U.S. NAVY PROGRAM IN SMALL CRYOCOOLERS

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ABSTRACT

If superconducting and cryogenically cooled electronic instrumentation are to be deployed in future Naval operational systems, there is an strong need for compact, highly reliable cryogenic refrigerators. Accordingly, several years ago, a Navy program was initiated to develop fractional-watt cryocoolers capable of operating below 10 K. Several varieties of Stirling coolers have been built and are under evaluation. In addition, helium gas compressors designed for use with small, closed cycle Joule-Thomson coolers are under development. An overview of the technical aspects of the program are presented. Many of the individual efforts supported under this program are discussed in detail elsewhere at this Conference.

INTRODUCTION

Superconductive electronic systems are fast becoming a practical reality. In addition, there is interest in the use of semiconductor devices and circuits operating at temperatures of 77 K and below. With the possible exception of cryogenic high speed, high density computer application, the required cooling capacity for most applications are quite modest, from microwatts to fractions of a watt at the operating temperature. Efficient, highly reliable, fractional watt closed cycle refrigeration systems ("cryocoolers") have been developed for operating temperatures near 77 K. However, there has been only limited activity in developing fractional watt coolers for the temperature region below about 50 K.

The realization that closed cycle refrigerators are essential to make cryogenic electronics a viable technology is not new. For example, Prof. S. C. Collins, the inventor of the Collins cryostat, made the following observations in 1958 when he was awarded the Kamerlingh Onnes Medal on the occasion of the 50th anniversary of the liquefaction of helium:[1]

> In recent years we hear much about ingenious devices for computer elements and amplifiers which require a very low temperature environment. . . . At long last it seems that a practical application for superconductivity has been found. The technical problems yet to

> be solved may be formidable but, if one may judge by the vigor and optimism with which many competent people are attacking these problems, solutions will soon be found.
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> The matter of suitable refrigeration presents a different kind of problem. It too, must be resolved before success is complete. For very large computers a supply of liquid helium might be accepted with reluctance. What is really demanded is a closed-cycle helium refrigerator of great reliability which can provide the required refrigeration at temperatures down to 1.2 K without interruption for months at a time. For large installations such a refrigerator, I believe, can now be produced and its performance guaranteed. But the field of application is much broader if one can have compact refrigerators of small power which can be plugged into a wall socket, as you do a household refrigerator. This is more difficult because small machines are much more sensitive to trouble of all sorts. Several groups, however, have set out to produce just such a unit. There is a general feeling that by the time the physicists are ready for them the refrigerators will be available.

These comments, both in regard to superconductivity as well as to small refrigerators, are true today as they were 24 years ago.

The U.S. Navy is exploring the feasibility of using superconductive electronic devices, circuits and systems in surveillance, communications and data processing applications. Since the highest known value of a superconducting transition temperature is 23 K, the refrigeration interest is in the region below 20 K, with strong interest below 10 K. In the research laboratory, the use of liquid cryogens such as boiling liquid hydrogen (20.4 K) and liquid helium (4.2 K) are commonly used to provide the needed cryogenic environment. However, if such systems are to be used away from the laboratory, the logistics of providing a continuous supply of liquid cryogens can be both tedious and difficult. Furthermore, the use of liquid hydrogen or helium is often considered too exotic for non-cryogenic specialists. Therefore, to expedite the introduction of superconductive or cooled semiconductor electronic systems in operational situations, a program was initiated several years ago by the Office of Naval Research to develop small, highly reliable, energy-efficient cryocoolers for the temperature region near 10 K.

SPECIFICATIONS

A summary of various 4 K refrigeration systems and the range of required cooling capacity is presented in Table I. In response to demand, commercial refrigerators are available with cooling capacities greater than several watts.[2] However, whenever there is a fractional watt requirement, larger refrigerators are used even though the weight, volume, electrical input power and cost may be excessive for the specific application. A survey of available coolers, both those operating near 10 K as well as at higher temperatures indicated that the efficiency (that is, the percent of Carnot efficiency for the particular operating and ambient temperatures) of small, fractional watt coolers was low compared to that realized in larger capacity machines (see Fig. 1).[3,4] Furthermore, it appears that there was a distinct penalty in weight, volume, electrical input power and cost in 4 K machines compared to coolers that operate near 10 K.[5] Since minimizing all of these parameters are crucial if superconductive electronic systems are to be deployed in most operational systems, the decision was made to develop closed cycle refrigerators operating below 10 K.

In considering the various applications in which superconductive and cooled semiconductor devices and circuits might be used in research, industrial or military situations, it became evident that no one set of parameters could satisfy all potential applications. In formulating goals for this program, a set of desired specifications was selected. However, throughout the program, the contractors performed trade-off studies to determine how varying one parameter influenced the other parameters.

The tentative design goals selected for the parameters of the cryocoolers to be developed under this Program are given in Table II. The weight and volume of the cooled package are typical for a superconducting gradiometer sensor and coil systems.[6] In many applications, both weight and volume to be cooled might be considerably smaller. The ultimate temperature of less than 8 K was chosen so that superconductive circuits fabricated from niobium (transition temperature of 9.2 K) might be used with these coolers. The reserved cooling capacity and three electrical loads were specified to emphasize that efficient use of intermediate cooling stations should be made and that coolers should have some reserve capacity for handling active loads at the low temperature. The goal for the electrical input power is 100 watts while a figure of 250 watts might be acceptable. (The input power figure includes all power required for the operation of the cryocooler such as vacuum pumps, cooling systems, etc.) These input power values correspond to a cooler coefficient of performance from 2,000 to 10,000 watts/watts, which is compatible with the data shown in Fig. 1. The total system weight and volume should, of course, be minimal. The time between routine maintenance and Mean Time Before Failure should be as long as possible, certainly months, while at times approaching a year of continuous operation would be desirable. Since one application of superconducting instrumentation is the SQUID magnetometer and magnetic gradiometer, care should be exercised to minimize the magnetic signature and mechanical vibration spectrum by proper design and the use of suitable materials. Although the sensitivity of SQUID systems is in the range of 10^{-14} tesla rms per root hertz (10^{-10} gauss rms per root hertz), the requirements for magnetic signature and vibration spectrum of cold finger were somewhat relaxed for this phase of the program. In subsequent phases of the program which may focus on interfacing cryocoolers with SQUID magnetic instrumentation, these specifications will probably have to be modified to reduce the interference signals from the cooler. The cool down time for a cryocooler is extremely dependent on the end use; in some cases, the system must be cooled from ambient temperature to operating temperature in minutes or less while in other applications, cool down time is irrelevant as the total system, once cooled, would be maintained at operating temperature for extremely long times. For this phase, it was specified that with the maximum mass to be cooled, the cooldown time could be as long as 24 hours although shorter times would be desirable.

PROGRAM

At the start of this program in 1980, new and novel concepts in cryocooler design were solicited which would satisfy the design goal outlined above. In addition to the complete system design, responses were also solicited in the areas of components, such as compressors, shaft seals, regenerative materials, etc. Some fifteen proposals were received and evaluated. In addition to these proposals inputs to the program were received from NBS-Boulder where development of a nylon and fiberglass Stirling cycle cooler had begun earlier under ONR support,[7,8] and from the U.S. Army Night Vision and Electro-Optics Laboratory, which had previously developed single stage Stirling coolers operating at 77 K, proposed to extend their technology to the 10 K region.[9]

The individual contracts thus far supported under this program are outlined in Tables III, IV and V. The entries in Table III are relate to Stirling cycle coolers. Descriptions of many of these activities can be found elsewhere in these Proceedings.

The second area of R&D under this program has been in the area of small Joule-Thomson cycle coolers and small helium gas compressors to enable small J-T coolers to be operated in a closed cycle mode. A J-T "cooler-on-a-chip" was developed by Little under ONR support.[10] More recently these efforts have been directed toward developing a small metal diaphragm compressor for use with this type of cooler-on-a-chip and eventually toward staging three J-T systems to achieve temperatures near 4 K. The Jet Propulsion Laboratory is working on polyurethane membrane compressors for (conventional) tubular J-T coolers, while Collins is developing a neoprene sleeve diaphragm compressor.

The final area of interest under this program has been to understand the problems associated with the use of cryocoolers to provide the required cryogenic environment for superconductive SQUID magnetometers and magnetic gradiometers. Zimmerman has operated one of his Stirling coolers with a SQUID gradiometer and has identified some of the interface problems and will be attempting to mitigate them.[6] Another effort is to document the sensitivity of SQUID magnetometers to the environment, such as temperature variation, vibrations etc. Finally, a facility has been established at the Naval Research Laboratory to study the magnetic signatures of cryocooler systems especially those to be used with magnetic sensors.

CURRENT STATUS OF PROGRAM

At the end of the Navy program on small cryocoolers in 1985, the goal is to have one or more complete systems, either Stirling or J-T, for integration with some cryogenic electronic device or circuit to demonstrate the feasibility of a closed cycle refrigeration system. This demonstration model will elucidate the interference problems and yield valuable information on how optimal system integration can be achieved without degrading the performance capabilities of the electronic device or circuit.

FUTURE DIRECTIONS

The completion of the Navy program in small, energy-efficient, highly reliable cryocoolers will not be the end of Navy interest in this technology. The current program will demonstrate the state of the art in this class of cooler and subsequent programs would be directed at interfacing and integrating these coolers into operational systems that will satisfy Navy requirements. In the non-military community, these cryocoolers may find their first use in cooling SQUID biomagnetic instrumentation. In this application, the major problem would be to minimize interference produced by the vibration and magnetic signature of the cooler which is probably the most serious problem to be encountered in integrating cryocoolers with electronic packages.

Because of the limited funds available under this program, many design concepts for cryocoolers have not been pursued. For example, in the case of cooling a magnetic sensor system, a split system might be used in which the motors and other moving parts would be located at a distance from the sensor to take advantage of the inverse cube fall-off of the magnetic signature. The motors, compressors and moving displacer would be remotely located from the cold station and the "cooling power" of the system transmitted by some means from the refrigerator to the electronic package to be cooled. If magnetic measurements do not have to be made continuously, for example, if a 10% duty cycle for measurements is acceptable, a thermal reservoir of large heat capacity might be used to maintain the SQUID system at the required operating temperature while measurements are being made and the cooler is not operating. Another area of interest is in extremely low power coolers which would operate for very long times but for which the cooldown could be done over a very long period of time or with the use of auxiliary cooldown modes using either liquid nitrogen or liquid helium.

These are only a few possibilities for new concepts and possible directions in small cryogenic refrigeration. They are only suggested here to indicate that the present Navy program is just touching the tip of the iceberg of cryogenic refrigeration. New and novel concepts in refrigeration are still welcome and encouraged so that this technology can continue to grow and mature.

Table 1. Cryogenic refrigeration requirements near 4 K.

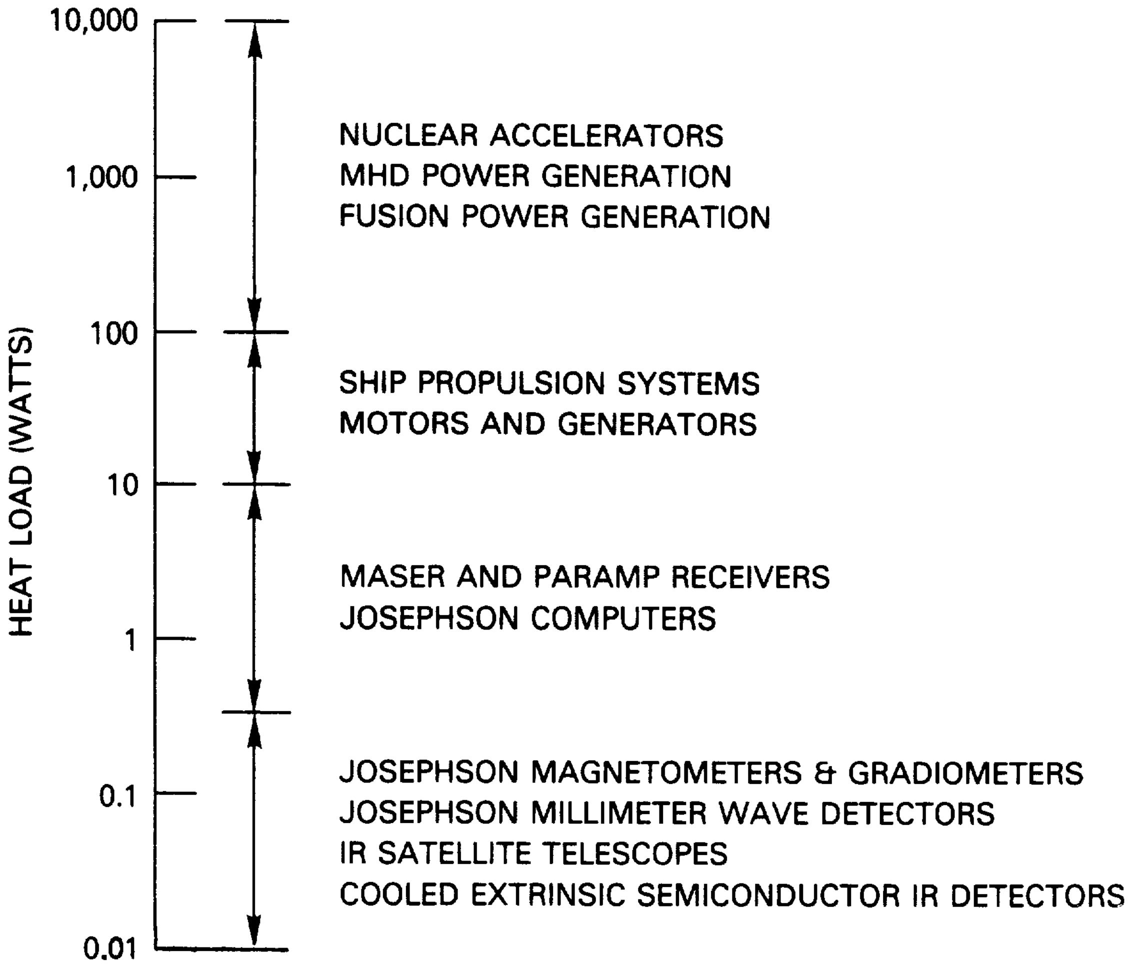

Table II. Cryocooler Specifications

PARAMETER	GOAL
Volume to be cooled	4 cm diam. x 15 cm long
Mass to be cooled	300 grams
Electrical leads into cold volume	3 coaxial leads
Ultimate operating temperature	< 8 K
Reserve cooling power at 10 K	50 mw
Temperature stability (without electrical heater feedback)	$\pm 10^{-2}$ K
Electrical input power	100 watts
System weight	4.5 kg
System volume	10^{4} cc
Routine maintenance	4000 hours
Mean Time Before Failure	8000 hours
Cooldown time	~ 8 hours
Mechanical vibration at cold station	$<10^{-7}$ rads
Magnetic signature at cold station	$<10^{-8}$ gauss rms/$\sqrt{\text{Hz}}$

Table III. Research in Stirling Cycle Cryocoolers

Organization	Investigators	Cooler Concept
National Bureau of Standards Boulder, CO	J. E. Zimmerman D. B. Sullivan	Nyon and fiberglass working materials: ceramic compressors
SHE Corporation San Diego, CA	R. Sagar	Nylon and fiberglass: He gas regenerator 3He working fluid
Cryogenic Technology, Inc. Waltham, MA	P. J. Kerney W. Prittle	MACOR[11] working material
Phillips Laboratories Briarcliffe Manor, NY	W. Newman A. Daniels	Triple expansion system: counterbalanced liner drive motor
Rockwell International Anaheim, CA	W. Hartwig	Gas adsorption compressors
Lake Shore-Cryotronics Westville, OH	W. Pierce	Pneumatic drive mechanism
Night Vision & Electro-Optics Laboratory Fort Belvoir, VA	W. Horn	Staged version of 77 K Stirling cooler

Table IV. Research in J-T coolers and small helium compressors

Organizations	Investigators	Concepts
MMR Technologies, Inc. Mountain View, CA	W. A. Little	J-T "cooler-on-a-chip"; grooves sandblasted in glass slides; metal diaphragm compressor
Jet Propulsion Laboratory Pasadena, CA	E. Tward	Polyurethene membrane compressor
Naval Research Laboratory Washington, D.C.	S. C. Collins	Neoprene sleeve compressor

Table V. Research in interfacing of cryocoolers to electronic systems

Organizations	Investigators	Concepts
Quantum Design, Inc. San Diego, CA	M. Simmonds	Interfacing SQUIDs to cryocoolers
Naval Research Laboratory Washington, D.C.	M. Nisenoff H. Weinstock	Facility to measure magnetic signatures of coolers

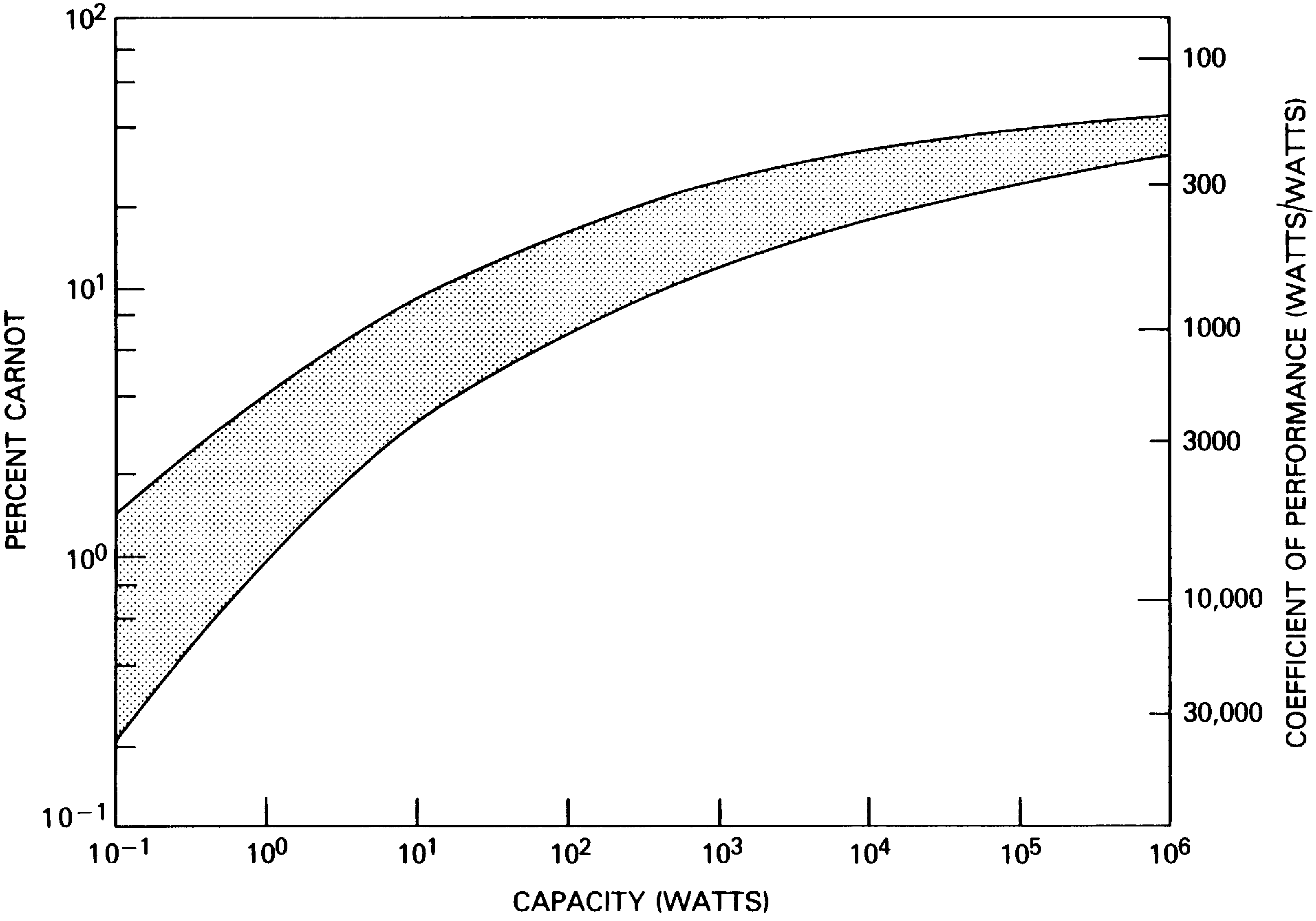

Fig. 1. Percentage of Carnot efficiency and Coefficient of Performance (COP) for 4 K closed cycle refrigerators as a function of cooling capacity. (The high temperature reservoir temperature was assumed to be 293 K.)

REFERENCES

1. Collins, S. C.: Recent Growth in Low Temperature Applications. Comm. Leiden, Suppl. 114c, 1958.

2. Crawford, A. H.: Specifications for Cryogenic Refrigerators. Cryogenics 10, 28 (1970).

3. Strobridge, T. R., and Chelton, D. B.: Size and Power Requirements of 4.2°K Refrigerators. Advances in Cryogenic Engineering, Vol. 12 (Plenum Press, New York, 1967), pp. 576-584.

4. Strobridge, T. R.: Cryogenic Refrigerators - An Updated Survey. NBS Technical Note 655 (Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, Catalogue No. C13.46:655; 1974).

5. Nisenoff, M.: Current Status of High Temperature Josephson Device Technology. Refrigeration for Cryogenic Sensors and Electronic Systems; NBS Special Publication 607 (Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, USA, 1981), pp. 195-209.

6. Sullivan, D. B., Zimmerman, J. E., and Ives, J. T.: Operation of a Practical SQUID Gradiometer in a Low-Power Stirling Cryocooler. Ibid., pp. 186-194.

7. Sullivan, D. B., and Zimmerman, J. E.: Very Low-Power Stirling Cryocooler Using Plastic and Composite Materials. Internat. J. Refrig. 2, 211 (1979).

8. Zimmerman, J. E., and Radebaugh, R.: Operation of a SQUID in a Very Low-Power Cryocooler. Applications of Closed Cycle Cryocoolers to Small Superconducting Devices; NBS Special Publication 508 (Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, USA; Catalogue No. 003-003-01910-1; 1978), pp. 59-66.

9. Horn, S. B., and Asher, M. S.: Theoretical Analysis of a 3-stage Stirling Cycle Cryocooler. Refrigeration for Cryogenic Sensors and Electronic Systems; NBS Special Publication 607 (Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, USA; 1981), pp. 30-48.

10. Little, W. A.: Design Considerations for Microminiature Refrigerators Using Laminar Flow Heat Exchangers. Refrigeration for Cryogenic Sensors and Electronic Systems. NBS Special Publication 607 (Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, USA, 1981), pp. 154-160.

11. MACOR is a registered trademark for a machineable ceramic manufactured by Corning Glass Works, Inc., Corning, NY, USA.