CRYOGENICS FOR SUPERCONDUCTORS

REFRIGERATION, DELIVERY, AND PRESERVATION OF THE COLD

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A collection of the materials of interest

OUTLINE

- **DISCOVERY of HELIUM and LIQUEFACTION**
- **DISCOVERY of SUPERCONDUCTIVITY**
- **APPLICATIONS of SUPERCONDUCTIVITY**
- **ADVANCEMENTS of HELIUM LIQUEFACTION**
- **PRESENT STATUS of HELIUM REFRIGERATORS**
- **HIGH TEMPERATURE SUPERCONDUCTORS**
- **DELIVERY of REFRIGERATION**
- **PRESERVATION of COLD (REFRIGERATION)**
- **FUTURE IN INSULATION**
- **CONCLUSIONS**

Discovery Of Helium

The discovery of helium was the first exception in the history of the science of matter

Helium came to light (literally) when first observed in the Sun, and then on the Earth

Pierre Janssen observed the **bright yellow line in the spectra** when studying the spectrum of the solar corona during an eclipse
August 18, 1868 at Guntur, AP, India

Spectra from “General Chemistry” by H. P. Cady

Discovery Of Helium Time Line

- **Pierre Janssen** observed the **bright yellow line** when studying the spectrum of the solar eclipse
in August 18, 1868
- **Lockyer and Frankland** confirmed Jassen's results and named it as **Helium** after the Sun "Helios"
in October 20, 1868
- **Luigi Palmier** detected existence of **Helium on earth**
in 1892
- **Sir William Ramsay** isolated the **Helium on earth**
in March 26, 1895
- **H. P. Cady and D. F. McFarland**, **Helium in natural gas (~2%)**
in 1905 (major source even today)

Liquefaction Of Helium

The helium was first liquefied by Kamerlingh Onnes on July 10, 1908 in Leiden, Holland

Onnes at the He Liquefier

First He Liquefier

Interest in Helium

US Government recognized the special properties of helium for critical applications, particularly for defense during World War I

US Government enacted the Helium Conservation Act in 1925.

This is replaced by the Helium Privatization Act of 1996.

Present Estimates of Helium

- **World Helium Reserves**

US	21%
Russia, Algeria, Qatar & Other	79%

- **World Helium Production**

US	77%
Other	23%

- **Present Use** **175 million cu. meters**

- **Projected Use by 2030** **300 million cu. meters**

Discovery of Superconductivity

*Experiments conducted under **Kamerlingh Onnes'**
direction by **Gilles Holst** with mercury lead to the
discovery of **super conductivity in April 8, 1911***
100 years ago

Type-I superconductors (exhibit a total Meissner effect)

Require low Temperature $\sim < 9.5\text{K}$ (LTS)

Explained by BCS theory

Type-II superconductors (Partly exhibit Meissner effect)

Some require low Temp.

Some can operate at higher Temp. (HTS)

Applications of Superconductivity Examples

- **Detectors:** Josephson junctions, Superconducting Quantum Interference Devices (SQUIDS), fast digital circuits
- **Science:** Particle accelerators using superconducting magnets or SRF cavities, fusion research
- **Biomedical:** Magnetic Resonance Imaging (MRI), SQUID devices, EEG, Magneto encephalography (MEG) to study the neural activity in brain, Magneto cardiography (MCG)
- **Transportation:** MagLev (super-conducting magnetic levitation – used for mass transit rail or orbital insertion of payloads)
- **Military:** Super conducting motors for ship propulsion, microwave radar
- **Energy:** SMES (for energy storage, power quality, pulse power, etc.), low loss power transmission systems
- **Other:** Cryogenically cooled super computers, communication systems, ore separation, SQUID based Non Destructive Testing (NDT)

PRODUCTION OF THE COLD: REFRIGERATION

**Today most of the superconducting devices
(all Type-I and some Type-II)
require helium refrigerators to operate**

- **First liquefier by Onnes and the following designs by others were difficult to operate and less reliable**
- **Most of them used hydrogen pre-cooling**

PRODUCTION OF THE COLD: REFRIGERATION (cont.)

- The systems developed by Kapitza (1934) used a single expander Claude cycle with Ln_2 precooling
- Kapitza was the first to apply adiabatic expansion to drop the temperature of helium below the inversion point
- National Bureau of Standards (NBS) was established in 1901 and in 1904 purchased two liter per hour (2 L/hr) hydrogen liquefier
- Lead the cryogenic research, established the standards for properties of helium and other

Collins Helium Cryostat

Collins at MIT built a simpler helium liquefier in 1946

- **Requiring no pre cooling**
- **Introduced Oil lubrication to compressors**
 - **Led to the use of oil flooded Screw compressors**
- **Widely used machine**
 - **(~ 500 of 1400 style machines produced)**

Advancements of Helium Liquefaction

- **Small Collins type liquefier systems**
Carnot Efficiency is ~10%
- **The demand for high capacity, high efficiency, reliable helium liquefiers grew exponentially in the 1970's. This lead to:**
 - **Development of more efficient cycles with many expansion stages**
 - **Adopted turbo expanders, plate fin heat exchangers, oil flooded screw compressors**

Present Status of Helium Refrigerators

The cycles are based on modified Claude-Brayton cycles based on constant pressure process

- **Design point exergetic efficiency ~ 30%**
- **Availability > 99%**

Present Status of Helium Refrigerators (cont.)

Helium system with high efficiency (low operating cost) also has low (or flat) capital cost

high efficiency systems require less mass flow; therefore:

- **fewer or smaller compressors**
- **smaller cold box**
- **smaller support systems e.g: Power, cooling, buildings etc.**

Requires more expansion stages

This is contrary to the intuition of many people.

Present Status of Helium Refrigerators (cont.)

Mismatch exists between the refrigerator design capacity and the load due to:

- **uncertainty in the estimation of loads**
- **high peak - low average load operations**
- **excess capacity required for short duration peak loads like cool down**
- **operation in different modes (e.g.: cool down, pump down , 2K/4K, filling etc.)**
- **uncertainty in the performance prediction of critical components (e.g.: Compressor flow +/- 5%)**
- **under performing components**
- **capacity for future needs**
- **adopting equipment designed for a different application**

Present Status of Helium Refrigerators (cont.)

Design capacity is traditionally 50 to 100% higher than estimated loads

Results in operation at off-design conditions and at substantially lower efficiency in the field

Constant-Pressure Ratio Floating Pressure Cycle
allows the system to operate and maintain close to peak efficiency at the required load automatically

Floating Pressure Process - System

Floating Pressure Process - System (Cont.)

As the “Claude Cycle” is essentially a constant pressure process and, the “Sterling Cycle” is a constant volume process the “Floating Pressure Cycle” is a constant pressure ratio process

$$p_r \equiv \frac{p_{h,2}}{p_{l,1}} = \left(\frac{\eta_v \cdot Q_C}{K_x} \right) \cdot \left(\frac{1}{\phi \cdot C_p} \right) \cdot \frac{\sqrt{T_{h,2}}}{T_{l,1}} \cong \text{Constant}$$

$$\eta_{carnot} = \frac{E_L}{\dot{W}_C} = \frac{\Delta \varepsilon_L}{w_C} \cong \text{Constant}$$

That maintains essentially constant Carnot efficiency over a very wide operating range

(100% to ~ 40% of maximum capacity in practical systems)

BNL RHIC Energy Savings

Electric Power History Graph, (Phase III “Goal” 5.4MW)

Exceeded 2003 Goal of 5.4MW.....46% Electrical Power Reduction Presently (2010) it is at 4.8 MW

NASA-JSC/JLab Collaboration

James Webb Telescope

Replaces Hubble
~1 million miles out

Telescope Mockup at the National Mall, D.C.

Floating Pressure Technology For Telescope Testing

Simulation Chamber-A, NASA-JSC

The existing 3.5 kW 20K cryogenic systems are converted to JLab's Floating Pressure Technology.

Improved temperature stability from 2.5K to 0.25K and efficiency (follows)

NASA-JSC 2008 3.5kW Plant Test Results

Expected Refrigeration System Efficiencies

CHL-II -Jlab

NASA -JSC

Approximate Usage of Input Power

Before mid 70's

Now 2011

No change to warm-compressor in input power loss fraction (~ 50%)

Carnot Work Required at Various Temperatures

Ideally (Min.) Required input Power per 1 W of Cooling (W/W)

	T _{load} (K)	P _{carnot} W / W
A / C Sys.	263.0	0.14
Methane	111.7	1.69
Oxygen	90.2	2.33
Argon	87.3	2.44
Nitrogen	77.3	2.88
Neon	27.1	10.07
Hydrogen	20.3	13.79
Helium	4.2	70.09
Helium @Lambda	2.2	137.25
Helium @ 2.0 K	2.0	149.00

Cryocoolers

Many applications require only a small amount of refrigeration capacity

Claude, Brayton and Stirling cycles are often too bulky, complicated and/or expensive

- **Gifford-McMahon (GM) cryocoolers**
- **Stirling cryocoolers**
- **Pulse Tube cryocoolers**

Cryocooler Efficiency

Radebaugh 2001

Efficiency1.ppt

Refrigerator Choices

Radebaugh 1999

asc1ca.cdr

Jefferson Lab

Thomas Jefferson National Accelerator Facility

High Temperature Superconductors (HTS)

Müller and Bednorz discovered high temperature superconductors (HTS) In 1986, in a brittle ceramic compound of lanthanum, barium, copper and oxygen with a critical temperature of 30 K

- **Since many milestones have been reached**
- **These are ceramic based compounds and are Type II superconductors**

High Temperature Superconductors (HTS)

The potential of HTS is estimated to be substantial, for electric power applications and other

- **Transmission lines**
- **Transformers**
- **Fault current limiters**
- **Josephson devices**
- **Mobile telecommunications**

Experience Differences: Supplier versus User

Guiding interests of the equipment supplier and the user in the decision making process are different

- **Questioning the customer can lead to conflicts**
- **Customer may not have the full knowledge of the system capabilities and flexibility**
- **Real system operates in many modes**
- **Constant pressure ratio floating pressure cycle is a result of having the experience on both sides**

DELIVERY OF REFRIGERATION

For large systems, typically liquid helium to support the load is supplied through vacuum-jacketed transfer lines e.g.:

- **CERN, RHIC, FERMI Lab, CEBAF**

Typical interfaces

- **permanent connections with isolation valves,**
- **field joints**
- **couplings (‘bayonets’)**
- **Some are designed for easy disconnection at positive pressures and at cryogenic temperatures**
- **Other bayonets-coupling designs can only be disconnected at ambient temperature**

Transfer Line Cross Sections

CHL SUPPLY TRANSFER LINE

LINAC SUPPLY TRANSFER LINE

CHL RETURN TRANSFER LINE

LINAC RETURN TRANSFER LINE

DELIVERY OF REFRIGERATION

Transfer lines at CEBAF connecting the cryo modules to the refrigerator

Transfer Line between CHL and ESR

Preservation of the Cold

Basic Idea

- **Superconductivity:**
 - Going nowhere without cryogenic refrigeration
- **Cryogenic refrigeration:**
 - Going nowhere without cryogenic insulation

Why nothing for 50 years?

- 1911 to 1961
- **Nothing much happened with superconductivity for 50 years.**
- **Then an explosion in activity.**
- **Why?**
 - Difficult and inefficient refrigeration process.**
 - Lack of high-efficiency insulated storage vessels.**

Three key inventions

- **What came about?**
 - **Welding of stainless steel and other advances in metallurgy**
 - **Accidental invention of Teflon**
 - **Invention of multilayer insulation (MLI)**
- **These three things happened during the 1940s to 1950s to enable the production of high efficiency storage vessels and apparatus:**
 - **Larger size vacuum-jacketed tanks**
 - **High vacuum level with longer retention life**
 - **Low heat flux insulation systems (from 10 to 100 times lower than evacuated perlite)**

Culmination in the 1950s

- During the same time frame, the Collins liquefier was invented.
- This refrigeration technology together with the new high efficiency cryogen storage technology enabled the explosion in liquid helium experimentation and hence research in superconducting applications.
- Number of labs with LHe capability:
15 in 1946
200+ in 1960

1960s – 1970s

- **Further development of MLI and getters/adsorbers led to higher thermal performance and longer life (vacuum)**
- **Development of vapor-cooled neck tubes for dewars**
- **Development of LN2 and then vapor-cooled shields led to large commercial tanks for world-wide shipping**

Radiation shields and MLI

Fig. 3.

INVENTOR
WILLIAM D. CORNELL
BY *John H. ...*
ATTORNEY

Fig. 2.

INVENTOR
LADISLAS C. MATSCH

BY *Kurt J. ...*
ATTORNEY

**Early cryogenic tank design
with multiple radiation shields**

MLI system concept

1980s – 1990s

- **Broader commercial production of piping, valves, and tanks for liquid helium.**
- **Proliferation of very large helium projects and machines.**

Future – part 1

- **Optimization of total system heat leakage rate: better thermal data and analysis tools.**
- **Improved support structures, feedthroughs, and piping penetrations (mechanical & thermal optimization)**
- **Instrumentation and knowledge of operational parameters employing wireless technology, non-intrusive sensors, fiber-optics, piezo-electric devices, environmental monitoring, and autonomous control software**

Future – part 2

- **Implementation of new materials and composites:**
 - **Robust and load-supporting MLI-based systems**
 - **Aerogel blankets**
 - **Aerogel/polymers composites (structures)**
 - **Polyimide foams (structures)**
 - **Glass bubbles and aerogel particles for bulk-fill (terminations & cold boxes)**
 - **Integral getters, adsorbers, and sensors (for better vacuum life!)**

Summary

Is,

‘Necessity is the mother of invention’, or,

‘Finding applications to the invention is the mother of creation for necessity’ ?

This is like...‘which came first, chicken or the egg?’
(does it matter?)

Onnes wrote in Paper 15 of his numerous communications,

“The fact that a pure metal can be brought to such condition that its electrical resistance becomes zero is certainly of itself of highest importance”

This experimental work was a significant discovery and led to many other developments of applications using this principle of the disappearance of electrical resistivity.

- this is a fundamental research philosophy

Summary (cont.)

Areas in need innovation for cryo systems

- Efficiency improvements
- Miniaturization
- Simplicity
- Cost reduction

The future use of low-temperature and HTS superconductivity applications is strongly tied to these!

Overall, much knowledge has been obtained by pushing on toward absolute zero over the last 100 years

Questions?