SPLIT-STIRLING, LINEAR-RESONANT, CRYOGENIC REFRIGERATORS FOR DETECTOR COOLING

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ABSTRACT

Unfortunately, for user and manufacturer both, the closed-cycle cryogenic cooler to date has deserved its reputation as the "weak-link" in IR systems. When the cooler requires service at intervals of a few hundred hours at best, the quality of the system it serves is unfairly diminished.

This paper addresses technological advances in the art of Stirling-cycle coolers which will increasingly cause that image of military cryocoolers to change for the better.

For the past decade, military IR systems have preferred to see cryogenic coolers provided as "split" units; separating the functions of compressor and cold-end for system packaging and vibration isolation reasons.

A family of split-cycle coolers designed for long MTBF and in the final stages of development is the focus of the discussion. Their technological evolution, from multi-year-MTBF satellite system Stirling coolers developed in the U.S., and the UA 7011 cooler (the first all-linear, military, production cooler) developed in Holland, is explained.

Two new split-cycle machines are discussed. They provide 1/4 watt and 1 watt (nominal capacity) at 80°K and 85°K respectively. These linear-resonant, free-displacer Stirling coolers are designed for thousands of hours of service-free operation. They are designed to be compatible with standard U.S. 60 element and 120/180 element detector/dewars,respectively.

The technologies of linear-resonant compressor and free-displacer expanders as embodied in these machines is discussed in sufficient detail that the reasons for their superior performance (i.e., service-free life, low acoustic noise) will be clear.

INTRODUCTION

The Stirling refrigeration cycle, in its fifth decade of development, is by now well known to the technical community. One will recall that in its simplest embodiment, two pistons (the compressor piston and the gas displacer) operating on a fixed charge of non-condensible gas (helium), cause the gas to be compressed, cooled, expanded and reheated repeatedly so that in a certain portion of the machine, net refrigeration at very low temperature is achieved.

The ideal Stirling cycle is "Carnot-limited", that is, its efficiency for cold production is the highest possible. It is not the intent of this paper to review the theory of operation; for that the reader is referred to the original references, Reference 1 and 2, or a number of later papers. Rather, we shall discuss new embodiments which have been developed recently from innovations introduced by the same research laboratories which "discovered" Stirling cycle technology in this century, the Philips Research Laboratories of N.V. Philips in Holland.

LIFE LIMITING CONSIDERATIONS IN STIRLING COOLERS

The most significant life-limiting mechanisms in conventional miniature Stirling refrigerators are wear and contamination.

Figure 1 is a schematic illustrating a conventional embodiment of the Stirling refrigerator, and useful for pointing out its weaknesses. The two pistons must reciprocate with a fixed phase relationship for the refrigerator to function; as shown, this is accomplished by using a kinematic mechanism to convert rotary motion from a motor/crankshaft into the required linear motion of the pistons. The mechanism requires bearings which in turn require lubricants. Since the dynamic seal around the piston is not hermetic, lubricant vapors can migrate and be "gettered" in the low temperature region of the machine. Alternatively, without adequate lubrication or lubricant containment in the bearing, bearing failure can result.

The kinematic mechanism inparts a side-load which must be carried by a dry-lubricated guide on the pistons. This load causes accelerated wear of the guide bearings and seals, which both decreases compression and produces particulate debris over time.

The processes of wear and contamination are inter-related. Particulate contamination is an obvious wear product, and can obstruct internal heat exchanger flow passages within the machine. Not as obvious are gases, which are evolved from freshly exposed wear surfaces, and vapors evolved from the lubricant under high shear stress and temperature. These gaseous contaminants freeze within the cold region of the machine and degrade cooling performance as well.

HISTORY OF THE PHILIPS LINEAR-RESONANT COMPRESSOR, FREE DISPLACER MACHINE

In 1968, recognizing that the weak-link in conventionally-driven embodiments of Stirling cryogenic coolers developed to date was the compressor (bearing, sealing, and contamination problems, as well as high cost to manufacture), work was begun in the Philips Research Laboratories in Holland on the concept of a linear-resonant compressor, driven by a linear motor, for application to the Stirling cooler. This type of "free-piston, free-displacer" machine concept has far fewer moving parts, has eliminated crankshaft, bearings, and side-loads on dynamic seals, embodies clearance seals, eliminates lubricants, and can preserve the inherent efficiency of the Stirling cycle (the purpose of the "resonant" portion of its nomenclature), thus lending itself to long life and low cost in production. This new construction is discussed in a later paragraph.

The first generation of linear-resonant Stirling cooler product developed in Holland was the non-military MC-80 (Miniature Cooler, 80°,K), 1W @ 80°K cooler, brought into limited commerical production in 1975 by the Science and Industry Division of N.V. Philips.

In 1976, a second generation of linear-resonant Stirling coolers began in parallel in Holland and the U.S. In Holland, Philips Usfa B.V., a manufacturer of military infrared systems and products, undertook the development of a new cooler, in effect, a militarized version of the MC-80 machine. Initially dubbed the MMC-80 (Militarized Miniature Cooler, 80°K), and later officially designated the UA-7011 (see figure 2), this cooler was designed for and met full specifications for field, vehicle and aircraft use. Utilizing rare-earth cobalt magnets in its linear motor, and hermetic sealing of the helium, that cooler was brought into production and remains in production through the present day. Of particular significance is the fact that the cooler is sold with a 2500 hour guarantee on service-free MTBF.

The UA-7011 is distributed as the Magnavox MX7011 cooler in the U.S.; it is produced for Magnavox by Philips Usfa B.V. in Holland. While not readily compatible with standard U.S. military FLIR system components, there is interest in this highly reliable machine for use as a satellite-borne unit for cryogenic cooling in space.

In the U.S., Philips Laboratories Division of North American Philips Corporation, a Magnavox affiliate, began R&D for NASA and DARPA, applying the design concepts of the linear-resonant construction to satellite system coolers intended for three to five years of maintenance-free operation (reference 3.)

Figure 3 is a photograph of the NASA machine, designed for 5 W @ 65°K of refrigeration capacity. Its refrigeration performance has been proven in recent tests.

Currently at Magnavox, there is ongoing a program to design, fabricate, and prepare for test the first prototype operational cyrogenic cooler of this type for future use in multi-year satellite systems.

The third generation of linear-resonant cooler product development activities is ongoing at present and is the subject of this paper. The design experience and production know-how established in the development of the UA7011 cooler has been brought to bear on development of a family of split-cycle linear resonant coolers. This family consists of a standardized compressor section and two cold fingers which are designed expressly to interface with U.S. 60 element and 120/180 element detector/dewar assemblies; the resulting coolers having 1/4 watt and 1 watt refrigeration capacities, respectively.

Magnavox/EOS is the U.S. distributor for these linear-resonant coolers. Currently, these coolers are produced in Holland.

DISCUSSION

The Stirling cycle requires the interphased reciprocating motion of its two major elements, the piston and the displacer. Traditionally, this motion was generated by either conventional crank-type mechanisms or by the special Philips rhombic drive. In both instances, the rotary motion supplied by an electric motor had to be translated into the required linear motions of the piston and displacer.

In the linear-resonant cooler, the piston is directly reciprocated by supplying an ac waveform to the coil of an electric motor. The piston, in turn, by fluidic coupling, drives the free-displacer.

Elimination of the direct-drive coupling to moving piston and displacer made the problem of analysis, optimization, and design of the coolers far more difficult. While formerly the analysis task was fundamentally a problem in thermodynamic modelling and analysis, the step to free piston-free displacer required the integration of equations of the dynamics of motion of the moving masses, the electrodynamic equations governing the performance of the linear-motor,and more careful analysis of the flow-losses in the system. Several years of research, experimentation, and development were spent in validating the design methods and principles applied to this new class of machines. References 4 and 5 discuss the thermodynamic/dynamic and electrodynamic theory and principle of operation of the machine in detail, and should be consulted by those desiring a detailed theoretical understanding of the linear-resonant, free displacer, free-piston Stirling cooler.

LINEAR-RESONANT COMPRESSOR

Figure 4 illustrates the construction of the linear-resonant compressor. The compressor contains a piston which is fixed to the moving coil of a rare-earth-cobalt permanent-magnet linear motor. The linear motor is an alternating current device, i.e., when a voltage of a given polarity is impressed across its coil windings it delivers a force proportional to the current in one direction, when the polarity is reversed the direction of the force is reversed.

A mechanical spring, connected between the base of the piston/coil subassembly and the housing, maintains the midposition of the piston.

A single piston seal/guide is needed to separate the compression space above the piston from the motor compartment below the piston.

All of the forces acting on the piston are in the direction of its motion; i.e., no side loads are imposed on the piston guide and seal. Hence, a clearance-type of seal design may be used, resulting in extremely low wear of the seal/guide surface. No lubricants are needed or used.

A spring/mass vibration absorber is incorporated in the compressor to automatically attenuate the momentum imbalance resulting from the reciprocating motion of the piston/coil assembly.

The helium transfer tube connects the compressor to the displacer. Through it, the pressure wave created by the piston can act upon the free-displacer inside the cold finger assembly.

The compressor unit is sealed by a closure weld in order to ensure helium containment.

FREE-DISPLACER COLD FINGER

Figure 5 illustrates the construction of the cold-finger and the free-displacer. The function of the displacer is to alternately move the gas from the expansion to the compression space. When the piston goes down (expansion) the displacer must be near its lower position, so that the expansion process occurs at the end of the cold-finger. When the piston goes up (compression) the displacer must be near its upper position.

A mechanical spring affixed to the displacer and the housing forms part of a spring-mass system which is tuned to help provide the proper phase relationship between the movement of the piston and that of the displacer.

Gas from the helium transfer tube flows alternately from the compressor space towards the expansion space through the body of the displacer, which is filled with a porous-metal regenerative heat exchanger.

Since the forces on the displacer, like that of the piston, act only in the directon of motion, the necessary seal at the base of the displacer is a simple clearance seal.

PERFORMANCE OF LINEAR-RESONANT, FREE-DISPLACER COOLERS

a) MX7011: 1 W @ 80K

The MX 7011 cooler currently in production (figure 2) as part of a complete product test program, was subjected to an endurance test. Five coolers were each tested for 5000 hours, preceded by a 400 hour "run-in" period. The purpose of this test was to demonstrate confidence in the 2500 hour MTBF warranted for the product.

The test was automatically controlled and each 24 hour cycle included a one hour warm-up to room temperature. Periodically, performance at temperature extremes was checked against specification.

None of the coolers exhibited mechanical problems during the test, impressively demonstrating the inherent reliability of the linear drive and the dry-running clearance seals. The worst degradation in cold-finger temperature observed during test was less than 5°K. At the end of the 5000 hour test, all coolers were still performing to specification, and the test was discontinued. Inspection of the units upon disassembly revealed negligible wear and tear.

Figure 6 is a comparison of the acoustic noise from a model HD1033, 1W @ 80°K Standard Common Module Cooler and the noise from an MX7011, as measured in an anechoic chamber. At a frequency of 1000 Hz, its noise level is 20 dB lower.

b) Magnavox MX7040 and MX7043 Coolers

The Magnavox MX7040 and MX7043 (figures 7 and 8) are the first split-cycle linear resonant coolers in existance. They are currently in the final stages of development testing, with initial production scheduled for 1983. These coolers are being produced for Magnavox by Philips Usfa B.V. for sale in U.S. markets. As with the MX7011, they are intended to deliver an MTBF of 2500 hours without service.

The MX7040 (figure 7) is a unit designed for 1/4 W of cold production at 85°K with less than 40 watts of input power required over full military ambient temperature extremes. It weighs 4.2 lbs.

The MX7043 (figure 8) is a unit designed for 1 W of cold production at 80°K with less than 55 watts of input power over full military ambient temperature extremes. It weighs 4.2 lbs.

Both coolers have a vibration absorber (passive countermass) contained within their common compressor.

Life tests of two prototype MX7040 coolers have each demonstrated over 6500 hours of operation without failure.

c) Magnavox MX7045 Cooler

The MX7045 Cooler was developed by Magnavox to provide a "form-fit and function" compatible, improved-reliability (true 1000 hour) cooler meeting the U.S. Government B2-Specification (#2104070122) for a "1/4 W-Split". It was developed for use in systems which could not employ the superior linear-resonant coolers. The design approach taken was to incorporate the same proven design principles embodied in the free-displacer portion of the linear-resonant coolers (mechanical restoring spring, clearance seal) into the MX7045 cold finger while utilizing the "U.S. Standard" brushless dc motor driven compressor design (with a few product improvements devised by Magnavox engineers).

Magnavox/EOS has demonstrated the life and reliability of this "hybrid" 1/4 W split-Stirling cryogenic cooler under a U.S. Army program. The unit delivers 1/4 W of cooling at 85°K with less than 25 watts of input power over full military ambient temperature extremes.

CONCLUSIONS

The linear-resonant embodiment of the Stirling cooler has proven itself as synonymous with long-life and high reliability through two generations of production hardware. The newest generation of product, the split-Stirling coolers discussed herein, promises to retain all of the positive characteristics of its antecedents while providing as well the advantages of split-cooler construction.

The challenge remaining is for the system designer to exercise imagination and skill in utilizing this reliable, cost-effective component to best advantage in the IR systems of the future.

REFERENCES

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5. A. Sereny, A. K. DeJonge, Analysis and Optimization of a Linear Motor for the Compressor of a Cryogenic Refrigerator, 1981 Cryogenic Engineering Conference, San Diego, CA., August, 1981.

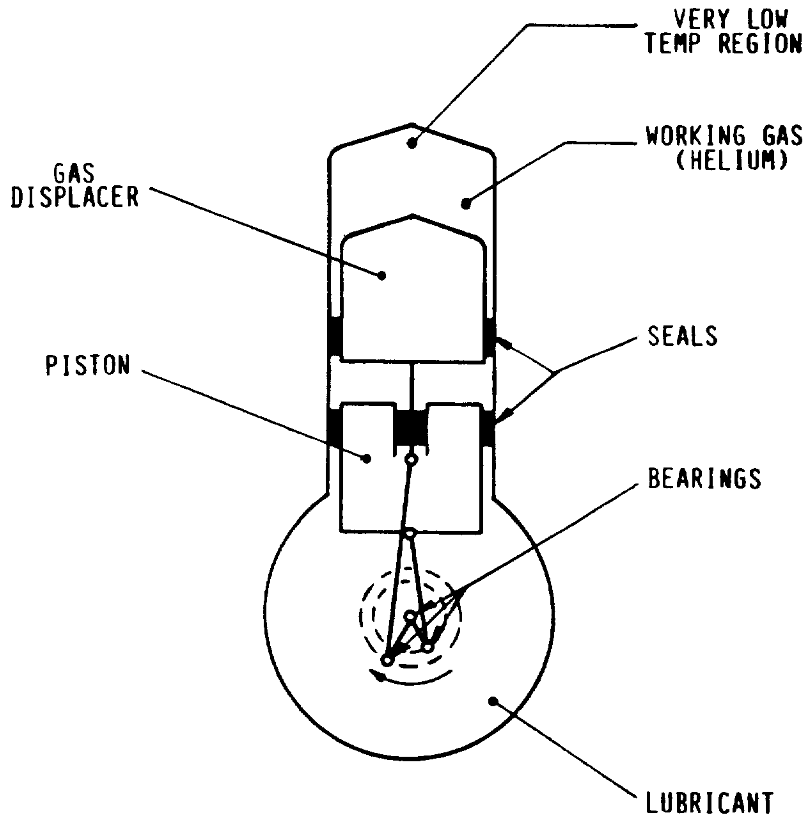

FIGURE 1. SCHEMATIC REPRESENTATION OF A CONVENTIONAL STIRLING REFRIGERATOR

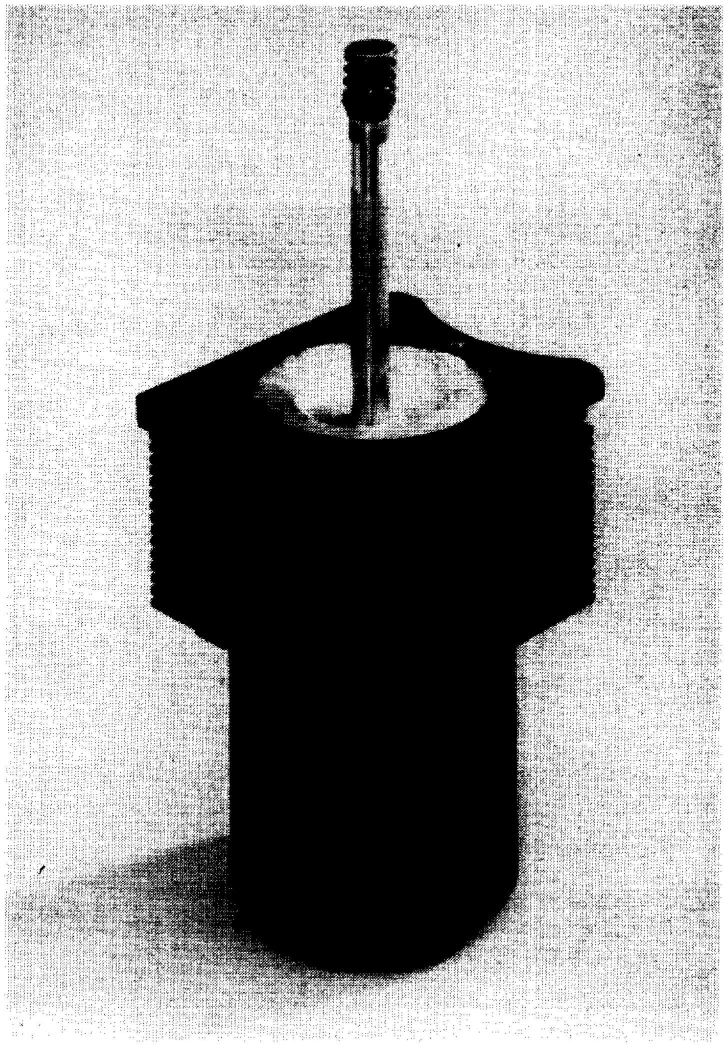

FIGURE 2. UA 7011/MX7011 LINEAR RESONANT COOLER

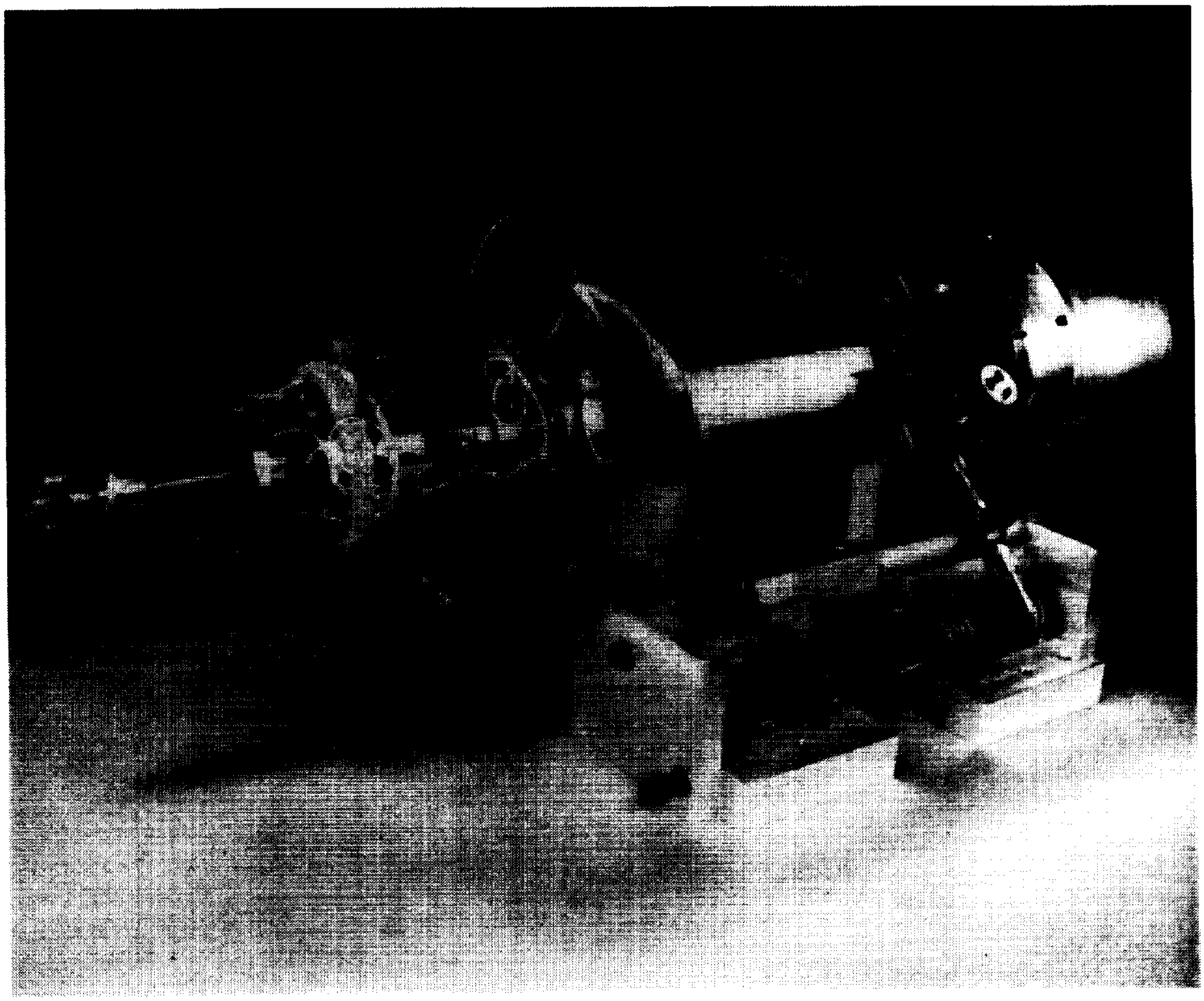

FIGURE 3. ULTRA-LONG LIFE PHILIPS LABS/NASA LINEAR-RESONANT, MAGNETIC BEARING STIRLING COOLER

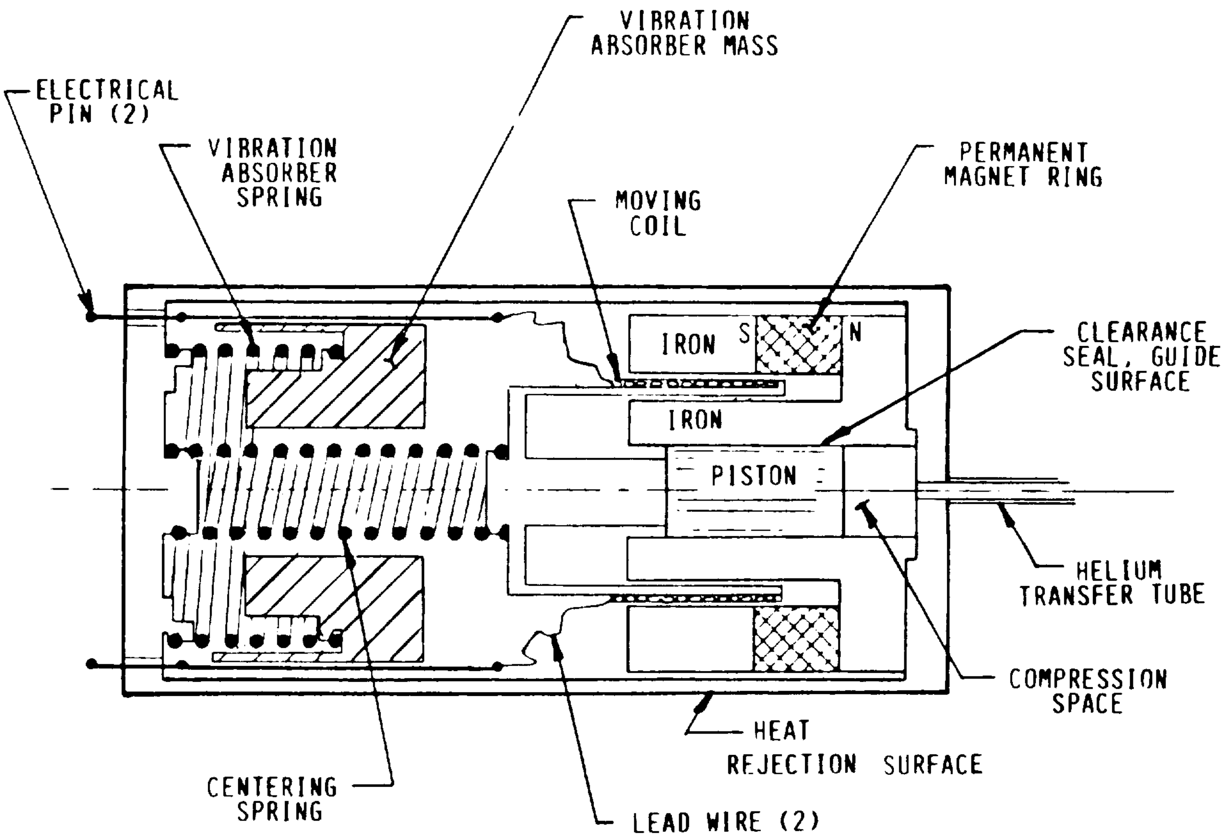

FIGURE 4. SCHEMATIC REPRESENTATION OF MAGNAVOX LINEAR-RESONANT COMPRESSOR

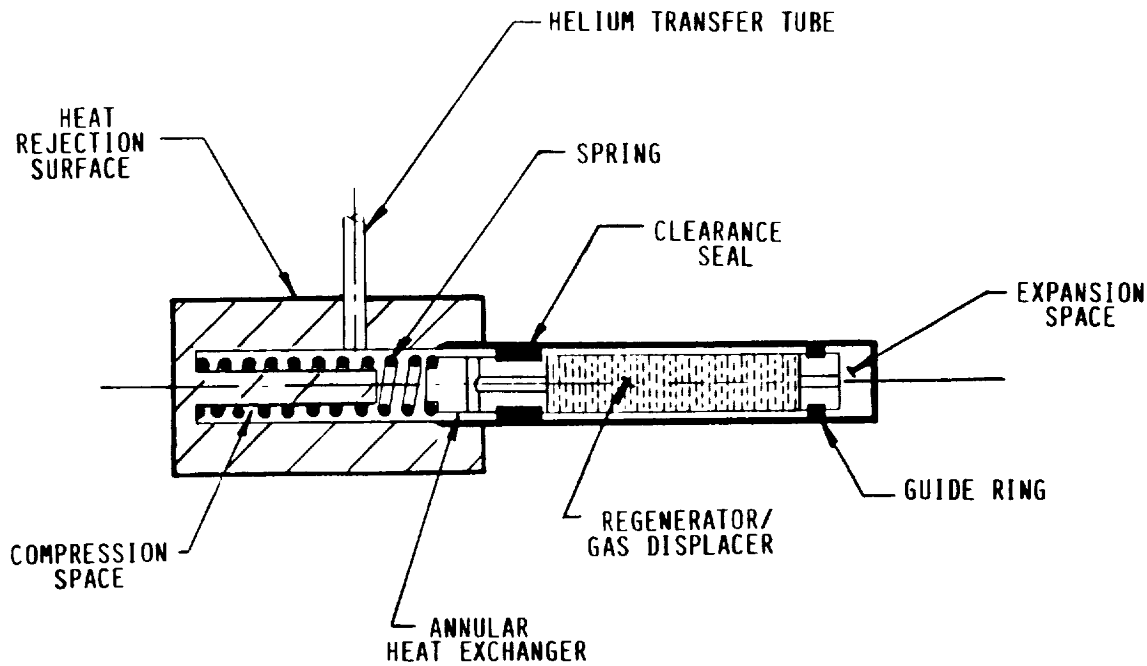

FIGURE 5. SCHEMATIC REPRESENTATION OF MAGNAVOX FREE-DISPLACER/COLD-FINGER CONSTRUCTION

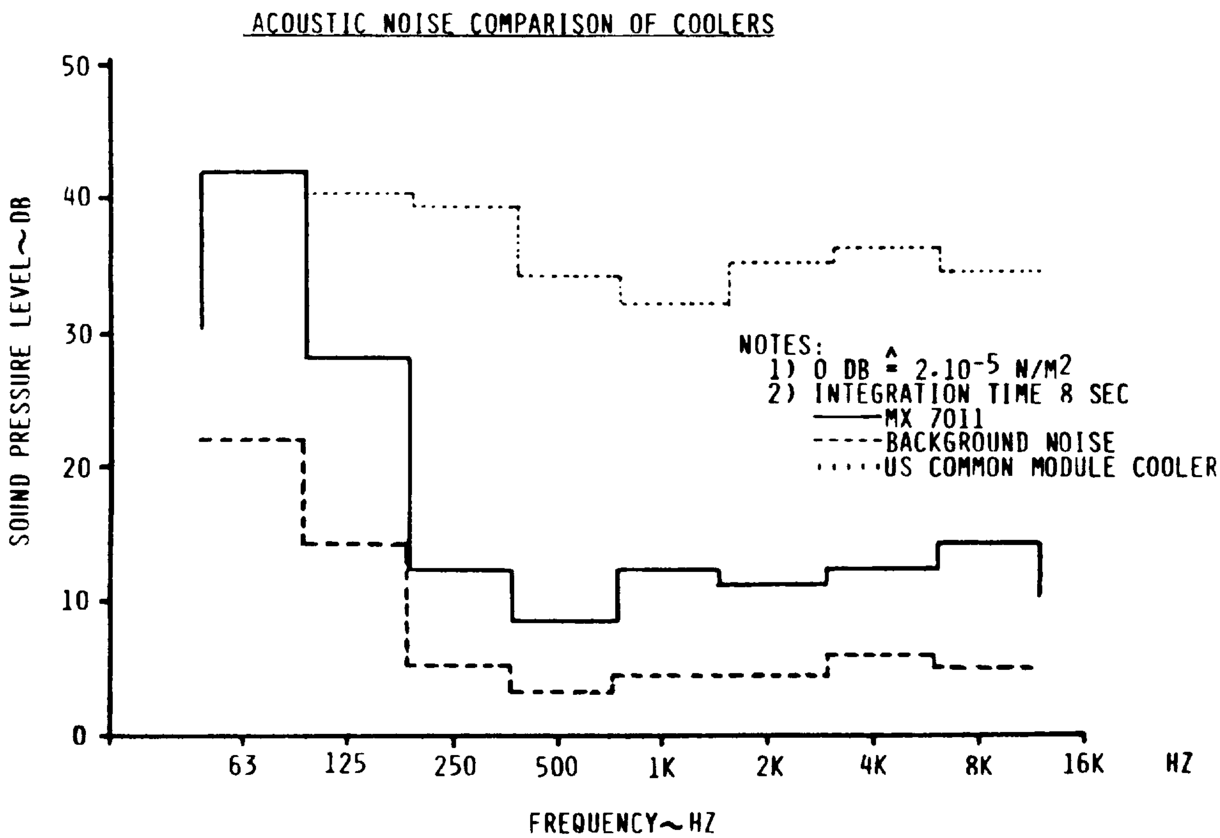

FIGURE 6. ACOUSTIC NOISE MEASUREMENTS

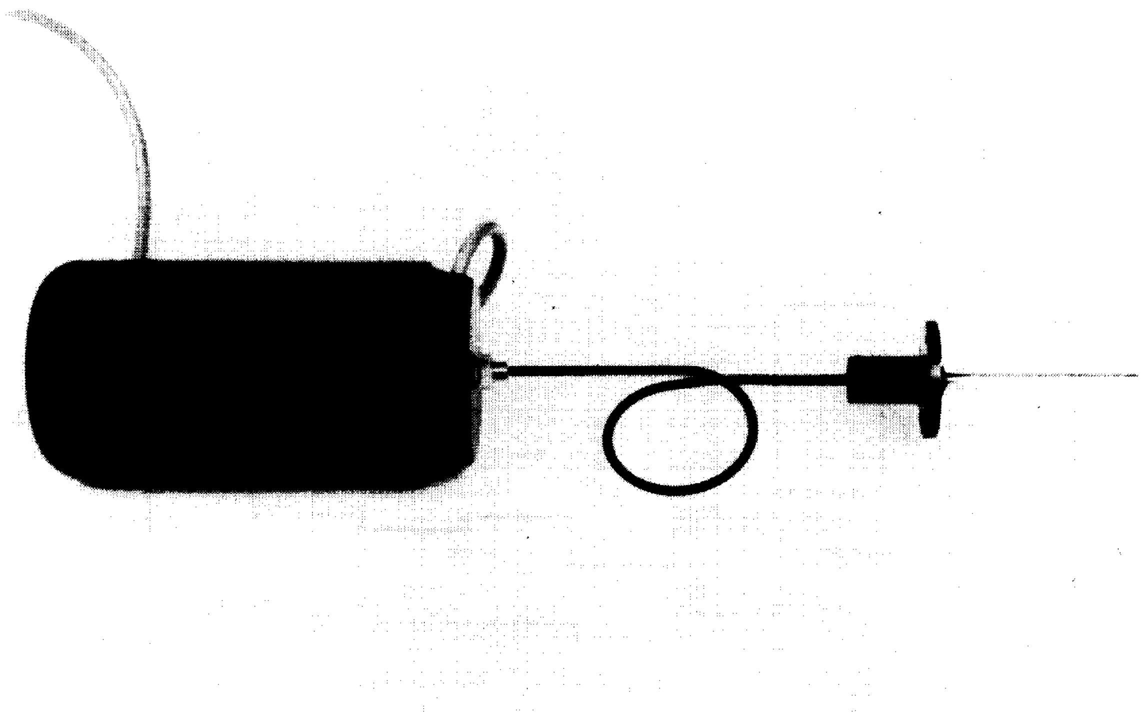

FIGURE 7. PROTOTYPE MX7040 SPLIT-STIRLING, 1/4 WATT LINEAR-RESONANT COOLER

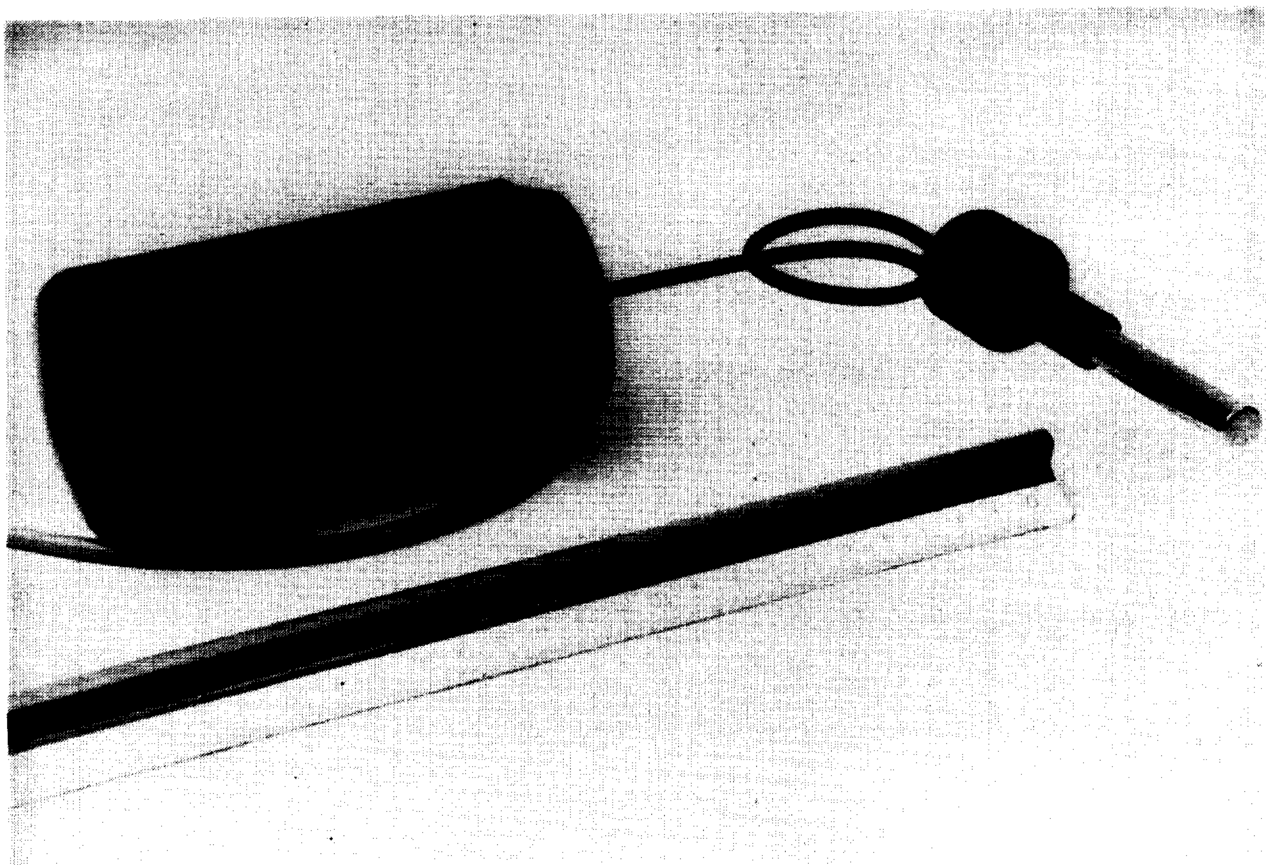

FIGURE 8. PROTOTYPE MX7043 SPLIT-STIRLING, 1 WATT LINEAR-RESONANT COOLER