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Survey of the State-of-the-Art of Miniature Cryocoolers for Superconductive Devices

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This document presents the results of a survey of the state-of-the-art as applied to cryocoolers to cool small superconducting devices. The survey included visits to over 100 facilities involved in the production or development of small cryocoolers in the United States, Japan and Europe. Specifications of commercially available cryocoolers having capacities of one of five watts in the 80 to 4 K range are presented. The survey was sponsored by the Office of Naval Research.

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CONTENTS

SURVEY OF THE STATE-OF-THE-ART OF MINIATURE CRYOCOOLERS FOR SUPERCONDUCTIVE DEVICES

I. Introduction and Summary

Full use of superconductive electronic devices requires the availability of miniature closed-cycle refrigeration devices which have high efficiency, high reliability, and low power requirements and operate in the 4 to 10 K range. Refrigerators meeting these requirements in the 80 K range have been developed over the past decade and are now produced by a number of manufacturers. Fractional watt refrigerators having low power requirements and suitable for cooling the present state-of-the-art superconductive electronic devices in the 4 to 10 K range are not generally available. It is the purpose of this report to review the current status and availability of equipment used for cooling electronic devices and to provide a data base from which to establish guidelines for future developmental efforts.

The status of miniature cryocoolers was reviewed in 1969 by Daunt and Goree [1]. Specifications for coolers available at that time are presented by Crawford [2]. Our purpose in this survey was to update Daunt's report. During our survey we contacted over 100 manufacturers and research facilities in the United States, Europe, and Japan. We followed up these contacts with visits to over 60 facilities in order to obtain first-hand information on the status of development activities pertinent to the production of fractional watt coolers in the 4 K range.

Over the past decade development of cryocoolers has been extensive in three areas: 1) the production of military use coolers for infrared detection devices in the 80 K range; these units are being produced in large quantities by a number of manufacturers, 2) the production of closed-cycle refrigerators for cryopumping operations, 3) the development of long-life coolers suitable for space operation.

Although the survey was aimed at fractional watt coolers suitable for operation in the 4 to 10 K range, it appeared desirable to include in the survey all small coolers in the temperature range 4 to 80 K. The requirement for large numbers of coolers for the infrared detector market has provided the impetus for development of highly reliable, efficient and compact units. This technology can be readily applied to the production of smaller low temperature devices once the requirement for large numbers of units manifests itself. Refrigerators in this category are described in Section III.

Significant advances in the state-of-the-art of cryocooler development over the past decade are reported in proceedings of conferences held at the US Air Force Academy, Colorado, in 1973; the American Institute of Physics Conference in Charlottesville, NC

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in 1978; the Proceedings of the Closed-Cycle Cryocooler Conference in Boulder, CO, Oct. 1977; Proceedings of the Refrigeration for Cryogenic Sensors Conference, Boulder, CO, Oct. 1980; and the second biennial confer nce on Refrigeration for Cryogenic Sensors held at NASA Goddard Space Flight Center in Dec 1982 [3-7]. Walker presents an overall view of cryocooler design fundamentals and developments in his book, Cryocoolers [8].

Refrigerators for cooling electronic devices are, in general, embodiments of the Stirling cycle, whether integral or split cycle devices [9]. Other cycles include the Gifford-McMahon cycle which finds widest application in ground-based units, the Vuilleumier cycle which has been applied to cryocoolers designed for long-term space operation and the Claude and reversed Brayton cycles. In general, the specific application of the cryocooler dictates the design requirements and plays a role in the selection of the cycle to be employed [10]. For example, the integral Stirling system while most efficient, has the drawback that the mechanical drive components must be in close proximity to the cold end refrigeration portion of the unit. This disadvantage is eliminated by using the split Stirling cycle. Requirements for long operating lifetimes favor the Vuilleumier cycle which has fewer moving parts and unbalanced forces that reduce the number of wear components in the system. Most of the developmental effort has focused on increasing efficiency and reliability of the various coolers now in production.

Cryocoolers under development are described in Section IV. These include one-of-a-kind coolers for long-term space application, the development of improved regenerators for lower stages of Stirling cycle systems, the development of gas adsorption refrigeration systems, and the development of magnetic refrigerators.

Areas of basic development activity are indicated in Section V where we have given some indication of the companies and facilities working in specific areas of improvement. These include novel heat exchanger designs, the design and development of more effective seals, development of materials to reduce the contamination problem in small systems, the design and development of compressors and expanders, and the development of more efficient regenerators which will permit operation of Stirling cycle machines at lower temperatures.

Although we have attempted to include an update of all significant developments which might lead to more effective and efficient refrigeration systems in the 4 K range, we are unable to report a number of developments which are subject to restrictions on the dissemination of information, either as a result of potential military application or as a result of proprietary commercial development.

The most significant change noted in this field since the time of the Daunt and Goree report (1969) is greatly intensified interest and activity in Josephson junction, NMR, and high vacuum applications of cryogenic technology and the increased production of cryocoolers in Europe and the emergence of extensive cryogenic systems development in Japan.

II. Key Opportunities for Further Development

Future requirements for cryocoolers in the 1-W, 4-K range dictate continued development in several areas. Our survey disclosed a number of key areas where research is necessary to permit the achievement of a reliable, efficient and compact cryocooler.

- In order to achieve a closed-cycle refrigerator with high efficiency, it is necessary to understand the basic loss mechanisms. The design and production of cryocoolers to date and those currently in operation are, in general, scale-ups or scale-downs of existing equipment. Basic developmental work is required to provide a means for understanding loss mechanisms so that more efficient units can be designed and fabricated and existing cryocoolers improved.
- The development of compressors which are free from contamination and which do not emit contamination products to the gas stream would contribute significantly to the reliability of cryocoolers operating in the 4 K range. Contamination-free compressors are particularly important in order to achieve satisfactory operation of all small cryocoolers.
- The development of efficient and compact heat exchangers and the understanding of heat transfer mechanisms in areas where the solid wall specific heat is small is a requirement of many systems. Development in this area could lead to the design and construction of highly efficient small cryocooler systems.
- A number of problems associated with the presently available equipment are related to the materials used in fabrication. These materials either wear away in areas where they are used as seals, thus reducing the efficiency of the machine in time, or the materials, through wear, contribute contamination particles to the system and eventually block the flow passages. Development is being carried out in many areas to provide materials which are acceptable as seals and wear surfaces for cryocooler equipment. Further development in this area could lead to systems which would have a higher degree of reliability and performance.

- One of the limitations of the Stirling cycle is that of the very low heat capacity of materials which are suitable for regenerators. Development in this area has been extensive over the past 10 or 15 years. Further development and discovery of suitable materials or new combinations of materials could lead to a generation of Stirling cycle coolers which would have their operating range extended from the present limit of about 10 K to a lower limit, making it possible to operate Stirling cycle cryocoolers at 4 K.
- As a result of the limitation of Stirling cycle systems noted above, it is desirable to investigate other cycles which might prove efficient at the 4 K range. These include combinations of other schemes in connection with the Stirling cycle and also Claude cycle refrigerators and vapor recompression cycle cryocoolers. The development of a viable vapor recompression cycle refrigerator would require design and development of a cold compressor.

Research and development in the areas listed above are being carried out by a number of commercial companies and by government laboratories and universities. However, it is the general consensus, particularly in the United States and Europe, that development programs aimed at the production of fractional watt 4 K coolers are being conducted on budgets that are inadequate to realize significant results in any specific area in the immediate future.

III. Commercially-Produced Cryocoolers

The first major requirement for small cryocoolers was brought about by the need to refrigerate ground-based parametric amplifiers for use in the satellite communication network at 4 K. Several units meeting this requirement were developed and built by A.D. Little, based on the Gifford-McMahon (G-M) cycle with a Joule-Thompson (J-T) circuit. These units produced a few watts at 3.8 - 4 K. Further development in amplifier performance led to an amplifier which would perform satisfactorily at 20 K. As a result, the major market for the Gifford-McMahon, closed-cycle, 20-K cooler evolved. Cryogenic Technology Inc. has produced close to 1000 of these units which are in continuous operation in the satellite communications network. This basic Gifford-McMahon cooler is also produced by Cryomech Inc. and by Air Products Inc. These two companies, as well as Cryogenic Technology Inc. (CTI Cryogenics), have built a number of G-M units for specific applications with the addition of a Joule-Thompson loop to provide a final stage of refrigeration at 4 K. Units of this type have also been furnished by Cryosystems Inc.

and by Cryogenic Consultants Ltd. in England. Installations include cooling of computer systems and cooling of superconducting magnets for magnetic separation processing and for NMR experiments. A typical G-M refrigerator is shown schematically in Figure 1.

The next major market to evolve was that of cooling infrared detectors. The initial requirements for I-R detectors were 0.25 - 2 W at 80 K. A number of manufacturers became involved in producing refrigerators for this level of refrigeration. Thousands of open cycle J-T units have been produced as well as several thousand integral Stirling and split Stirling refrigerators. These units are used for cooling military infrared (IR) detectors and are produced both in the United States and abroad. A typical Stirling IR cooler is shown in Figure 2.

This requirement for large numbers of coolers for infrared detectors in the military system led to development of a common module cryocooler meeting specific size, weight, and performance requirements. These units are manufactured by a number of companies in the U.S. and by companies abroad in order to serve their own government defense systems. These companies, in addition to CTI-Cryogenics and Air Products Inc., include Hughes Aircraft, Texas Instruments, H.R. Textron, and Magnavox in the U.S.; Telefunken Co. in Germany; L'Air Liquide and A.B.G. Semca in France, Hymatic in England; Philips in Holland; Ricor Ltd. in Israel; and Galileo Corp. in Italy.

The third major commercial market to open up was that of cryopumping. A number of G-M and Stirling cycle refrigerators were installed on cryopumping systems in the early 1970's. However, the market did not fully develop until coolers were required for semiconductor production.

The general range of cooling required for cryopumping systems is 50 - 65 W at 80 K and 5 W at 12 - 15 K. Closed cycle refrigerators for cryopumps in this range are produced by CTI-Cryogenics, Air Products, and CVI Inc. In addition, the major vacuum equipment companies produce their own refrigerator systems. These include Balzers High Vacuum, Varian Inc., Sargent Welch Inc. in the U.S.; L'Air Liquide in France; Leybold-Heraeus in Germany; and Osaka Oxygen Industries, Suzuki Shokan Ltd., Ulvac Cryogenics Inc., and Toshiba Corp. in Japan.

The major manufacturers of closed cycle cryocoolers are listed in Table I. Figure 3 indicates the refrigeration capacity and operating temperature range of commercially-available cryocoolers. The specifications for these units are presented in Appendix B.

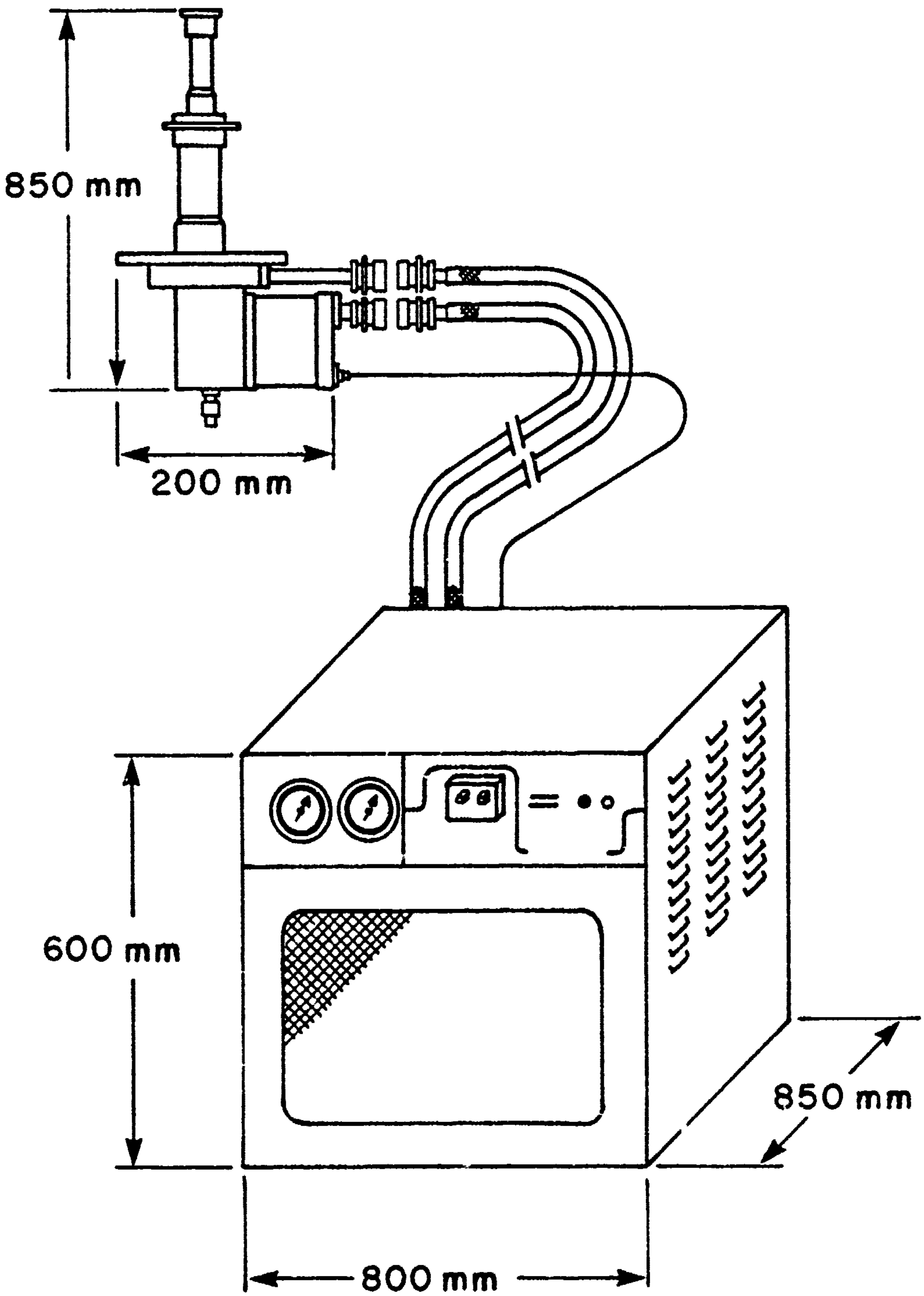

Fig. 1 — Typical G-M cryocooler
1 watt at 4 K
weight 350 kg

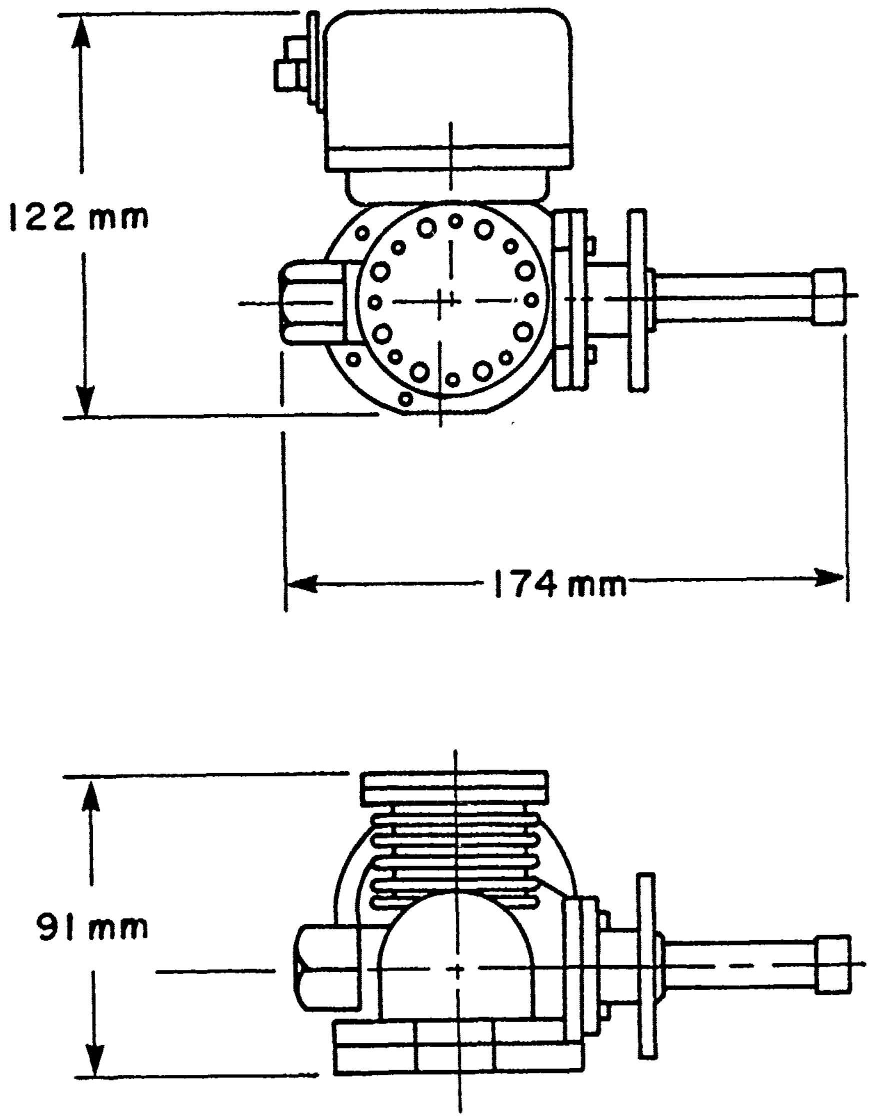

Fig. 2 — Typical stirling cryocooler
1 watt at 80 K
weight 1.7 kg

Table Ia

Commercial and Production Cryocoolers

USA

	4-5 K 1-4 W	10-20 K 1-5 W	Cryopump 20 K & 80 K 4 W & 60 W	Closed Cycle 80 K 0.25-2 W	J-T 80 K 1-2 W
Manufacturer					
Air Products & Chemicals	×	×	×		×
AiResearch				×	
Balzers High Vacuum			×		
Cryomech Inc.		×	×		
Cryosystems Inc.	×	×	×	×	
CTI-Cryogenics	×	×	×	×	
CVI Incorporated			×		
Hughes Aircraft Co.				×	
MMR Technologies					×
Magnavox				×	
Sargent Welch			×		
Texas Instruments				×	
H.R. Textron				×	
Varian			×		

Table Ib
Commercial and Production Cryocoolers
Outside the USA

Manufacturer	4-5 K 1-4 W	10-20 K 1-5 W	Cryopump 20 K & 80 K 4 W & 60 W	Closed Cycle 80 K 0.25-2 W	J-T 80 K 1-2 W
UK					
Cryogenic Consultants	×	×	×		
Hymatic Engineering					×
Holland					
N.V. Philips				×	
France					
L'Air Liquide			×	×	
A.B.G. Semca				×	
Germany					
Leybold-Heraeus			×		
Telefunken AG				×	
Italy					
Galileo				×	
Israel					
Ricor				×	
Japan					
Aisin Seiki			×		
Hitachi	×				
Ulvac			×		
Toshiba			×		

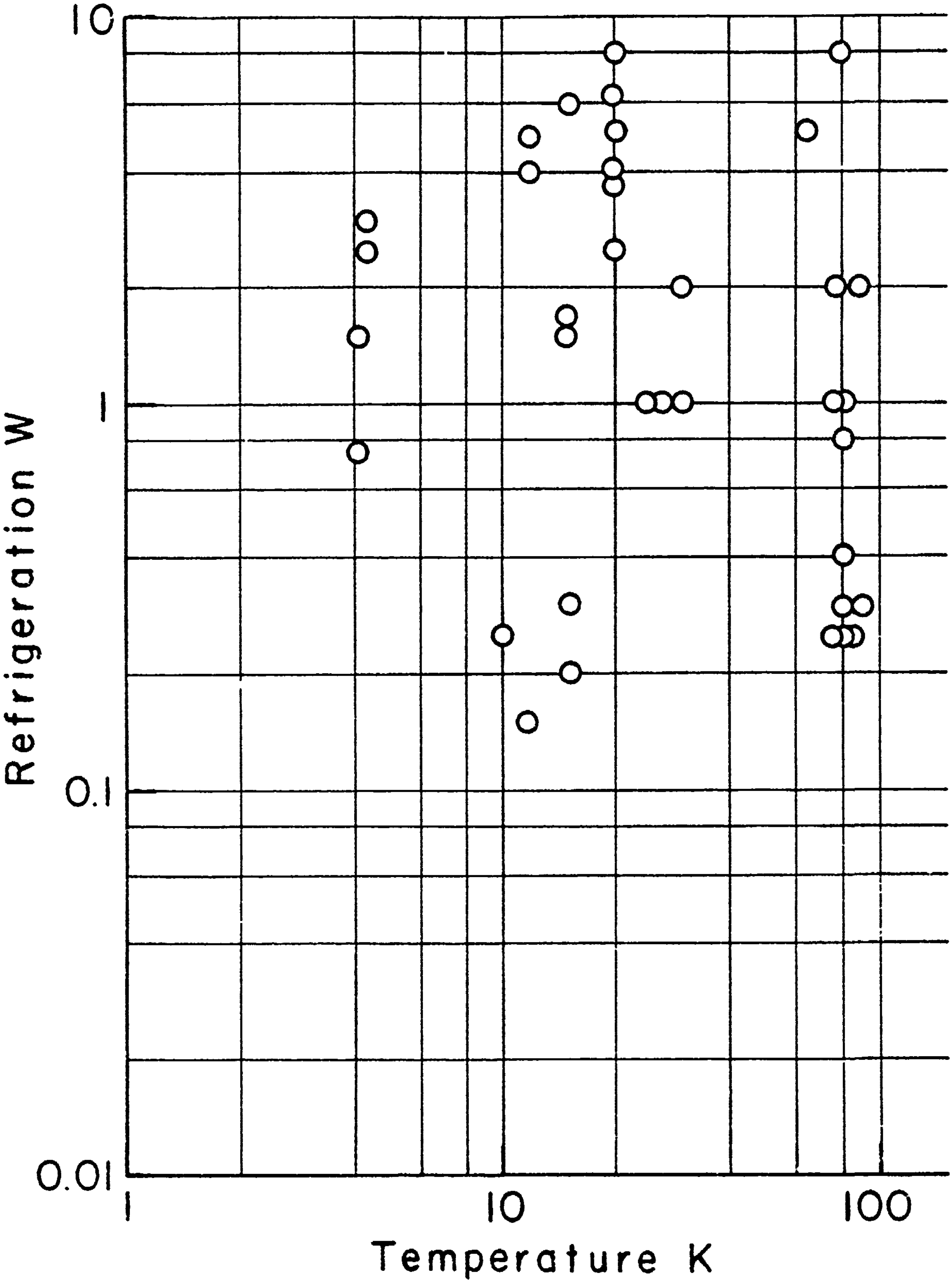

Fig. 3 — Commercially available cryocoolers

Performance characteristics of production cryocoolers are shown in Figure 4 which indicates the ratio of compressor input power to available refrigeration Wc/Q vs. temperature.

Figure 5 shows the weight vs capacity of cryocoolers for several temperature levels.

Although there are no companies producing many refrigerators meeting the requirements of 1 W at 4 K with a reasonable efficiency and size suitable for cooling small superconductive devices, the major manufacturers contacted have the capability to develop such systems. Development, however, would require a major funding effort: reliable operating systems would only become available through production of hundreds of units. Companies are unwilling to invest large sums of research money in advancing the technology unless they can be assured of large production contracts through which they can recover their investment.

IV. Cryocoolers Under Development

In this section, we review a number of cryocoolers under development. Several have been developed under specific contracts for a defined purpose; others are aimed toward improved operating reliability or toward improving a manufacturer's marketing position. In addition to those discussed, there are several units under development for use in tactical defense systems, both in the U.S. and abroad, for which data are of a restricted nature.

Several coolers have been developed and tested specifically for long life (5 year) space operation. Particular effort has been expended to reduce the number of moving parts and to eliminate as far as possible any wear which might cause contamination. These programs, listed below, have been under development for the past 10 years with substantial funding from the U.S. space program.

- A.D. Little has developed a rotary reciprocating refrigerator operating on a 2-stage reverse Brayton cycle with a capacity of 1.2 W at 12 K.
- Hughes Aircraft has built six operational units based on the Vuilleumier cycle. The refrigerator uses sliding seals and a rotating crank which produces a 90 degree phase shift between the hot and cold displacers. This unit produces 0.15 W at 11.5 K in its 3-stage embodiment.
- Philips Laboratory has built a magnetically-suspended linear drive system operating on the Stirling cycle. In tests the unit produced 5 W at 64.6 K with an input power of 220 W.

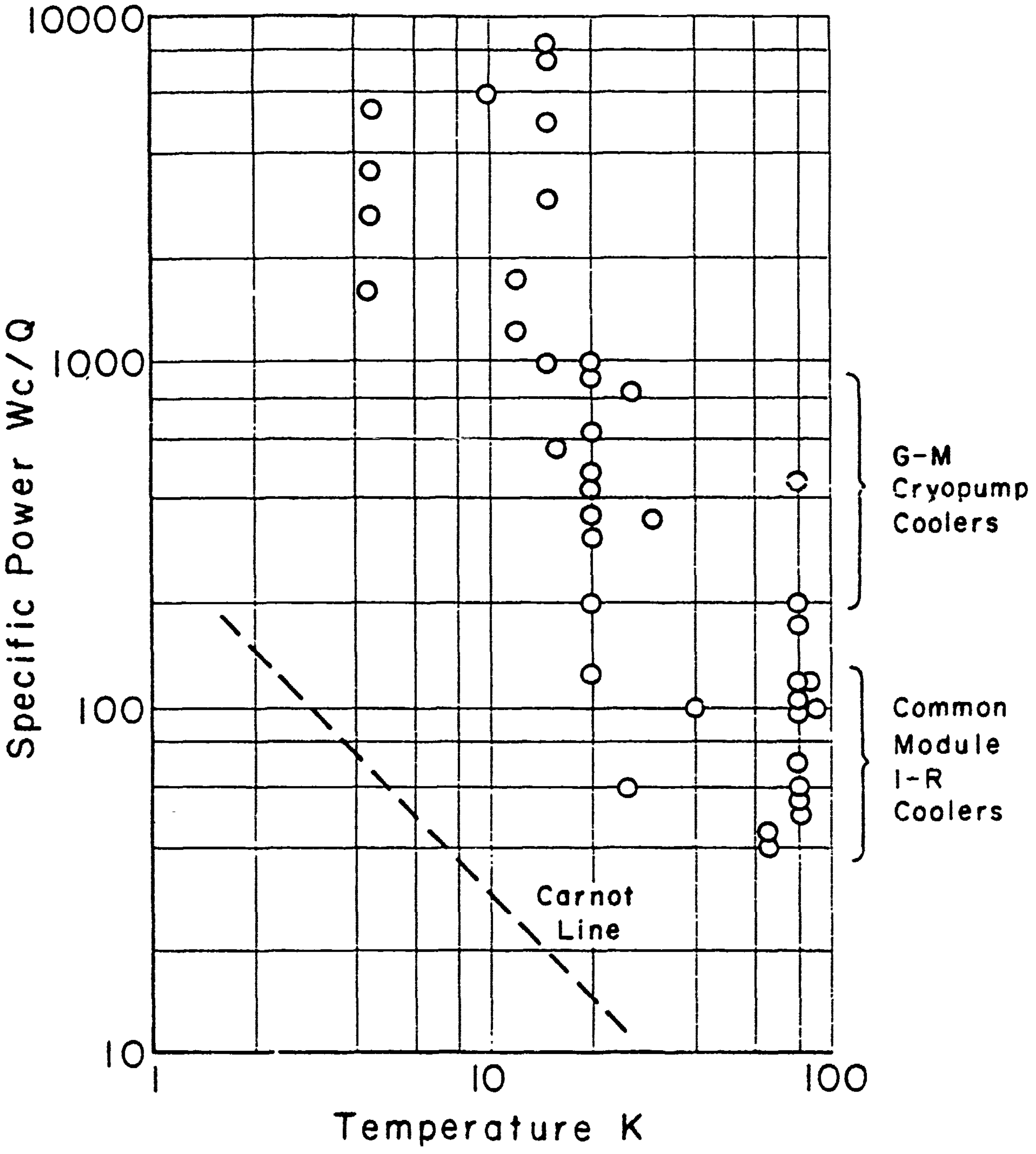

Fig. 4 — Specific power of commercial cryocoolers

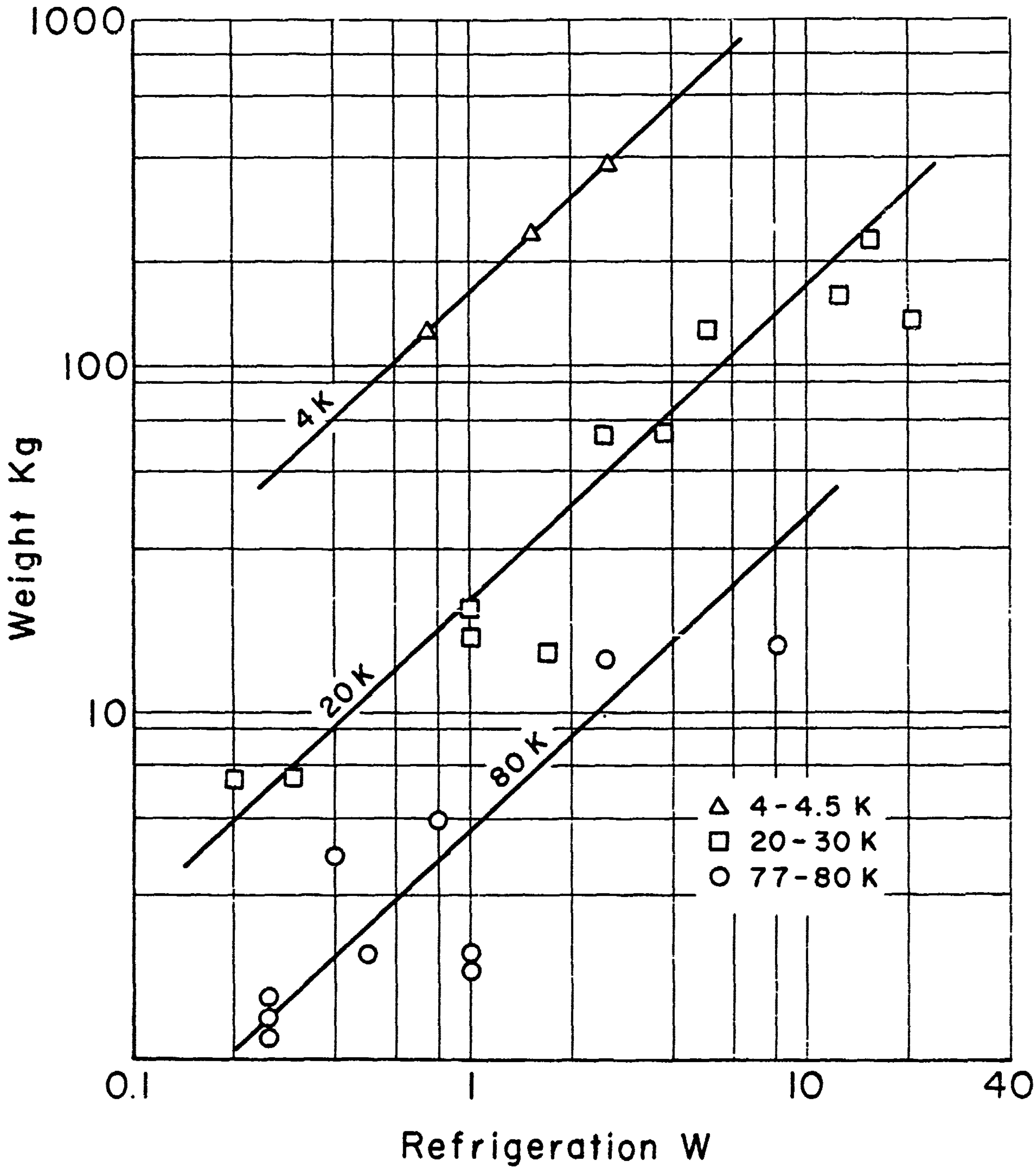

Fig. 5 — Weight of commercial cryocoolers

- AiResearch has produced a prototype turbo refrigerator which operates on the reverse Brayton cycle using a helium-neon mixture as the working fluid. The turboexpander is suspended on foil-type gas bearings. The system has a capacity of 20 W at 20 K.

These refrigerators, along with predictions of future performance capabilities, are described in detail by Johnson [11].

Several organizations have developed prototype systems aimed at low power and high efficiency, with long operating life characteristics. These developments are indicative of what is required to produce a 1 W, 4 K cooler.

- J.E. Zimmerman, at NBS, Boulder, has constructed a low power split Stirling cryocooler, using a tapered epoxy-glass composite displacer and neoprene diaphragm compressor. The unit has reached a temperature of 7.6 K.
- S.H.E. Corporation designed and built a 4-stage G-M cooler using a gap regenerator and a G-10 fiberglass epoxy displacer which operated at 7.6 K. Tests were run using ^{3}He to reach lower temperature. Additional testing was carried out where the fourth stage was replaced with a Malone stage heat exchanger in anticipation of increased performance.
- A "no moving part" gas adsorption refrigerator has been developed by the Jet Propulsion Laboratory. Components have been built and upper stages tested. A cooler in the 4 K range would require adsorption stages of neon, argon, hydrogen, and helium. They predict a capacity of 1 W at 20 K with an input power of 129 W.
- Jet Propulsion Laboratory has under development a diaphragm compressor using an oil-backed polyurethane diaphragm. This compressor is incorporated in a closed-cycle cascade J-T cycle refrigerator, using $CF_4/N_2/H_2/He$ which could produce 0.025 W at 4.5 K with an input power of 100 W.
- Magnetic refrigeration systems have a potential for operation as an additional stage in the lower temperature ranges. Several developments in this area have been carried out and are being continued. The magnetic refrigerator uses as a working substance gadolinium gallium garnet which has a relatively high entropy density and high heat conductivity. The refrigerators are operated in a Carnot cycle. Development has been carried out at Los Alamos on a rotating system, moving the crystal in and out of a magnetic field, and at NASA Lewis, using a reciprocating motion. In Japan, Toshiba Corp. and Tokyo Institute of Technology have built a refrigerator working between 4.2 and 20 K. In this unit, the magnet is energized and deenergized to

operate the cycle. The laboratory at CEN Grenoble, France has built a magnetic refrigerator which operates between 4.2 and 1.8 K. This unit has been very successful and work is continuing toward development of a magnetic refrigerator which will operate between 4.2 and 20 K. This unit uses a reciprocating mechanism to move the gadolinium gallium garnet crystal in and out of a 5 tesla magnetic coil. Work on a small magnetic refrigerator is in the preparatory stage at the MIT Cryogenic Engineering Laboratory. The development work on magnetic refrigerators appears to be most advanced at CEN Grenoble.

- Cryocoolers under development for the infrared cooling range include a three-stage Stirling-type refrigerator being developed at the Night Vision Laboratory at Fort Belvoir, Virginia.

- One of the most significant developments in small cryocoolers is that of microminiature refrigerators. MMR has developed means of producing a Joule-Thompson type refrigerator on a glass substrate using fabrication methods developed in the semiconductor industry. The heat exchanger and J-T valve can be hermetically sealed and perform satisfactorily as open cycle J-T refrigerators. MMR is currently developing compressors to match the heat exchanger systems and to provide closed-cycle devices.

- General Pneumatics has built a cooler for infrared detector refrigeration based on the Claude cycle, using a diaphragm compressor. Energy Research & Generation has developed split Stirling refrigerators to cool infrared detectors. Also, Kryovac Scientific has built a split Stirling refrigerator with a double transfer line. These units produce 1 W at 80 K.

- In England, the Hymatic Co., which produces thousands of open-cycle J-T coolers have developed a compressor to permit closed-cycle operation for cooling infrared detectors. A prototype refrigerator at Oxford University consists of a split Stirling cycle refrigerator which is operated with a linear drive motor and is suspended on spring-mounted bearings. This unit is under development by several companies in England for the British military infrared detector systems.

- L'Air Liquide in France is carrying out development work on a split Stirling system which has improved drive motor characteristics.

- Philips, in Holland, produces large numbers of coolers for infrared detector cooling and have developed a linear drive motor for their split Stirling cryocooler.

- Development of closed-cycle refrigerators in Japan has proceeded rapidly over the past decade through support from the Japanese government and the Japanese National Railway, aimed at providing refrigerators for the magnetically-levitated rail vehicle. As a result of this activity, three companies in Japan have built refrigerators in the capacity range of 30 W at 4 K. These units are much larger than any required for cooling superconducting electronic devices. However, they have placed these companies in Japan in a position to develop small-scale refrigerators for electronic equipment cooling.
- Aisin Seiki has developed a commercial Stirling cycle cryocooler that uses a swash plate drive mechanism which has been used as a cryopump at 20 K. Plans are underway in Japan to develop a smaller unit having a 50 mW capacity to be used for SQUID cooling.

Table II summarizes the major activity in cryocooler development and Figure 6 indicates the capacity vs. temperature for a number of cryocoolers under development. Specifications for a number of developmental units are presented in Appendix C.

V. Basic Development Activity

In this section we attempt to identify the organizations (see Table III) which are expending a concentrated effort in basic areas of development applicable to advancing the technology of low temperature, efficient cryocooler production. Each of the companies listed in Section III continues to carry out development programs across the board to improve reliability of their systems and work continues on improvement of the developmental coolers cited in Section IV. Activities listed here are those in which a major concentrated effort is being expended in a key area. Once again, we are restricted from presenting details of many developments due the proprietary nature of the work. The areas in which basic development activity is under way include cycle analysis and loss analysis, regenerator development, heat exchanger design, expander design and development, compressor development, seal material, and contaminant elimination.

- Cycle analysis. Jet Propulsion Laboratory has a program to develop adsorption cycle refrigeration systems. They have built two-stage systems and are now looking at going to lower temperatures by adding more adsorption cascade units. At MIT, analysis and development is being carried out on the application of the Saturated Vapor Recompression cycle. General Pneumatics is developing equipment which will

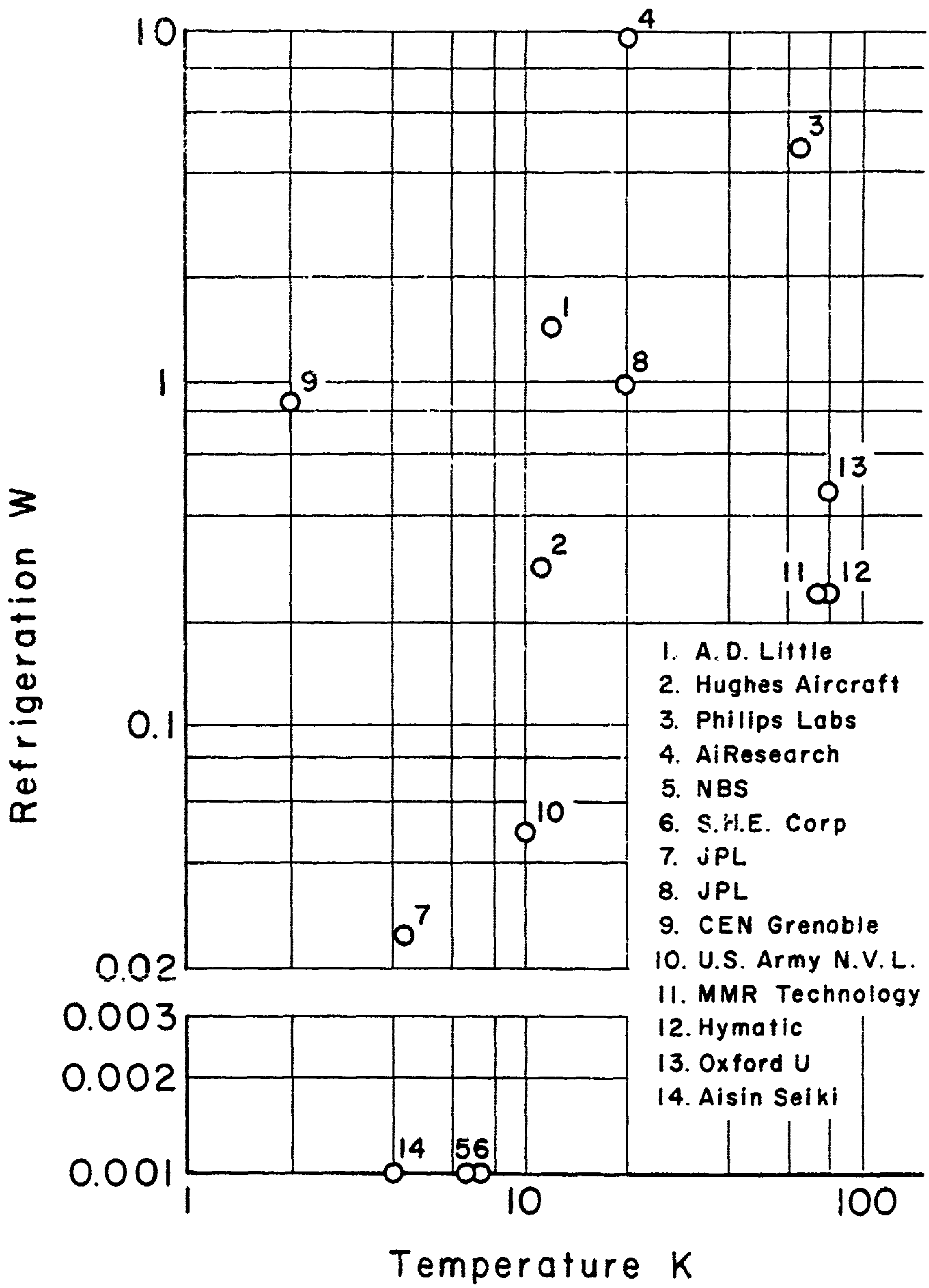

Fig. 6 — Cryocoolers under development

Table II
Cryocoolers Under Development

	4 K Stage	Military IR	Long Life Space	Squid Cooler	Magnetic Refrig
AiResearch			×		
Air Products & Chemicals Inc.	×				
Carlisle Cryotronics	×				
CTI-Cryogenics	×				
CVI Inc.	×				
Energy Research & Generation		×			
General Pneumatics Corp.		×			
Hughes Aircraft			×		×
Kryovac Scientific		×			
A.D. Little			×		
Philips Laboratories	×		×		
S.H.E. Corp.				×	
U.S. Army N.V.L.		×			
Jet Propulsion Laboratory			×		
Los Alamos Scientific Lab.					×
National Bureau of Standards				×	
Oxford University		×			
Hymatic Engineering		×			
L'Air Liquide		×			
CEN Grenoble					×
Mitsubishi	×				
Sumimoto	×				
Suzuki	×				
Hitachi					×

Table III
.Basic Development

	Cycles	Regenerators	Heat Exchangers	Expanders	Compressors	Seals	Materials
Air Products & Chemicals Inc.			X		X		X
Carlisle Cryotronics					X	X	
Creare Inc.				X			
CTI-Cryogenics	X					X	
CVI Inc.	X						
Energy Research & Generation					X		
General Pneumatics Corp.	X						
Hughes Aircraft	X						
Lakeshore Cryotronics				X			
MMR Technologies			X				
Magnavox				X		X	
Mass. Inst. Technology	X						
Mechanical Technology Inc.					X		
Metal Bellows Corp.					X		
Philips Laboratories		X					X
Santa Barbara Research			X				
Jet Propulsion Laboratory	X				X		
National Bureau of Standards		X					
Naval Research Lab					X		
Oxford University				X		X	
Hymatic Engineering					X		
N.V. Philips	X						
L'Air Liquide				X	X		
Aisin Seiki	X						
Daikin Industries Inc.				X	X		
Hitachi		X					
Sumitomo	X		X	X	X		
Toshiba	X		X	X	X		

operate on the Claude cycle to provide temperatures below 10 K. CVI in the USA, Philips Laboratories in Holland, and Aisin Seiki Co. in Japan are working on J-T circuits which will permit the use of Gifford-McMahon or Stirling refrigerators to provide refrigeration at 4 K.

- Regenerators. The development of a regenerator having sufficient heat capacity to permit a Stirling cycle stage at 4 K would be a real breakthrough in cryocooler technology. Philips Laboratories in Briarcliff, Air Products in Allentown, and Hitachi in Japan have programs aimed at developing suitable regenerators for low temperature operation.

- Heat exchangers. A key component of small, efficient refrigeration systems is the heat exchanger. MMR Technologies continues their work to develop further their etched heat exchanger. A similar program, but using metallic heat exchangers, is being carried out at Santa Barbara Research. Air Products also has a program for the development of compact heat exchangers.

- Expanders. Creare Inc. has a program to develop small rotary expanders for use in small refrigeration systems.

- Compressors. A major restriction in the production of cryocoolers is the lack of a noncontaminating compressor for small size coolers. A number of organizations are working on the development of noncontaminating compressors of either the bellows type or the diaphragm type. Those companies which are most active in compressor development include the Naval Research Laboratory, Creare, Mechanical Technology Inc., Jet Propulsion Lab, Carlisle Cryotronics, and Air Products in the USA, and Hymatic in England.

- Seals. Development of moving seal systems which do not generate contamination is a severe problem, particularly in very small refrigerator systems. Cryogenic Technology Inc. has a program for seal development. Work is also being conducted at Oxford University in England and at Carlisle Cryotronics.

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APPENDIX A
CONTACTS

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APPENDIX B
COMMERCIALLY AVAILABLE CRYOCOOLERS

Information reported here was obtained from the various manufacturers in reponse to our survey. Some details have been omitted due to their proprietary or classified nature. It is suggested that the reader contact the manufacturer directly for more complete specification and application data.

CRYOCOOLER

Manufacturer	Air Products	Air Products	Air Products	Air Products
Model	CS 308	CS 208L	CS 208R	CS 204SL
Type/Cycle	Mod Solvay + J-T	Mod Solvay	Mod Solvay	Mod Solvay
Fluid	He	He	He	He
Refrigeration Range (K)	4.2	10	10	10
Capacity (W)/Temp (K)	1.7/4.2	12/20	8/20	8/10
Input Power (W)	9000	6300	6300	3200
Dimensions (mm)	150×830 787×609×832	150×609 787×610×838	150×609 787×609 ×832	150× 457 508×432×508
Weight (kg)	344	280	280	100
Cooldown Time (min)	1800	40	40	30
Quantity	several	—	—	—
Application	laboratory	cryopump	cryopump	cryopump

CRYOCOOLER

Manufacturer	Air Products	Air Products	Air Products	Air Products
Model	CS 204	CS 202	CS 201	CS 108
Type/Cycle	Mod Solvay	Mod Solvay	Mod Solvay	Mod Solvay
Fluid	He	He	He	He
Refrigeration Range (K)	10	10	12	35
Capacity (W)/Temp (K)	4/20	2.25/20	0.6/20	100/77
Input Power (W)	3200	1700	1700	6300
Dimensions (mm)	150×609 508×432×508	150×457 508×432 ×508	150×330 508×432×508	150 ×482 787×610×838
Weight (kg)	105	75	71	316
Cooldown Time (min)	60	40	45	15
Quantity	—	—	—	—
Application	cryopump	cryopump	cryopump	cryopump

CRYOCOOLER

Manufacturer	Air Products	Air Products	L'Air Liquide	L'Air Liquide
Model	CS 104	CS 102	RC 400	RCF 30-4
Type/Cycle	Mod Solvay	Mod Solvay	open J-T	G-M
Fluid	He	He	N_2, Air, Argon	He
Refrigeration Range (K)	35	35	77,82,87	20
Capacity (W)/Temp (K)	60/77	30/77	2/77	30/80: 4/20
Input Power (W)	3200	1700	—	1500
Dimensions (mm)	150×482 508×432×508	150×380 508×432×508	7.23×40	440× 280 470×470 ×470
Weight (kg)	103	75	—	99
Cooldown Time (min)	20	15	1	60
Quantity	—	—	production	50-100 per year
Application	cryopump	cryopump	IR cooling	cryopump

CRYOCOOLER

Manufacturer	AiResearch Manufacturing	Aisin	Balzers High Vacuum Corp.	Cryogenic Consultants Ltd.
Model	851310	—	—	R400
Type/Cycle	J-T closed cycle	Stirling	G-M	G-M + J-T
Fluid	N_2	He	He	He
Refrigeration Range (K)	80	20	12	4.5
Capacity (W)/Temp (K)	2.5/80	15/20; 150/100	5/12; 65/80	0.75/4.2
Input Power (W)	500	6600	—	5000
Dimensions (mm)	298×406×197	380×660×690	—	1150×500×900
Weight (kg)	14.3	240	—	125
Cooldown Time (min)	6	20	—	40
Quantity	2500-	several	50 year	5/year
Application	military aircraft IR	cryopump	cryopump	magnet cooling

CRYOCOOLER

Manufacturer	Cryogenic Consultants Ltd.	Cryomech	Cryomech	Cryomech
Model	R700	GB07	GB04	GB03
Type/Cycle	G-M + J-T	G-M 2 stage	G-M 2 stage	G-M 2 stage
Fluid	He	He	He	He
Refrigeration Range (K)	4.5	16	12	20
Capacity (W)/Temp (K)	1.5/4.2	15/16	4/12; 9/20	5/20
Input Power (W)	8500	8500	5000	5000
Dimensions (mm)	1150×1000×915	1150×1000×915	1150×500×900	1150×500×900
Weight (kg)	242	242	125	125
Cooldown Time (min)	40	40	40	40
Quantity	5 year	5-10/year	5-10/year	several/year
Application	magnet cooling	cryopump	cryopump	cryopump

CRYOCOOLER

Manufacturer	Cryomech	Cryomech	Cryomech	Cryosystems
Model	AL05	AL03	AL01	21
Type/Cycle	G-M 1 stage	G-M 1 stage	G-M 1 stage	G-M
Fluid	He	He	He	He
Refrigeration Range (K)	40	30	25	10
Capacity (W)/Temp (K)	50/40: 120/80	2/30: 9/80	20/80; 3/27	0.25/10
Input Power (W)	5000	700	1200	1500
Dimensions (mm)	1150×500×900	—	—	229×114× 292 498×495×426
Weight (kg)	125	21.3	36	55.5
Cooldown Time (min)	15	30	15	20
Quantity	several	several	50-100	several
Application	cryopump	IR cooling	commercial	laboratory

CRYOCOOLER

Manufacturer	Cryosystems	CTI-Cryogenics	CTI-Cryogenics	CTI-Cryogenics
Model	LTS 1020	21	22	350
Type/Cycle	G-M + J-T	G-M	G-M	G-M
Fluid	He	He	He	He
Refrigeration Range (K)	4.5	10-20	10-20	10-20
Capacity (W)/Temp (K)	3/4.5; 15/77	0.3/15; 7.5/77	0.2/15; 7.5/77	1.5/15; 19/77
Input Power (W)	8000	1500	1500	1500
Dimensions (mm)	533×304×150 1304×838×863	231×152×286	231×152×286	302×152×470
Weight (kg)	—	6.5	6.5	15
Cooldown Time (min)	—	25	25	40
Quantity	5-10/year	—	—	—
Application	laboratory	cryopump	—	—

CRYOCOOLER

Manufacturer	CTI-Cryogenics	CTI-Cryogenics	CTI-Cryogenics	CTI-Cryogenics
Model	1020	1050	CM-2	CM-4
Type/Cycle	G-M	G-M	Stirling	split Stirling
Fluid	He	He	He	He
Refrigeration Range (K)	12-20	10-20	80	80
Capacity (W)/Temp (K)	0.6/15; 37/77	1.7/15; 62/77	1/80	1/80
Input Power (W)	5000	5000	50	60
Dimensions (mm)	369×152×521	369 ×152×502	7.85×12.25× 17.45	55×88
Weight (kg)	15	15	1.72	2
Cooldown Time (min)	40	40	10	10
Quantity	-	—	—	—
Application	—	—	—	—

CRYOCOOLER

Manufacturer	CTI-Cryogenics	CTI-Cryogenics	CTI-Cryogenics	CTI-Cryogenics
Model	CM-5	SP 77A	VM-1	120
Type/Cycle	split Stirling	split Stirling	VM (split)	G-M
Fluid	He	He	He	He
Refrigeration Range (K)	80	80	80	80
Capacity (W)/Temp (K)	0.3/80	0.8/80	0.8/80	8/80
Input Power (W)	30	140	370	830
Dimensions (mm)	38×44×140	140×80×80 190×110×70	5.6 ×17×60 100×80×250	—
Weight (kg)	1.13	2.5	4.8	15.8
Cooldown Time (min)	10	10	10	10
Quantity	—	—	—	—
Application	—	—	IR	—

CRYOCOOLER

Manufacturer	CTI-Cryogenics	CVI Inc.	Galileo Corp.	H.R. Textron
Model	120	TM	—	—
Type/Cycle	G-M	G-M	Stirling	split Stirling
Fluid	He	He	He	He
Refrigeration Range (K)	26	20	80	80
Capacity (W)/Temp (K)	1/26	75/77, 8/20	0.25/80	0.25/80
Input Power (W)	830	5000	30	—
Dimensions (mm)	—	—	—	—
Weight (kg)	15.8	—	1.5	—
Cooldown Time (min)	13	210	5	—
Quantity	—	—	—	thousands
Application	—	cryopump	IR	IR

CRYOCOOLER

Manufacturer	Hughes	Hughes	Hughes	Hughes
Model	SIRE	CM	CM	—
Type/Cycle	VM	split Stirling	split Stirling	split Stirling
Fluid	He	He	He	He
Refrigeration Range (K)	11.5	77	77	30
Capacity (W)/Temp (K)	8.3/75; 1.9/26.5; 0.15/11.5	1/77	0.25/77	1/30
Input Power (W)	—	—	—	—
Dimensions (mm)	—	—	—	—
Weight (kg)	—	—	—	—
Cooldown Time (min)	—	—	—	—
Quantity		—	—	7 month
Application	IR	IR	IR	—

CRYOCOOLER

Manufacturer	Hymatic	Hymatic	Hymatic
Model	MAC 222 Series	MAC 227 Series	MC8, MAC 108 Series
Type/Cycle	self regulating J-T cooler	self regulating J-T cooler	fixed orifice J-T cooler
Fluid	Air, N_2, Ar, Freon	Air, N_2, Ar, Freon	Air, N_2, Ar
Refrigeration Range (K)	80	80	80
Capacity (W)/Temp (K)	—	—	—
Input Power (W)	—	—	—
Dimensions (mm)	7.23 dia.	5.2 dia.	7.2 dia.
Weight (kg)	—	—	—
Cooldown Time (min)	—	—	—
Quantity	> 5000	3000	> 10,000
Application	IR	IR	IR

CRYOCOOLER

Manufacturer	Hymatic	Hymatic	Leybold Heraeus	Leybold Heraeus
Model	MAC 901 Series	MAC 219	RG580/RW3	RG580/RW6
Type/Cycle	self regulating J-T cooler	fast response J-T	G-M	G-M
Fluid	Ar, Air, N_2	Ar, Air, N_2	He	He
Refrigeration Range (K)	80	80-100	20	20
Capacity (W)/Temp (K)	—	—	3.75/20-37.5/80	6.3/20-100/80
Input Power (W)	—	—	1800	4000
Dimensions (mm)	5.2 dia.	—	130×473 400×445×400	130×473 625×550×710
Weight (kg)	—	—	64	160
Cooldown Time (min)	—	0.3	28	20
Quantity	>9000	>100	200/year	200/year
Application	IR	IR	cryopump	cryopump

CRYOCOOLER

Manufacturer	Leybold Heraeus	Leybold Heraeus	MMR	MMR
Model	RG1040	RG 210/RW3	K7701,K7702,K770T	R.01
Type/Cycle	G-M	G-M	J-T	J-T
Fluid	He	He	N_2, Ar, air	Ar
Refrigeration Range (K)	20	20	77	90
Capacity (W)/Temp (K)	12.5/20-43/80	2.5/20; 15/80	0.25/77	3/90
Input Power (W)	4000	1800	—	—
Dimensions (mm)	$13\phi \times 473$ $625 \times 550 \times 710$	130×441 $400 \times 445 \times 400$	$70 \times 40 \times 25$	25 dia.
Weight (kg)	160	64	1	0.2
Cooldown Time (min)	20	33	15	0.08
Quantity	—	200/year	>500	>50
Application	cryopump	cryopump	laboratory	military IR

CRYOCOOLER

Manufacturer	Magnavox	Magnavox	Magnavox	Magnavox
Model	MX 7040	MX 7045	MX 7043	HD1033C/UA
Type/Cycle	split Stirling linear resonant	split Stirling	split Stirling linear resonant	integral Stirling
Fluid	He	He	He	He
Refrigeration Range (K)	85	85	80	80
Capacity (W)/Temp (K)	0.25/80	0.25/85	1/80	1/80
Input Power (W)	30	25	55	50
Dimensions (mm)	5.8×2.8	139×44×44	147×71 ×71	122×91×175
Weight (kg)	1.2	1.1	2.1	1.7
Cooldown Time (min)	5	5	10	15
Quantity	quantity prod.	quantity prod.	production	--
Application	military IR	IR common module	military IR	IR common module

CRYOCOOLER

Manufacturer	Magnavox	Osaka Oxygen	Philips USFA	Philips USFA
Model	MX 7011	cryomini D	UA 7044/00	UA 7011
Type/Cycle	Stirling linear resonant	modified Solvay	split Stirling	Stirling
Fluid	He	He	He	He
Refrigeration Range (K)	80	11-20	80	80
Capacity (W)/Temp (K)	1/80	2.5/20	1/80	1/80
Input Power (W)	—	2400	55	—
Dimensions (mm)	—	—	10 dia.×88	—
Weight (kg)	—	84	1.8	—
Cooldown Time (min)	—	35	—	—
Quantity	production	—	hundreds	production
Application	IR common module	cryopump	military IR	military IR

CRYOCOOLER

Manufacturer	Philips USFA	Ricor Ltd.	Ricor Ltd.	Ricor Ltd.
Model	UA 7039/00	K 413G	K 505	K 405
Type/Cycle	split Stirling	split Stirling	integral Stirling	VM
Fluid	He	He	He	He
Refrigeration Range (K)	80	80	80	80
Capacity (W)/Temp (K)	0.25/80	0.4/80	0.25/80	1/80
Input Power (W)	30	40	30	150
Dimensions (mm)	5 dia.×49	180×100×100	124×45 ×128	227×180×234
Weight (kg)	1.5	3.8	1.35	3.8
Cooldown Time (min)	5	5	5	15
Quantity	production	—	—	—
Application	military IR	military IR	military IR	military IR

CRYOCOOLER

Manufacturer	ABG Semca	Telefunken AG
Model	—	—
Type/Cycle	split Stirling	split Stirling
Fluid	He	He
Refrigeration Range (K)	80	80
Capacity (W)/Temp (K)	0.25/80	0.25/80
Input Power (W)	—	—
Dimensions (mm)	—	—
Weight (kg)	—	—
Cooldown Time (min)	—	—
Quantity	—	production
Application	military IR	military IR

APPENDIX C

CHARACTERISTICS OF A NUMBER OF CRYOCOOLERS UNDER DEVELOPMENT

Information reported here was obtained from the various manufacturers in reponse to our survey. Some details have been omitted due to their proprietary or classified nature. It is suggested that the reader contact the manufacturer directly for more complete specification and application data.

<u>CRYOCOOLER</u>

Manufacturer	Air Products	Air Products	Air Products	L'Air Liquide
Model	CS 308L	CS 304	CS 302	RH 820
Type/Cycle	Mod Solvay + J-T	Mod Solvay + J-T	Mod Solvay − J-T	split Stirling
Fluid	He	He	He	He
Refrigeration Range (K)	3.7	3.7	3.7	80
Capacity (W)/Temp (K)	1/4.2	0.5/4.2	0.25/4.2	1/80
Input Power (W)	9000	4800	2.5	—
Dimensions (mm)	150×832 787×609×832	—	—	—
Weight (kg)	350	170	127	–
Cooldown Time (min)			1800	—
Quantity	development	development	development	prototype
Application	—	–	—	IR cooling

CRYOCOOLER

Manufacturer	L'Air Liquide	AiResearch	AiResearch	AiResearch
Model	RH 520	IR TECH/ASD	—	—
Type/Cycle	split Stirling	reversed Brayton 2 stage turbo	reversed Brayton turbo refrigerator	VM
Fluid	—	He, Neon	Neon-He/He	He
Refrigeration Range (K)	80	20	4	80
Capacity (W)/Temp (K)	0.5/80	20/20	5/20	0.25/80
Input Power (W)	—	4000	2200	—
Dimensions (mm)	—	900×1000×700	900×1020×640	—
Weight (kg)	—	136	90.3	—
Cooldown Time (min)	—	—	480	—
Quantity	prototype	prototype	prototype	prototype
Application	IR cooling	IR space	continuous: >5 yr life	IR cooling

CRYOCOOLER

Manufacturer	CEN Grenoble	CTI-Cryogenics	General Pneumatics
Model	—	Design Study (ONR)	COBRA
Type/Cycle	double acting, reciprocating magnetic refrigerator	integral Stirling 4 stage	Claude
Fluid	He - Gadolinium Gallium Garnet	He	He
Refrigeration Range (K)	1.8 from 4.2	10	80
Capacity (W)/Temp (K)	0.92/2.1	0.05/10	0.25/80
Input Power (W)	2.88	250	—
Dimensions (mm)	—	629×278	—
Weight (kg)	—	—	—
Cooldown Time (min)	—	—	—
Quantity	1	design only	prototype
Application	experimental	—	IR

CRYOCOOLER

Manufacturer	Hitachi	Hitachi	Hughes	Hughes
Model	II	III	Hi Cap	—
Type/Cycle	Claude	Claude	VM	split Stirling
Fluid	He	He	He	He
Refrigeration Range (K)	4	4	12	20
Capacity (W)/Temp (K)	30/4.5	5/4.5	12/75; 10/33; 0.3/11.5	1/20
Input Power (W)	—	—	2700	—
Dimensions (mm)	—	—	—	—
Weight (kg)	165	45	—	—
Cooldown Time (min)	—	—	—	—
Quantity	developmtl.	developmtl	6	developmtl.
Application	—	—	developmtl.	—

CRYOCOOLER

Manufacturer	Hymatic	Hymatic	Jet Propulsion Laboratory	Jet Propulsion Laboratory
Model	MAC 251 Series	MAC 252 Series	prototype	GAR-MII
Type/Cycle	self regulating J-T	J-T minicooler	cascade J-T	gas adsorption J-T
Fluid	Air, N_2, Ar	Air, N_2, Ar	$CF_4/N_2/H_2/He$	He/H_2 /Ar/Neon
Refrigeration Range (K)	80	80	4.5-180	80-4
Capacity (W)/Temp (K)	—	—	3/165; 1/84: 0.15/22; 0.025/4.5	1/20
Input Power (W)	—	—	100	129
Dimensions (mm)	5.18	—	60 O.D. × 180	.50×100×100
Weight (kg)	—	—	—	2
Cooldown Time (min)	—	—	360	1
Quantity	developmtl.	exptl. samples	1 prototype	developmtl.
Application	—	low cost J-T minicooler	IR	no moving parts refrigerator

<u>CRYOCOOLER</u>

Manufacturer	A.D. Little	Magnavox	Mitsubishi	Mitsubishi
Model	rotary reciprocating	(DARPA)	—	—
Type/Cycle	reverse Brayton 2 stage	2 stage Stirling linear magnetic bearing	2 stage G-M + J-T	3 stage Stirling + J-T
Fluid	He	He	He	He
Refrigeration Range (K)	12	—	4.4	4.4
Capacity (W)/Temp (K)	40/60; 1.5/12	10W, 5W at classified temp	5/4.4	5/4.4
Input Power (W)	2670	700	8000	5000
Dimensions (mm)	1473×304 dia.	1420×280 dia.	—	—
Weight (kg)	210	82	—	—
Cooldown Time (min)	—	—	—	—
Quantity	1	developmtl.	developmtl.	developmtl.
Application	prototype	space flight	—	—

CRYOCOOLER

Manufacturer	NBS	Oxford University	Philips Lab	Philips Lab
Model	gap regenerator	—	—	JHV/APL
Type/Cycle	split Stirling	split Stirling linear drive	Stirling	2 stage Stirling rhombic drive bellows seal
Fluid	He	He	He	He
Refrigeration Range (K)	7	80	65	75
Capacity (W)/Temp (K)	0.001/6.9	0.5/80	5/64.6	1.5/1:0, 0.3/90
Input Power (W)	—	35	200	30
Dimensions (mm)	—	—	—	154×180×307
Weight (kg)	—	2	—	7.2
Cooldown Time (min)	—	—	—	—
Quantity	experimental	several	prototype	6
Application	squid cooling	IR cooling	space IR	space electronics

CRYOCOOLER

Manufacturer	Philips Lab	Quantum Technology Corp.	S.H.E. Corp.
Model	(NASA)	100	4 K cryocooler
Type/Cycle	Stirling magnetic bearing	open cycle J-T	4 stage Stirling
Fluid	He	He	He
Refrigeration Range (K)	65	4.2	6
Capacity (W)/Temp (K)	5/65	0.002/4.2	0.001/7
Input Power (W)	220	requires refrigeration to 12 K	—
Dimensions (mm)	—	—	—
Weight (kg)	—	—	—
Cooldown Time (min)	20	—	—
Quantity	1	several	1
Application	5 year space electronics	squid cooling	squid

CRYOCOOLER

Manufacturer	Sumimoto	Toshiba
Model	—	—
Type/Cycle	Claude	Claude
Fluid	He	He
Refrigeration Range (K)	4.5	4.4
Capacity (W)/Temp (K)	—	4/4.4
Input Power (W)	—	—
Dimensions (mm)	—	—
Weight (kg)	—	—
Cooldown Time (min)	—	720
Quantity	developmtl.	developmtl.
Application	—	—

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