lower part of the regenerator gap. This latter condition must be prevented in the ultimate system, but when produced experimentally it is compensated for to a large extent by the stiffness of the drive mechanism.

This type of displacer drive is related to the so-called "free-displacer" mechanisms that have been used or tested rather extensively for small high-speed (> 10 Hz) cryocoolers for infrared detectors. These generally achieve the appropriate phase relation between displacer motion and pressure wave by tuning the mechanical resonant system consisting of the displacer-plus-piston mass and a gas spring - the mechanical analog of inductance and capacitance. So far as we are aware, there is no previous report of our type of drive, consisting of the analog of resistance and capacitance.

We might reiterate here again the feature of the gas drive which is of most profound significance from the point of view of eliminating magnetic interference and vibration, namely that it allows essentially perfect mechanical and spatial isolation of the pressure-wave generator from the cryostat.

PRELIMINARY TESTS OF THE SYSTEM

When an operating system like that shown in figure 1 was first assembled, using the components described in the preceding paragraphs, it achieved a temperature in the neighborhood of 30 K - exceedingly poor performance relative to the expected 6 or 7 K. Since the displacer and sleeve wall thicknesses had been machined somewhat greater than the design analysis called for, (∿ 5 mm instead of 3 mm), conduction heat input was expected to be correspondingly larger. The sleeve was subsequently machined to a thickness of 3 mm, but in so doing the machine tool cut into the titanium-foil diffusion barrier near the lower end, which caused a leak. On the basis of this and related evidence, it was concluded that the epoxy had not bonded well to the titanium. We were not successful in repairing the leak, so this particular displacer and sleeve was abandoned. Currently, the system is operating in the neighborhood of 10 K using the 5-stage displacer and sleeve described in earlier papers [1,3], still considerably short of expectations. Basically, the problem is that the amount of gas required for the displacer drive was underestimated, so neither the ceramic pressure-wave generator nor the diaphragm type has sufficient displacement (70 cm^3 and 100 cm^3, respectively) to produce the compression ratio of 3.7 at which a bottom end temperature below 7 K was previously achieved with the 5-stage displacer. Corrections to the present system would seem to be fairly obvious and straightforward, and the performance of the optimized system will be the subject of a future report.

With regard to reliability, no problems have been encountered. Except for the ceramic pressure-wave generator, none of the new components of the system has had extensive testing. The displacer drive mechanism has been operated about 1000 hours and the neoprene-diaphragm pressure-wave generator for over 2000 hours.

NOTE ADDED IN PROOF: Since this paper was submitted, two cryocoolers have been put into operation, using a concept which has evolved significantly beyond that shown in figure 1. A compressed-air-driven diaphragm, labeled (b) in figure 1, is used to produce the pressure wave in the working fluid, as shown. The displacer drive piston, however, is actuated through a separate helium line by a second, smaller air-driven diaphragm. The "phase-shift" components indicated in the figure are therefore dispensed with. The air-control valves for the two diaphragms are electric solenoid types, and their opening and closing times are programmed through a low-cost, fully dedicated microcomputer. The merits of this system as an experimental developmental device can hardly be adequately described in one paragraph, and full details will be submitted for publication later. The programmable control system allows independent control of onset, rate of change, and amplitude of both the pressure changes and the displacer motion; in other words, it provides arbitrary independent control of every part of the thermodynamic cycle, and the computer can be programmed to go through an optimization procedure in which each of a large number of parameters are successively varied to achieve lowest temperature, or most efficient operation at a particular temperature, or whatever is desired.

The two cryocoolers presently operating incorporate the 4-stage and the 5-stage displacers taken from cryocoolers described earlier [1,2,3], which used conventional piston-type pressure-wave generators and mechanical displacer drives. Both of the new systems reach temperatures significantly below what was reported previously, 7.6 K compared to 8.2 K for the 4-stage displacer, and comparable improvement for the 5-stage displacer, although owing to thermometer malfunction the latter has not been precisely measured.

Our attention now has returned to the task of fabricating and testing a continuously tapered displacer shaped according to the analysis given in the accompanying paper [4].

REFERENCES

[1]. J. E. Zimmerman and D. B. Sullivan, "A Study of Design Principles for Refrigerators for Low-Power Cryoelectronic Devices," NBS Tech. Note 1049. U. S. Government Printing Office, Washington, D. C. (Jan. 1982). (This and the following two references are available free from the authors. Address: National Bureau of Standards, Mail Stop 724.03, Boulder, CO 80303).

[2]. J. E. Zimmerman and T. M. Flynn, "Applications of Closed-Cycle Cryocoolers to Small Superconducting Devices," NBS Special Publication 508, U. S. Government Printing Office, Washington, D. C. (April 1978).

[3]. J. E. Zimmerman, D. B. Sullivan, and S. E. McCarthy, "Refrigeration for Cryogenic Sensors and Electronic Systems," NBS Special Publication 607, U. S. Government Printing Office, Washington, D. C. (May 1981).

[4]. D. B. Sullivan, R. Radebaugh, D. E. Daney, and J. E. Zimmerman, "An Approach to Optimization of Low-Power Stirling Cryocoolers," Second Biennial Conference on Refrigeration for Cryogenic Sensors and Electronic Systems, NASA CP- , 1983. (Paper of this compilation.)

[5]. K. Myrtle, W. Winter, and S. Gygax, "A 9-K Conical Stirling-cycle Cryocooler," Cryogenics 22, 139 (1982).

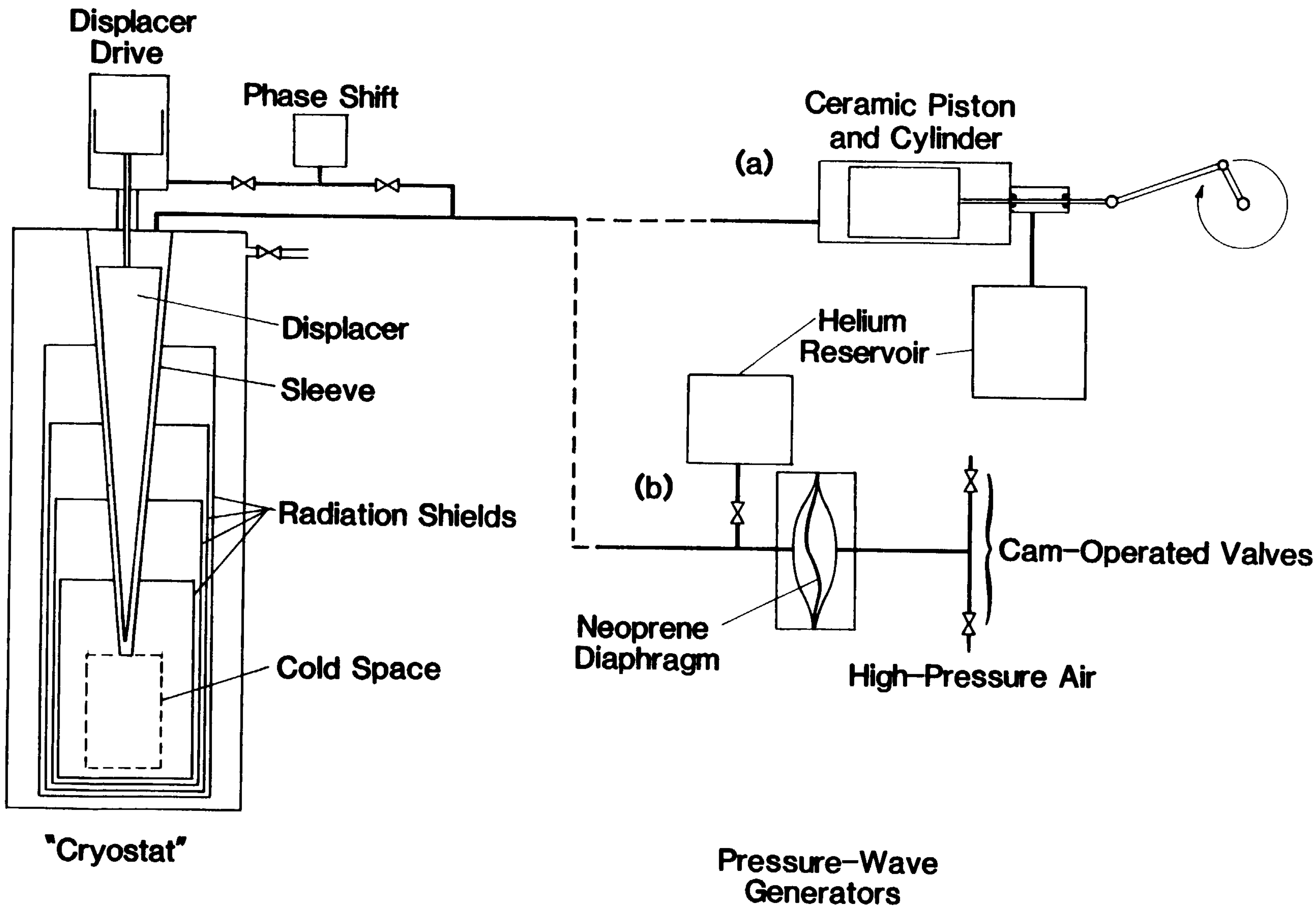

Figure 1. Conceptual Design of a Low-interference Cryocooler, with Two Different Options for the Pressure-wave Generator (a and b)

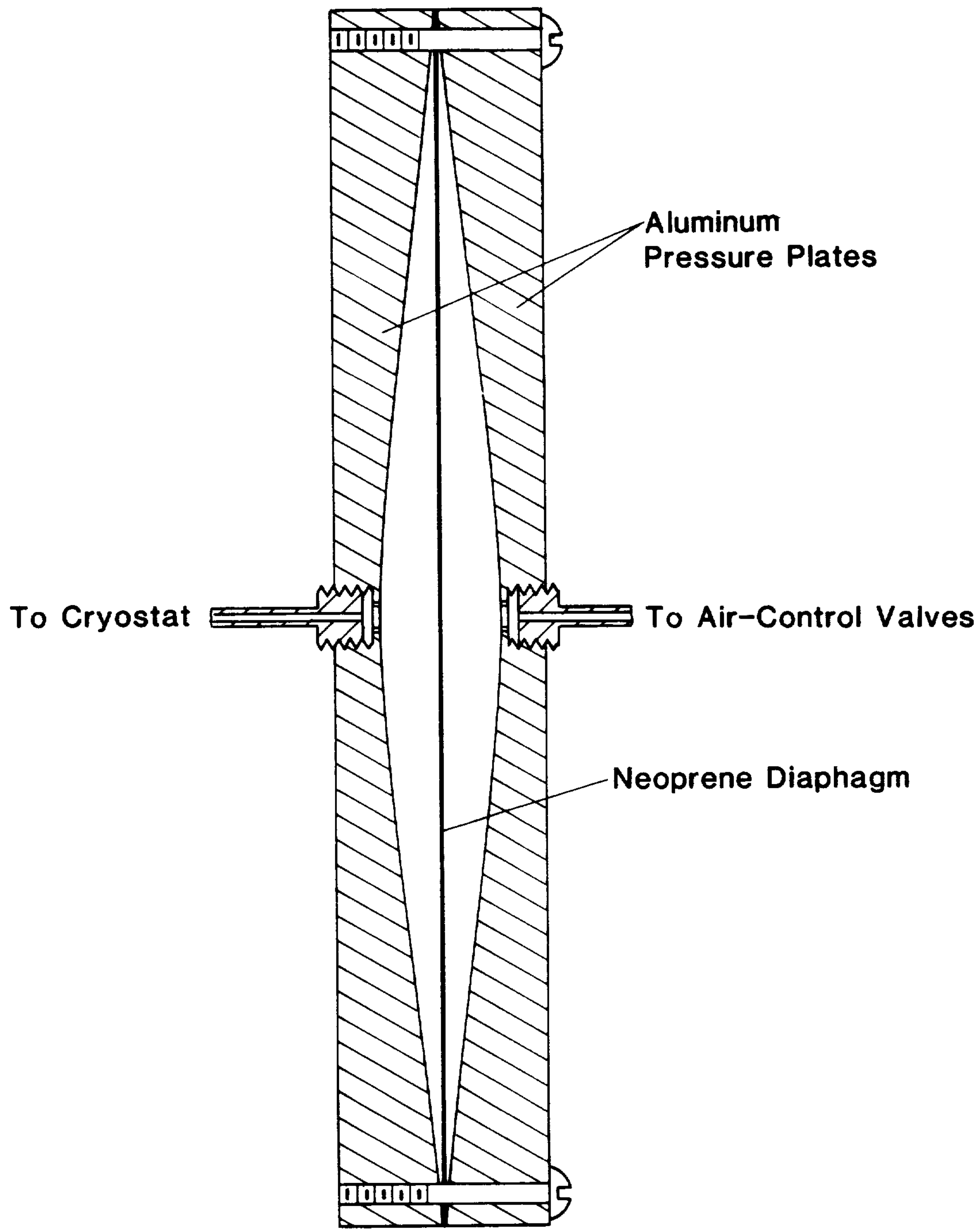

Figure 2. Diaphragm Pressure-wave Generator Driven by Compressed Air

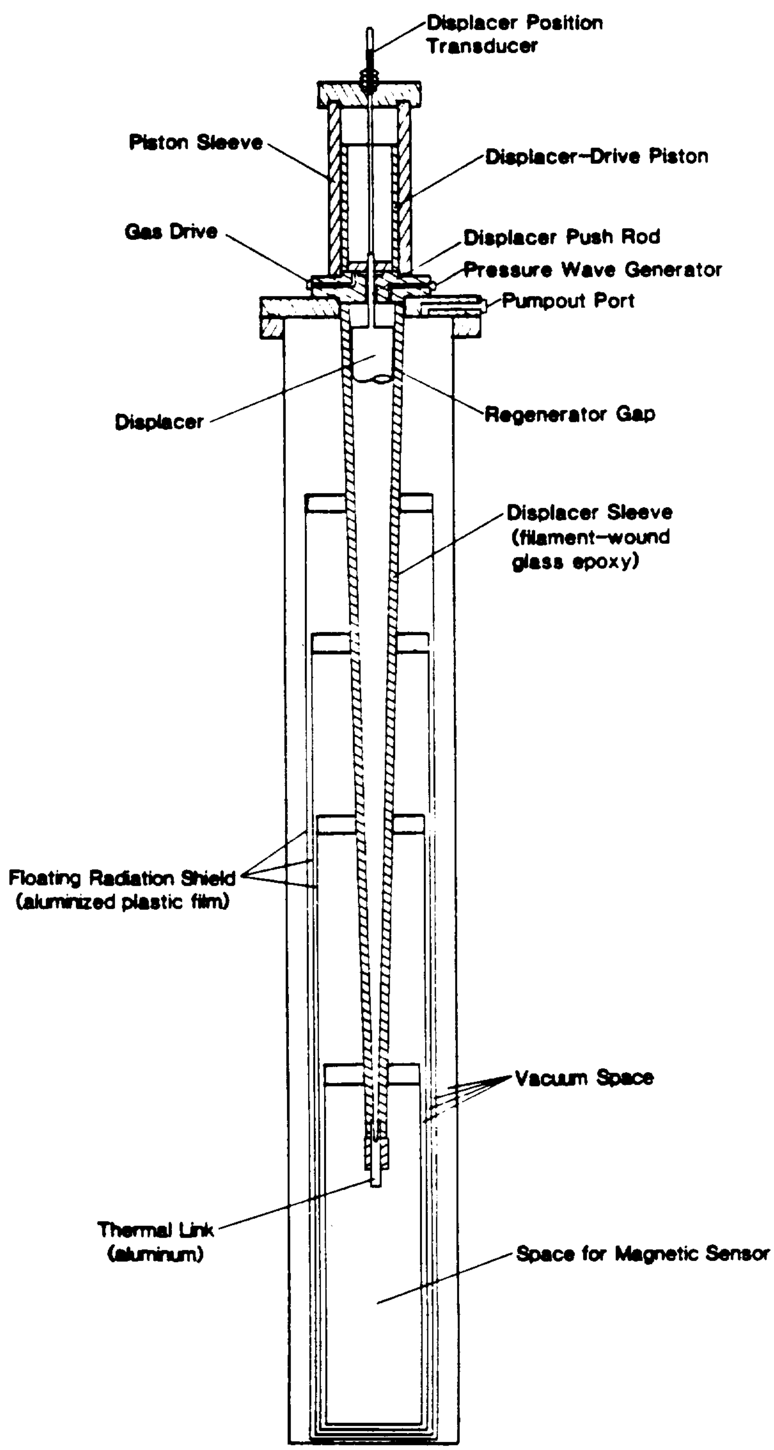

Figure 3. Tapered Displacer and Sleeve, Drive Mechanism, Radiation Shields, and Vacuum Jacket (collectively referred to in the text as the "cryostat")