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Overview of the Cryogenic Refrigeration Systems

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Abstract: The term cryogenic simply means very low temperature. Cryogenic cooling uses refrigerants, such as liquid nitrogen or solid carbon dioxide, directly. Cryogenic freezing is often treated as a specific type of freezing method on its own; however, it is essentially an immersion/spray system, depending on how the cryogen is utilized. The cryogenic refrigeration system is a significant part of any superconducting magnetic energy storage (SMES) system. Matching the designs of the magnet and refrigeration system could reduce the required cooling power and lead to a smaller, less expensive refrigeration system. The aim of this work is to provide the basic information needed to understand the technology of producing low and very low temperatures, i.e., cryogenic refrigeration system. This paper addresses the refrigeration, absorption, and liquefaction processes from the engineering point of view.

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1- Introduction

Use of cryogenic cooling by the Deep Space Network (DSN) includes both open-cycle refrigeration (OCR) and closed-cycle refrigeration (CCR) systems. The temperatures achieved by these systems range from 1.5 kelvins (K) to about 80 K, depending upon the type of system used. These cryogenic systems are used to cool low-noise preamplifiers and some of the antenna feed system components for the DSN's receivers. Liquid nitrogen (LN2) was used to cool reference loads (resistive terminations) used for noise temperature measurements, and liquid helium (LHe) was used to cool reference loads and antenna-mounted ruby masers. Russell B. Scott in Cryogenic Engineering [1] explains many aspects of cryogenic technology in terms that are easily understood. Progress since 1959, has given us many types of CCR systems that can be used for cooling low-noise microwave amplifiers. Cryogenic refrigeration is a term that may be applied to the process of cooling equipment and components to temperatures below 150 K. The net capacity of a cryogenic refrigeration system at a particular temperature is the amount of heat that can be applied to a "cold station" in the system without warming the station above that particular temperature. The cold station may be a bath of cryogenic fluid, or the cold station may be a conductive surface cooled to the bath temperature to which equipment may be fastened. Cryogenic refrigeration systems are different from the refrigeration equipment we encounter in our everyday environment. The refrigerants used in cryogenic systems are often helium (He), hydrogen (H2), or nitrogen (N2). Insulation techniques used to minimize heat leaks into the cooled parts of the systems usually depend on the use of high-vacuum technology, radiation shields, and structural materials with low thermal conductivity. Systems that use stored cryogens such as liquid helium, liquid hydrogen, or liquid nitrogen in a container called a "dewar" are usually refilled on a periodic basis. Solidified gases (such as hydrogen or methane) can also be used for cooling purposes, much as solid carbon dioxide (dry ice) is used to refrigerate perishable foods during shipment, but this has not been done in the DSN.

Development of cryogenic refrigeration equipment and systems for laboratory, military, and commercial purposes began many years before development of the ruby masers and other low-noise equipment used in the DSN. This was fortunate, but the personnel developing the DSN's low-noise amplifiers did not have all of the knowledge and expertise needed for developing or purchasing cryogenic equipment and systems. There was much to be learned and many pitfalls to be avoided.

2- General Characteristics of Refrigeration and Cryogenic Installations

It is a natural phenomenon that heat flows in the direction of decreasing temperature, i.e., from high temperature to low temperature regions. The reverse process, however, can take place, not in violation of the second law of thermodynamic but by the addition of work.

The heat transfer from a low-temperature region to a high-temperature one requires therefore, intermediate devices and systems called refrigerators. The difference between a refrigeration and a cryogenic system lies in the achievable temperatures, with the dividing line being set at −100°F or −74°C. The methods used and the physical principles applied to achieve low temperatures are shown in Table 1.

Table 1 Methods and principles for low temperature achievement.

Method	Physical principle
Cyclic processes	
Vapor compression cycle	Evaporation
Steam ejection	Evaporation
Absorption cycle	Evaporation
Gas refrigeration cycle	Adiabatic expansion
Open processes	
Linde liquefaction	Joule Thompson effect
Claude liquefaction	Joule Thompson effect and adiabatic expansion

Refrigerators are systems that operate on a cyclic principle involving a working fluid called a refrigerant. The working principle of a refrigerator is shown schematically in Figure 1.

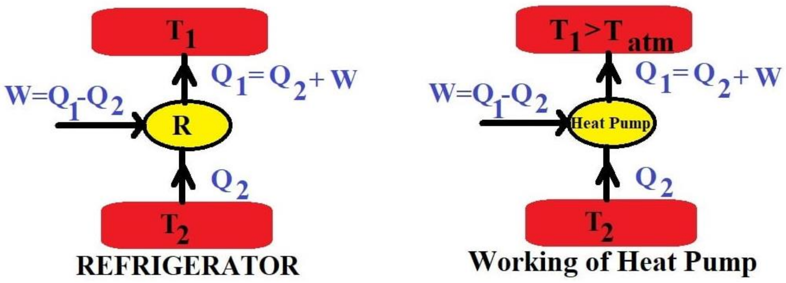

Figure 1 Refrigerator and heat pump working principle.

A refrigerator is a reversed heat engine, where heat is pumped from low temperature (cold body> Q1) to high temperature (hot bod>Q2). So, Work **WR** is required to be done on the system can be expressed as:

WR = Q2-Q1

The performance of a refrigerator is the "ratio of the amount of heat taken from the Cold body Q1 to the amount of work to be done on the system WR.

(C.O.P)R = Q1/ WR = Q1 / (Q2-Q1)

Any refrigerating system is a heat pump, which extracts heat from a cold body and delivers it to a hot body. Thus, there is no difference in the operation cycle of a refrigerator and a heat pump

- The main difference between them is in their operating temperatures.
- A refrigerator works between cold body temperature (T1) and atmospheric temperature (Ta) whereas the heat pump operates between hot body temperature (T2) and the atmospheric temperature (Ta).
- A refrigerator used for cooling in summer can be used as a heat pump for heating in the winter season.
- So

Wp = Q2-Q1

(C.O.P) hp = Q2/ WR = Q2 / (Q2-Q1)

Where hp-heat pump.

The major differences between Refrigerator and Heat Pump are presented below in the form of a table.

Table 2 The major differences between Refrigerator and Heat Pump.

Refrigerator	Heat Pump
A refrigerator is a reversed heat engine, where heat is pumped from a body at low temperature to a body at high temperature.	Any refrigerating system is a heat pump, which extracts heat from a cold body and delivers it to a hot body.
The network done by the refrigerator is given by WR= Q2-Q1	The network done by the heat pump is given by Wp= Q2-Q1
The C.O.P. of Refrigerator is (C.O.P)R = Q1/ WR = Q1 / (Q2-Q1)	The C.O.P. of heat pump is (C.O.P)hp = Q2/ WR = Q2 / (Q2-Q1)

3- Achieving Cryogenic Temperatures

This section covers the most popular methods for obtaining cryogenic temperatures for usable exploitation, including both passive and active cryo-refrigeration devices, sometimes known as cryo-coolers. The main working concepts and engineering elements of the leading cryocooler types: Stirling, pulse-tube, Gifford-McMahon, Joule-Thomson, and Brayton are articulated in separate subsections. Because this is such a broad topic, the study's purpose is to provide an overview of the various technologies as well as a summary of the important decision variables and technical considerations in the purchase and usage of cryogenic cooling systems.

3-1 Passive Cooling Systems

For many years, stored cryogen systems have provided a stable and relatively simple way of cooling over a large temperature range—from below 4 K for liquid helium to 77 K for liquid nitrogen and up to 150 K for solid ammonia. To cool the desired load, these systems rely on the boiling or sublimation of low-temperature fluids or solid cryogens. The temperature obtained for solidcryogens can be adjusted to a degree by adjusting the backpressure on the vented gas from atmospheric pressure to a hard vacuum.

In most situations, stored-cryogen cooling technology has been well-developed, with well-established design principles and many years of industry experience. Temperature stability, independence from vibration and magnetic interference, and low power needs are all advantages of these systems. The systems' short life or continual replenishment requirements, inability to properly control the cryogenic load over a wide temperature range, and the substantial weight and volume penalty generally associated with long-life, stand-alone systems are all downsides.

In systems where the temperature stability and heat transfer associated with cooling with a liquid cryogen are beneficial, adding a mechanical refrigerator to the cryogen dewar can often extend the useful life of the cryogen or greatly reduce the need for replenishment by either recondensing the boiled off vapor and returning it to the dewar, or simply intercepting a significant fraction of the parasitic thermal load entering the dewar.

The use of stored cryogens like liquid nitrogen or liquid helium has long been the preferred method for cryogenic cooling of a wide range of devices, from laboratory instruments to hospital-based MRI machines. Normal two-phase liquid-vapor (subcritical), low-pressure liquid-vapor (densified), and high-pressure, low-temperature single-phase (supercritical) cryogenic liquids can be utilized for cooling in a variety of states. Subcritical fluids, such as low-pressure helium, have long been the preferred cooling medium for space astronomy missions' very-low-temperature (1.8 K) equipment.

Solid cryogens are often utilized below their triple point, where direct sublimation to the vapor state occurs. They provide a number of advantages over liquid cryogens, including the elimination of phase separation difficulties, increased density and heat capacity, and more stable temperature control, all of which are desirable in many applications.

3-2-1 Available Temperatures from Various Cryogens

For those constructing cryogenic systems, comprehensive thermodynamic properties of typical cryogens are accessible in the literature. However, a quick discussion of the practical operating temperature ranges and features of typical cryogens, as well as an introduction to their thermodynamic operating regimes in solid, liquid, vapor, and gas phases, is useful.

The working temperatures of 10 popular cryogens that can be utilized to directly cool cryogenic loads or other components are shown in Figure 2. A bar that stretches from its lowest operating temperature as a solid — based on sublimation at a vapor pressure of 0.10 torr— to its highest operating temperature— its critical point, which is the highest temperature at which a cryogen can exist as a two-phase liquid vapor, represents each cryogen. The shaded area indicated at its highest temperature by the cryogen's triple point, which is the maximum temperature at which a cryogen may exist as a solid, denotes the region of solid phase within each bar. The dashed line above indicates the cryogen's boiling point at one atmospheric pressure. The temperature can be lowered if the ability to pull a stronger vacuum is available, hence 0.10 torr is used to indicate the lowest attainable temperature for convenience.

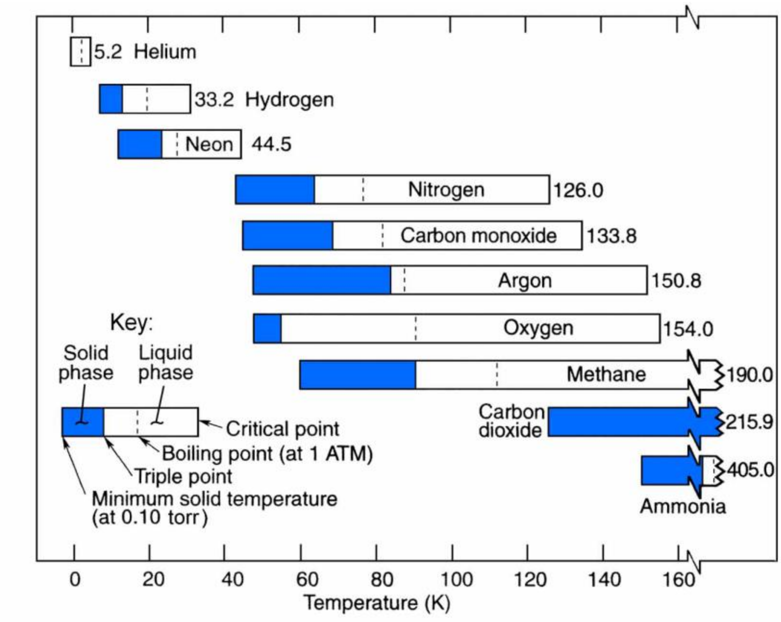

Figure 2 Operating temperature ranges for common expendable coolants.

3-2-2 Thermodynamic Principles of Cryogen Coolers

Understanding the limitations and constraints of stored-cryogen system operating states requires a basic understanding of thermodynamics. Figure 3 shows an idealized temperature-entropy (T-S) diagram for a pure cryogenic fluid, which expands on the key fluid parameters mentioned in Figure 2. The T-S chart is useful not only to depict the borders between fluid states, but also to quantify the amount of heat transmitted when a fluid experiences a change of state, because entropy is defined as the heat transferred divided by the temperature at which the transition happens.

The apex of the dome is termed the critical point, and the conditions at that point are called the critical pressure, critical temperature, and so on, starting with point C. When a fluid reaches or exceeds the critical temperature, it cannot exist as a liquid and must instead exist as a single-phase, homogeneous gas. Cryo-gases are fluids that have been stored in these conditions.

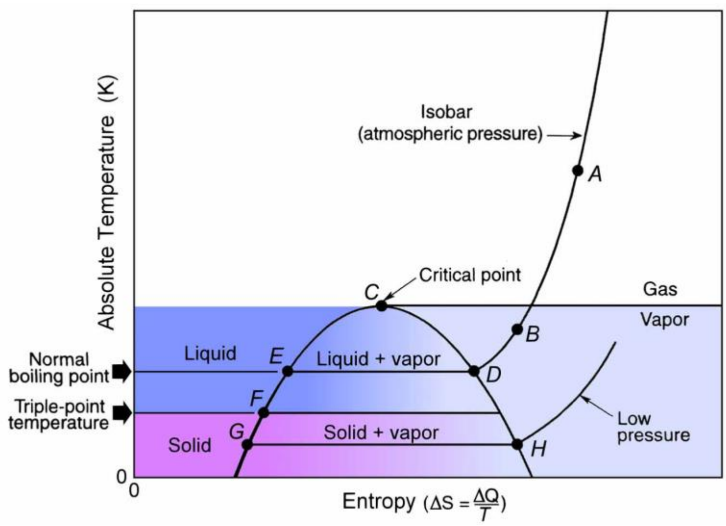

Figure 3 Idealized temperature-entropy diagram for a cryogenic fluid.

Figure 4 elaborates on Figure 3 by demonstrating the relationship between external pressure and boiling point or sublimation temperature for popular cryogens. The triple point, where the cryogen becomes a solid, is also observed. External contaminating gases, such as water vapor, will begin to condense on cryogenic surfaces such as low-emittance shields and MLI at the temperature and pressure indicated in this plot. Managing radiant parasitic loads on low-emittance shields and cryogenic surfaces requires preventing such condensation.

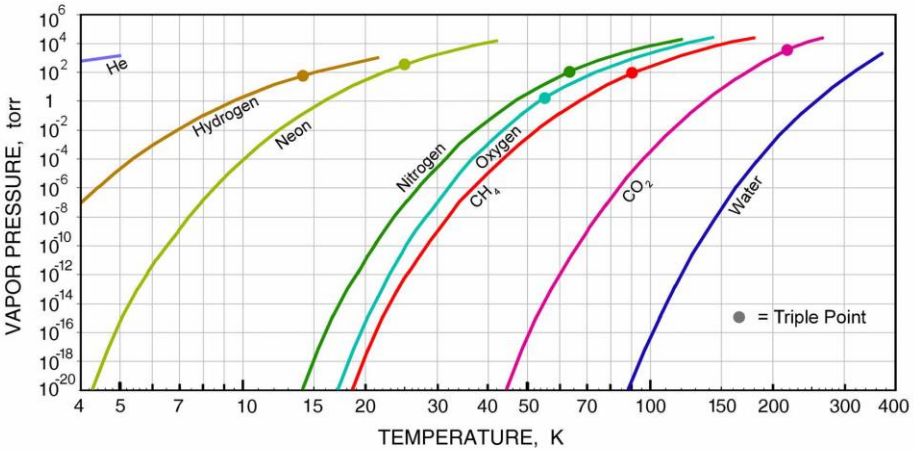

Figure 4 Boiling-point temperature of common gases as a function of external pressure.

3.2.3 Cooling with Liquid Cryogens

Many liquid cryogenic systems have been conceived, constructed, and tested in both terrestrial and space conditions over the years. They span a wide range of cryogen fluids and construction features in terms of storage volume, pressure and temperature limits, and parasitic heat leaks relative efficiency. Many of these systems use liquid helium to reach temperatures between 1.4 and 4 degrees Celsius, or liquid nitrogen to reach temperatures about 77 degrees Celsius.

Liquid helium must be held under partial vacuum conditions to achieve temperatures below 4.2 K. Liquid helium may reach temperatures of 1.4 K to 1.8 K at pressures ranging from 10 to 40 torr.

Features of a Dewar Construction. Liquid cryogen systems commonly use a nested storage tank idea, in which the inner tank, which holds the liquid cryogen, is suspended inside an outer vacuum shell with low-conductivity structural supports, as shown in Figure 5. To ensure great structural efficiency and minimum conductivity between the two tanks, these structural supports are often built of low-conductivity tubes, struts, or tension bands. The space between the two tanks is then emptied and Multilayer Insulation is used to fill it (MLI). A high efficiency dewar may also have one or more strategically placed vapor-cooled shields (VCS) that are cooled by the evaporating cryogen as it exits the inner tank.

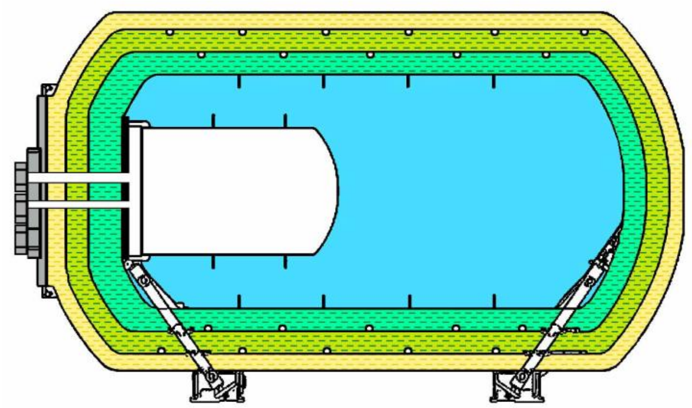

Figure 5 Example liquid cryogen dewar construction features.

3.2.4 Cooling with Solid Cryogens

The frozen state is a second efficient technique to employ stored cryogens. A solid cryogen cooler's regular operating regime is below its triple-point temperature, as shown in Figure 6. The addition of heat in this region leads the solid to convert directly to vapor through the process of sublimation, bypassing the liquid state. Fluid management and phase separation issues connected with fluid systems are also eliminated when operating below the triple point. Working with the solid phase provides better density (and consequently reduced storage volume) and higher heat content per unit mass of cryogen from an efficiency standpoint. A solid cooler's other benefits include its relative simplicity, lack of moving components, lack of noise and vibration, great temperature stability, and lack of power requirements.

A limited number of suitable cryogens, very large mass and volume required for large heat loads or long design lives, the need for significant ground servicing facilities and manpower support, and safety implications associated with venting toxic or flammable vapors or having a vent become clogged—causing an explosion—are the main limitations or disadvantages.

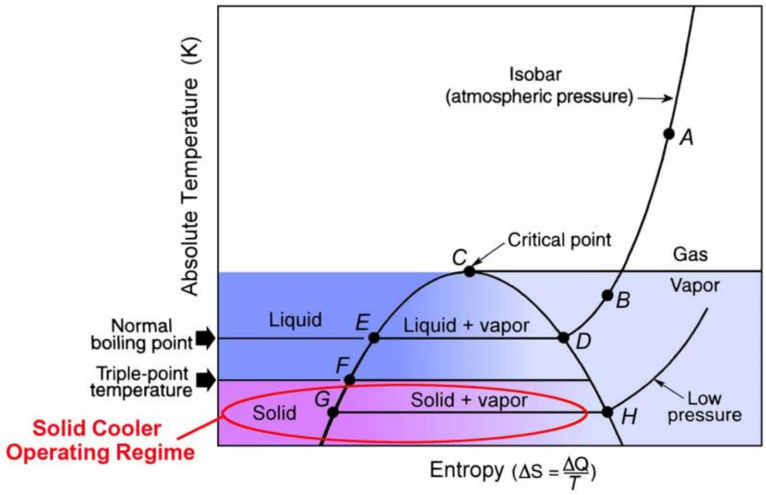

Figure 6 Solid cryogen operating regime.

3.2.5 Radiation to Deep Space

Cryogenic temperatures as low as 40 to 60 K can be achieved for spaceborne applications employing extremely carefully engineered radiant cooler systems radiating into deep space. Despite the fact that the effective radiation temperature in space is only 3 K, reaching temperatures of 40 to 60 K requires sophisticated cryoradiators on spacecraft that are well separated from the considerably warmer environment of Earth orbit. Practical cryoradiator temperatures in Earth orbit are closer to 80 Kand higher.

When attempting to reach cryogenic temperatures higher than these, radiative cooling to deep space can be a successful and cost-effective method of cooling, albeit sophisticated shields from the sun and Earth, as well as the heated environment of the supporting spacecraft, are still required.

Cryoradiators provide the advantage of very consistent long-term performance without the requirement for power or concerns about mechanical wearout, electronics problems, or cryogen supply depletion. The somewhat difficult design associated with achieving sufficiently low parasitic heat loads while maintaining structural strength to endure the launch loading environment offsets this appeal. Constraints on the spacecraft's geometric configuration and orbital attitudes are usually required to achieve useful performance.

3-3 Active Refrigeration Systems

Mechanical refrigerators, or cryocoolers, are generally the chosen design solution for cryogenic applications where stored cryogens such as liquid nitrogen and liquid helium are not readily available or are cumbersome to use. The difficulties of cryogen storage, resupply, and safety for cryogen systems, as well as the demand for electrical power and a mechanism of heat rejection for cryocoolers, are the key considerations that distinguish mechanical refrigerators from stored cryogen cooling systems. Because cryocoolers, or cryorefrigerators, are usually powered by electrical compressors, there must be a way to provide both the electrical power and the mechanism to reject the heat dissipation that results. The issue of power dissipation is particularly critical since the ensuing heat reject temperature has a significant impact on the cryocooler's thermodynamic efficiency. The considerable likelihood of measurable amounts of equipment vibration, EMI, and audible noise that may interact poorly with the intended cryogenic use is a second element of the electrically driven compressor. The cryocooler development industry has placed a strong emphasis on achieving low levels of vibration and noise, which is a key differentiating feature of specific cryocooler kinds and structures. Another significant benefit of a cryocooler is its ability to deliver cooling across a wide temperature range with a single device, many with closed-loop temperature control.

Cryocoolers are used to achieve high vacuum levels in semiconductor processing facilities, to cool infrared detectors and superconducting devices in a wide range of military, space, and laboratory instruments, and to reliquefy cryogens to provide a zero-boil-off recapture of the cryogen in systems using liquid helium or nitrogen. The operational cost, complexity, and reliability/maintenance of the cooling system are all important considerations.

3-4 Cryo-cooler

All mechanical refrigerators work by expanding a gas from a high pressure to a low pressure to cool it. How the compression is accomplished, what pressure-ratio is used, what method of expansion is used to achieve the cold temperature, how well and where heat is rejected, and how well thermodynamic efficiency is maintained using heat exchangers, regenerators, and recuperators are the primary distinguishing features between cycles. The nature of the refrigerant flow within the cryo-cooler is perhaps the most fundamental distinction between cryo-cooler types: either alternating flow (AC systems) or continuous flow (CF systems) (DC systems). This distinction is often referred to as regenerative vs. recuperative systems, depending on the type of heat recovery heat exchanger used: regenerators for alternating flow (AC system) or recuperators for continuous flow (CF system) (DC system).

3-5 Stirling and Pulse Tube Cryocoolers

Stirling coolers (mechanical displacer and pulse tube-based) are one of the most used cryorefrigerator types for small remote and aeronautical applications. The importance of minimal size and bulk, as well as great thermodynamic efficiency, is crucial. These applications are frequently located far from available utility-supplied power and have limited mass and space. Remote cell phone towers, military infrared vision sensors, and spacecraft instrument infrared and gamma-ray sensors are also examples of Stirling usage. However, development of large commercial-scale Stirling-type pulse tube coolers has recently accelerated, with the goal of improving efficiency and reliability for large cost-sensitive continuous cooling applications such as cooling high-temperature superconductors, liquid oxygen/nitrogen production, and LNG production and boil-off prevention in LNG storage tanks. Based on net useful cooling capacity approximately 650 watts at 77 K and 8.5 kW total electrical power to the cryocooler, efficiencies as high as 22% Carnot have been achieved for these big coolers with multi-kilowatt input powers.

3-5-1 Stirling Thermodynamic Cycle & Operational Features

Stirling-cycle coolers are often divided into two types: those that use a mechanical-displacer to achieve the thermodynamic cycle and those that use a pneumatic Pulse Tube (PT) circuit. The AC flow required by the cold head is generated by an oscillating-flow compressor in both cases. The pulse tube variant, on the other hand, replaces the conventional Stirling cycle's mechanical displacer with a pneumatic (non-moving part) expander to produce the ideal mass flow/gaspressure phase relationship required for high thermodynamic efficiency. Lower expander vibration and the reduction of complexity and possibly mechanical wear related with the moving displacer are two advantages of the PT version. Pulse tube expanders are now being used by the majority of the industry.

Most Stirling-based coolers employ helium in the 10 to 35 bar pressure range as the refrigerant gas and work at 30 Hz to 70 Hz due to the direct link between the compressor drive frequency and the expander drive frequency. This high AC frequency is beneficial for cooling at temperatures over 80 K, but it is detrimental for achieving high efficiency at low working temperatures (below 20 K), where the reduced specific heat of regenerator materials severely limits heat storage between cycle phases.

The thermodynamic cycles of the mechanical Stirling-cycle cryocooler are depicted schematically in Figure 7. The regenerator and displacer are usually integrated in one single device for the mechanical-displacer Stirling cycle, as mentioned.

3-5-2 Pulse Tube Stirling Cycle

The pulse tube variant of the cooler, unlike the traditional Stirling cycle's mechanical displacer, employs a tuned pneumatic circuit with no moving components to perform the same gas position management functions as the traditional Stirling mechanical displacer.

The basic elements of an electrical Resistance-Inductance-Capacitance (RLC) phase shifting network are equivalent to the fundamental elements of a pulse tube tuned circuit. The reservoir volume, which gives the capacitance function, and an inertance tube, whose flow resistance offers the resistance function, are mechanical analogs in the pulse tube. The inductance or inertia function gets its name from the inertia of the gas passing through the inertia tube. The circuit's goal is to achieve a 70-degree phase shift between the mass flow through the regenerator and the instantaneous pressure from the compressor during design. This is accomplished by fine-tuning the RLC parameters of the pulse tube cold head: the length and diameter of the inertance tube, as well as the reservoir volume.

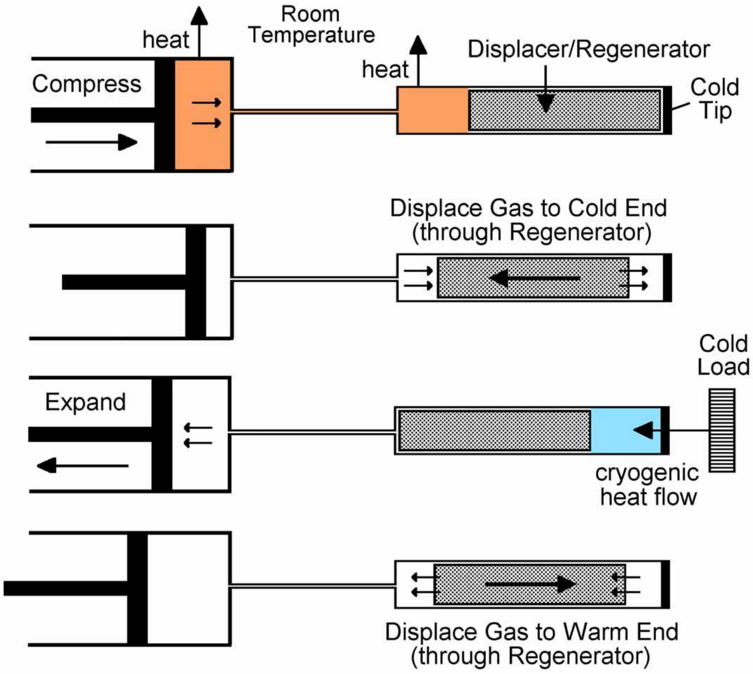

Figure 7 Schematic of Stirling cooler refrigeration cycle.

The pulse tube is responsible for the expander's gas displacement function. It is the name given to a short hollow tube between the inertance tube circuit and the regenerator, in addition to being the name of this type of expander. The hollow pulse tube's purpose is to insulate the regenerator's cool end from the hot gases returning from the inertance tube circuit. This is accomplished by carefully stratifying temperatures throughout the length of the pulse tube and having enough volume such that the gas at the hot (inertance) end of the pulse tube never reaches the cold-load interface end during each pressure/expansion cycle. To achieve this precise temperature stratification, the pulse tube design must carefully avoid any gas mixing in the pulse tube induced by turbulent flow or gravity-driven convection.

Figure 8 depicts the four cyclic stages of the pulse tube cooler. A virtual-displacer symbolizes the cold and hot borders of the stratified gas plug that oscillates back and forth in the pulse tube during the cooler's operation in this diagram, indicating the pulse tube's displacer function.

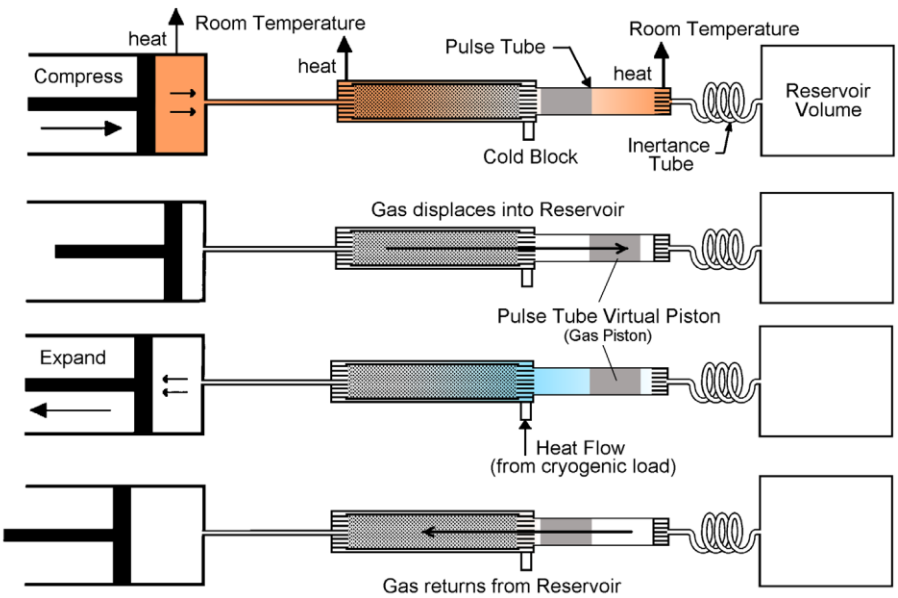

Figure 8 Schematic of pulse tube cooler refrigeration cycle.

3-5-3 Engineering Aspects of Stirling and Pulse Tube Cryocoolers
Stirling cooler compressors are piston-type compressors that are either driven by a rotating crankshaft, like a vehicle engine, or by a linear voice-coil motor, like a HiFi loud speaker, to support the demand for an alternating fluid flow at a frequency of 30 to 70 Hz**.**
Rotary Crank Compressor. The rotary-crankshaft design has the advantage of allowing the displacer to be driven off the same crankshaft as the piston, allowing both gas compression and displacer control to be accomplished with the required phase relationship from the same drive motor. The longevity concerns related with piston, displacer, and bearing wear, as well as contamination of the helium working fluid by outgassing products of the needed bearing lubricants are the main disadvantages of the rotary crank design. A rotary compressor is essentially a variable-frequency constant-stroke compressor, with the frequency determined by the motor drive speed (rpm). Figure 9 shows a tiny Ricor K508 rotary-drive Stirling cooler.

Figure 9 Miniature Ricor K508 rotary Stirling cooler (500 mW at 80 K).

Compressors that are linear. To achieve improved dependability and longer life, the vast majority of Stirling coolers have transitioned to a linear compressor arrangement over the last 25 years. Figure 10 shows an example of a DRS (previously Texas Instruments) 1.75W at 80 K twin piston linear drive Stirling cooler. To achieve high drive motor efficiency, this design uses a variable stroke and constant drive frequency, with the mechanical resonant frequency of the linear piston well aligned with the drive frequency.

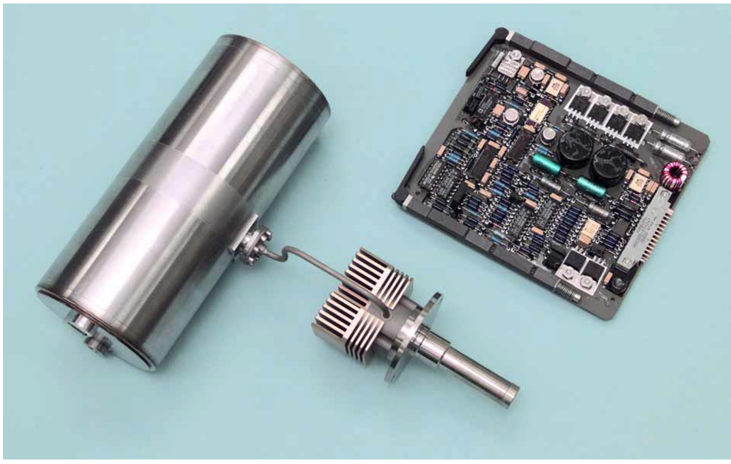

Figure 10 1.75 W at 80K DRS linear-motor dual-piston Stirling cooler.

4- Conclusion
It has been demonstrated in this paper that there are several typical methods of generating cryogenic temperatures, including both passive systems involving the use of liquid and frozen cryogens and active cryo-coolers, are available.

References

[1] R. B. Scott, Cryogenic Engineering, Princeton, New Jersey: D. Van Nostrand Company, Inc., 1959.

[2] R. C. Lee, A. Dada and S. M. Ringo, "Cryogenic refrigeration system for HTS cables," in IEEE Transactions on Applied Superconductivity, vol. 15, no. 2, pp. 1798-1801, June 2005, doi: 10.1109/TASC.2005.849291.

[3] X. Chen et al., "Design and Manufacture of a Helium Refrigeration System for HL-2M Tokamak," 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), 2020, pp. 1-2, doi: 10.1109/ASEMD49065.2020.9276310.

[4] X. Chen et al., "Study on Characteristics of the Helium Refrigeration System of HL-2M Tokamak," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 8, pp. 1-4, Nov. 2021, Art no. 4903204, doi: 10.1109/TASC.2021.3110465.

[5] X. Chen et al., "Status of the Domestic Large Helium Refrigeration System of HL-2M Tokamak," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 8, pp. 1-4, Nov. 2021, Art no. 4203104, doi: 10.1109/TASC.2021.3110462.

[6] E. A. Marakhova, A. A. Novikova, E. A. Barkhanskaya and D. A. Uglanov, "Research of Parameters of On-board Cryogenic Cooling System," 2021 5th International Conference on Smart Grid and Smart Cities (ICSGSC), 2021, pp. 88-91, doi: 10.1109/ICSGSC52434.2021.9490412.

[7] J. Lee, G. Seo, J. Mun, M. Park and S. Kim, "Thermal and Mechanical Design for Refrigeration System of 10 MW Class HTS Wind Power Generator," in IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 5201905, doi: 10.1109/TASC.2020.2973117.

[8] Masood A. Masood, I.S. Naser, Abdussalam Ali Ahmed, Zayad M. Sheggaf, Ahmad A. M. Idris, " Evaluation And Influence Of Hot Exhaust Gas Recirculation Technology On The Performance Of A Single-Cylinder Diesel Engine And Emission Levels," *the 4th International Conference on Innovative Studies of Contemporary Sciences*, July 29-31,2021, Tokyo, Japan.

[9] Alhusein N, Ahmed A.Climate Change Impacts on Future Solar Photovoltaic System Performance and Power Output in Libya. Alq J Med App Sci.2022;5(1):185-192. https://doi.org/10.5281/zenodo.6396004

[10] Abdussalam Ali Ahmed, Omar Ahmed Mohamed Edbeib, Aisha Douma, and Ibrahim Imbayah Khalefah Imbayah, Electric vehicles revolution: The future, challenges, and prospects in the Arab countries, Global Journal of Engineering and Technology Advances, 2021, 06(03), 081-087,DOI:10.30574/gjeta.2021.6.3.0040.

[11] Abdussalam Ali Ahmed, Renewable Energy Home Design in Bani Walid City/Libya, Saudi Journal of Engineering and Technology (SJEAT), Vol. 4, Issue 9, September 2019.

[12] Mon, G.R., Smedley, G.T., Johnson, D.L. and Ross, R.G., Jr., "Vibration Characteristics of Stirling-Cycle Cryocoolers for Space Application," Cryocoolers 8, Plenum Publishing Corp., New York (1995), pp. 197-208.

[13] Ravex, A., Trollier, T., Sentis, L., Durand, F., Crespi, P., "Cryocoolers Development and Integration for Space Applications at Air Liquide," Proceedings of the Twentieth International Cryogenic Engineering Conference (ICEC 20), Elsevier (2005), pp. 427-436.

[14] A. A. Ahmed and A. F. Saleh Alshandoli, "On replacing a PID controller with Neural Network controller for Segway," 2020 International Conference on Electrical Engineering (ICEE), 2020, pp. 1-4, doi: 10.1109/ICEE49691.2020.9249811.

[15] A. Ali Ahmed and M. Emheisen, "Analysis of Vehicle Handling Using a Simple Track Model of Automobile," 2019 19th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), 2019, pp. 130-133, doi: 10.1109/STA.2019.8717244.

[16] A. A. Ahmed, J. Santhosh and F. W. Aldbea, "Vehicle Dynamics Modeling and Simulation with Control Using Single Track Model," 2020 IEEE International Women in Engineering (WIE) Conference on Electrical and Computer Engineering (WIECON-ECE), 2020, pp. 1-4, doi: 10.1109/WIECON-ECE52138.2020.9397983.

[17] A. A. Ahmed and O. S. M. Jomah, "Modeling and Control of Car Active Suspension System Using a Neural Network-based Controller and Linear Quadratic Regulator Controller," 2020 IEEE 2nd International Conference on Electronics, Control, Optimization and Computer Science (ICECOCS), 2020, pp. 1-6, doi: 10.1109/ICECOCS50124.2020.9314426.

[18] A. A. Ahmed and A. F. Saleh Alshandoli, "Using Of Neural Network Controller And Fuzzy PID Control To Improve Electric Vehicle Stability Based On A14-DOF Model," 2020 International Conference on Electrical Engineering (ICEE), 2020, pp. 1-6, doi: 10.1109/ICEE49691.2020.9249784.

[19] A. A. Ahmed and O. S. M. Jomah, "Vehicle Yaw Rate Control For Lane Change Maneuver Using Fuzzy PID Controller And Neural Network Controller," 2020 IEEE 2nd International Conference on Electronics, Control, Optimization and Computer Science (ICECOCS), 2020, pp. 1-6, doi: 10.1109/ICECOCS50124.2020.9314541.

[20] Johnson, D.L., Collins, S.A. and Ross, R.G., Jr., "EMI Performance of the AIRS Cooler and Electronics, “Cryocoolers 10, Plenum Publishing Corp., New York (1999), pp. 771-780.
[21] Gifford, W.E. and Longsworth, R.C., “Pulse Tube Refrigeration Progress,” Advances in Cryogenic Engineering, Vol. 10B, Plenum Press, NY (1965), pp. 69-79.
[22] Kotsubo, V.Y., Johnson, D.L., and Ross, R.G., Jr., “Calorimetric Thermal-Vacuum Performance Characterization of the BAe 80 K Space Cryocooler,” SAE Paper No. 929037, Proceedings of the 27th Intersociety
[23] Energy Conversion Engineering Conference, P-259, Vol. 5, San Diego, California, August 3-7, (1992), pp. 5.101-5.107.
[24] Mon, G.R., Smedley, G.T., Johnson, D.L. and Ross, R.G., Jr., “Vibration Characteristics of Stirling-Cycle Cryocoolers for Space Application,” Cryocoolers 8, Plenum Publishing Corp., New York (1995), pp. 197-208.