SPACECRAFT-BORNE LONG LIFE CRYOGENIC REFRIGERATION

STATUS AND TRENDS

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ABSTRACT

The status of cryogenic refrigerator development intended for, or possibly applicable to, long life spacecraft-borne application is reviewed. Based on these efforts, the general development trends are identified. Using currently projected technology needs, the various trends are compared and evaluated. The linear drive, non-contacting bearing Stirling cycle refrigerator concept appears to be the best current approach that will meet the technology projection requirements for spacecraft-borne cryogenic refrigerators. However, a multiply redundant set of lightweight, moderate life, moderate reliability Stirling cycle cryogenic refrigerators using high-speed linear drive and sliding contact bearings may possibly suffice.

INTRODUCTION

To establish bounds for this overview, figure 1 illustrates possible spacecraft-borne long life cryogenic cooling needs, while suggested methods are shown in figure 2 and current program design regimes appear in figure 3. Expendable mass cryogenic heat sinks are excluded from consideration due to the excessive weight and volume that results when such a system is sized to the long life requirement (5 to 10 years). A hybrid system which would use a refrigerator to balance the tankage heat leaks and a stored cryogen for the actual cooling effect may, in some instances, prove to be the optimum system; however, such integrated systems are beyond the purview of this paper.

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For the higher cryogenic temperatures, the use of conductive-radiative or convective-radiative cooling methods, possibly incorporating heat of fusion thermal storage, cryogenic heat pipes (conventional, variable conductance, and diode), and/or thermal switches will suffice--especially if the vehicle orbit, orientation, and configuration can be somewhat constrained. With the exception of diode heat pipes and cryogenic thermal switches, this segment of spacecraft cryogenic cooling technology is sufficiently well developed to be immediately applicable. However, some areas could be improved, e.g., spectrally selective surface coatings, improved insulation, and low specific weight radiator designs.

For low heat loads at intermediate range cryogenic temperatures, thermoelectric (Peltier) cooling is an available mature technology that will suffice when coupled with low temperature radiators. Lockheed Research Laboratories are currently developing Nernst-Ettinghausen thermo-magneto-electric cryogenic cooling materials. This is a high risk program that might result in developing materials with improved direct conversion efficiencies; however, even if the material development is successful, engineering hardware probably will not be available until 1990.

Adiabatic demagnetization is the thermodynamic process used to obtain extremely low temperatures. Recently, Stegert (ref. 1) at Los Alamos has suggested that this technique might be extended to develop a high efficiency cryogenic refrigerator applicable to the "midband" region (5 - 50K; 1-10 W). At this time, it appears to be a high risk endeavor due to the complex mechanical system configuration, extremely high magnetic field requirements (superconducting magnetics), and the lack of materials with significant magnetocaloric properties to cover the temperature range from heat source to heat sink.

As evidenced in figures 1 and 2, the majority of the spacecraft-borne long life cryogenic cooling needs can be met effectively only with the use of mechanical refrigerators. Projections of the performance characteristics of such hardware which could be developed, up to the year 2000, are summarized in table I.

STATUS

The lack of reliable cryogenic refrigerators for spacecraft use has been recognized as a constraining technology for over 20 years. Tens of millions of dollars of federal research funds have been spent on this technology. A totally successful product has yet to be developed. The status of four current programs specifically directed towards the development of long life spacecraft-borne refrigerators is summarized below followed by comments on other cryogenic refrigerator programs which exhibit features potentially adaptable to this development.

1. Arthur D. Little Rotary Reciprocating Refrigerator (fig. 4). This design uses rotary motion to create a gas bearing effect as well as reciprocating motion for compression and expansion to create the refrigeration effect. This concept has been under development since 1962. The

design can be thermodynamically configured as either an Ericsson cycle or a Stirling cycle. In the Ericsson cycle configuration, the rotary motion is synchronized with the reciprocating motion so that slide valve porting can be simply accommodated. The bearing and porting requirements imposed on the low temperature displacer result in the need for a close tolerance, small clearance part which has proven to be difficult to make. The Stirling cycle configuration should reduce this problem, since the valving would be eliminated, much higher rotational speed could be used, and the clearance could thereby be increased. The Ericsson cycle hardware has not yet successfully operated as a complete system. The Stirling cycle hardware has not yet been built. Component-demonstrated life is approximately 10,000 hr.

2. Hughes Aircraft Company Vuilleumier Refrigerator (fig. 5). This design is based on the Vuilleumier cycle which uses heat rather than mechanical energy to cyclically pressurize the working gas. The hardware has been in development since 1967. The design uses sliding composite seals and riders and a rotary to reciprocating mechanical drive to shuttle the displacers while a 90° phase angle is maintained between the relative positions of the hot and cold displacers. The drive mechanism uses dry-lubricated ball bearings and Bendix flexure bearings. The design is wear and fatigue life limited.

Maximum demonstrated life is approximately 6,000 hr. The design has low efficiency due to the thermodynamic losses in the conversion of electrical energy to heat to mechanical energy. The Hughes Vuilleumier refrigerator appears to be an acceptable unit for a one-year mission; however, the electrical power required is high in comparison to the alternatives, resulting in increased vehicle weight and cost unless on-board heat (e.g. nuclear) is provided.

3. AiResearch/Garrett Turbo Brayton Refrigerator (fig. 6). This design uses foil-type gas bearings, a high-speed compressor, and a turbo-alternator expander. The hardware has been under development since 1977. Full system operation has been demonstrated; however, the system did not meet design goals due to a design error in the cold regenerator. The performance test is scheduled to be rerun with a larger cold regenerator and improved insulation. There have been less than 1000 hr of full system operation. This design is based on concepts and principles that should result in a five-year service life, high reliability unit, although further life testing will be required to verify this. The power required is high when compared to most other refrigerator configurations in the design regimes of current interest.

4. Philips Laboratories, U.S.A., Magnetic Bearing-Free Piston Stirling Cycle Refrigerator (fig. 7). This concept has been under development since 1978 and had a successful first run in March 1982. Magnetic bearings are used to support the moving elements thereby eliminating mechanical wear, thus trading mechanical simplicity with wear for electro-magnetic complexity with zero wear. The design offers promise of being a successful long life, high reliability, efficient cryogenic refrigerator, but it will be necessary to perform further life tests to

establish the reliability of the magnetic bearing system. The existing design will need modification for spacecraft use; however, the test data from the development model show that all performance requirements, including zero wear, have been met. A multi-stage linear Stirling refrigerator would offer the same advantages as the single stage; unfortunately, such a unit is yet to be built and demonstrated.

5. Other Programs of Interest. Philips designed and constructed a "one-year" rhombic drive cryogenic refrigerator, four of which were flown on the STP 78-1 spacecraft experiment (fig. 8). Three of the refrigerators have continued to operate (periodically) for over 36 months, but with a continually degrading performance primarily due to helium leakage. Probably some contamination of the regenerator also exists due to the rhombic drive lubricant and seal wear. The design could be improved by replacing the elastometric static seals with hermetic welded joints to eliminate helium leakage and by adding a bellows (not included in the flight versions due to unsatisfactory performance) to separate the working gas from the gear lubricants to eliminate regenerator contamination. In this way, a two- to three-year life design should result. (Test data on candidate metal bellows show seal failure at 10,000 hr.) It is probably more cost-effective and energy efficient, however, to complete the redesign and qualification of the NASA Goddard single stage linear Stirling refrigerator.

Philips Einhoven, Netherlands, has developed a line of extremely simple linear drive, free piston, Stirling cycle refrigerators. These units, intended initially for laboratory use, are guaranteed for 2,500 hr. The basis of this claim is an experiment in which five units were operated 23 hr/day until 5,000 hr were accumulated on each unit. Apparently no significant change occurred in performance after the first few hundred hours. Philips Einhoven is currently developing several different militarized versions of this refrigerator. Schematics of the units are shown in figure 9. (These machines are not designed for spacecraft operation.)

Davey (ref. 2) has reported on the development of a long life, high reliability, spacecraft-intended split Stirling component refrigerator which appears to be very similar in configuration to the Philips Einhoven unit, except that flexure bearings have been incorporated to support the compressor piston to eliminate wear, and a linear drive has been added to the displacer in order to control the phase angle. The flexure bearing design is apparently derived from that developed by Johnston (ref. 3) for an artificial heart Stirling engine. The current status of this development is uncertain. Figure 10 is a schematic of this unit.

A linear drive helium prototype compressor was developed at Mechanical Technology, Inc., and a mating prototype reciprocating helium expander/liquifier was developed at Cryogenic Technology, Inc. The development, which was not completely successful, was intended to be used for a shipboard liquid helium source, but the technology may be applicable to spacecraft-borne use. There are similarities between the Arther D. Little and the Mechanical Technology, Inc., linear compressors; both are linear resonance machines using gas springs. However, the Mechanical Technology Inc., design uses hydrostatic gas bearings, reed valves, and a linear magnetic induction motor, whereas the Arthur D. Little compressor uses hydrodynamic bearings, slide valves, and a linear solenoid motor.

The Night Vision Laboratory is funding the development of a split component Stirling cycle refrigerator somewhat similar to the Philips Einhoven/Davey-Oxford designs. Although intended for ground and airborne use, the unit might prove useful in spacecraft applications.

TRENDS

Considering the thermodynamic cycles suitable for cryogenic refrigerators, the current state of the art of the elements used in long duration spacecraft cryogenic refrigerators, and the active development programs, it is possible to create a morphological array which provides some insight into possible future trends in the technology. The thermodynamic cycles of interest are the Stirling, Ericsson (Brayton), and Claude/Collins. The Vuilleumier refrigerator can be considered to be a Stirling power engine driving a Stirling refrigerator. Possible bearing systems are low pressure sliding contact, flexures, hydrodynamic gas, hydrostatic gas, and electromagnetic. For linear refrigerators, the motor choice includes moving coil, moving iron, and moving magnet. For rotary dynamic refrigerators, induction and permanent magnet rotor motors are possible, the latter being superior due to higher efficiency. The three variables--thermodynamic cycle, bearing type, and motor type--can be used to generate a morphological array. The current development efforts are noted on the resulting map (fig. 11). Apparently, very few of the possible combinations are currently being pursued. As an additional possibility for bearing systems, Mechanical Technology, Inc., has suggested that piezoelectrically energized squeeze film bearings might be developed for this type of hardware. Similarly, piezoelectric drives ("benders") or magnetostrictive drives might prove useful as an alternative to linear electromagnetic motors, especially as displacer actuators.

To establish a basis for evaluating trends, note that three major design parameters of importance to spacecraft-borne cryogenic refrigerators are: service life/reliability (which implies a mean time between failure), cooling capacity at temperature, and specific power (power in per cooling effect) at temperature. Technology projection values for these parameters, in essence "design requirements," have been presented in table I for the 1980-2000 time period. It is interesting to compare these design parameters against the intrinsic capabilities of the generic type of refrigerator typified by each of the four major development programs currently being funded: the Arthur D. Little Rotary Reciprocating Refrigerator, the Hughes Vuilleumier Refrigerator, the AiResearch Turbo-Brayton Refrigerator, and the Philips Linear Drive, Magnetic Bearing Stirling Refrigerator.

First consider the service life/reliability parameter. The close tolerance, small clearance development problem of the Arthur D. Little Refrigerator development must be resolved before the design can meet the one-year/85% reliability requirement. If a suitable thermally stable material can be found, if the unit is designed so that all materials used are never stressed beyond the fatigue limit, and if the position sensor life proves to be adequate, the design may meet the five-year service life/90% reliability. To develop a longer life/higher reliability version, advanced materials and/or alternate concepts/applications are considered necessary. These items are addressed later in this paper.

The Hughes Vuilleumier Refrigerator program must complete the regenerator composite seal development effort before the design is considered to have met the one-year/85% reliability requirement. To proceed much beyond this point, a complete redesign is required to eliminate wear, reduce material fatigue stresses, and stop working fluid leakage. This could be accomplished by changing to a linear drive (thereby eliminating the Bendix flexure and the dry-lubricated ball bearings), changing from sliding contact composite seals to clearance seals, and converting from a bolted flange, O-ring seal to a welded enclosure which is designed so that the stresses remain well within the material fatigue limit. To meet the 10-year service life/95% reliability, advanced materials and/or alternate concepts/applications are considered necessary.

The thrust bearing currently used in the AiResearch Turbo-Brayton Refrigerator turbo-expander/alternator unit may not be the design recommended for the flight configuration. When this question is resolved, the design should be capable of meeting the five-year service life/90% reliability requirement if the motor stator end windings can survive and if the shutdown/restart cycles do not wear the foil bearings excessively. Ten-year service life with 95% reliability appears to be beyond the capabilities of this design unless advanced materials and/or alternate concepts/applications are utilized.

The Philips Linear Drive Magnetic Bearing Stirling Refrigerator was conceived and designed to meet the five-year service life/90% reliability requirement. The existing hardware is an engineering development design configuration, thus the refrigerator needs to be redesigned to a flight configuration. If the unit is designed so that all materials used are never stressed beyond the fatigue limit, and if the position sensor life proves adequate, the fundamental design would appear to meet the 5-year, 190% reliability requirement. Figure 12 graphically summarizes the service life/reliability development issues discussed above.

If a thermally stable material can be obtained for the close tolerance, small clearance requirements of the Arthur D. Little Rotary Refrigerator design, then all four development concepts can be considered as capable of meeting both the 5 W at 65°K to 20 W at 20°K design spectrum and the 0.2 W at 10°K to 2 W at 10°K design spectrum by appropriate component sizing and/or staging. To meet the 0.1 W at 4°K to 5 W at 4°K design spectrum, an additional stage would be required for the AiResearch Turbo-Brayton design incorporating a final stage recuperator and a Joule-Thompson (J-T) valve (possibly aided with a jet pump). This effectively changes the configuration to a Collins cycle, as shown in figure 13. The Arthur D. Little, Hughes, and Philips designs would require a secondary loop using recuperators, a compressor, and a J-T valve (possibly aided by a jet pump) to meet the 0.1 W at 4°K to 5 W at 4°K design spectrum. Figure 14 graphically shows the essence of this hybrid configuration. The cooling capacity at temperature development issues discussed above are illustrated in figure 15.

Considerations of the issues relating to specific power at temperature show that the Arthur D. Little and Philips refrigerator concepts can be utilized, subject to appropriate sizing, staging, and incorporation of additional components, to meet the design requirements for all three spectra identified. The Hughes Vuilleumier design concept can only meet the specific power at temperature requirements in the 10 kW power-in/W cooling at 10°K region--effectively the 1980 technology point. The AiResearch Turbo-Brayton refrigerator concept can be sized to meet the specific power at temperature design requirements, but only if the cooling loads are greater than those identified under the cooling capacity at temperature design requirements. Figure 16 shows the comparison between the four refrigerator concepts for the specific power and temperature development issues.

To meet the technology projections, "advanced materials" may be required. Some candidate materials and their potential use are summarized in Table II. Of particular interest are dimensionally stable materials with low, isotropic coefficients of thermal expansion suitable for use down to 4°K, materials with high fatigue limit strength at 10^9 cycles, and materials suitable for non-wearing sliding contact bearings.

Alternate approaches to meet the technology projections exist. One method would be to use a number of moderate life, high reliability, lightweight, high efficiency refrigerators coupled in parallel to the cryogenic load through cryogenic thermal diodes. If one unit failed, another unit would be activated. Figure 17 depicts such a redundancy-based refrigeration system. The Philips Einhoven, Davey-Oxford, and Night Vision Laboratory split component Stirling cycle designs are candidate refrigerators for this concept. A second method would be to incorporate a large cryogenic heat sink with a greatly oversized non-wearing refrigerator (and a cryogenic thermal diode) that could operate with a low duty cycle and still provide the average cooling needs. The number of stop-start cycles would necessarily increase; however, the total running time on the refrigerator would decrease and the efficiency would increase (due to the unit being sized to a larger heat load). Overall system advantages might also result, since a better match could be obtained between power needs and power availability. These alternate approaches have not been examined in sufficient detail to validate their usefulness nor to influence the design parameters used in the current development programs.

CLOSURE

In order to meet the life-reliability requirements identified for spacecraft-borne long duration applications, cryogenic refrigerators should be designed to eliminate component wear, material fatigue, working fluid contamination, and working fluid leakage. The Turbo-Brayton refrigerator design appears to satisfy these criteria; there is no sliding contact (other than startup), no pressure cycling, no sources for contamination in contact with the working fluid, and effectively no leakage (The entire unit is welded together thereby hermetically sealing the working gas.). The compressor and turbine wheel blades are subjected to low level, high frequency cyclic stresses as are the unsupported copper end windings and the ferromagnetic laminations in the motor. Proper material selection and structural design should result in keeping the stresses in these elements well below the fatigue limit. Unfortunately, this design does exhibit a relatively low efficiency in comparison to the periodic refrigerator designs in the mid-cryogenic temperatures, mid-cooling effect region. Several technology innovations exist which could be developed and incorporated in the Turbo-Brayton design to improve efficiency (three-dimensional flow turbine/compressor "wheels," higher speed components, magnetic bearing on the turbo-alternator, lower loss rotors, higher effectiveness heat exchangers, a more efficient insulation system); however, even if all the improvements were successfully incorporated, the design still would only be power competitive in the higher cryogenic temperature or the higher heat load regions.

The Vuilleumier cycle refrigerator, as embodied in the Hughes Aircraft Corporation design, experiences wear (bearings, seals, riders), material fatigue (flextures, housing pressure cycling), potential working fluid contamination (breakdown of organic wear products), and working fluid leakage (bolted closures-elastometric seals). Through conversion to a linear drive, incorporation of clearance seals, and enclosure of the unit in a hermetic housing, most of these difficulties could be eliminated (except for housing pressure cycling). The design would still be considerably less efficient than the Stirling and Ericsson cycle refrigerators; thus it would be non-competitive from an effective total weight basis unless an on-board low penalty heat source were available (waste heat, nuclear, solar thermal).

The Rotary Reciprocating Refrigerator, as designed by Arthur D. Little, and the magnetic bearing-supported linear Stirling cycle refrigerator as developed by Philips Laboratories both appear to possess most of the attributes deemed necessary for long life, high reliability operation together with relatively high operation efficiency. The Stirling cycle variant of the Rotary Reciprocating Refrigerator seems to be superior to the Ericsson cycle version due to a less critical displacer clearance requirement, the inherent simplicity of a regenerator in comparison to a recuperator, and a higher overall cycle efficiency (due to the higher effectiveness obtained from a regenerator in comparison to a recuperator). (Only the Ericsson cycle version is presently under development.) Both the Arthur D. Little and the Philips Laboratories designs have potential failure modes which have not been completely evaluated, one being the failure of the position sensor(s) necessary for the proper operation of the unit, and the other possibility being enclosure failure from material pressure cycle fatigue. Neither appears to be an insurmountable problem.

At this time, the linear drive non-contacting bearing Stirling cycle refrigerator concept appears to be the best approach to meet the technology projection requirements for spacecraft-borne cryogenic refrigerators; however, a system based on the use of a number of lightweight, moderate life, moderate reliability cryogenic refrigerators (e.g., Philips Einhoven, Davey-Oxford, Mico-Vision Laboratory) coupled in parallel via cryogenic thermal diodes may prove to be competitive, especially since any spacecraft system specification will probably mandate the incorporation of at least one redundant refrigerator.

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2. Davey, G.: "The Oxford University Miniature Cryogenic Refrigerator," International Conference on Advanced Infrared Detectors and Systems, Institute of Electrical Engineers, London, October 1982.

3. Walker, G.: "Stirling Engines," Clarendon Press, Oxford, 1980.

TABLE I. - SPACECRAFT-BORNE CRYOGENIC REFRIGERATORS

TECHNOLOGY PROJECTIONS

ITEM \ YEAR	1980	1985	1990	1995	2000
SERVICE LIFE/RELIABILITY (MTBF* - HR)	1 YR/85% ($5X10^4$)		5 YRS/90% ($4X10^5$)		10 YRS/95% ($2X10^6$)
COOLING CAPACITY @ TEMP.	0.2W @ 10K	2W @ 10K 5W @ 65K	0.1W @ 4K	20W @ 20K	5 W @ 4K
SPECIFIC POWER @ TEMP. - POWER IN PER WATT COOLING	10KW/W @ 10K	2.5 KW/W @ 10K 30 W/W @ 65K	10 KW/W @ 4K	250 W/W @ 20K	2.5 KW/W @ 4K

* MTBF - Mean Time Between Failure

TABLE II. - SPACECRAFT-BORNE CRYOGENIC REFRIGERATORS

POTENTIALLY USEFUL MATERIALS

ITEM	USE
SINGLE CRYSTAL METALS	HIGH FATIGUE LIMIT PARTS
CERAMICS	CLOSE TOLERANCE,, SMALL CLEARANCE PARTS
GLASSY METALS	HIGH MAGNETIC PERMEABILITY MATERIAL
RARE EARTH ELEMENTS/COMPOUNDS	REGENERATOR MATRIX MATERIAL HIGH ENERGY PRODUCT HIGH COHESIVE STRENGTH MAGNETICS - FOR MOTOR/MAGNETIC BEARINGS
ADVANCED COMPOSITES	HIGH STRENGTH FATIGUE RESISTANT HOUSINGS; OTHER MEMBERS
PIEZO ELECTRIC/MAGNETOSTRICTIVE MATERIALS	LINEAR MOTORS/FLEXURES (BENDERS) SQUEEZE FILM GAS BEARING GENERATORS
DIAMOND MATRIX COMPOSITES	HARD-ON-HARD SLIDING CONTACT BEARINGS

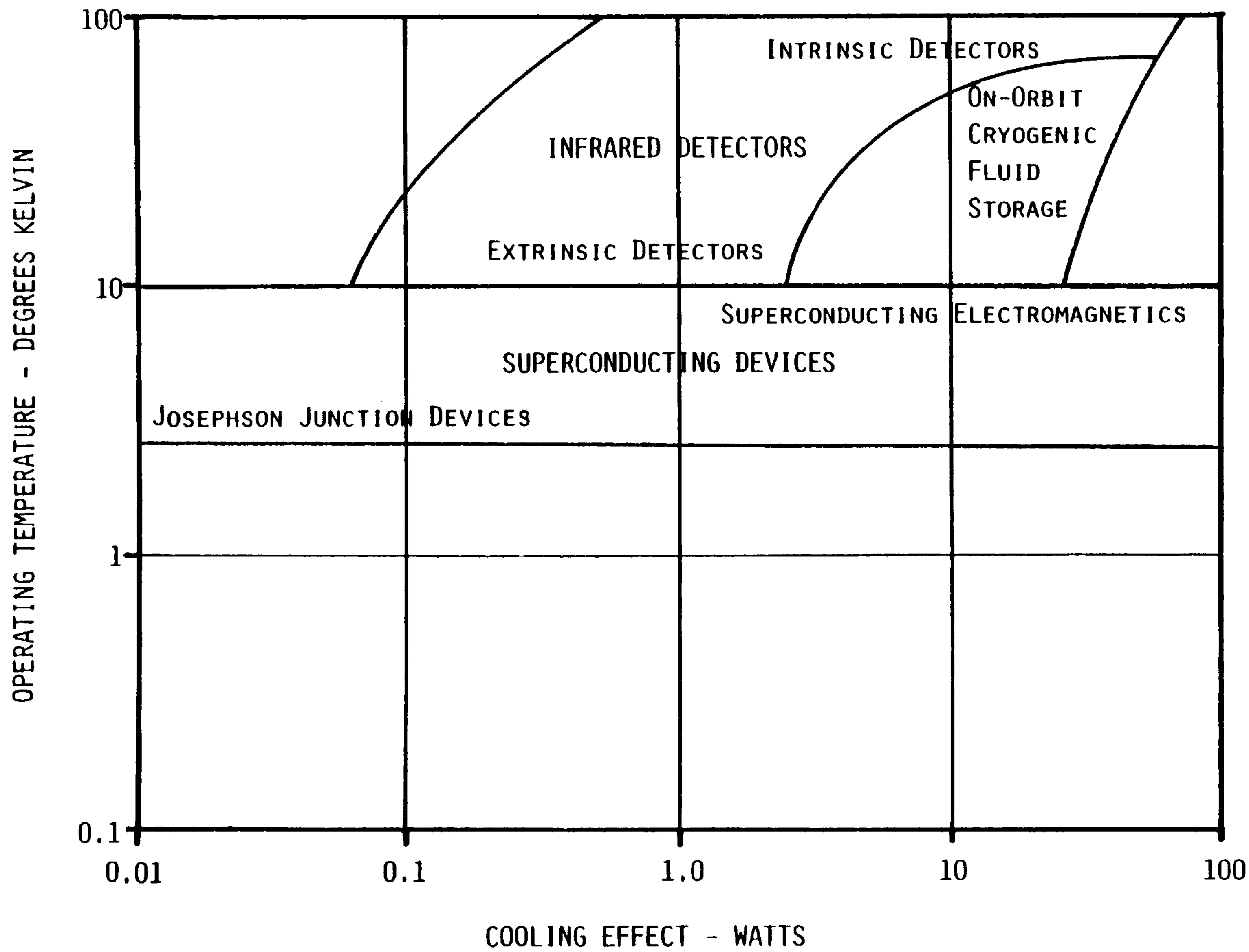


Figure 1. Cryogenic Cooling Considerations for Long Duration Spacecraft Applications--Needs

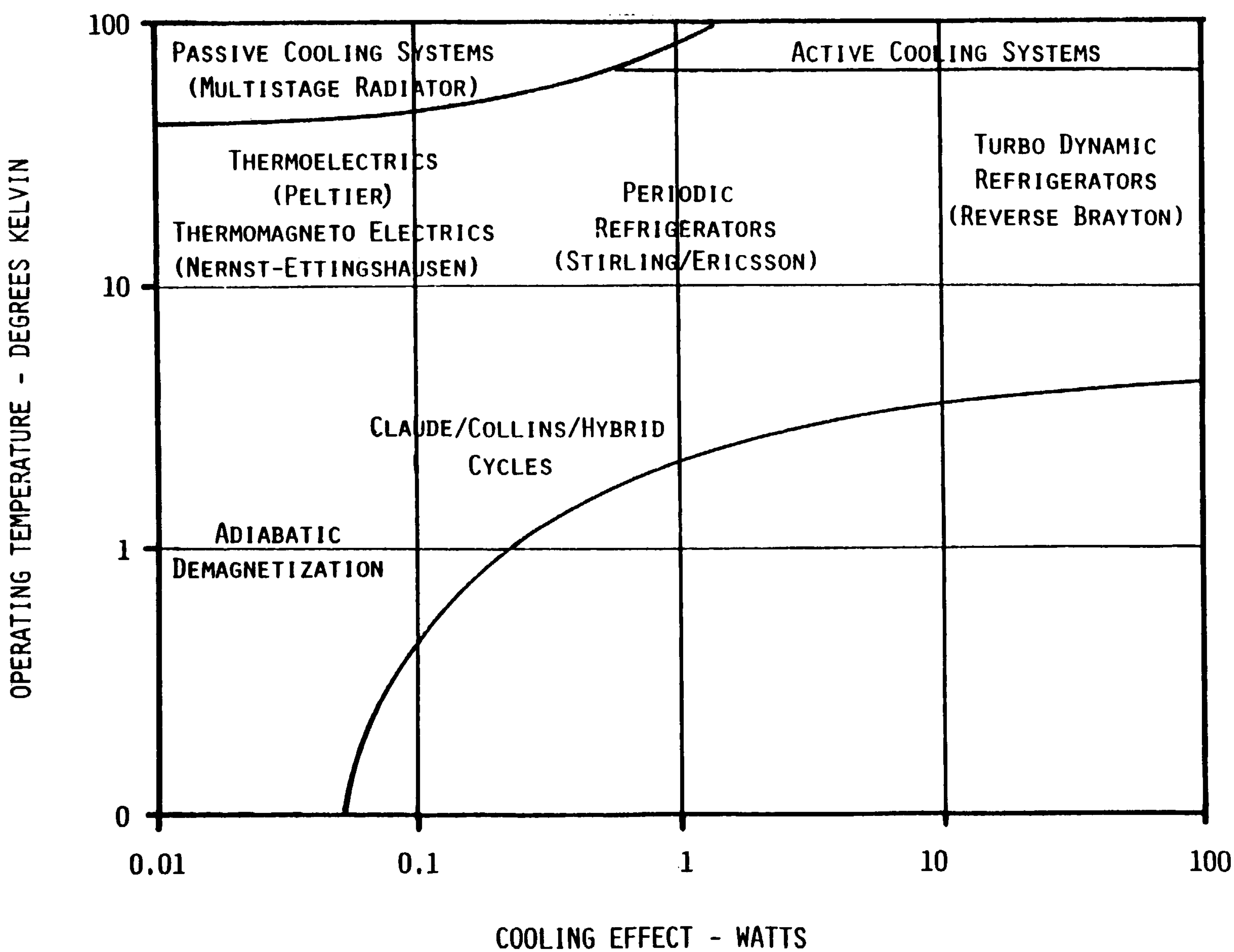


Figure 2. Cryogenic Cooling Considerations for Long Duration Spacecraft Applications--Methods

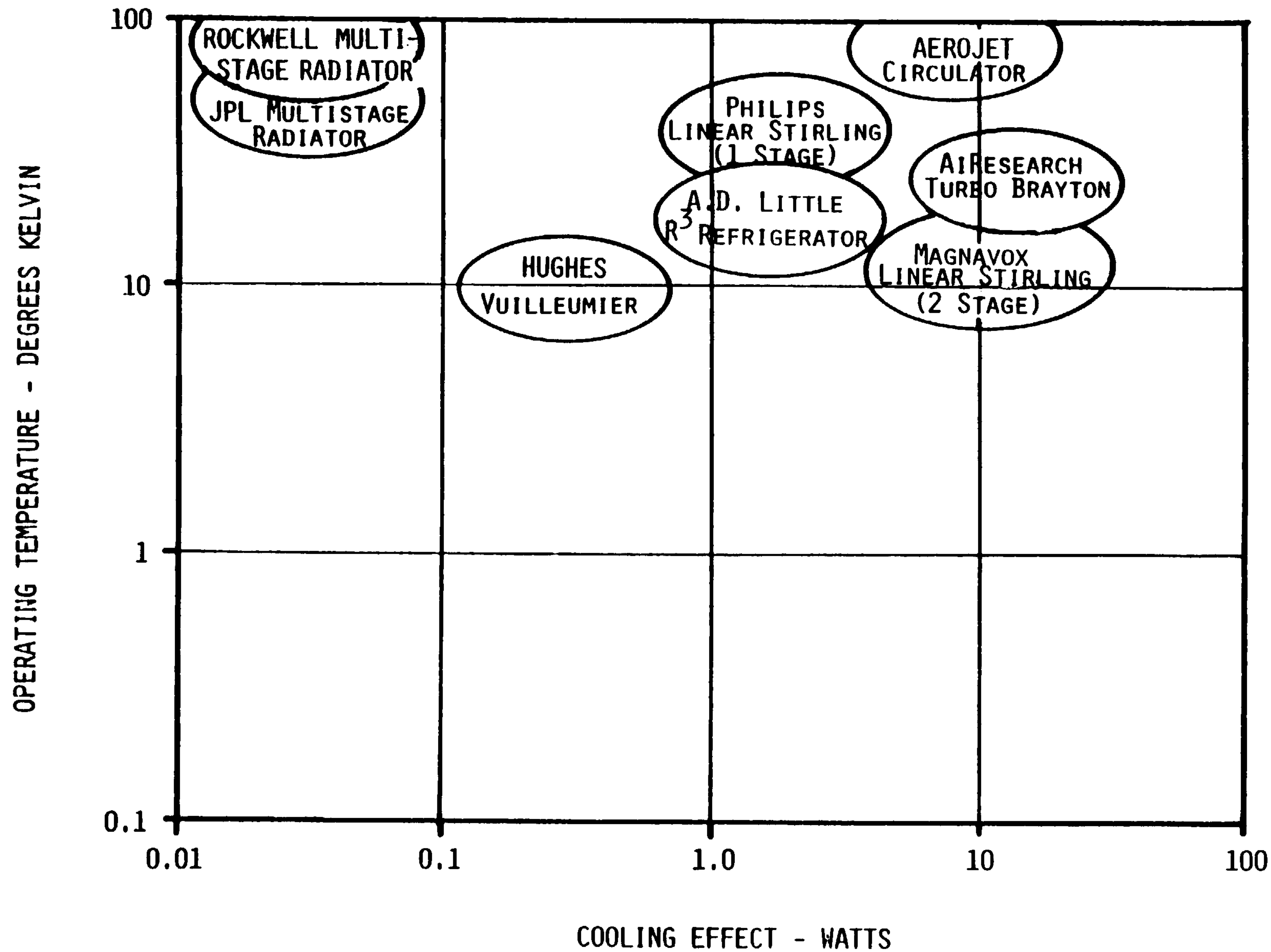
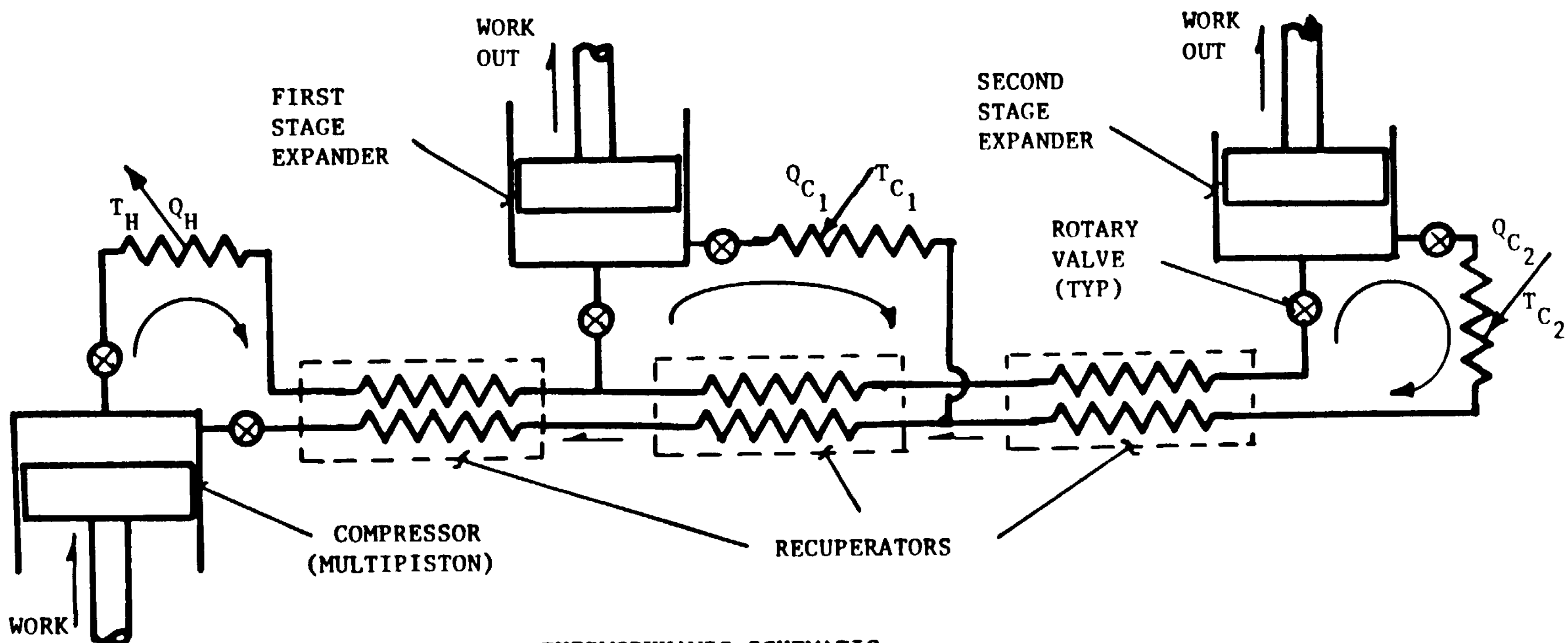


Figure 3. Cryogenic Cooling Considerations for Long Duration Spacecraft Applications--Developments



THERMODYNAMIC SCHEMATIC

Figure 4a. Arthur D. Little Two-Stage Rotary Reciprocating Refrigerator

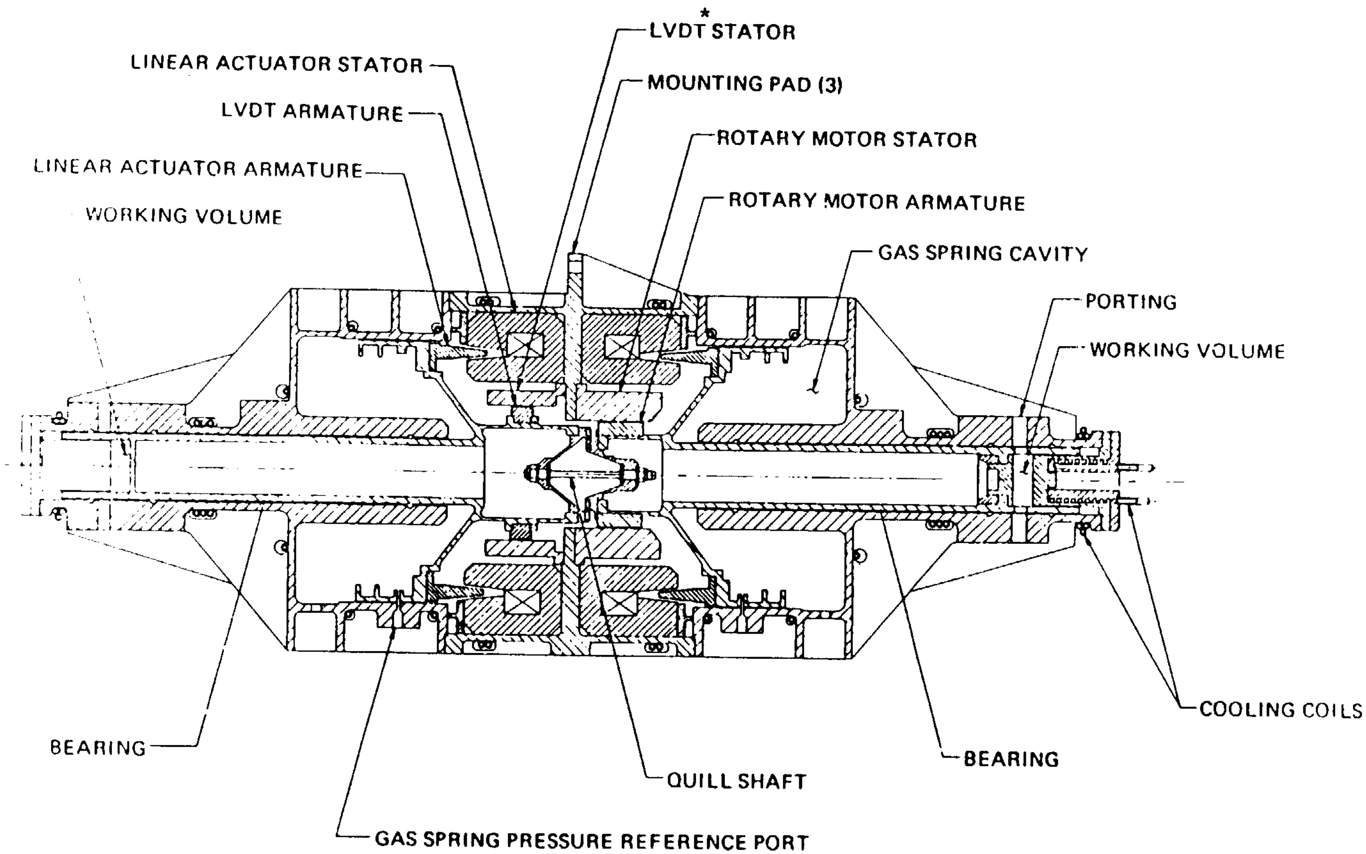
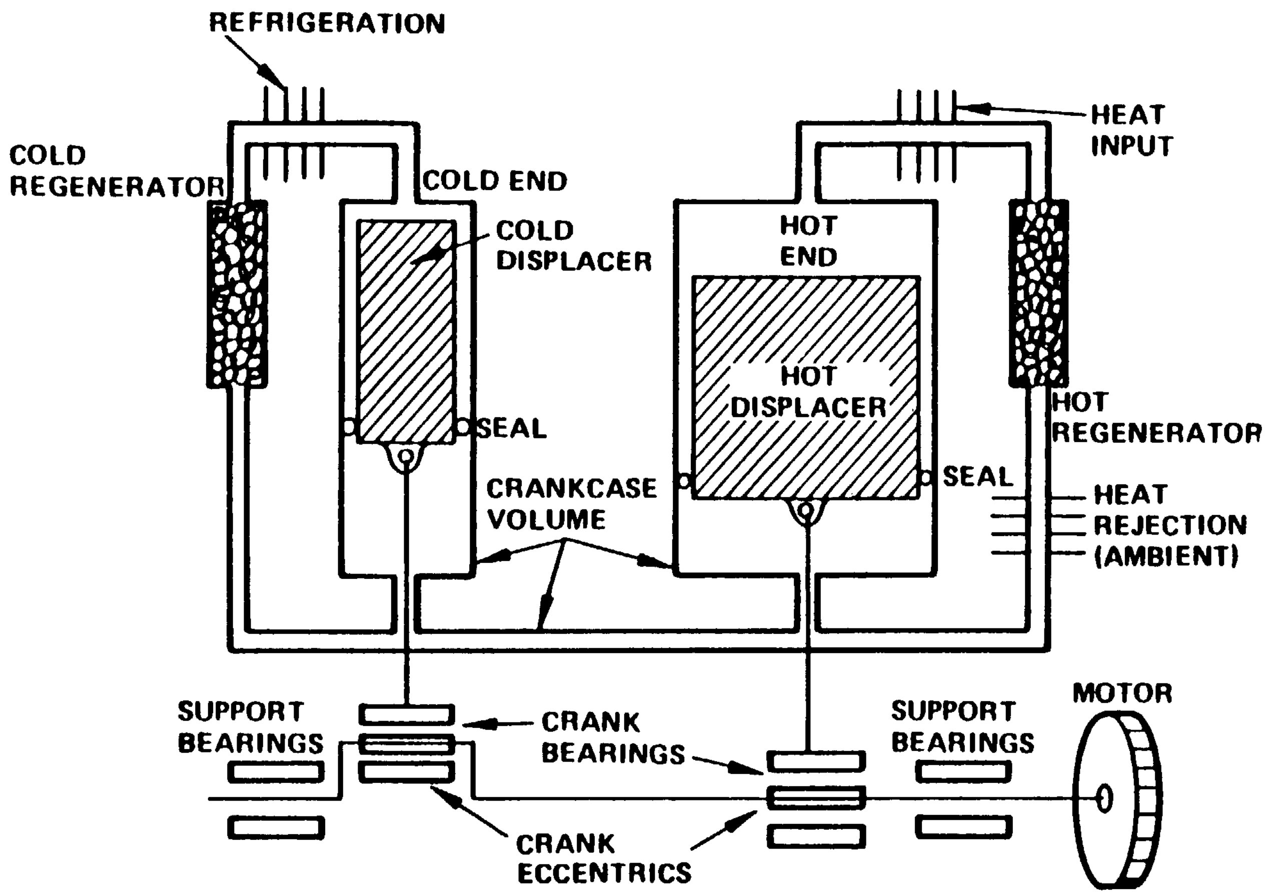


Figure 4b. Arthur D. Little Rotary Reciprocating Refrigerator Compressor details.

Ref.: Breckenridge, R.W., "Refrigerators for Cooling Spaceborne Sensors," Proceedings of the Society of Photo-Optical Instrumentation Engines, 29-30 July 1980, San Diego, CA.

*Linear Variable Displacement Transducer



- **CONSTANT VOLUME MACHINE**
- **MOTOR MAKES UP FRICTION IN MACHINE**
- **90° PHASING ELIMINATES NEEDS FOR VALVES**

Figure 5a. Hughes Vuilleumier Cycle Refrigerator fundamnetal schematic.

Ref.: Doody, R.D., "The High Capacity Spaceborne Vuilleumier Refrigerator," Proceedings of the Society of Photo-Optical Instrumentation Engines, 29-30 July 1980, San Diego, Ca.

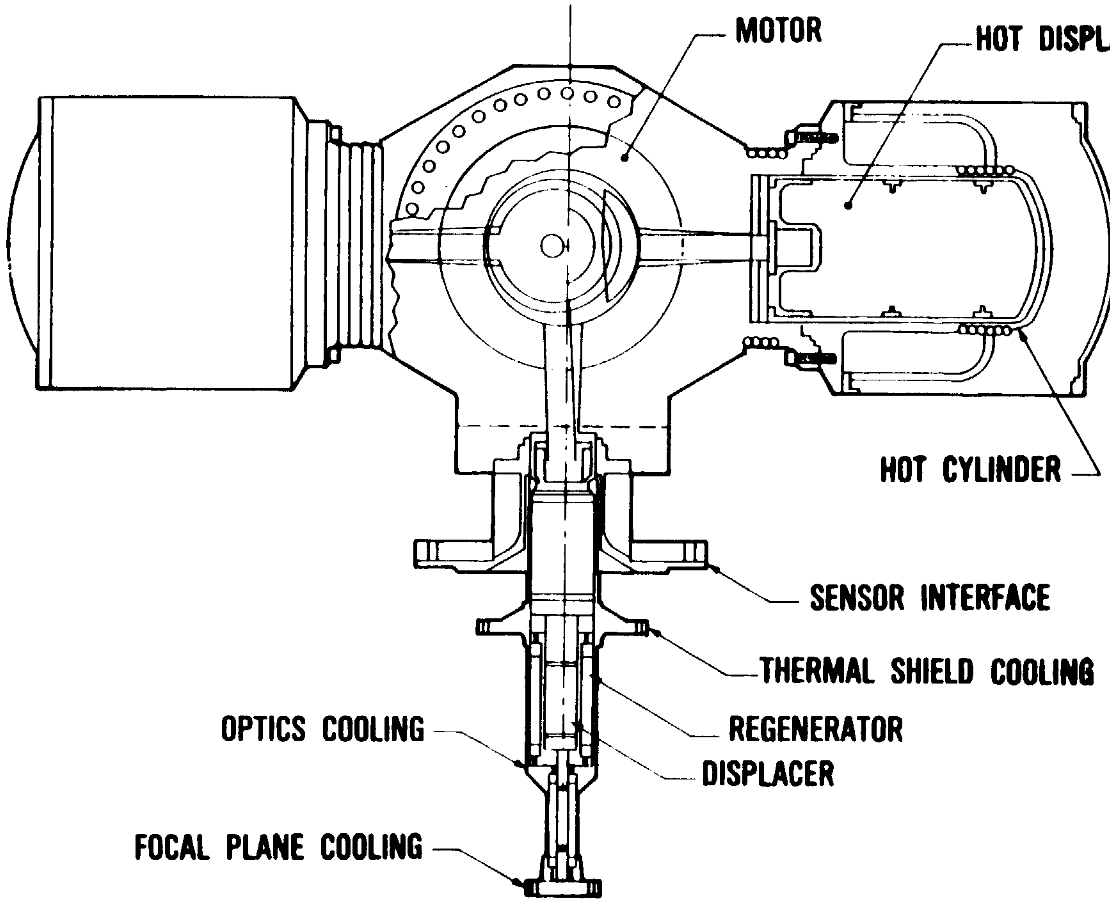


Figure 5b. Hughes Vuilleumier Cycle Refrigerator general layout.

Ref.: Doody, R.D., "The High Capacity Spaceborne Vuilleumier Refrigerator," Proceedings of the Society of Photo-Optical Instrumentation Engines, 29-30 July 1980, San Diego, CA.

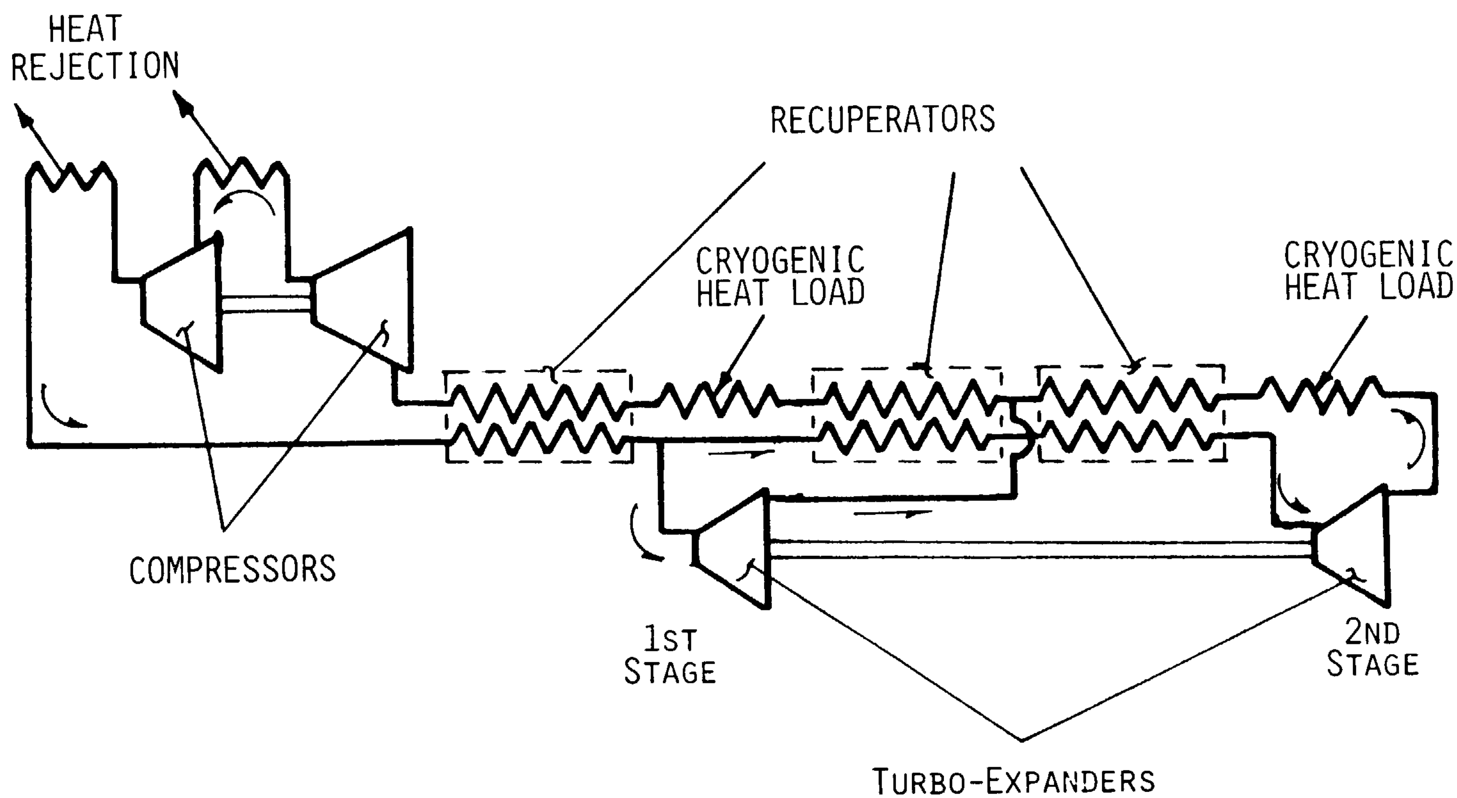


Figure 6a. AiResearch Turbo Brayton Refrigerator schematic.

Ref.: Wapato, P.G. and Norman, R.H., "Long Duration Cryogenic Cooling with Reversed Brayton Turbo-Refrigeration," Proceedings of the Society of Photo-Optical Instrumentation Engines, 29-30 July 1980, San Diego, CA.

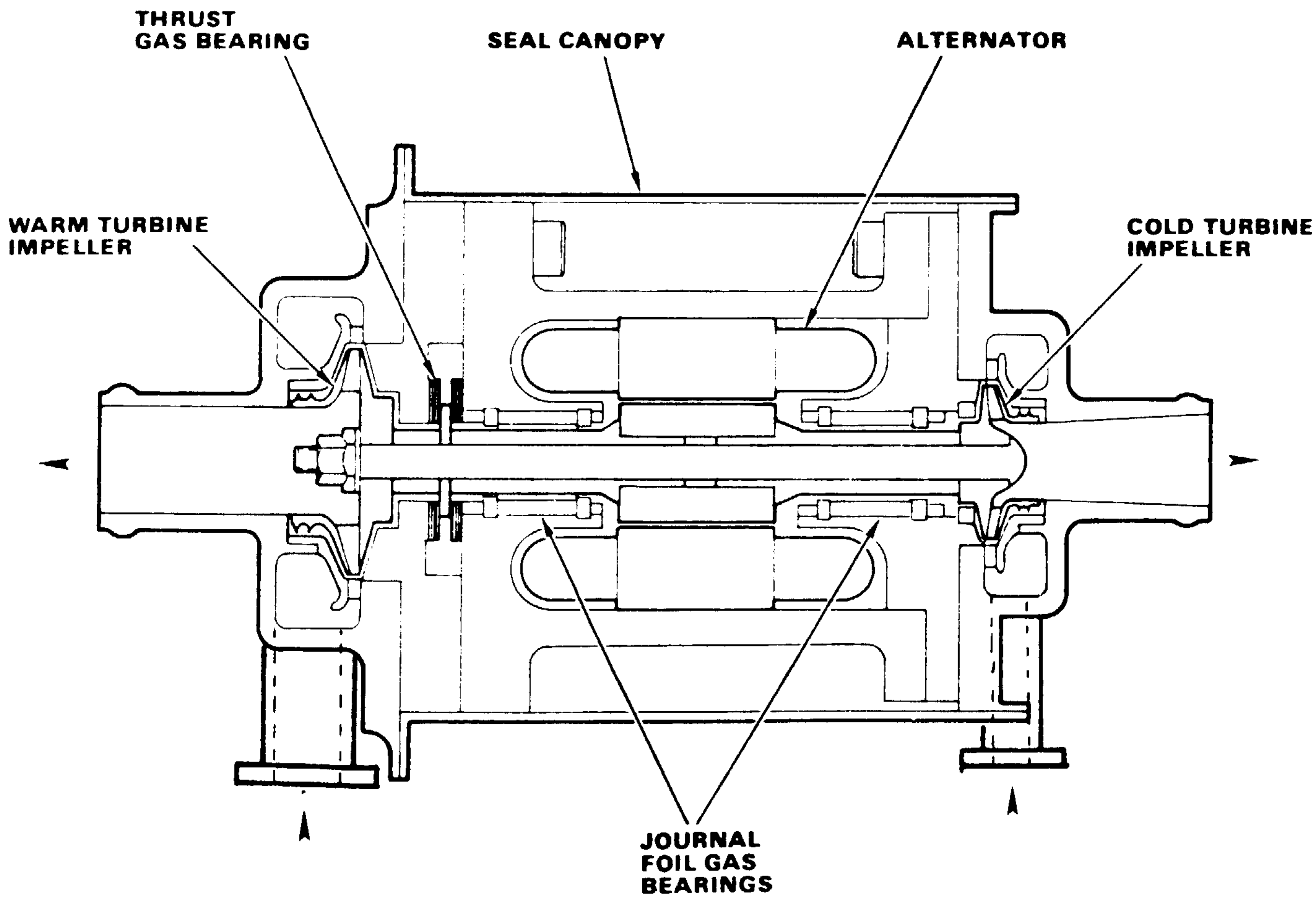


Figure 6b. AiResearch Turbo Brayton Refrigerator, Single Shaft, Integrated Turboalternator.

Ref.: Wapato, P.G. and Norman, R.H., "Long Duration Cryogenic Cooling with Reversed Brayton Turbo-Refrigeration," Proceedings of the Society of Photo-Optical Instrumentation Engines, 29-30 July 1980, San Diego, CA.

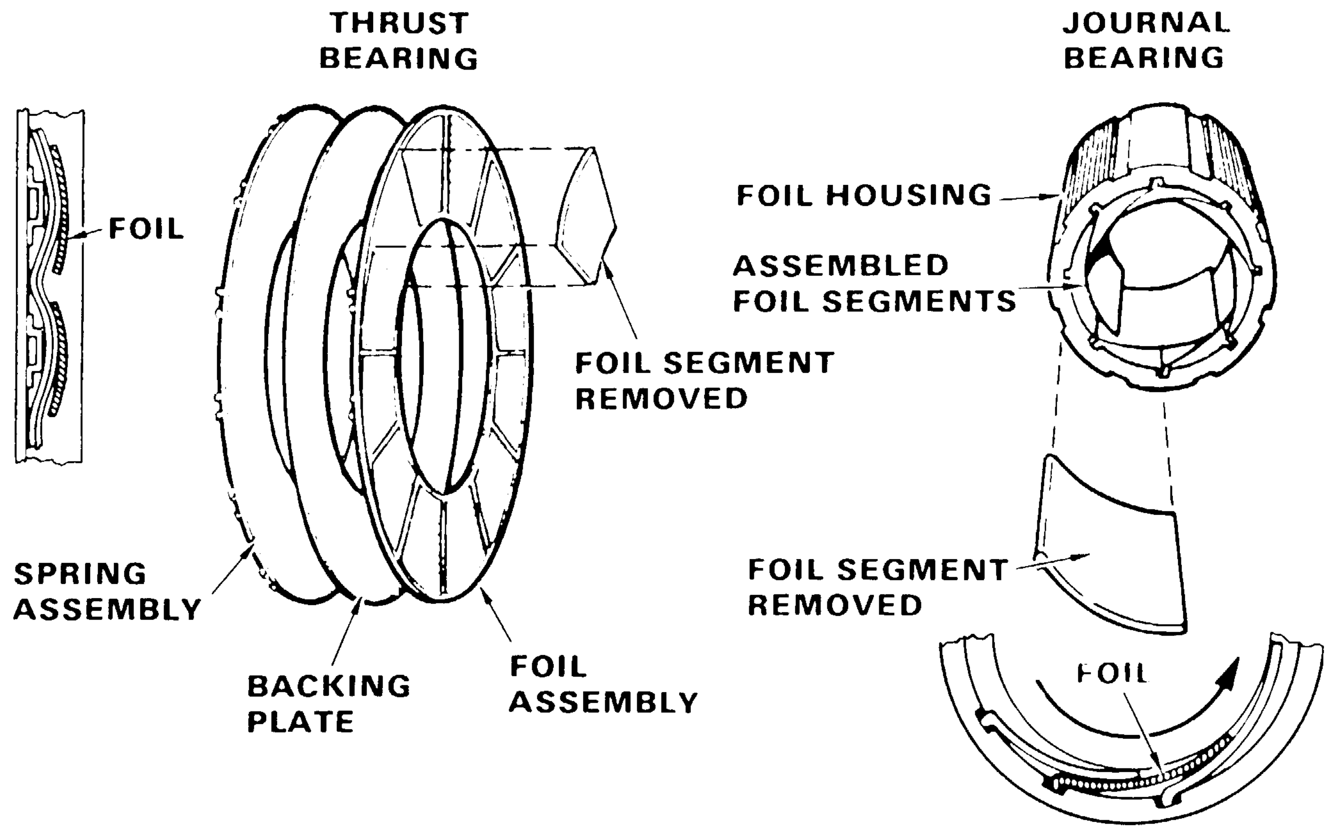


Figure 6c. AiResearch Turbo Brayton Refrigerator, Foil Gas Bearing Concept.

Ref.: Wapato, P.G. and Norman, R.H., "Long Duration Cryogenic Cooling with Reversed Brayton Turbo-Refrigeration," Proceedings of the Society of Photo-Optical Instrumentation Engines, 29-30 July 1980, San Diego, CA.

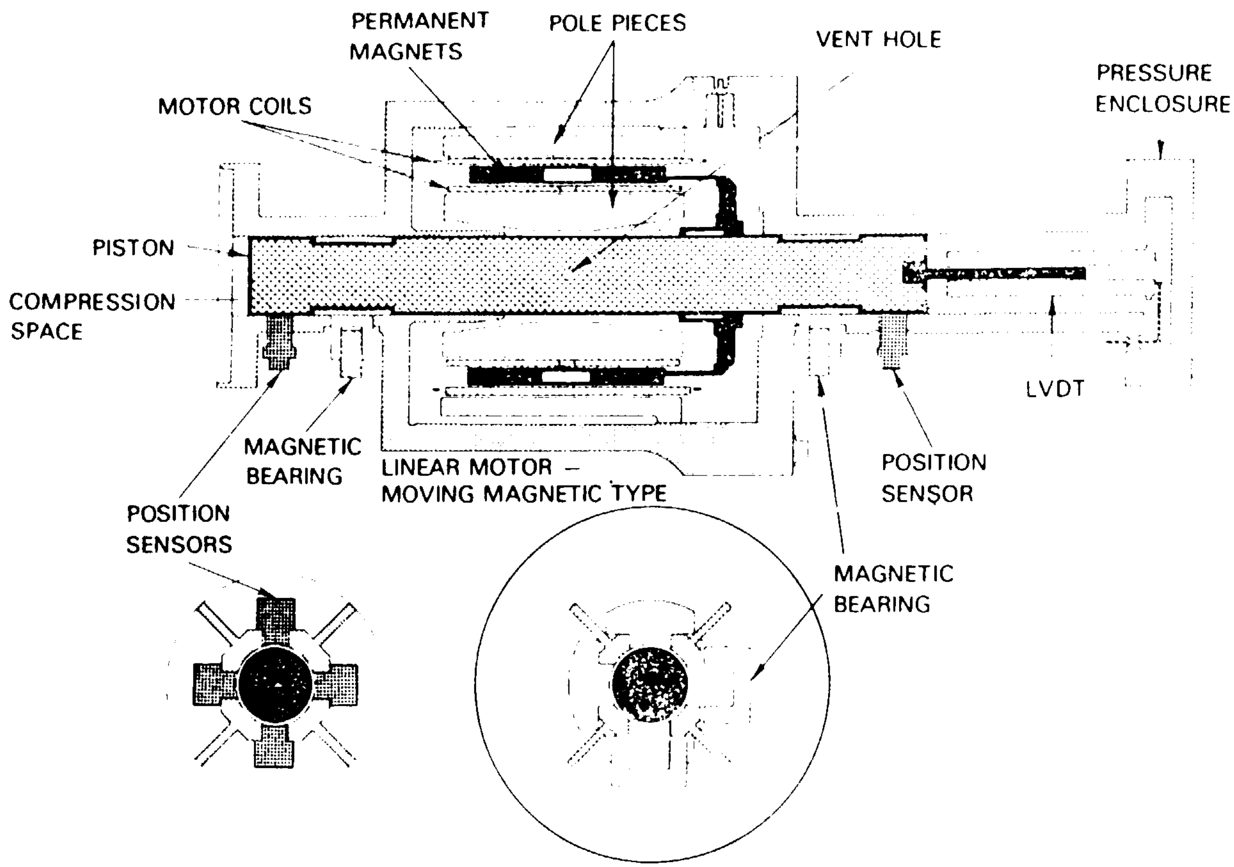


Figure 7a. Philips Laboratories Linear Stirling Cycle Compression Section.

Ref.: Gassen, M.G., Sherman, A., and Beale, W., "Developments Towards Achievement of a 3-5 Year Lifetime Stirling Cycle Refrigerator for Space Applications," Refrigeration for Cryogenic Sensors and Electronic Systems, U.S. Separtment of Commerce, NBS Special Publication 607, May 1981.

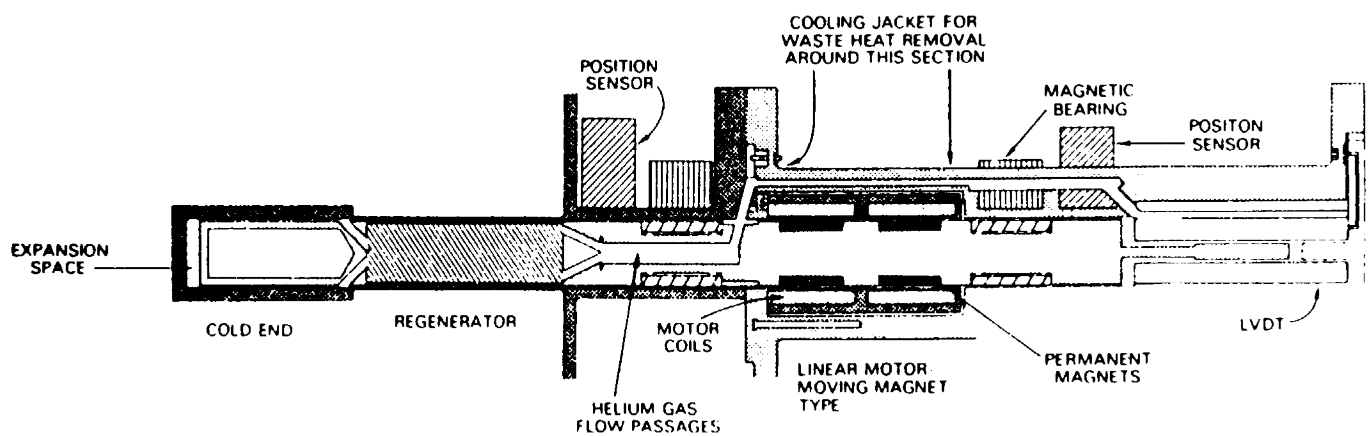
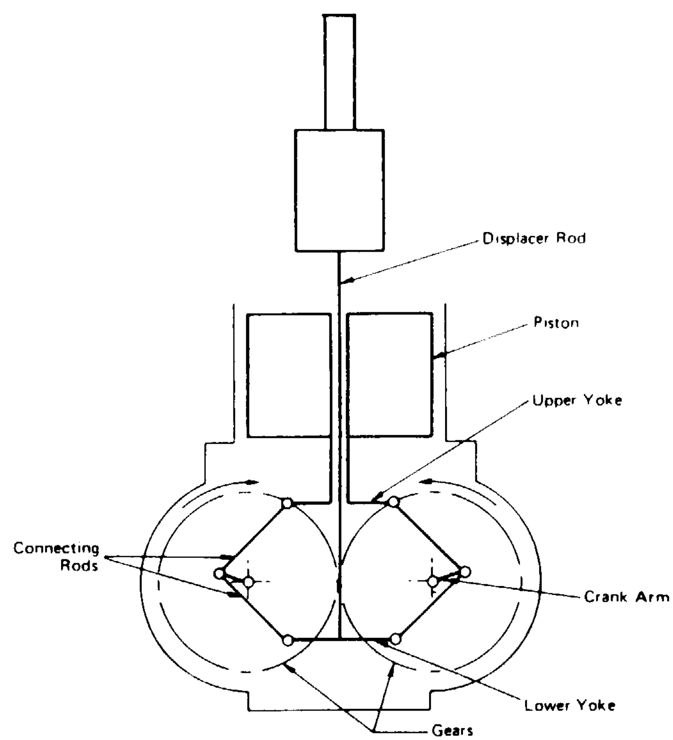
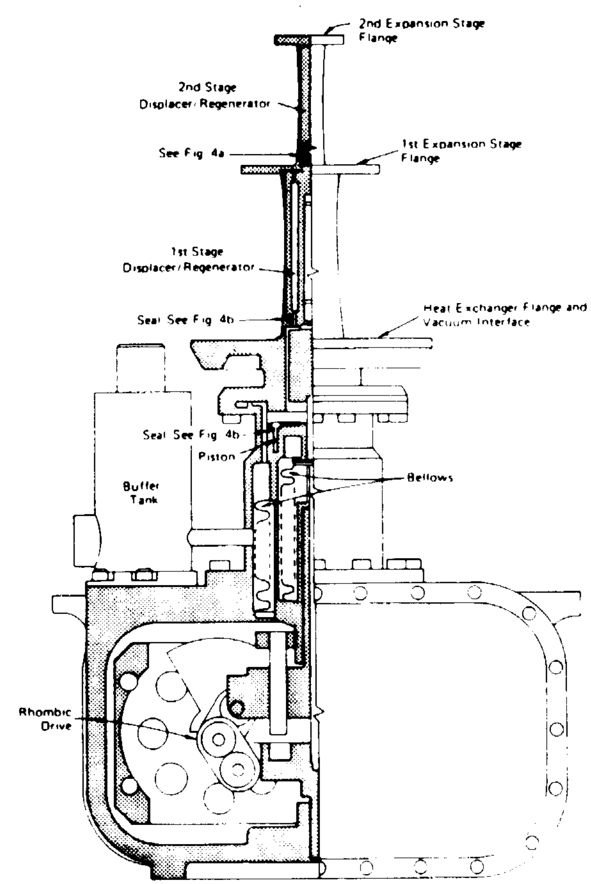


Figure 7b. Philips Laboratories Linear Stirling Cycle Expansion Section.

Ref.: Gassen, M.G., Sherman, A., and Beale, W., "Developments Towards Achievement of a 3-5 Year Lifetime Stirling Cycle Refrigerator for Space Applications," Refrigeration for Cryogenic Sensors and Electronic Systems, U.S. Department of Commerce, NBS Special Publication 607, May 1981.



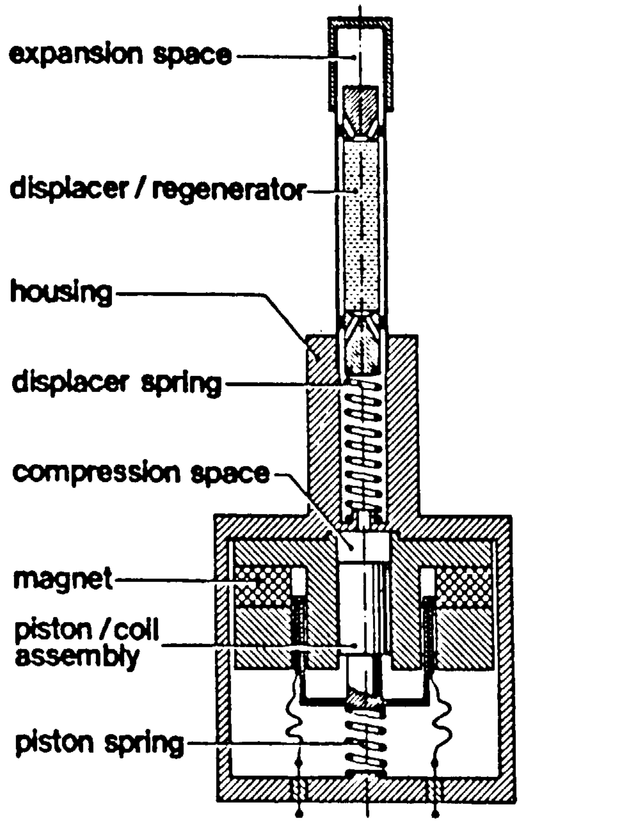
Schematic Diagram of Conventional Rhombic Drive Mechanism



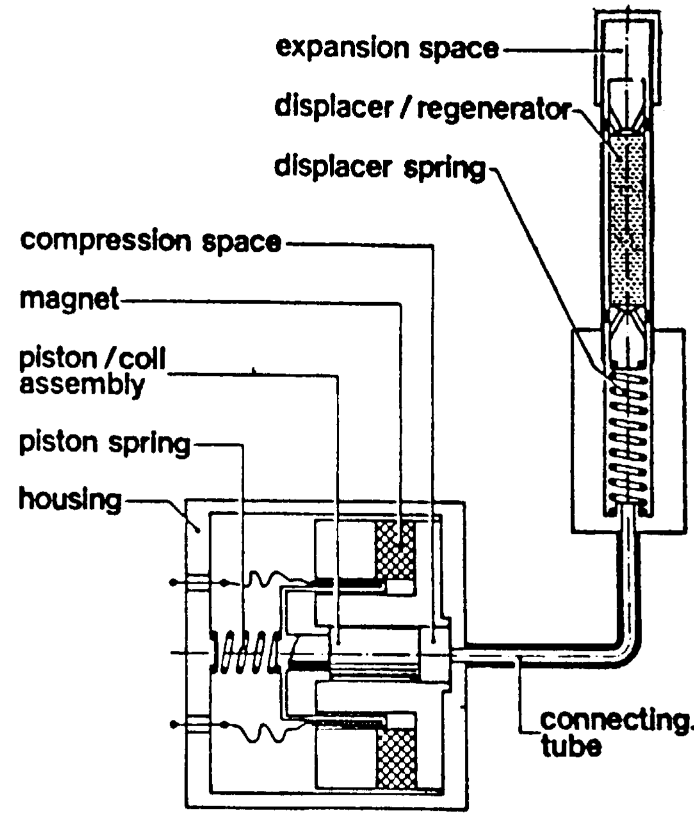
Cross Section through the Cold Finger (simplified)

Figure 8. Philips Two-Stage Rhombic Drive Spacecraft Stirling Refrigerator, STP-78-1.

Ref.: Leffel, C.S. and Vonbriesen, R., "The APL Satellite Refrigerator Program--Final Report," Johns Hopkins University, Applied Physics Laboratory, March 1981.



Diagrammatic cross section of the monoblock Stirling refrigerator with electrodynamic drive



Diagrammatic cross section of the split Stirling refrigerator with electrodynamic drive

Figure 9. Philips-Einhoven Miniature Stirling Cycle Cryogenic Refrigerators.

Ref.: deJonge, A.K., "A Small Free-Piston Stirling Refrigerator," Proceedings of the 14th Intersociety Energy Conversion Engineering Conference, Boston, 5-10 August 1979.

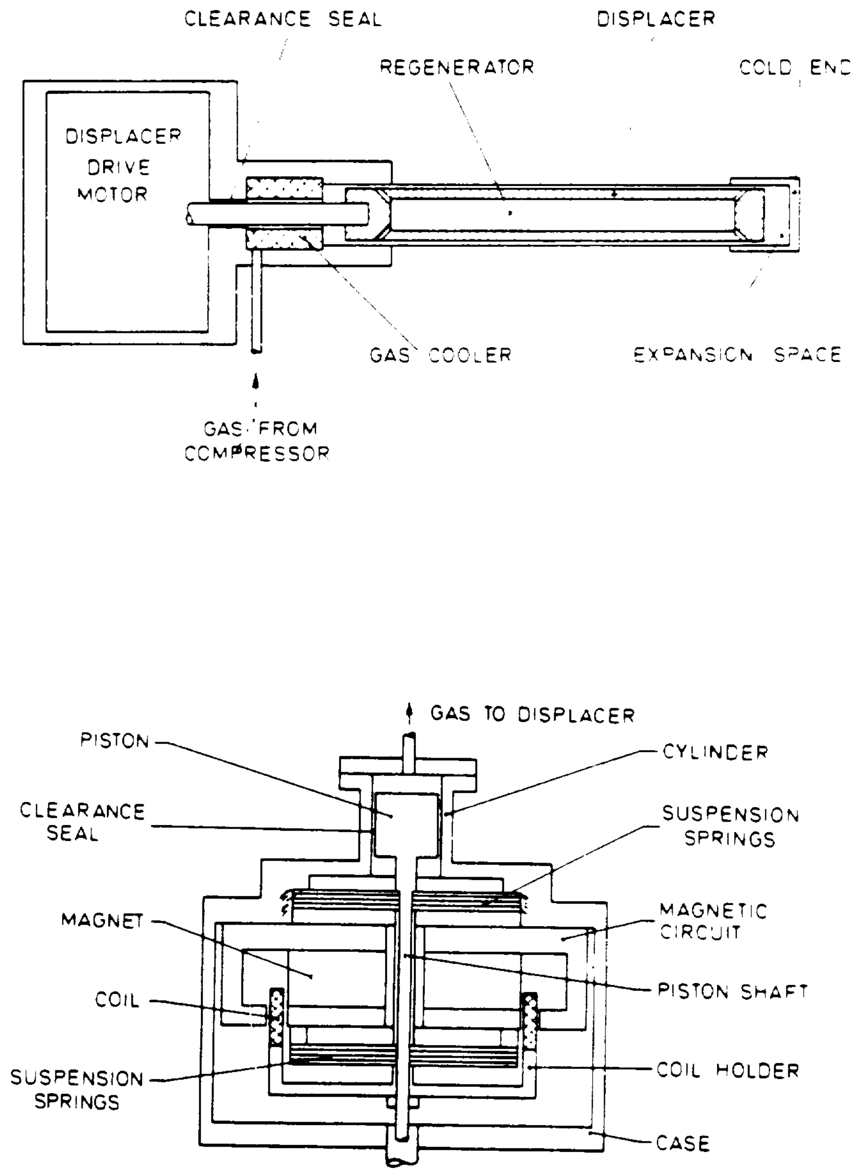


Figure 10. Oxford University Miniature Cryogenic Refrigerator.

Ref.: Davey, G., "the Oxford University Miniature Stirling Refrigerator," International Conference on Advanced Infrared Detectors and Systems, IEE, London, 29-30 October, 1981.

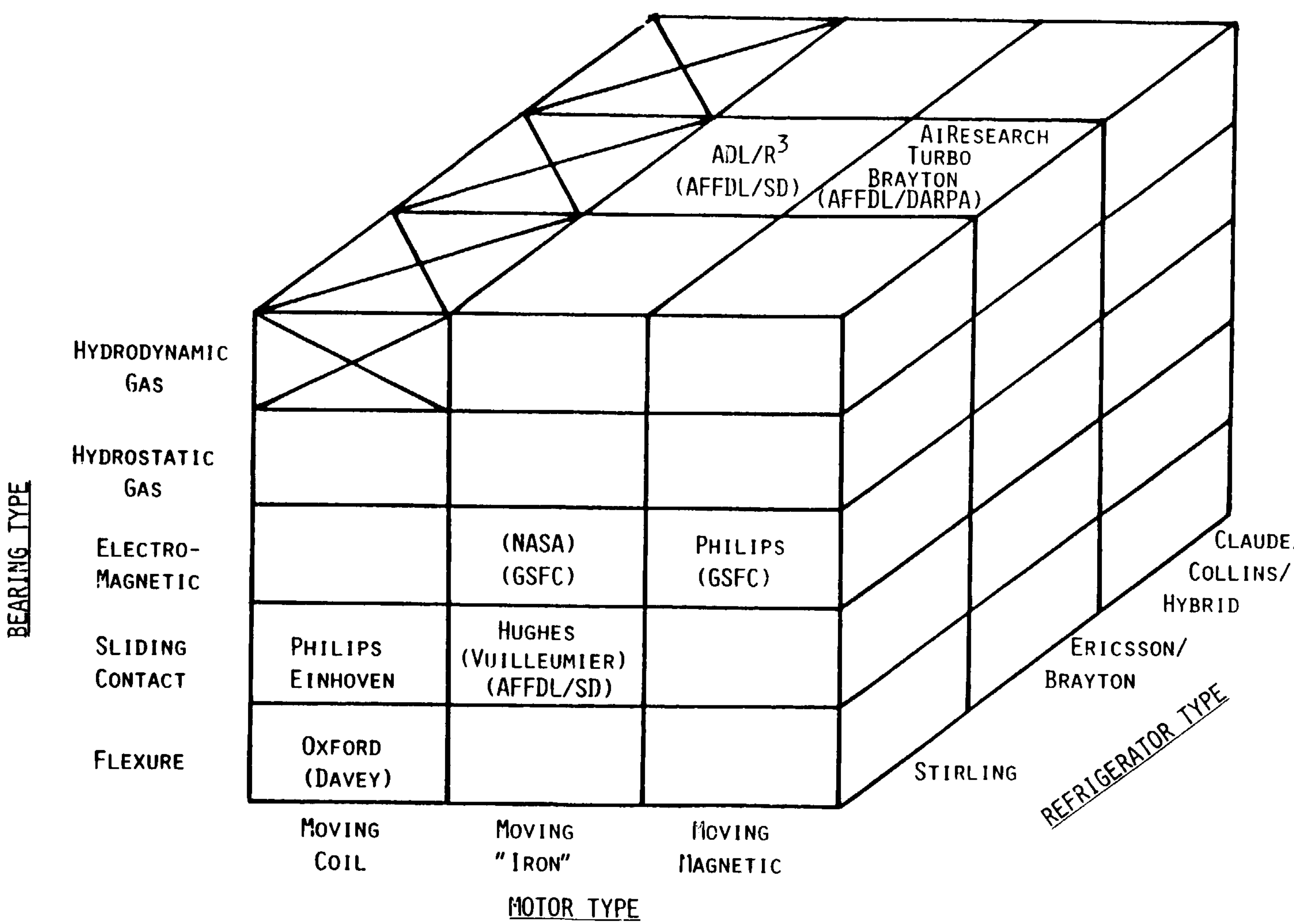


Figure 11. Long Life Spacecraft-Borne Cryogenic Rfrigerator Morphological Array

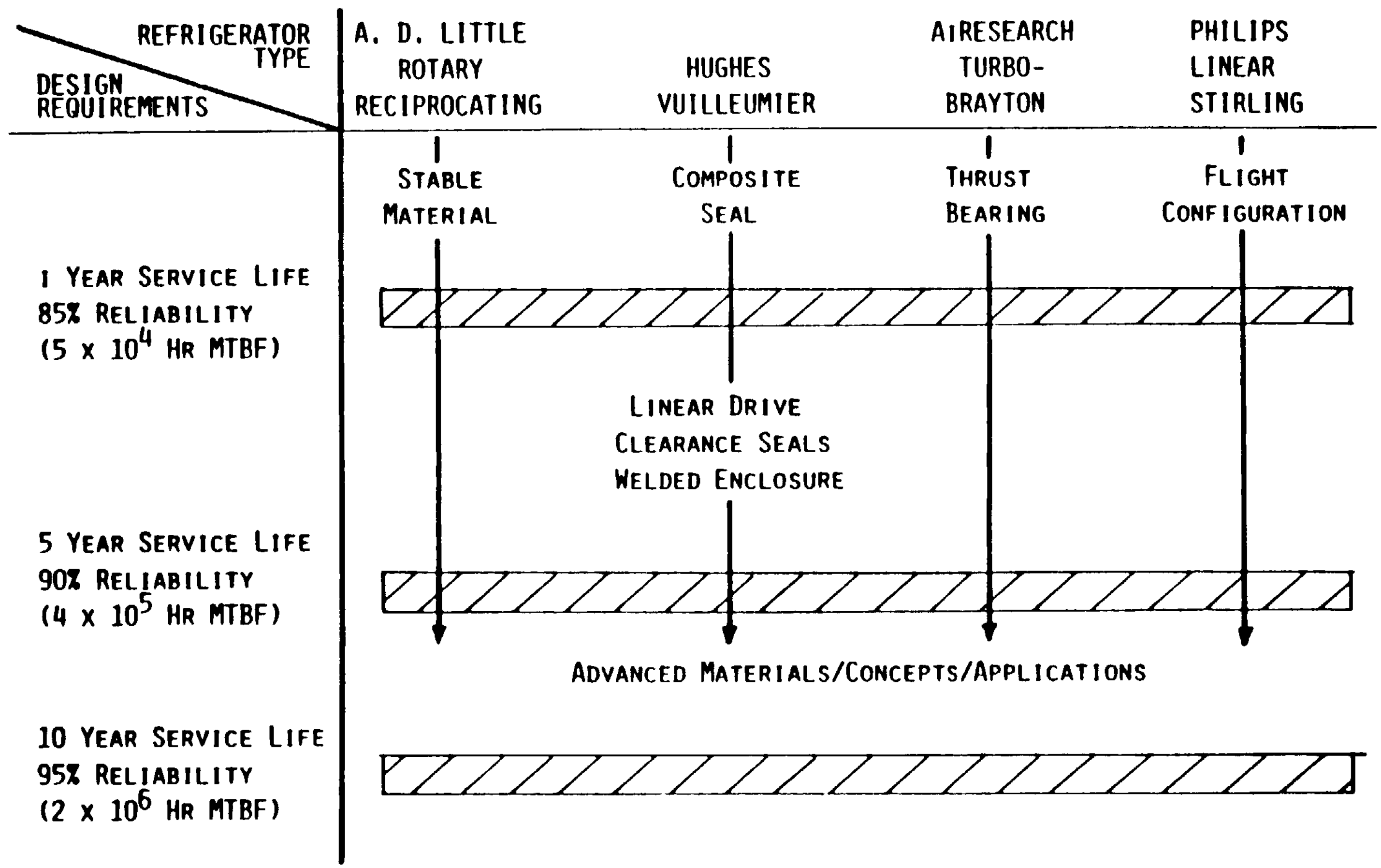


Figure 12. Spacecraft-Borne Cryogenic Refrigerators, Service Life/Reliability Development Issues

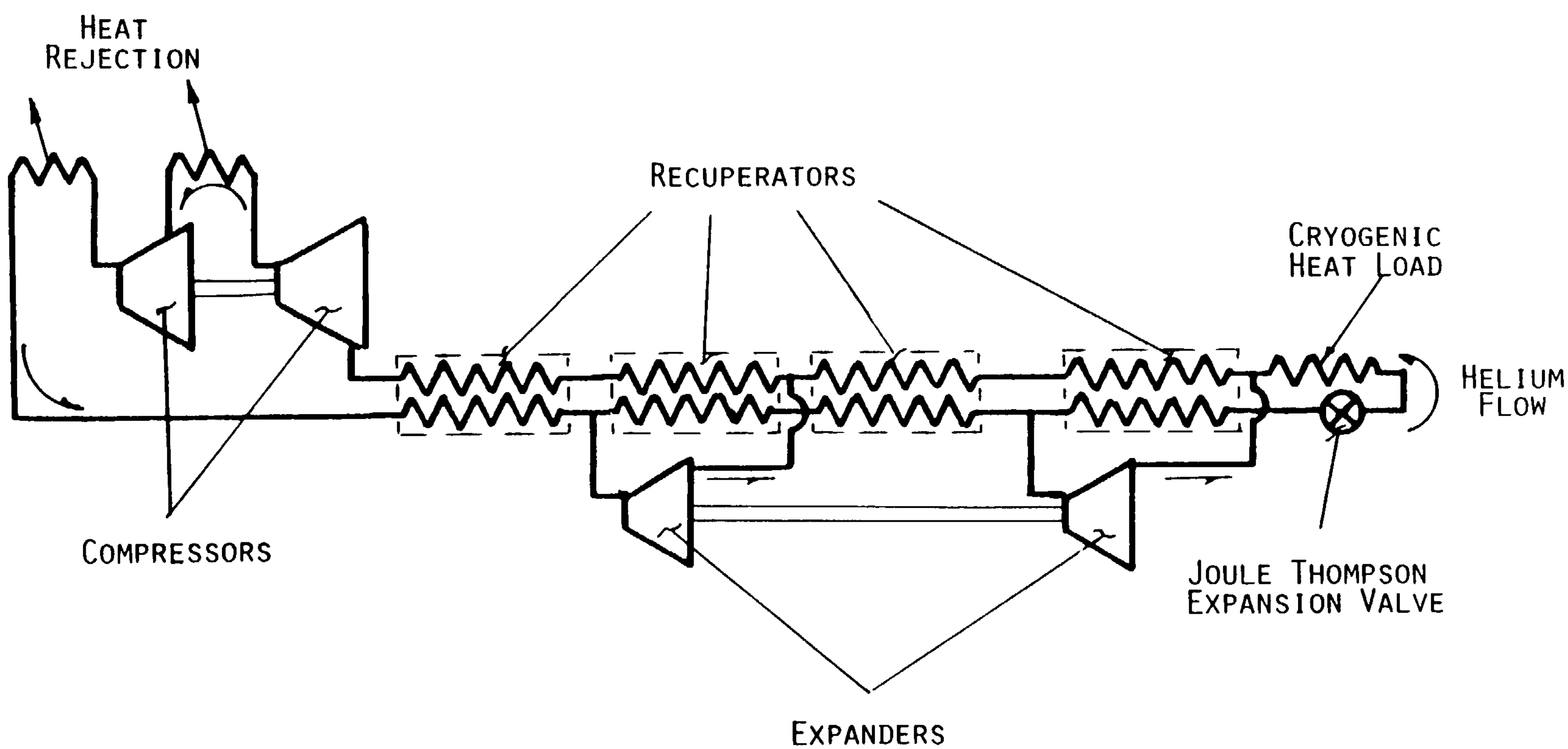


Figure 13. Collins Cycle Cryogenic Refrigerator

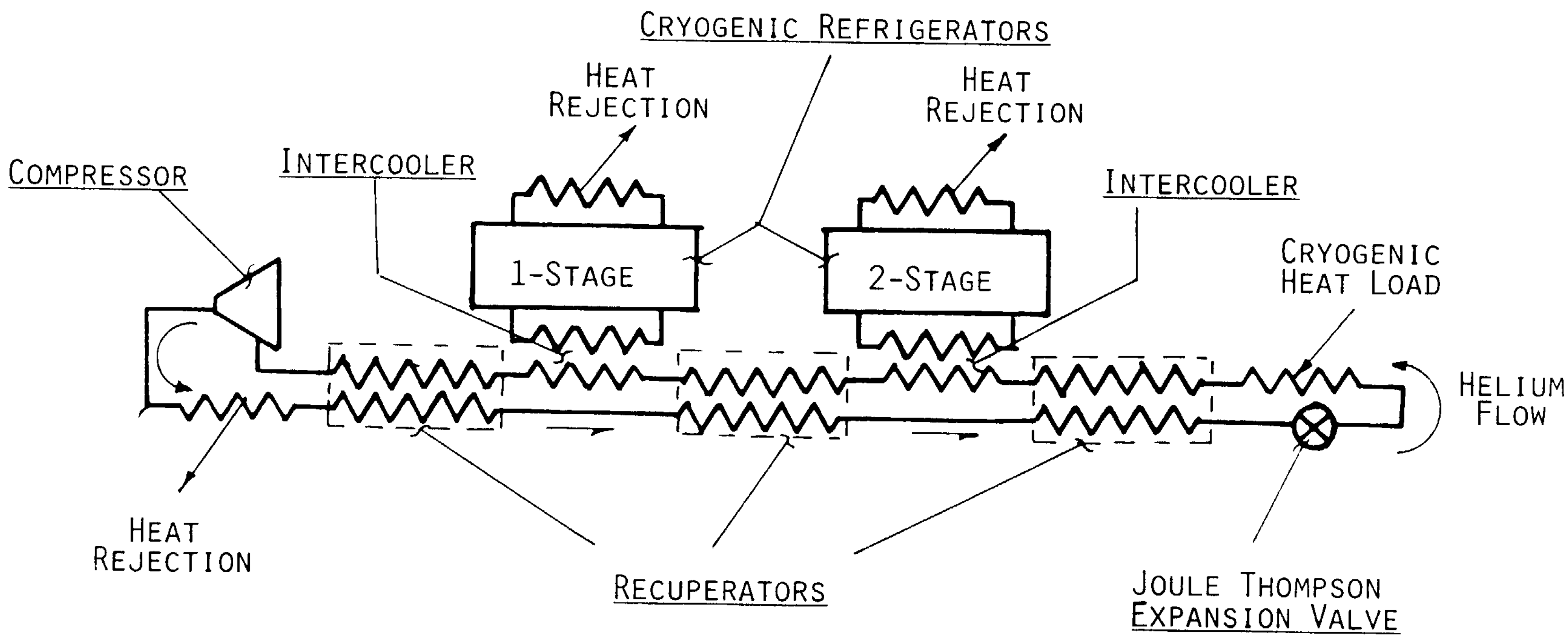


Figure 14. Hybrid Cryogenic Refrigerator Schematic

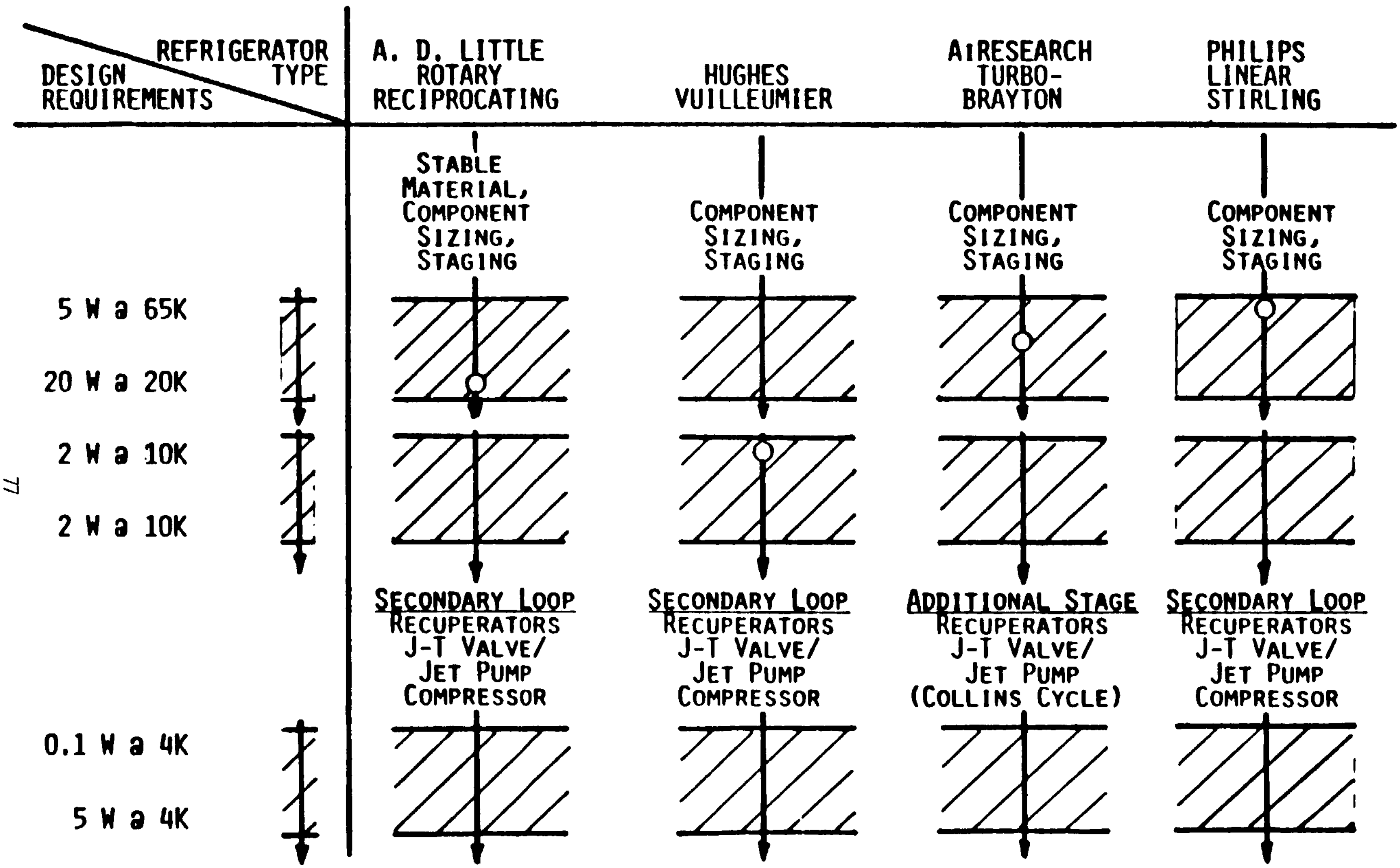


Figure 15. Spacecraft-Borne Cryogenic Refrigerators, Cooling Capacity at Temperature Development Issues

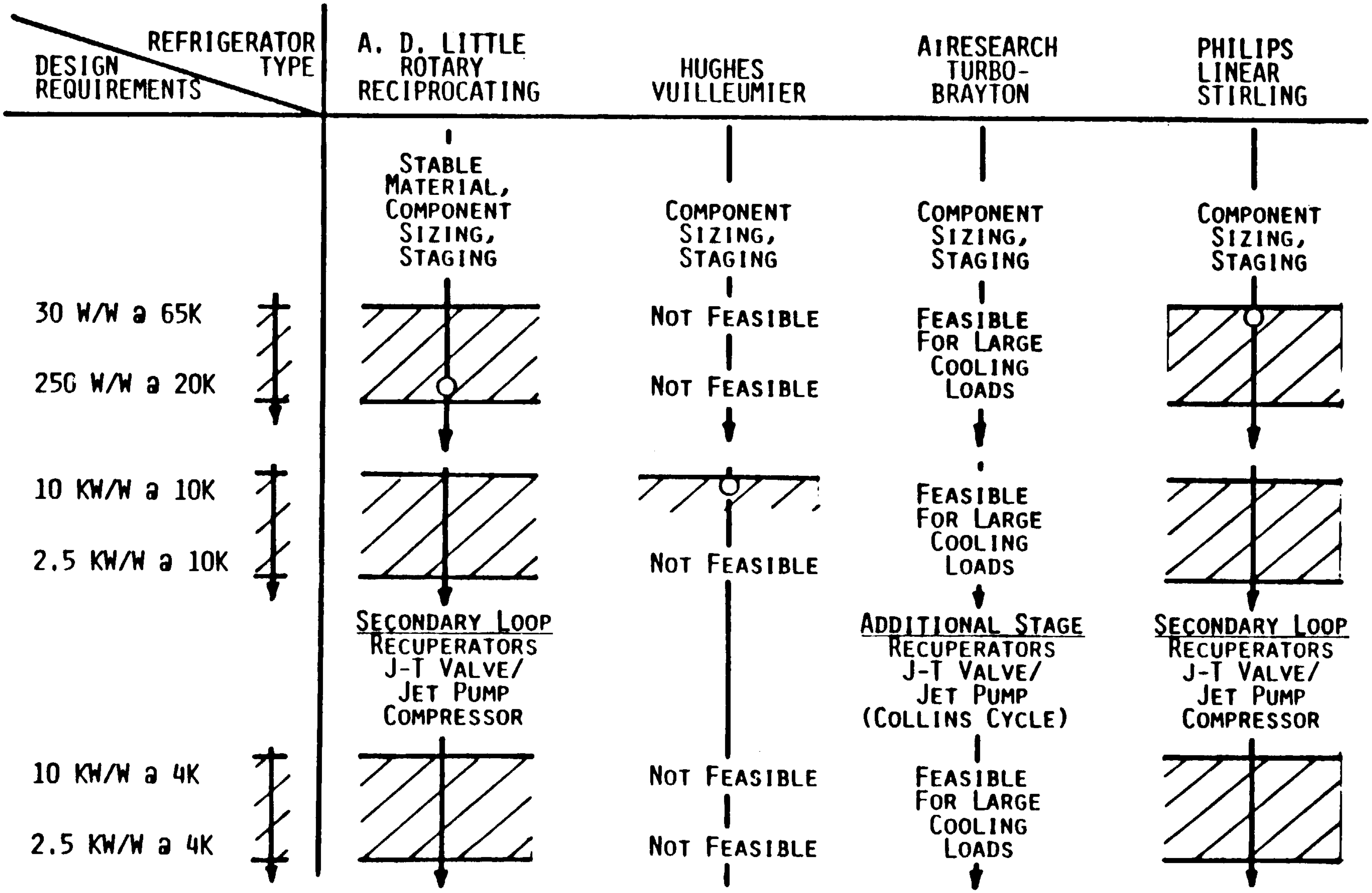


Figure 16. Spacecraft-Borne Cryogenic Refrigerators, Specific Power at Temperature Development Issues

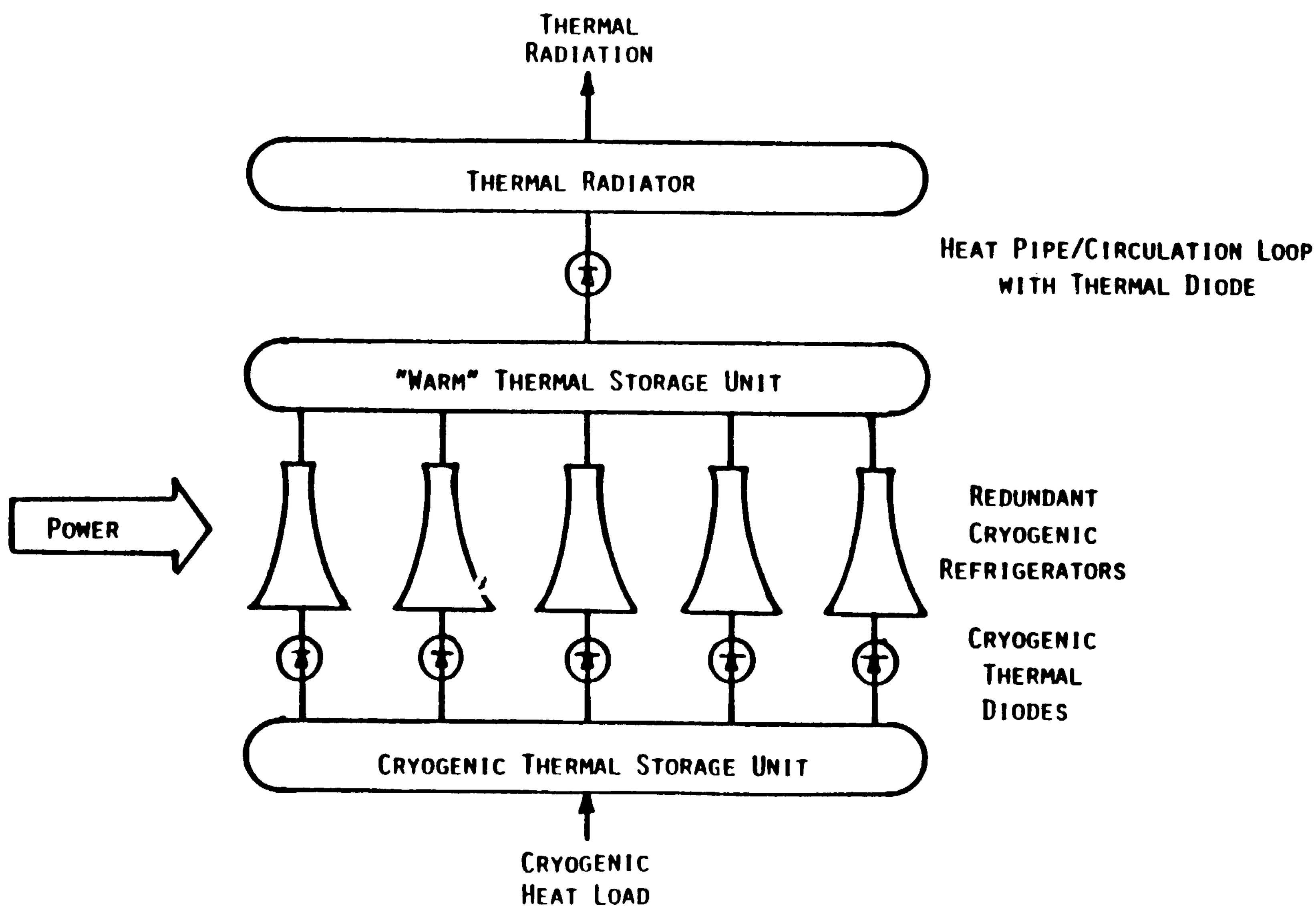


Figure 17. Redundancy-Based Spacecraft-Borne Long Life Cryogenic Refrigeration