AD 299 709

299 709

AEROSPACE CORPORATION

DOCUMENT CHANGE NOTICE

TO: Copyholder

DATE: 22 January 1963

SUBJECT: Cycles and Equipment for Producing Low Temperatures; 15 January 1963; Report No. TDR-169(3711-01)TN-1

FROM: Publications

Revised Cover and Title Page

The cover and title page of the referenced report are in error as to the author's organizational affiliation. Please remove the present cover and title page and substitute therefore the herein enclosed revised cover and title page. The affected pages are unclassified.

SSD-TDR-63-9

Report No.
TDR-169(3711-01)TN-1

CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES

Prepared by

G. H. Zenner
Applied Research Program Support Office

AEROSPACE CORPORATION
El Segundo, California

Contract No. AF 04(695)-169

15 January 1963

Prepared for

COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

SSD-TDR-63-9

REPORT NO.
TDR-169(3711-01)TN-1

Cycles and Equipment for Producing Low Temperatures

15 JANUARY 1963

Prepared by G. H. ZENNER
Applied Research Program Support Office

Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

LABORATORIES DIVISION • AEROSPACE CORPORATION
CONTRACT NO. AF 04(695)-169

SSD-TDR-63-9

REPORT NO.
TDR-169(3711-01)TN-1

Cycles and Equipment for Producing Low Temperatures

15 JANUARY 1963

Prepared by G. H. ZENNER
Physical Research Laboratory

Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

LABORATORIES DIVISION • AEROSPACE CORPORATION
CONTRACT NO. AF 04(695)-169

SSD-TDR-63-9

Report No.
TDR-169(3711-01)TN-1

CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES

Prepared by

G. H. Zenner
Physical Research Laboratory

AEROSPACE CORPORATION
El Segundo, California

Contract No. AF 04(695)-169

15 January 1963

Prepared for

COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

ABSTRACT

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, efficiency, and availability.

CONTENTS

ABSTRACT iii

I. INTRODUCTION 1

II. JOULE-THOMSON REFRIGERATION 4

III. EXPANSION ENGINE REFRIGERATION 7

IV. CYCLES 9

V. DISPLACERS 14

FIGURES

1. J-T Refrigeration Cycle 5

2. Brayton Cycle 10

3. Claude Cycle 12

I. INTRODUCTION

There are only three practical methods for producing cryogenic refrigeration. These are:

a) Vapor-compression refrigeration, which is normally limited to temperatures above about -60°C but which can be staged to produce liquid nitrogen temperature (77°K). The cost and complexity of staged vapor-compression cycles, however, has caused them generally to be abandoned.

b) The Joule-Thomson (J-T) effect, as used in the classic Linde cycle for liquefying air.

c) Expansion engines, which are frequently combined with a throttled stream as in the Claude or Heylandt cycles.

Adiabatic demagnetization is used extensively in certain laboratories to produce temperatures in the range from about 0.001°K up to about 0.8°K. The basic nature of magnetic cooling, however, is such that it is not suitable for higher temperatures and therefore the method has found no application except for research in the region below 0.8°K.

Thermo-electric cooling has been the subject of much recent research, but at present, does not appear practical for cryogenic temperatures. Current models achieve only a 30 to 50°C reduction in temperature from ambient (the higher value at no load). It is expected that a temperature in the vicinity of -80°C (at no load) could be achieved by a three-stage unit. Further staging appears impractical since the power input required per stage multiplies by a large factor while the temperature difference falls off at low temperatures. It will require a major development in materials, such that the thermal conductivity is reduced by a factor of 10 to 100, while electrical conductivity and Seebeck coefficient are kept high or increased above present values, before thermo-electric cooling will be applicable to cryogenics.

Other proposed schemes, such as the Ranque or Hilsch tube, are still further removed from possible practical use.

Power consumption is a major consideration in all systems for producing refrigeration at low temperatures. The theoretical minimum of power for one watt of refrigeration at any low temperature, T_L, is given by the Carnot cycle, as

$$P(\text{watts}) = \frac{T_o - T_L}{T_L}$$

where T_o is the ambient temperature. (T_L and T_o are, of course, absolute temperatures.) In a practical case, this figure must be multiplied by five or more. Note that T_L is in the denominator of this expression and, therefore, the required power becomes infinite as T_L approaches zero. An apparently minor change in T_L, such as lowering it from 10^oK to 5^oK, will result in doubling the required power. It is obviously important to avoid demanding a lower temperature than is necessary for a given situation.

Since liquid nitrogen (77^oK) is readily obtainable in large quantities, use thereof as a refrigerant is quite customary where its temperature is suitable. Liquid hydrogen (20^oK) is now similarly available in large quantities, but its combustion and explosive properties preclude its use for many possible applications. Liquid neon (27^oK) can be obtained on special order for liter quantities but at present it is too expensive for most uses. Liquid helium (4.2^oK) is also commercially available in liter quantities and is used widely as a refrigerant. However, the combination of its high volatility and relatively high cost preclude its use in many cryogenic situations where a steady refrigeration load of some magnitude is encountered.

In general, enough data are available to permit design of an operable machine for production of practically any low temperature. The final choice of cycle will depend on such factors as the capacity, the characteristics and temperature levels of the refrigeration load, limitations on weight and power consumption, need for operating attention, problems of cleaning the fluid stream, availability of suitable expanders and heat exchangers, need for proven reliability, time and money for development, etc. These are engineering problems where a background of closely allied experience is of great value. Solution of these problems, however, should not be confused with research in low temperature physics, as for example: properties of Helium II (superfluidity, understanding of the basic nature of matter, second sound, etc.) researches at less than $1.0^{\circ}K$, and other similar investigations. A successful machine for producing low temperatures will depend largely on the ingenuity and experience of engineers in devising and developing practical equipment which meets the specific need.

II. JOULE-THOMSON REFRIGERATION

The simple throttling cycle for producing low temperature refrigeration can be employed whenever there is a positive J-T effect, that is, when there is a drop in temperature as a result of throttling.

Figure 1(A) is a schematic presentation of a simple throttling cycle; Fig. 1(B) is an elementary T-S diagram thereof roughly representing the properties of air. Throttling from an initial high pressure P_1 (200 atm) and temperature T_1 to P_2 (one atm) yields a refrigerating effect of C_p $(T_1 - T_2)$, where C_p (the specific heat) is taken at P_2. This quantity is also equal to $h_1 - h_2$ (h = enthalpy). If the initial temperature at P_1 is dropped to T_3, the resulting refrigerating effect, represented by $T_3 - T_4$, is greater than $T_1 - T_2$.

For hydrogen and helium, the J-T effect is negative at ambient temperatures, that is, there is an increase in temperature upon throttling. This effect is reversed only at quite low temperatures, for which reason it is necessary to forecool such fluids to very low temperatures. In the liquefaction of H_2 by J-T effect alone, liquid N_2 is commonly used under vacuum to produce a forecooling temperature of about 64°K (the triple point). Similarly, in the liquefaction of helium by J-T effect, a forecooling temperature of 14°K is used, obtained by employing evacuated LH_2 as a forecooling fluid.

The high pressure stream is normally compressed to a pressure at which the enthalpy approaches a minimum for the given temperature. For air at 295°K, the minimum enthalpy occurs at about 400 atm although for practical reasons operating pressures seldom exceed 200 atm. Low pressures, such as at P_b, provide such a small J-T effect as to make throttling cycles ineffective. Helium at 14°K has a maximum J-T effect at about 30 atm. High pressures have therefore, been used for air liquefaction but are not appropriate with helium. Hydrogen at 66°K reaches a minimum enthalpy at about 150 atm.

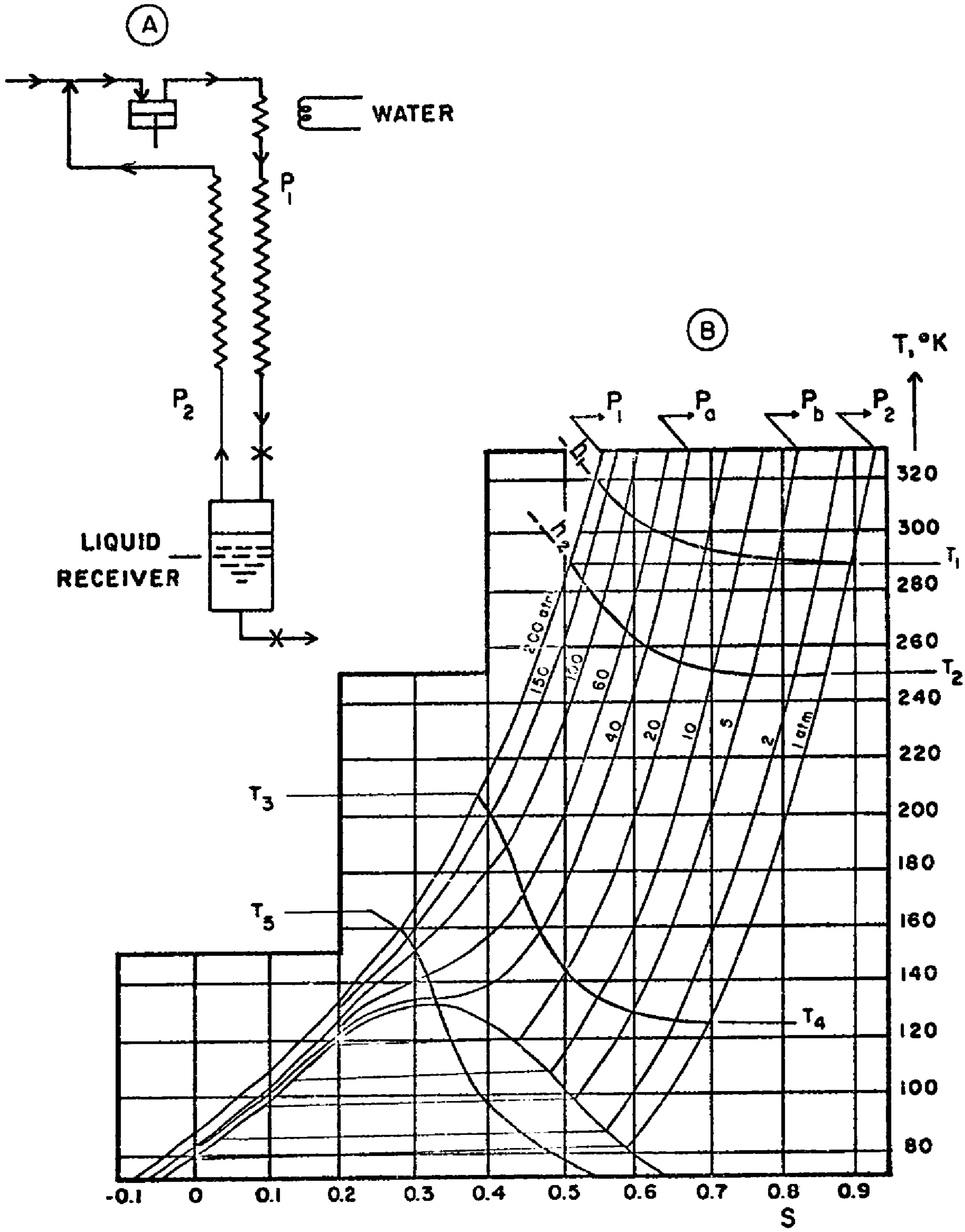

FIGURE 1

J-T REFRIGERATION CYCLE

Intermediate pressures, in the vicinity of the critical pressure such as P_a, shown in Fig. 1(B), are seldom used because the enthalpy-temperature relationship is extremely non-linear at low temperatures. This causes excessive temperature differences in the counter-current heat exchanger. The Claude cycle solves this problem to some extent by reducing the ratio of high pressure to low pressure fluid in the colder portion of the heat exchanger.

A counter-current heat exchanger is always used ahead of the throttle valve, as shown in Fig. 1(A), so that the high pressure stream before throttling is cooled by the outgoing low pressure stream. If the outgoing low pressure stream leaves the warm end of the heat exchanger in the same quantity and at the same temperature as the incoming high pressure stream, the total amount of refrigeration produced by throttling remains unchanged, but is now available at a lower temperature. A low temperature limit is reached when a liquid is produced after throttling, or when the losses equal the refrigeration produced. Important losses are: (1) the temperature difference at the warm end of the heat exchanger, (2) heat leak to the cold region, and (3) gas or liquid losses (or withdrawals) from the cold region. The production of a liquid fraction is illustrated in Fig. 1(B) by throttling from T_5.

The principal objections to the simple throttling system are:

a) The high pressure and relatively low efficiency of the cycle require a heavy compressor and drive. The high power requirement may be objectionable.

b) If forecooling is used to increase efficiency or to permit liquefying hydrogen or helium, simplicity is lost and weight and extra equipment are added.

The chief advantages of the simple throttling cycle are:

a) Simplicity

b) Reliability

III. EXPANSION ENGINE REFRIGERATION

If a compressed gas is expanded in an engine (or turbine) with the resultant work rejected outside the cycle, the expanded gas undergoes a sharp drop in temperature. Ideally this temperature drop can be calculated for any gas by following a constant entropy line from inlet conditions (P_1 and T_1) to exhaust pressure (P_2). Figure 1(B) serves to illustrate the greater efficiency of an expander. From an initial pressure of 200 atm and 290°K, and expanding to one atm, an ideal engine would follow a constant entropy line and would therefore have a small fraction of liquid air in the exhaust at a temperature of about 82°K. Throttling from the same initial conditions to one atm would reduce the air temperature to about 250°K, a drop of only 40°C.

In practice, due to various losses, the temperature (and enthalpy) drop is always less than the ideal. The efficiency of an expander is then defined as

$$\eta = \frac{\Delta \text{ h actual}}{\Delta \text{ h ideal}}$$

The following remarks apply to cycles employing expanders:

a) A most important requirement is that the expander efficiency must be high (usually above 75%), regardless of the fact that the power output may be wasted.

b) The amount of refrigeration obtained from a single expander, operating through a given pressure ratio, falls off as the inlet temperature is lowered. Thus, it may be advisable to employ several expanders, each operating at a different inlet temperature if the refrigeration load covers a broad temperature range.

c) Since only a limited amount of refrigeration is obtainable per lb of gas expanded when low pressure ratios are used, certain cycles employ a large re-circulation of gas. Temperature differences and pressure drops in the heat exchangers then increase and can make such a cycle relatively inefficient.

d) Both reciprocators and turbines are used, but each presents difficulties when attempts are made to change its capacity. Throttling ahead of the expander inlet is a most inefficient method of control.

e) Reciprocating expanders present such mechanical problems as isolation of warm and cold parts of the machine, operation without fluid lubrication, frictional heating and rapid wear in the expansion cylinder, and generally poor accessibility for maintenance. The pulsating power may present a problem for energy absorption.

f) Turbo-expanders must usually operate at very high speeds (30,000 to 300,000 rpm). High efficiency is increasingly difficult to achieve as size is reduced, due principally to relatively high internal leakage, and there may be serious problems with bearings, vibration, fatigue, control, gearing, etc.

g) It is not feasible to operate expanders in a regime where the exhaust becomes wet. For this reason, all refrigeration from an expander is in the form of a cold gas which must increase in temperature as it picks up heat. If the load is at constant temperature, the resulting temperature differences are a source of inefficiency which becomes very serious in the liquid helium range.

h) Very close clearances are sometimes employed between metal parts, as between piston and cylinder wall of an engine or in an air-bearing on a turbine. These parts then become sensitive to solid particles entering the clearance space.

IV. CYCLES

A variety of combinations of working fluids, pressures, heat exchangers, expanders, and throttling devices is possible, all having the object of producing low temperature refrigeration. All are amenable to straightforward design computation and none is so outstanding that it should always be used in preference to any other. The choice is often dictated by the availability and reliability of equipment, particularly expanders and heat exchangers, to meet a given set of requirements.

The simple expander cycle, often called the Brayton cycle, is shown in idealized form as Fig. 2. Figure 2(A) indicates points on a T-S diagram whereas Fig. 2(B) indicates the same points on a P-V diagram. A gas (usually helium) is compressed at ambient conditions from 1 to 2. Cooling from 2 to 3 is at constant pressure, followed by adiabatic expansion from 3 to 4, and constant pressure warming from 4 to 1. Cooling from 2 to 6 is by external means, usually with water or ambient air. Cooling from 6 to 3 occurs in a counter-current heat exchanger, after which the gas is expanded isentropically to 4. Warming from 4 to 5 provides the refrigeration to the load. Warming from 5 to 1 occurs in the counter-current exchanger against the gas cooling from 6 to 3. The lowest temperature, T_4, which can be attained, is the saturation temperature of the fluid at pressure P_4. Normally P_4 is at atmospheric pressure, so that with helium, T_4 must be above 4.2°K. If the load is at a constant temperature, it cannot be cooled below about 10 to 15°K, as the refrigeration cycle has practically no capacity below this level.

The Stirling cycle employed in the Philips Norelco "Cryogenerator" is thermodynamically similar to the Brayton cycle except that the heating and cooling steps are performed at constant volume instead of at constant pressure. This difference is primarily a matter of design convenience.

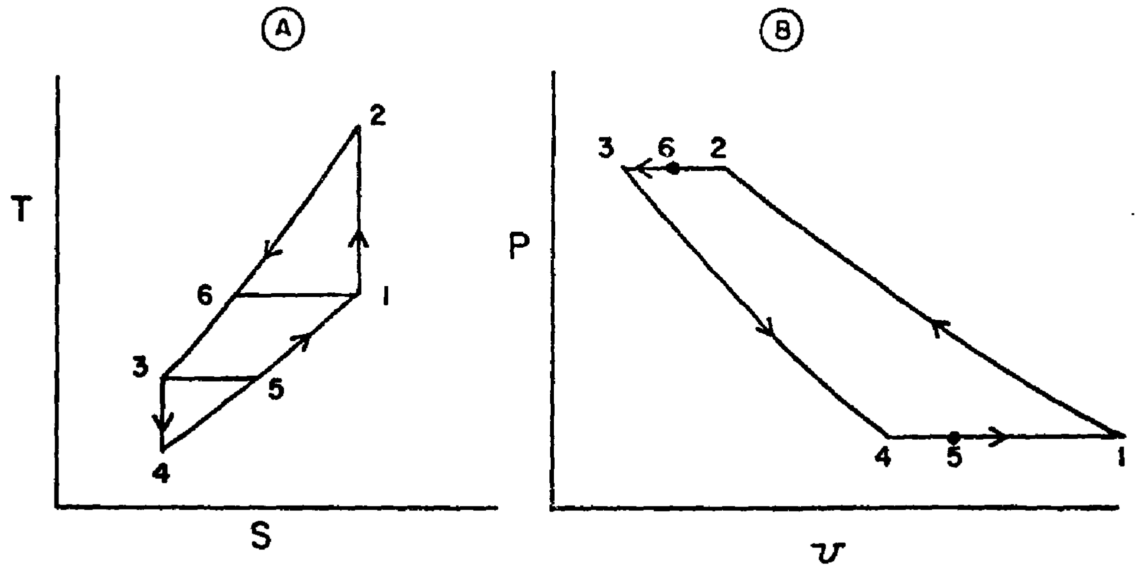

FIGURE 2

BRAYTON CYCLE

If a liquid is to be produced, an auxiliary compressed gas stream is normally employed, with the fluid being throttled after cooling. The Brayton cycle could, for example, be used to supply refrigeration to a second compressed gas stream after it leaves its counter-current coil but before throttling. Such an arrangement may be unattractive for practical reasons, principally, in that two separate compressors and heat exchanger systems are employed.

A simple, single-fluid arrangement is the classical Claude cycle shown in Fig. 3, as used to produce liquid air. Auxiliary details, such as stages of compression, CO_2 and H_2O removal equipment, etc., are omitted from the sketch for simplicity. After passing through the warm end of the heat exchanger, a portion of the compressed air is withdrawn to an expander, the remainder passing through the cold section of the heat exchanger and then being throttled. The temperature of extraction to the expander is critical and is selected so that the expander exhaust is near saturation temperature. This exhaust joins the vapor from the separator and passes out through the heat exchanger.

If a large fraction of liquid is desired, the head pressure is raised to about 200 atm and the expander inlet is taken from nearer the warm end, or from a point just ahead of the heat exchanger. In this case, the cycle becomes the Heylandt cycle. One of the problems with the Claude cycle is maintaining the proper temperature at the expander inlet. An increase in air flow to the engine, changes the heat balance in the counter-current exchanger so that the extraction temperature is reduced. This will tend to further increase the flow through the expander thus making the cycle unstable. Controls must be provided to avoid such problems.

The Stirling and Brayton cycles are most efficient when the refrigeration load is entirely at low temperature. The Claude or Heylandt cycles are better suited for efficient production of a cryogenic liquid where a portion of the refrigeration load is in the superheat range between saturation and ambient temperature. The balance of the refrigeration load is, of course, at the low temperature necessary to absorb the heat of vaporization.

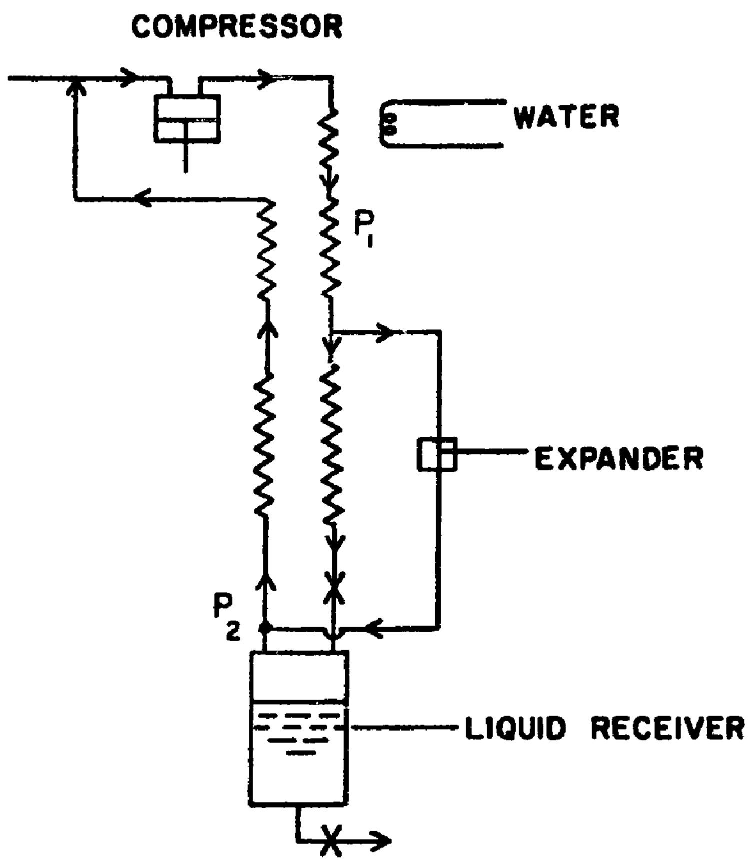

FIGURE 3

CLAUDE CYCLE

Forecooling, as with Freon or ammonia refrigeration, may be employed with practically any cycle depending on circumstances. Forecooling normally increases efficiency and also effectively removes water vapor from the compressed gas stream.

When both a throttled stream and an engine-expanded stream are used in parallel, optimum efficiency occurs at a particular ratio of expanded to throttled gas. Heat exchanger warm end losses are at a mimimum with a low (or zero) ratio. On the other hand, the net refrigeration to the cycle is increased as the percentage of expanded gas is increased to the optimum ratio. Beyond this point, the warm end losses increase so rapidly that a net loss occurs. Usually there is considerable latitude in the allowable deviation from optimum ratio without appreciable loss in efficiency.

An expander in such combination cycles often takes the place of a forecooler, and also is more flexible as to the temperature at which it supplies refrigeration.

V. DISPLACERS

Displacers are currently employed in the Norelco (North American Philips) and Cryodyne (Arthur D. Little, Inc.) refrigerators. In the Norelco machine (a modern version of the Stirling engine) the displacer permits the warm lubricated compressor piston to act, for a portion of its stroke, as the low temperature expansion piston. Lubrication problems at low temperatures are thereby eliminated. The cycle is such, however, that only a single expansion occurs which takes place at the lowest temperature. In this respect the cycle is somewhat inefficient, and it is generally limited to the temperature of liquid nitrogen (77°K).

The Cryodyne employs a novel method for producing refrigeration, that is, by blowing down (throttling) the compressed gas from a fixed volume, whereby the residual gas in the chamber drops in temperature in the same manner as if it had expanded against a piston. (This principle was used by Simon to liquefy helium.) A displacer then moves this residual cold gas out through heat exchangers where the refrigeration is utilized. Other heat exchangers are employed which increase cycle efficiency and permit reaching low temperatures. This device also has the advantage enjoyed by the Norelco, namely, that no low temperature mechanical expander is needed, - the only reciprocator being the compressor. The throttling step, however, is somewhat inefficient. On the other hand, several temperature levels of expansion can readily be employed with a single compressor so that extremely low temperatures (down to 4°K) can be obtained.

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20]p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20]p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20]p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20]p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20] p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20] p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20] p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

Aerospace Corporation, El Segundo, California.
CYCLES AND EQUIPMENT FOR PRODUCING LOW TEMPERATURES, prepared by G. H. Zenner.
15 January 1963. [20] p. incl. illus.
(Report TDR-169(3711-01)TN-1)
(Contract AF 04(695)-169) Unclassified report

An operable machine for production of practically any low temperature is possible using presently available equipment and cycle theories. Various equipment and cycles are herein analyzed and discussed with respect to theoretical aspects, practicality, cost, and availability.

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED