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INVESTIGATION OF EXTERNAL REFRIGERATION SYSTEMS FOR LONG TERM CRYOGENIC STORAGE

PREPARED FOR MANNED SPACECRAFT CENTER UNDER CONTRACT NAS9-10412

SUMMARY REPORT

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DIVISION

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SPACE SYSTEMS DIVISION · SUNNYVALE, CALIFORNIA

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INVESTIGATION OF EXTERNAL REFRIGERATION SYSTEMS FOR LONG-TERM CRYOGENIC STORAGE

SUMMARY REPORT

PREPARED FOR

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FOREWORD

A 14-month study was conducted by Lockheed Missiles & Space Company for the Propulsion and Power Division of the Manned Spacecraft Center of the National Aeronautics and Space Administration under Contract NAS9-10412. The study, entitled Investigation of External Refrigeration Systems for Long-Term Cryogenic Storage, was initiated to present sufficient information and procedures for evaluating the usefulness of a small closed-cycle cryogenic refrigeration system for space applications.

The material developed in the study is presented in four documents as follows:

- An investigation of External Refrigeration Systems for Long-Term Cryogenic Storage - Systems Review Report LMSC- A903162 28 May 1970
- An Investigation of External Refrigeration Systems for Long-Term Cryogenic Storage - Final Report LMSC-A981632 22February 1971
- Handbook of External Refrigeration Systems for Long-Term Cryogenic Storage LMSC-A984158 22 Feb 1971
- An Investigation of External Refrigeration Systems for Long-Term Cryogenic Storage - Summary Report LMSC-A984159 22 February 1971

The material contained herein is the Summary Report (the fourth of the above mentioned documents).

CONTENTS

INTRODUCTION

During the process of planning future space missions and determining the role of cryogenic fluids for use in those missions it is necessary to evaluate many different options. One option that the designer/planner may want to evaluate is the use of refrigeration systems to maintain the cryogenic state of the fluids of interest. Cryogens can be stored in space for a considerable time, with proper care and appropriate design conditions the storage time can be six months or more. Boil off nearly always occurs; however, for cryogens like hydrogen that have a high heat of vaporization the penalty paid from a weight standpoint is sometimes acceptable. In some cases the cryogen loss may not be acceptable and other constraints such as volume and orbit control may make it more effective to utilize a refrigeration system.

In order to provide the needed data to evaluate the various options the National Aeronautics and Space Administration at the Manned Spacecraft Center initiated a timely study to investigate external refrigeration systems for cooling cryogenic storage systems in long term space applications. The study was a 14 month effort extending from December 22, 1969 to February 22, 1971.

A cryogenic refrigeration system is simply a device that will transfer heat from a very low temperature source to a high temperature sink. In order to conduct tradeoff studies something has to be known about each element of the heat transfer system so that the proper consideration can be given to it. In this study the complete system that was evaluated is made up of the refrigerator unit itself, the heat transfer mechanisms used to reject the waste heat and to absorb the heat, and the power supply. The power supply is included in the system because the efficiency of cryogenic refrigerators is low enough that the type of power and the way it is put into the system becomes an important design consideration.

STUDY OBJECTIVE

The purpose of performing this study is to provide the designer/planner with all of the basic information necessary to conduct rapid and accurate cryogenic refrigeration systems studies. The data and material presented in the final report provides the base from which a refrigeration systems handbook was prepared. The handbook will be used to conduct step-by-step tradeoff analyses of refrigeration systems. Each element of the system including refrigerator units, failure characteristics, thermal environment, tankage, waste heat rejection, cryogen to refrigerator heat exchanger, and power supply have been evaluated and data for each is given in the report and the handbook. For completeness and to facilitate the use of the report and handbook a limited amount of cryogenic property data is included. Also included is a comprehensive set of conversion units particularly applicable to thermal work. The conversion units have been included because a great deal of information on refrigeration systems is in terms of mixed International and English units.

RELATIONSHIP TO OTHER NASA PROGRAMS

This study provides basic information to evaluate the usefulness of cryogenic refrigeration systems in space applications. A cryogenic refrigeration system can be used to cool instruments as well as increase the storage life of cryogens. Potential applications to orbital propellant depots, lunar storage bases and nuclear stages should be considered as well as conducting experiments that might fly "piggy-back" to some of the Apollo program launches.

METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The study was mainly oriented toward developing procedures and information that can be used to determine the performance, weight, and the size of a complete refrigeration system. There are several elements in the refrigeration system, any one of which could easily occupy the time and effort available for this study. Therefore, by necessity, only enough analyses was conducted in each area to provide the engineer/planner with the information required for him to determine the overall system performance, weight, and volume and to conduct system operating tradeoffs. The data provided covers a range of parameters as indicated below.

- Cooling load .1 to 100 watts (3.4 to 341 BTU/HR)
- Cryogenic tankage 20 to 280 cu. ft.
- Temperatures at which cooling is required 7.5° to 200°R (4.2 to 110° K)
- Mission duration 6 to 24 months

The study was initiated by reviewing reports, data sheets, and development programs available on small cryogenic refrigerators. A bibliography was obtained from NBS and the pertinent reports therein identified were reviewed. This activity was conducted over the first four months of the contracted effort and a refrigerator systems review report* was published in May 1970. Following this effort additional information was collected on refrigeration systems and the data in the report was continuously updated and extended. Effort was also initiated for other elements of a refrigeration system.

Power supplies were reviewed and descriptive information developed on all types of power supplies that might be used in conjunction with refrigerators. In some cases, e.g., a nuclear reactor power source, it is not likely that the power source would be used only for refrigerator operation; however, it was felt that enough descriptive information should be given so that if an application arises the designer will have a handy source of information to provide him understanding and insight to the problem areas. He can also evaluate ways of integrating the power supply requirements with the refrigerator requirements.

Environmental conditions were evaluated with the effort being aimed at establishing the thermal environments, mainly because the thermal environment contributes the greatest interaction to system tradeoff analyses. Other environments that are encountered during terrestrial (salt, wind, rain transportation, etc.) and ascent (max. acceleration, vibration, acoustic) operation are generally specified and little tradeoff interaction is available.

Refrigerator analyses were conducted to develop procedures and methods for estimating cool down times, for estimating performance over operating regions where no data presently exists, and for estimating refrigerator characteristics at various heat rejection temperatures. The approach used for most of these analyses was to utilize data on existing cryogenic refrigerators and modify it by consideration of the ideal performance characteristics. It is very difficult, and sometimes misleading to predict the performance of a cryogenic refrigerator on analytical procedures alone. To develop methods of accurately doing this was beyond the scope of this study. However, by careful evaluation

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* Investigation of External Refrigeration Systems for Long Term Cryogenic Storage - Systems Review Report, LMSC-A903162, May 28, 1970.

of the operating performance and characteristics of existing and in-development refrigerators, a great deal of useful data and curves were generated.

The failure characteristics of the cryogenic refrigerators were examined. Most existing refrigerators require frequent maintenance intervals and no refrigerator presently exists that will operate in an unattended space environment for 6 to 24 months. The effort in evaluating the failure characteristics was primarily directed toward developing means to permit the designer/planner to estimate overall system weight and reliability characteristics. A convenient measure of system advantages and disadvantages from a refrigerator failure point of view is the probability of failure. These probability numbers, as used in this report, are not meant to give hard and exact values because none really exist on these systems, rather, they are meant to give the user a "feel" for what is required in the way of necessary operating life and/or redundancy.

An extremely large variation in operating life of the various refrigerator systems is obtained as one consults various manufacturers. Consequently, it would be prudent for the user to directly ascertain the expected operating life of a particular machine for a particular application after he has performed the desired tradeoff studies and has obtained some insight to his requirements and problems.

Analyses of waste heat rejection and heat absorption methods were performed. The primary emphasis for the waste heat rejection portion was placed on radiator definition and design. Detailed and simplified procedures were developed to determine tube and fin size for radiators suitable for rejecting the amount of heat and in the environments appropriate to this study. A comprehensive discussion of heat pipe designs was also prepared and should provide the user with one of the most up to date sources of heat pipe information available at this time.

In order to provide the engineer with information to estimate complete system performance,methods of transferring heat from the cryogenic tank to the refrigerator were also investigated. A great deal of time could be devoted to defining the exact performance parameters; however, to stay within the scope of this study only sufficient data and material were developed to give the designer approximate weights and performance characteristics. The use of cryogenic heat pipes was also investigated and included in this section.

To facilitate the use of the material in this study a limited amount of cryogen properties data and conversion charts were prepared. In evaluating the processes involved with intermittent operation of a refrigeration system, it is necessary to investigate the pressure profiles in cryogen tanks. To aid the designer in the computational process a set of pressure-internal energy charts were prepared. A considerable amount of effort was required to put the data in this format but having it thus should markedly increase the speed of calculating intermittent refrigerator operations.

BASIC DATA GENERATED AND SIGNIFICANT RESULTS

During the course of the study analyses were performed and data gathered on each of the main elements that directly contribute to the design and operation of a refrigeration system. These elements are the refrigerator itself, the tankage in which the cryogen is stored, the devices and techniques for transferring heat from the cryogenic tanks to the refrigerator, the devices and techniques for transferring and rejecting waste heat from the refrigerator to space, and the power supplies.

The nucleus of the study was the refrigerator and a considerable amount of data was gathered for the types of refrigerators that would be applicable to this study.

Most of the data are applicable to cooling loads of 1 to 100 watts and cooling temperatures of 20°K to 110°K. To date no closed cycle refrigeration system has been used in space, although a few elementray short life open cycle systems have been flown and a few programs presently underway will place closed cycle refrigerators in space in the near future. Consequently, such systems must be developed and proven for space use.

The current state of refrigerator technology is governed largely by a combination of technical performance limitations and prevailing economic market. The interaction of these influences may be divided into three categories. In the first would be those purely technical limitations imposed by an incomplete understanding of the basic physical processes, or by fundamental limits of the processes themselves. Refrigerator designs are based on the best available heat transfer, fluid flow and material property data and an upper limit of thermodynamic performance will be set by the adequacy of these data, the methods of handling the data for design purposes, and the techniques for obtaining the performance of actual machines. In a second category of influences would be the influence of the market on refrigerator technology. One of the reasons that spaceborne refrigerators are not available is that until recently there has been no demand for them. Although a need for such refrigerators is now emerging it does not promist to be profitable and private development is unlikely. This can only be remedied by support of the refrigerator market by research and development programs such as those funded by various arms of the Defense Department. These programs effectively permit systems of limited economic appeal to be developed to their full technical capabilities. In the third category are those limitations placed by an interaction between market requirements, mechanical design and refrigerator performance. For example, the thermodynamic performance, reliability and physical dimensions of commercial refrigerators are optimized with respect to terrestiral physical and economic conditions. It is very probable that substantially improved performance could be obtained from these designs with development, and the cost of such development must be compared with that of establishing radically different designs.

From a knowledge of the current state of technology one may select a suitable refrigerator system, define a program leading to the design or development of a satisfactory hardware from existing technology, or define a program of research and development on one or more new types of refrigeration systems.

Refrigeration Cycles

The cycles selected for discussion were limited to those which it was felt had potential for satisfying the requirements of this study, i.e., the potential for long-term operation, low weight and volume and high thermal efficiency. The data on operating characteristics of the various units has been obtained from an extensive search of the literature and from contacts and discussions with the companies and agencies engaged in the production and development of the units.

Although most cycles are basically related to the Brayton cycle, their practical execution has led to a wide variety of machine configurations. Most refrigeration systems can, however, be placed into one of two subgroups whose members are closely related. These systems are as follows: those employing counterflow heat exchangers and those employing regenerative heat exchangers (see Fig. 1). If counterflow exchangers are used, then the working fluid flow rate at any point in the refrigeration system is constant with time. The working fluid flows at constant rate and direction through all the system components. These components can hence be designed for continuous steady-state operation at prescribable conditions. This category includes Claude, Joule-Thomson, and orthodox Brayton-cycle systems. On the other hand, those systems which employ regenerative heat exchangers must make some provision for intermittently reversing the direction of flow and alternately compressing and decompressing the working fluid in the regenerator. This can be performed in a refrigerator in which the cycle processes are executed successively in different regions of the same component. The working fluid is compressed while it occupies the warm end and the regenerator spaces, and is expanded while it occupies the cold end and regenerator spaces.

It is noted that the work of compression can always be reduced by multistaging in those systems which use separate compressors. The efficiency of expansion can similarly be improved by multistage expansion. The efficiency of heat exchange may be improved by what might be referred to as multistage heat exchange by splitting the exchanger into sections to reduce the temperature range. Between heat exchange stages the temperatures of the two streams are brought together by supplying refrigeration at this point by means of an intermediate expansion engine.

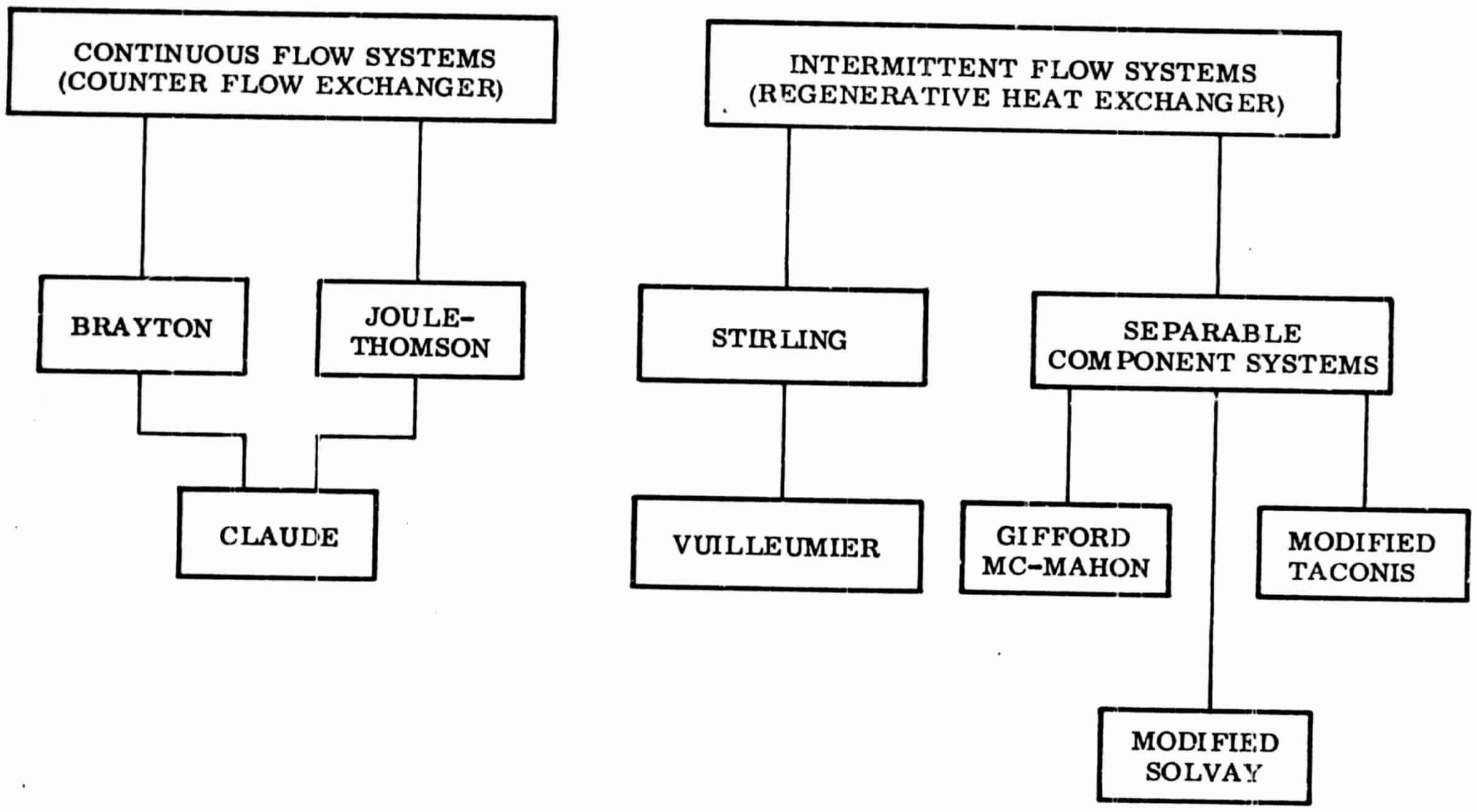


Fig. 1 Cycles Included for Analysis

The additional refrigeration required for staging the heat exchanger can be supplied by expanding a portion of the working fluid at the chosen interstage point. Likewise, cooling of external loads at intermediate temperatures can be achieved by expanding working fluid at that temperature. The possibility of expansion at more than one temperature level introduces complexity and arbitrariness to the basic cycle types.

A summary of the pertinent types of refrigerators and some comments on their development status is shown in Table 1.

The performance and weight are shown in Figures 2 to 5.

Coefficient of Performance vs Cooling Load

An indication of the thermal efficiency of the refrigerator is given by the coefficient of performance (COP) as defined as the net refrigeration produced divided by the input power.

Figure 2 shows the COP data for five different cycles at 20°K as a function of the net refrigeration produced.

The value of COP for a reversible (Carnot) refrigerator is given by

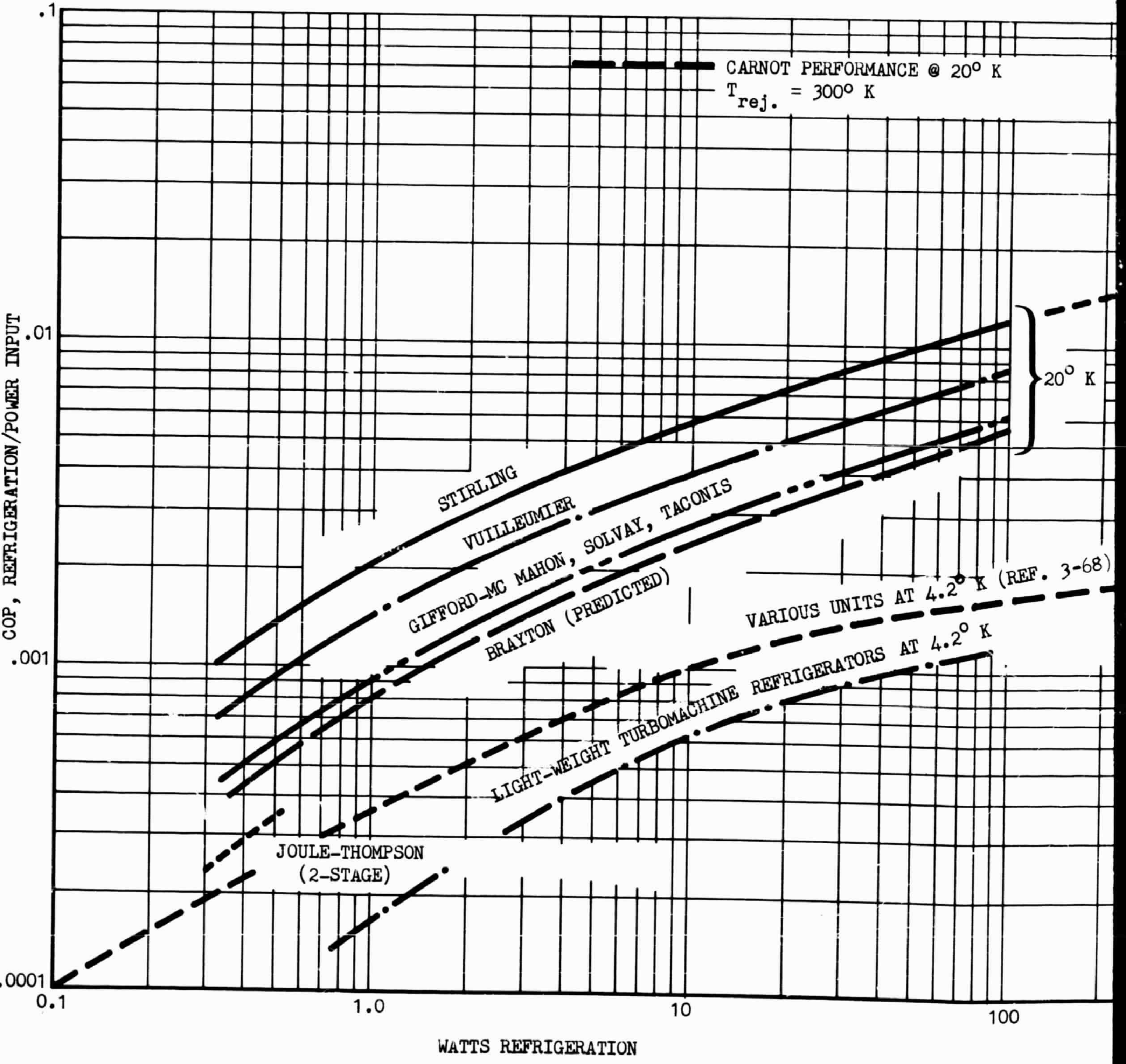
$$\text{COP} = \frac{T_c}{T_h - T_c}$$

where T_c is the temperature at which cooling takes place, and T_h is the temperature of the surroundings (300°K for these units). The approach of the real refrigerators to the ideal (Carnot) performance can be seen by comparison with the COP for the Carnot engine.

Figure 3 shows COP data for the various cycles at 77°K, a temperature at which the majority of data is available. The curve for the Brayton cycle is based on prediction plus one experimental point and the agreement with a previous study at higher cooling loads is satisfactory. The values for COP are substantially higher than at 20°K, and this is shown by the expression for the Carnot performance.

TABLE I DEVELOPMENT STATUS OF CLOSED CYCLE CRYOGENIC REFRIGERATORS

SYSTEM SYSTEM	MAINTENANCE FREE OPERATING LIFE HRS	NUMBER OF UNITS MANUFACTURED	DEVELOPMENT STATUS	PRIMARY MANUFACTURERS
Stirling	1000	< 2000	Fully developed and operational for 6 years in aircraft. Mose efficient thermally. Lightweight, small volume. Applicable to space flight with minor modifications	U. S. Philips Hughes Aircraft Malaker
Vuilleumier	1000 hrs. demonstrated to date	9	Recently developed, no operational experience, little life test data. Utilizes heat source directly for power. Efficiency approaching that of Stirling, significant development activity for space usage.	Phillips Laboratories Hughes Aircraft Stirling Electronics Garrett AiResearch
Solvay, Taconis Gifford-McMahon	5000	< 400	Fully developed system operational on aircraft for several years. Recently developed for airborne use utilizing dry-lube compressor. Longest maintenance free operating life. Efficiency substantially below Stirling cycle.	Cryogenic Technology, Inc. Air Products U. S. Phillips Cryomech
Joule-Thomson	300	<2000	Fully developed, extensively used on aircraft for cooling infrared systems for ≈6 years. Efficiency of system among the lowest. Does not appear to have potential for long life.	Garrett AiResearch Air Products Hughes Aircraft
Brayton	≈ 1000	2	Limited development in 77°K versions. Components have been developed for lower temperature usage, but have not been run as a complete system. Limited development activity at this time. May have potential for long life because of gas lubricated bearings.	Garrett AiResearch General Electric Arthur D. Little


CARNOT PERFORMANCE @ 20° K
T rej. = 300° K
20° K
STIRLING
VUILLEUMIER
GIFFORD-MC MAHON, SOLVAY, TACONIS
BRAYTON (PREDICTED)
VARIOUS UNITS AT 4.2° K (REF. 3-68)
LIGHT-WEIGHT TURBOMACHINE REFRIGERATORS AT 4.2° K
JOULE-THOMPSON
(2-STAGE)
COP, REFRIGERATION/POWER INPUT
.1
.01
.001
.0001
0.1
1.0
10
100
WATTS REFRIGERATION

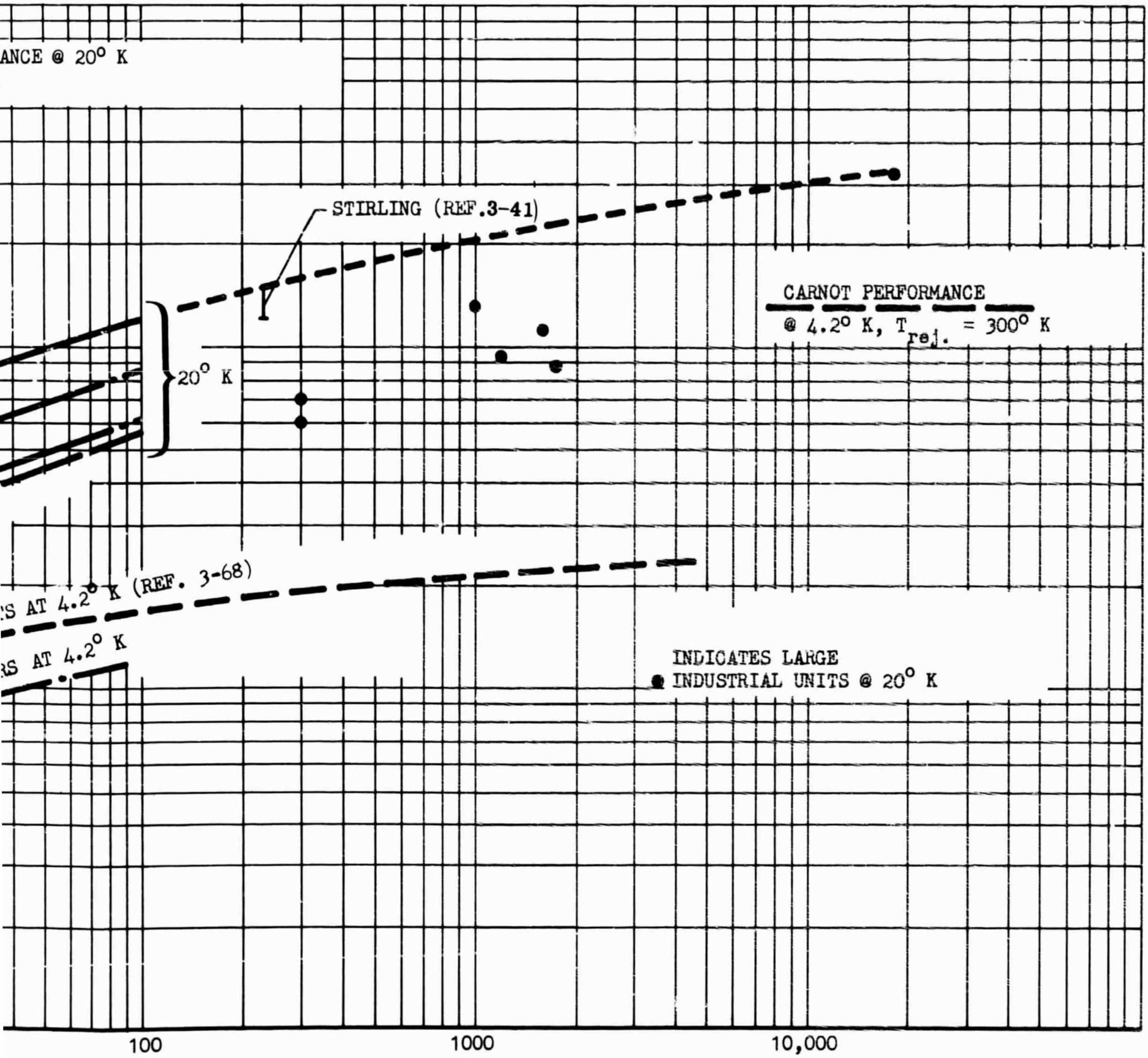
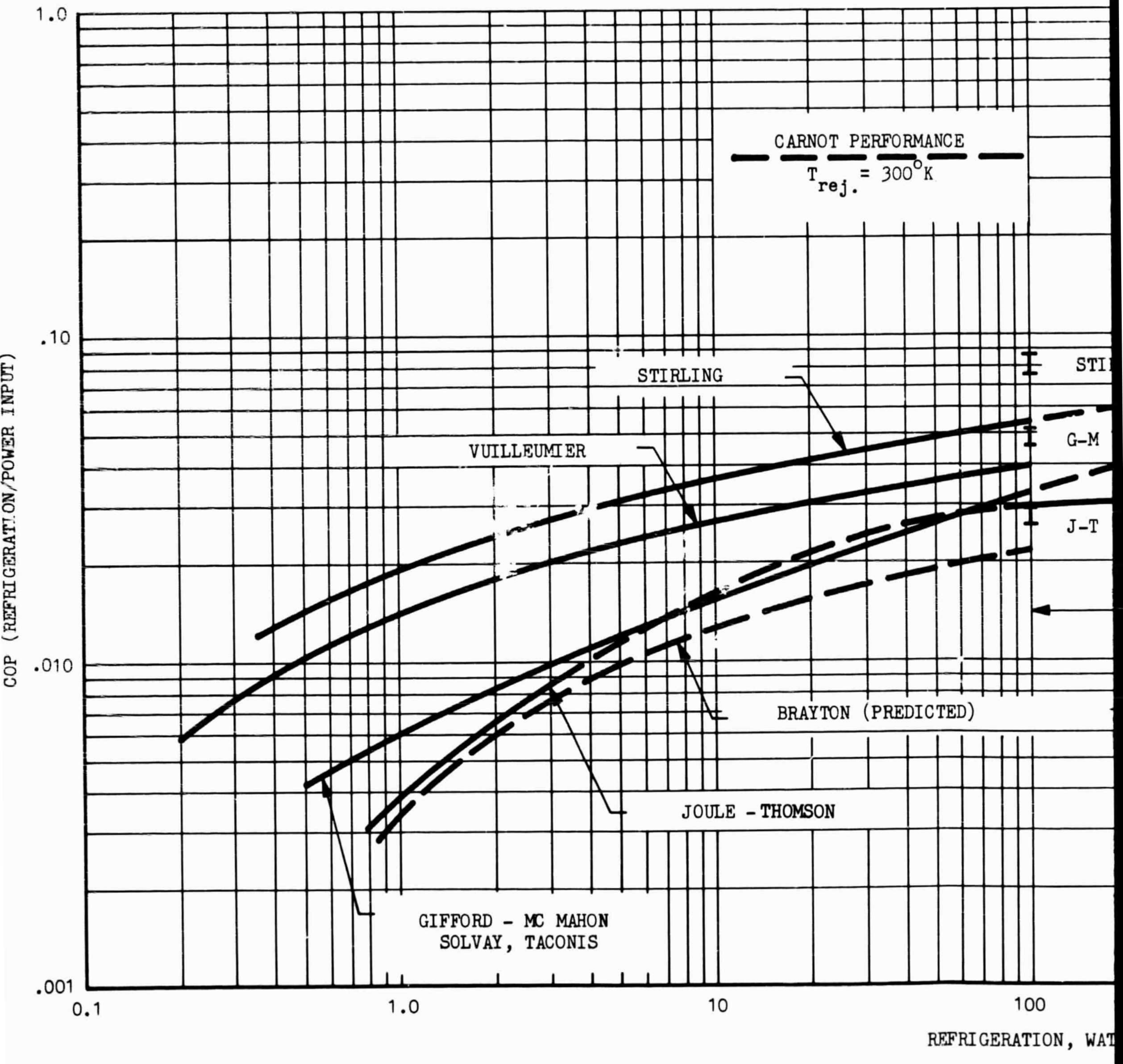


FIGURE 2 SUMMARY OF REFRIGERATOR COEFFICIENT OF PERFORMANCE FOR VARIOUS CYCLES AT 20°K AND 4.2°K



FOLDOUT FRAME 1

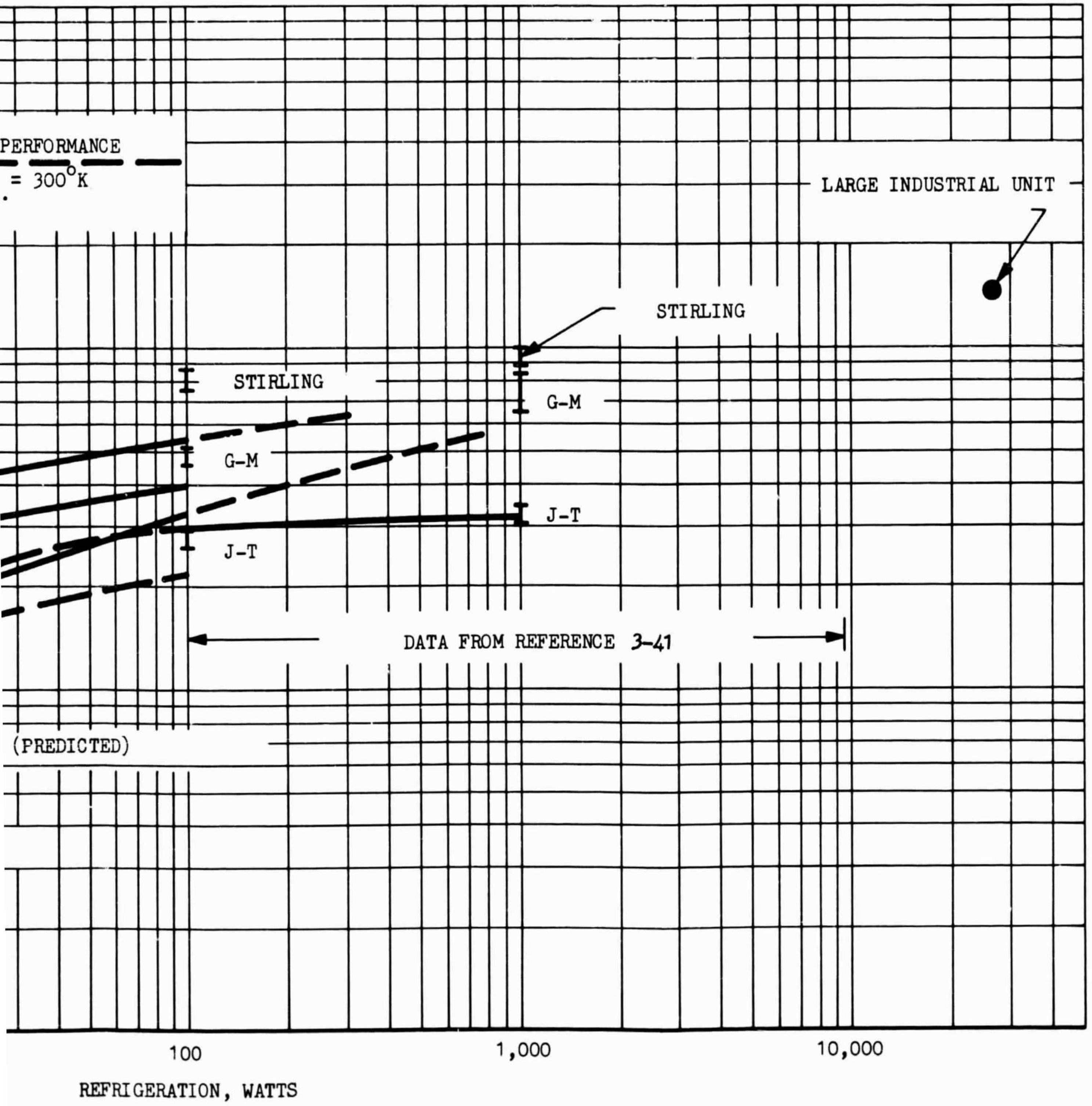


FIGURE 3 SUMMARY OF REFRIGERATOR COEFFICIENT OF PERFORMANCE VERSUS REFRIGERATION FOR VARIOUS CYCLES AT 77°K

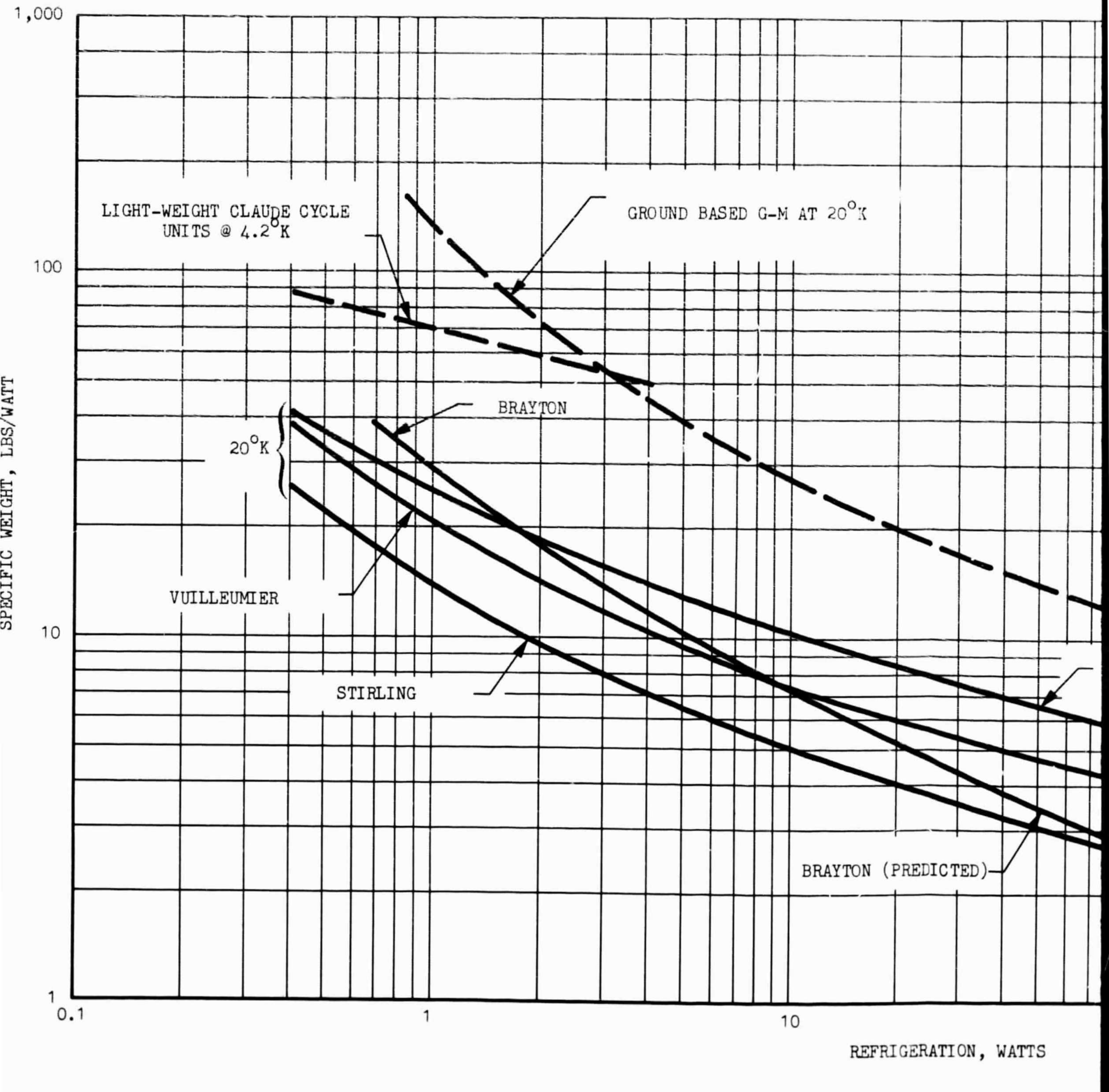
Weight vs Cooling Capacity

Figure 4 shows the comparison of weights for the various cycles at 20°K. Wherever possible, data for operating flight weight systems was utilized. For those cases where sufficient data were lacking, weights were estimated, based on a combination of the curve fits for COP previously described and the system weights vs power input. As might be expected, the lower weight cycles are those with the highest thermal performance (COP) values, the Stirling units being the lightest weight systems, while the Brayton cycle shows a relatively improved position at the higher cooling rate. The weight of heavy units for ground use (oil-lubricated compressor, etc.) is shown for the GM, Taconis, and Solvay units for comparison with what is expected for a weight-optimized unit for those cycles. Weight-optimized versions of the Solvay and GM cycle units have been built, and are operating in the cooling range near one watt.

In addition, a curve is shown for lightweight Claude cycle refrigerators at 4.2°K. This curve is based primarily on predicted values and requires experimental verification before it can be used with any degree of confidence.

All of the curves show a reduction in specific weight as the refrigeration level is increased. This tendency is primarily a consequence of the variation of the coefficient of performance vs cooling rate, and the character of the curves is similar to the COP vs refrigeration curves.

Figure 5 shows the specific weight data for the 77°K cooling level. More operating data on actual units were available for this case than at 20°K. The same general comments are applicable to this curve as for the 20°K case. The weight of the units is substantially less than at 20°K.



FOLDOUT FRAME 1

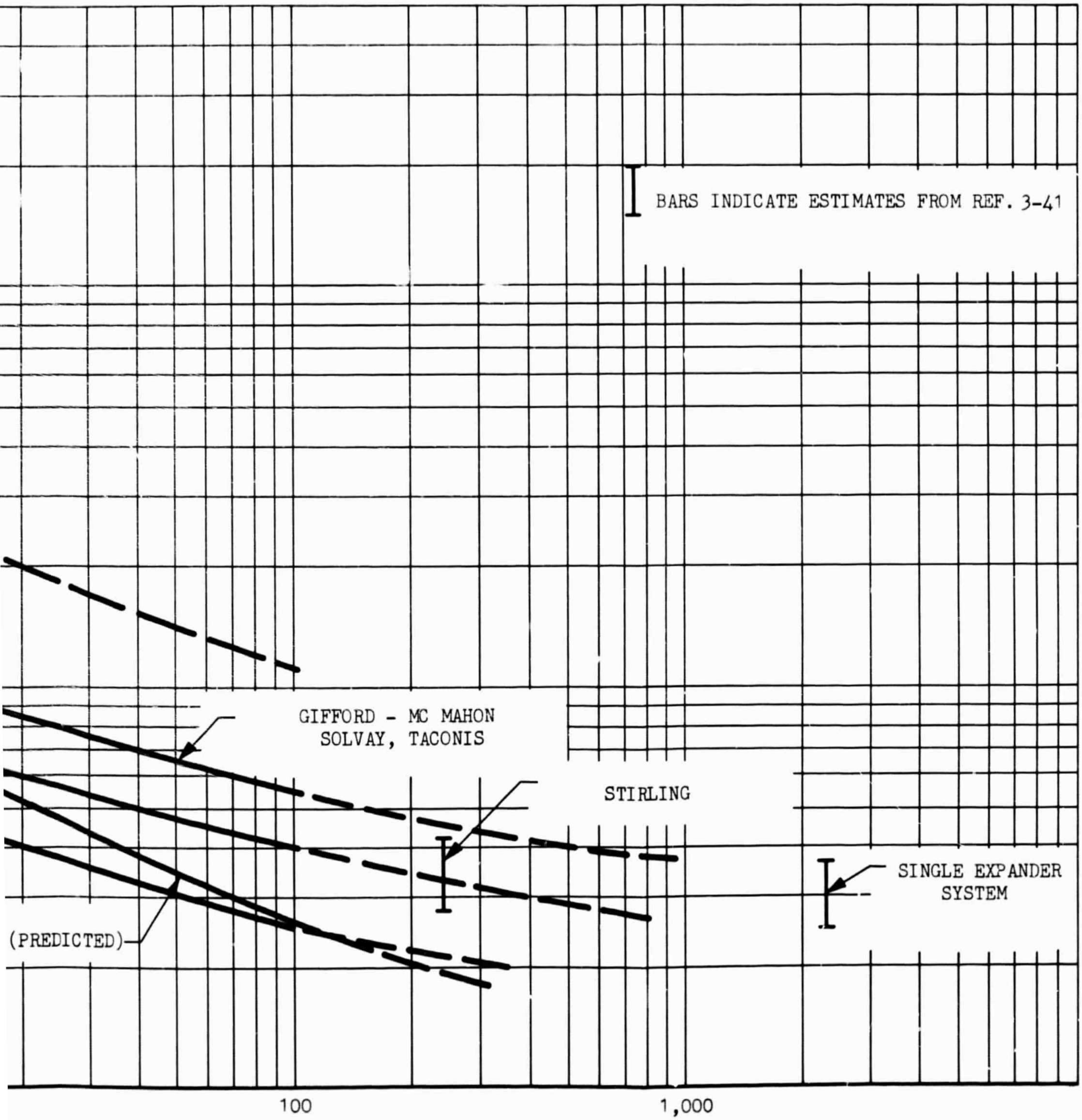
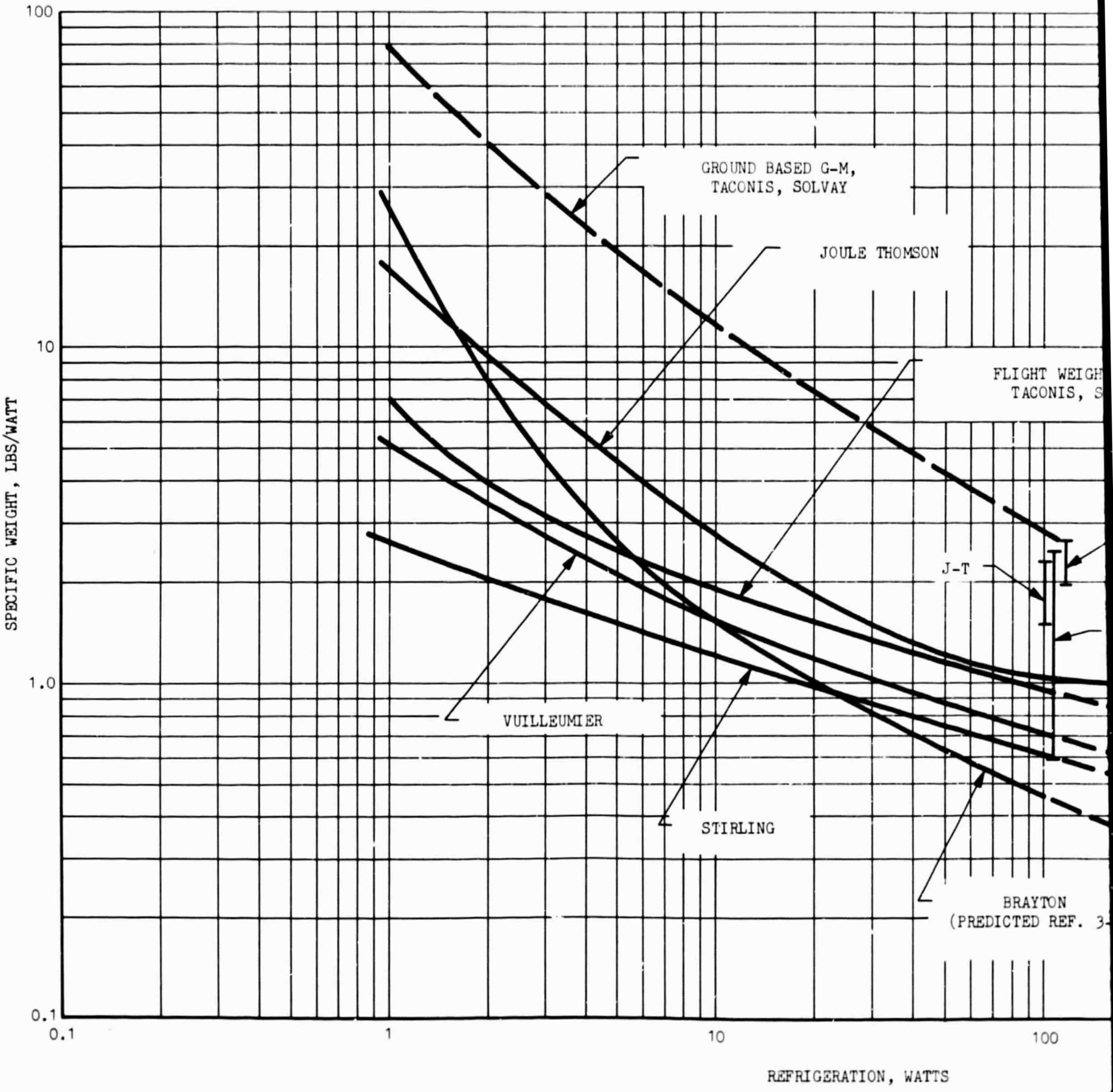


FIGURE 4 SUMMARY OF REFRIGERATOR WEIGHTS VERSUS REFRIGERATION FOR VARIOUS CYCLES AT 20°K AND 4.2°K



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FOLDOUT FRAME 1

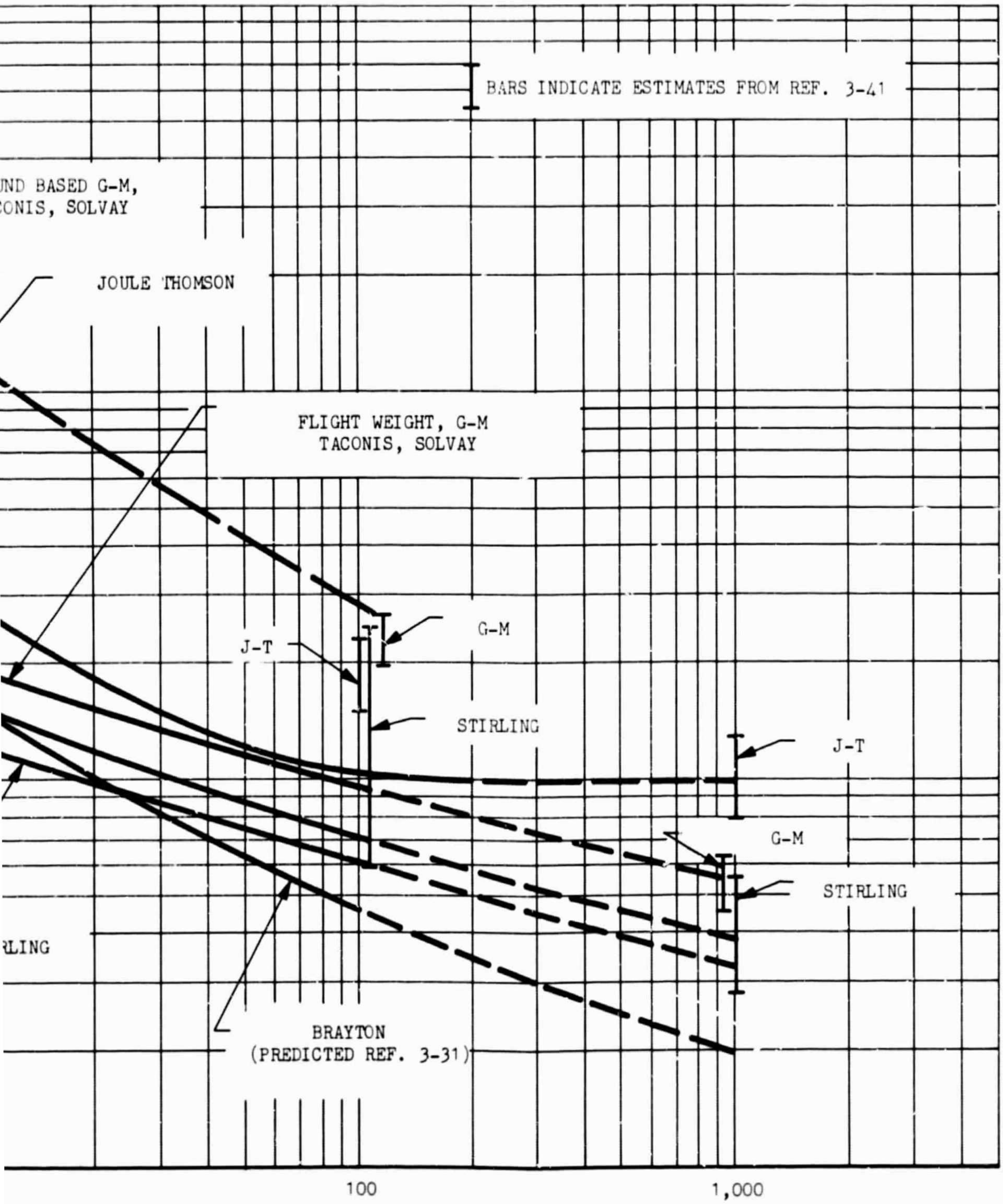


FIGURE 5 SUMMARY OF REFRIGERATOR WEIGHT VERSUS REFRIGERATION FOR VARIOUS CYCLES AT 77°K

Power Supply

Another major element in the refrigerator system is the power supply. As can be seen from the C.O.P. data, closed cycle cryogenic refrigerators are not very efficient. A considerable amount of power must be supplied to the refrigerator in order to accomplish the desired rate of cooling, and in performing any weight tradeoff or systems optimization analyses, the power supply must be considered.

A survey of space electrical power systems which could serve as electrical power sources for external refrigeration systems for long-term cryogenic storage was conducted. Brief descriptions were prepared on the candidate power sources with schematics, figures, and tables to aid in screening and selecting an electrical power system. A brief summary of the systems and guidelines is shown in Table 2.

The possible use of radioisotopes or solar collector/absorbers as a source of thermal energy for a heat-powered refrigeration device was also examined and descriptions of these two types of heat sources were prepared.

For long-life space electrical power systems in the 100 - 1,000-watt range, rigid solar photovoltaic systems and RTG's are the primary candidates. Typically, solar photovoltaics will provide 8 - 10 watt/lb and RTG's 1 - 2 watt/lb. RTG's are small (a 40-watt SNAP-19 requires about $2^{1}/2$ ft^{3}), are not constrained by sun-orientation requirements, but do create potential radiological hazards for the mission. Solar photovoltaic systems should be sun-oriented for maximum efficiency and large panel areas may be required (about 10 watt/ft^{2}). Both solar photovoltaic systems and RTG's have been used in space missions and have been designed to satisfy launch environmental requirements.

Table 2

SUMMARY OF CANDIDATE SPACE ELECTRIC POWER SYSTEMS

Energy Source	Conversion Device	Primary Constraints
Chemical	Battery Fuel Cell	Energy
Solar	Photovoltaic Thermionic*	Sun intensity Shade, Orientation, Extended Surface Area
Radio-Isotope	Thermoelectric Brayton-cycle	Isotope availability, Nuclear safety, Heat projection area
Nuclear Reactor	Thermoelectric Rankine-cycle Brayton-cycle Thermionic*	Nuclear safety, Heat projection area, Reactor coolant temp.

* Probably not available before late 1980's

GUIDELINES

- Use solar photovoltaic power systems unless mission constraints preclude their use.
- Use RTG's in 0.1 - 1.0 kilowatt range if solar photovoltaics cannot be used.
- Use radioisotope Brayton-cycle in 1.0 - 10.0 kilowatt range if solar photovoltaics cannot be used.
- Nuclear reactor power systems would normally not be selected unless large amounts of power 10 kw were required, or unless they were to be the primary spacecraft power source, and much of the shield and system weight were already charged to the spacecraft.

Heat Rejection

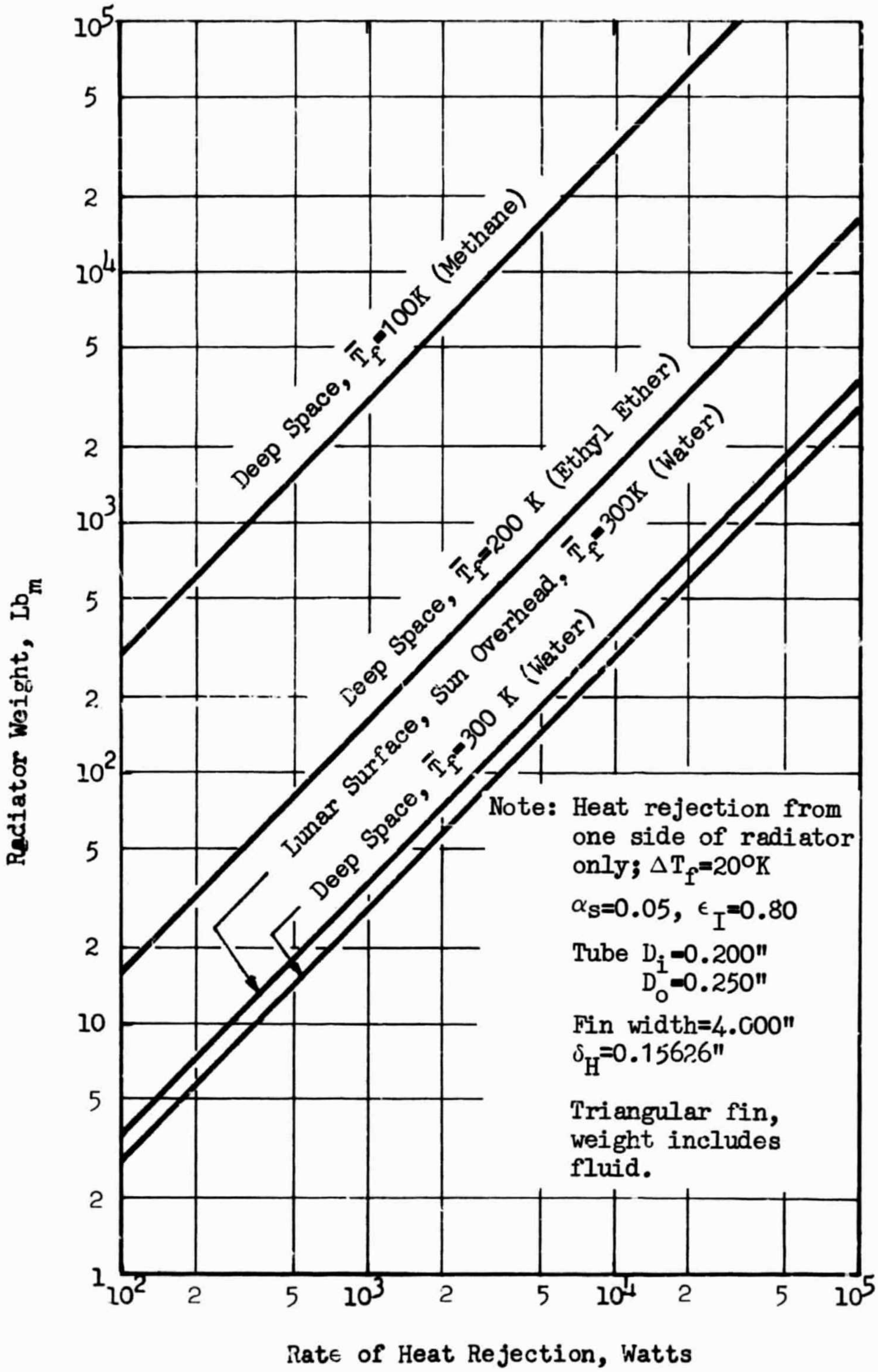
A third major element in the system are the heat rejection devices. Detail design procedures were developed and presented in the final report and handbook for radiators, heat pipes, solid conduction devices, fluid circulation pumps and heat exchangers. All of these items contribute to the weight of the system and are important in establishing the performance characteristics of the refrigeration system. The most significant weight contributer of these is the radiator. The design procedures were used to compute radiator weights for selected thermal environment conditions. These are shown in Figure 6.

All of the necessary data on the major refrigeration system elements has been developed and presented in the refrigeration system handbook. The engineer/planner can utilize this data to decide on refrigeration system applications. He can develop size, weight, and performance data in order to establish future requirement, development, and research programs. Only a few of the major elements of the system have been reviewed here so that the reader may quickly obtain some "feel" for the size, weight and performance of a cryogenic refrigeration system.

STUDY LIMITATIONS

This study was conducted in order to provide the nation with the type of data required to conduct broad cryogenic refrigeration systems evaluation and definitions. The study was limited to analyses and data gathering on system elements only to the depth required to obtain a first estimate of system weight, size, and performance. The refrigerators considered were of the closed cycle, external type; systems utilizing the cryogens themselves in an expansion-cooling process were not included. All elements of the system were to be kept outside of the tank.

In some cases, such as those dealing with failure rates and characteristics, a great deal of hard factual data was not available. Therefore estimates and judgments had to be made; however, whenever this was the case it has been clearly identified as such.



Note: Heat rejection from one side of radiator only; ΔT_f=20°K

α_s=0.05, ϵ_I=0.80

Tube D_i=0.200"
D_o=0.250"

Fin width=4.000"
δ_H=0.15626"

Triangular fin, weight includes fluid.

FIGURE 6 RADIATOR WEIGHT FOR DEEP SPACE AND LUNAR SURFACE OPERATION

It is felt that the study provides much useful information for conducting systems tradeoff studies; however, the data cannot be used to conduct detailed design studies on refrigerators.

IMPLICATIONS FOR RESEARCH

Most government research programs for closed cycle cryogenic refrigeration have emanated from Wright-Patterson Air Force Base. A considerable amount of effort has been devoted toward systems capable of small cooling capacities at low temperatures. There are current programs to improve the operating life of the systems. There are also programs to develop the Vuilluemier (heats powered) systems.

Of all the development and design considerations the most difficult single development problem is to provide long life in an unattended space environment.

SUGGESTIONS FOR ADDITIONAL EFFORT

The material developed in this study and presented in the handbook should be used to review the missions and functions for which cryogenic refrigerators may have potential applications. Having thus identified the potential applications and having examined the relative tradeoffs the refrigeration system requirements and characteristics can be roughly specified. The detail characteristics of the refrigeration system can then be studied and particular design features such as types of refrigerator, its cooling capacity, its performance, size, and weight, its heat rejection temperature, its lifetime, the type of heat rejection system, the type of power supply, and the heat transfer devices can be accurately specified. System cost and development time can thus be established. A complete picture of the refrigeration system will then be available for decisions as to what type research and development program are required to achieve the goals.