CEC Sessions

Tuesday, 07/17/07 Poster 9:00am - 10:30am

C1-B JT, Magnetic and Non-Aerospace Coolers

C1-B-01 Development of JT Coolers Operating at Cryogenic Temperatures with Non-Flammable Mixed Refrigerants

A.N. Khatri, *M. Boiarski, Advanced Research Systems. Inc..*

Throttle cycle coolers, operating with mixed refrigerants (MR) have been used in applications at temperatures down to 70 K. Industrial single-stage, oil lubricated compressor can be used to provide both a relatively low cost and long operational time. Application of nonflammable MR is important for safety, transportation, operation, service and maintenance. However, it is more difficult to provide a required refrigeration performance and long-term reliability due to properties of nonflammable MR.

The paper presents experimental and modeling data for single-stage coolers providing up to 10 W of refrigeration capacity. The selected nonflammable components to build the MR are commercially available.

A comparative experimental and modeling performance data is presented for both flammable and nonflammable MR. A gas refrigerant supply (GRS) technology is used for a single-stage cooler design. A minimal achievable temperature is restricted by the freezing point of MR. The GRS technology restricts a maximal refrigeration capacity. However, it allows to compromise between stable, long-term reliable operation and simplicity of equipment design with required refrigeration capacity.

Stability of operation of small-scale, highly reliable MR coolers has been proven by the data accumulated over long-term testing.

C1-B-02 Experimental Investigations on Mixed Refrigerant Joule-Thomson (MR J-T) Cryocooler

N.S. Walimbe, ***M.D. Atrey****, Indian Institute of Technology Bombay, Mumbai,India; K.G. Narayankhedkar, Veermata Jijabai Technological Institute, Mumbai,India.*

Mixed Refrigerant Joule Thomson (MR J-T) cryoocoolers have obvious advantages, such as low cost, high reliability, higher cooling effect at 80 K, low vibrations and simplicity in design layout. As a result of this, their use for different applications has become a major threat to conventional cryocoolers.

The performance of the MR J-T cryocooler, in terms of cooling power at low temperatures, depends significantly on the components of the gas mixture and their concentration. An experimental set up has been developed in our laboratory to analyse various gas mixtures. An efficient counter flow heat exchanger, Hampson type, has been fabricated and tested in the set up. The present paper gives experimental results for various gas mixtures so as to get maximum cooling effect for a given temperature. The paper also presents the effect of working pressure of the optimized gas mixture on the performance of the cooler.

C1-B-03 Performance of a mixed refrigerant Nitrogen gas cooler

M. Siva Sankar*, G. Venkatarathnam, Indian Institute of Technology Madras.*

Mixed refrigerant processes are widely used for the liquefaction of natural gas. J-T cryocoolers operating with refrigerant mixtures are also being developed worldwide. Mixed refrigerant processes can also be used for the liquefaction of air, nitrogen etc. A number of patents have been granted on the liquefaction of nitrogen using non flammable mixtures recently. Two large commercial mixed refrigerant precooled air separation plants have also been tested recently [1]. Nitrogen gas coolers operating with mixtures of nitrogen, methane, ethane, propane etc. are under development in our laboratory.

In this paper we describe the performance of our prototype nitrogen gas cooler. The system comprises of a pre-cooling circuit and a mixed refrigerant circuit. Tests have been carried out with different nitrogen flow rates, different refrigerant mixtures and heat exchangers. In the current prototype, nitrogen can be cooled from room temperature to about 105 K at a flow rate of 0.1 g/s. The power input to the system is about 1200 W. The performance of our system and comparison between experimental results and simulations are also presented.

References

1) Bonaquist, D..P., Prosser, N.M., and Arman, B. (2003). Advances in refrigeration for air separation --- using mixed refrigerant cycles toreduce cost and improve efficiency, Paper ICR0524, Proceedings of the International Congress of Refrigeration 2003, Washington D.C., p 1-7.

C1-B-04 Pressure drop and heat transfer characteristics in a helical tube of Joule Thomson refrigerator

Y-J. Hong*, S-J. Park, Korea Institute of Machinery & Materials; Y-D. Choi, Korea University.*

The thermodynamic performance of a miniature Joule Thomson refrigerator is highly depends on the hydraulic and heat transfer characteristics of the recuperative heat exchanger. The typical recuperative heat exchanger has the double helical tube and fin configuration. The incoming high-pressure gas enters a helical tube, and expands to the cold end of the refrigerator. After the Joule-Thomson expansion, the cold gas exhausts through a complex passage that is enveloped by the double helical tube and fin, mandrel and inner surface of the Dewar. The present study focuses on the pressure drop and heat transfer characteristics in the helical tube. In general way, the curvature ratio of the helical tube has substantial influences on the pressure drop and heat transfer characteristics. In this study, the heat and fluid flow is studied numerically on the high pressure gas in a helical tube. To account for the thermodynamic properties of the high pressure gas, the real gas model as a function of pressure and temperature was used. The effects of the mass flow rate, heat flux, pitch of the tubes and curvature ratio were studied by commercial CFD packages.

C1-B-05 A Study of Active Magnetic Regeneration using Permanent Magnets

S. Kito*, K. Kamiya, H. Nakagome, S. Uchimoto, Chiba University; T. Kobayashi, A. Takahashi Saito, S. Kaji, Toshiba Corporation.*

In recent years, magnetic refrigeration techniques based on the magnetocaloric effect attracts attention from a viewpoint of earth environment protection, because the magnetic refrigeration is technology with little environmental load in order not to use chlorofluorocarbons. Especially, a new type of refrigeration cycle, the active magnetic regenerator (AMR) cycle, is suitable for a room temperature region, and the AMR cycle is expected to attain high efficiency.

We developed a room temperature magnetic refrigerator with permanent magnets, and operated the AMR cycle by using Gd and Gd-R alloys for the magnetic refrigerant. The AMR cycle with changing in the magnetic field and a movement of the heat transfer fluid was operated for various parameters such as cycle frequency, amount of the heat transfer fluid movement, etc.

In this report, we will show the result of the observing temperatures span (- Tmax) between hot end and cold end in the heat exchanger while the AMR cycle operation and the temperature gradient of magnetic refrigerant in the heat exchanger, in which several thermocouples were inserted. - Tmax is depending on cycle frequency of the AMR. Moreover, a numerical analysis of the AMR cycle was performed in order to investigate the correspondence to the experimental result. It was revealed that - Tmax increased with the cycle frequency, and almost agreed to the calculation result.

C1-B-06 Magnetocaloric Effect of Sintered GGG

***D.L. Kim**, B.S. Lee, Y.S. Choi, H.S. Yang, Korea Basic Science Institute; S.H. Yeom, Chungnam National University; J.H. Park, Korea Astronomy & Space Science Institute.*

Magnetic cooling is one of the effective method to get low temperature without cryogen.
GGG is a good candidate material to reach ~1K after precooled by cryocooler. GGG sample is made by sintering the granular type of GGG. The sample is tested the magneto-caloric effect in various magnetic field and temperature conditions with PPMS that has a 9T superconducting magnet and minimum temperature of 1.5K. The results of the magnetocaloric experiments are presented.

C1-B-07 Scaling of thermoacoustic refrigerators

*Y. Li, J.C.H. Zeegers, **H.J.M. ter Brake**, Eindhoven University of Technology.*

Thermoacoustic refrigerators pump heat from a low-temperature source to a high-temperature sink using acoustics. Their simplicity leads to high reliability and low cost, which is attractive for practical applications. However, very large dimensions are common for thermoacoustic machines of order 10 m. In the paper, the possibility of scaling-down thermoacoustc refrigerators is investigated via theoretical analysis. Standing-wave systems are considered as well as travelling-wave. In the case of standing-wave refrigerators, a reference system is taken that consists of a resonator tube (25 cm) with a closed end and a PVC stack (length 5 cm). Helium is used at a mean pressure of 1 bar and an amplitude of 0.1 bar. The resulting operating frequency is 1 kHz. The variation of the performance of the refrigerator when scaled down is computed under the prerequisites that the temperature difference over the stack or energy flux or energy flux density are fixed. The analytical results show, as expected, that there is a limitation for scaling-down of a standing-wave thermoacoustic refrigerator due to heat conduction. In the paper, trends are discussed as well as means to widen the scaling range. Furthermore, similar scaling trends are considered in travelling-wave refrigerators, again with thermal conductance forming a practical limitation.

C1-B-08 Performance improvement of a single stage GM cryocooler at 25 K

***C. Wang**, P.E. Gifford, Cryomech, Inc..*

Some HTS applications, such as motor and generator, require large cooling capacity at 25-27 K. Cryomech, Inc. has redesigned and improved a single stage GM cryocooler, model AL330, to have maximum capacity at 25K. The losses for the low temperature single stage GM have been analyzed. In the new design, the losses associated with rotary valve, shuttle heat transfer, seals and regenerator, have been reduced. A 10 kW compressor, model CP1010, is employed for the new designed single stage GM cryocooler, model AL325. The AL325 reaches the bottom temperature of 10 K and provides a cooling capacity of >100W@25K.

C1-B-09 Experimental study on the double-evaporator thermosiphon for cooling HTS (High Temperature Superconductor) system

***J. Lee**, Y. Kim, S. Jeong, KAIST.*

Cryogenic thermosiphons are highly efficient heat transfer elements between a cryocooler and the thermal load that is to be cooled. This paper presents an idea of thermosiphon that peculiarly utilizes two evaporators to satisfy spatial restriction. The single condenser that is made of copper with the inner diameter of 42 mm is cooled by a GM cryocooler and the fallen liquid film from the condenser stays at the evaporator 1 (the upper evaporator). As the liquid pool of the evaporator 1 is full to its brim, the liquid film goes down from the evaporator 1 to the evaporator 2 (the lower evaporator). In the experiment, these copper evaporators are electrically heated to simulate their realistic cooling load conditions for the HTS (High Temperature Superconductor) system. The double-evaporator thermosiphon is to be used for cooling two HTS bulk parts that are separated vertically. Since nitrogen is the proper working fluid of the thermosiphon in this application, we selected the operating temperature and pressure as 70 K and 38.5 kPa respectively. We report the experimental results of this sub-atmospherically operating thermosiphon by analyzing its dynamic performance with existing theories. The innovation can probably provide a simple and compact cooling solution to the HTS system.

This work was supported by ETEP (Electric Power Technology Evaluation and Plannig) and KOSEF (Korea Science and Engineering Foundation)

C1-B-10 Stirling-Type Pulse Tube Cryocooler with 1kW of Refrigeration at 77K

*S.A. Potratz, **T.D. Abbott**, K.B. Albaugh, M.C. Johnson, Praxair, Inc.*

A large capacity Stirling-type pulse tube cryocooler has been successfully developed by Praxair, Inc. Performance testing of prototype and initial production models of the pulse tube coldhead has demonstrated a refrigeration capacity of 1kW at 77K when a 20kW, dual-opposed pressure wave generator from CFIC, Inc. is used to generate acoustic power for the cryocooler. These results were obtained through multiple experiments utilizing gas liquefaction and direct nitrogen subcooling test methods. The coldhead design incorporates sophisticated geometry to successfully minimize streaming and other loss mechanisms that have reduced the performance of other large pulse tube cryocooler designs. These cryocoolers are intended for application in the HTS (High Temperature Superconductivity) market. The initial production models of this pulse tube refrigerator will be deployed for field testing at an operating HTS cable installation in Columbus, Ohio where their reliability and performance will be measured.

C1-C Fluid Mechanics - I

C1-C-01 Gravitational Capillary Viscometer for Subcooled Liquid Para-Hydrogen*

*M. Gnos, Y.K. Kim, **D.K. Hilton**, S.W. Van Sciver, NHMFL/FSU.*

A pressurized gravitational capillary viscometer was developed for subcooled low-temperature liquids, necessary for aerospace engineering. It acquires accurate absolute dynamic viscosity measurements with an uncertainty of 1% at a 95.5% confidence level, in the pressure domain from 0.15 MPa to 1.0 MPa, and in the temperature domain from the normal boiling point to near the freezing point. It has been modified by the addition of a two-stage ortho- to para-hydrogen converter. The converter uses a heat-treated, iron hydroxide powder catalyst, 25 g in the precooling first stage, and 1350 g in the second stage that is thermally connected with the viscometer cell. The conversion is monitored with a calibrated platinum thermometer. Dynamic viscosity measurements for subcooled liquid para-hydrogen are presented.

**Research supported by NASA Grant NAG 3-2751.*

C1-C-02 PIV Measurement of Slush Nitrogen Flow in Pipe Part II

***M Maeda**, M Murakami, T Takakoshi, University of Tsukuba; M Ikeuchi, R Ono, K Matsuo, MAYEKAWA MFG. CO., LTD..*

The use of slush nitrogen as a refrigerant for high-temperature superconductive power cable is considered to lead to further improvement in refrigerant capability. As the realization of a stable flow of slush nitrogen is a key technology for the application, the detailed investigation of flow characteristics is very important. This study primarily focuses on the measurement of the nitrogen particle velocity distribution in a circular test section. The application of PIV to the slush nitrogen flow in a pipe was initiated two years ago. In the previous study, the velocity in the boundary layer region could not be clearly resolved. In this experiment, some improvements were made with respect to the inner diameter and the cross sectional form of the test section to avoid the optical refraction effect for imaging. As a result, the velocity distribution even in the boundary layer of the test section could be fairly well resolved, and thus the whole solid particle velocity distribution throughout the cross section could be obtained. Furthermore, the application of minute particles of H2O instead of solid nitrogen is pursued for more systematic parametric study. The control of particle parameters of H2O is much more easily made, and the dynamic range of H2O particle parameters is wider than solid nitrogen particles.

C1-C-03 Natural Circulation Loop of Subcooled Liquid Nitrogen

***M.J. Kim**, H.M. Chang, Hong Ik University.*

An experimental study is performed to investigate the thermal and flow characteristics of subcooled liquid nitrogen in a natural circulation loop. This study is directed to a simple cryocooling system for small load HTS power applications, where a cryocooler should be installed on a separate cryostat and liquid nitrogen is circulated between the main and auxiliary cryostats. An experimental apparatus is designed and constructed such that a test loop made of circular tube with a uniform diameter is cooled at the top by a cryocooler and heated nearly at the bottom by cartridge heaters . Steady state is obtained by controlling the heating power to the cartridge heaters and a thin-film heater to reduce the cooling power of the cryocooler. Temperature is measured at several locations of the loop and the mass flow rate through the loop is estimated from the energy balance in terms of the measured temperatures. Experiment is repeated for various values of vertical height between the cooling and heating parts. The results show that the heat transfer capability of the loop has a maximum at a certain value of height. The optimal height to maximize the heat transfer is in a good agreement with our analytical prediction to take into account the buoyancy and viscous forces in the loop tube.

This work is supported by the research funds from the Center for Applied Superconductivity Technology under the 21C Frontier R&D Program in Korea.

C1-C-04 Pressure Drop Reduction of Slush Nitrogen in Turbulent Pipe Flows

***K. Ohira**, Institute of Fluid Science, Tohoku University ; N. Koizumi, Tohoku University; J. Ishimoto, Institute of Fluid Science, Tohoku University; T. Kamiya, Mitsubishi Heavy Industries, Ltd..*

Slush fluid such as slush hydrogen and slush nitrogen is a two-phase (solid-liquid) single-component cryogenic fluid containing solid particles in liquid, so that its density and cooling capacity increase compared with liquid state fluid. In this study, the experimental tests were performed with slush nitrogen (63 K) to obtain the frictional pressure drop characteristics flowing in a 15 mm internal diameter, 625 mm long, horizontal, stainless steel pipe. The primary objective of this study is to investigate the pressure drop reduction phenomenon with the changes of the velocity and the solid fraction. From the experimental results, the pressure drop correlation between the friction factor and Reynolds number was obtained and an empirical equation was derived. Flow patterns and behaviors of solid particles were also observed by a high speed camera.

C1-C-05 Numerical analysis of LN2 flow and thermal transfer in inner pipe of DC-SC power transmission line

***A. Sasaki**, M. Hamabe, T. Famakinwa, S. Yamaguchi, Chubu University; A. Radovinsky, Massachusetts Institute of Technology; H. Okumura, Mie University; M. Emoto, T. Toyota, National Institute for Fusion Science.*

Computational fluid dynamics (CFD) and theoretical analysis are conducted for fundamental designs of the circulation of liquid nitrogen (LN2) as a coolant in SC power cables.
The pressure drop of bellows and corrugate inner pipes may be higher than that of straight pipes. Since surface areas of the bellows and corrugate pipes are wider than that of the straight pipes, the heat leakage of the straight pipes by radiation will be lower those of the bellows and corrugate pipes. Therefore, our design of DC-SC power transmission line uses the straight pipe for one HTS cable.
CFD analysis is powerful to obtain the optimum design of the straight pipe, however this can't be applied for long distance pipes because of the limit of computer memories and CPU power. Hence, theoretical analysis is also important to fix the design of the longer pipes. In this paper, we describe the method of CFD and the analytical model to get the optimum designs of the longer pipe.

This work is supported in part by "University-Industry Research Project for Private Universities matching fund" by subsidy from MEXT, Japan, 2005-2009.

C1-D Pulse Tube Cryocoolers (Non-Aerospace)

C1-D-01 Single-stage Coaxial GM type Pulse Tube Refrigerators Below 20K

*B.Y. Du, **L.W. Yang**, J.H. Cai, J.T. Liang, Technical Institute of Physics and Chemistry, Chinese Academic of Sciences.*

Pulse tube refrigerators have demonstrated many advantages with respect to temperature stability, vibration, reliability and lifetime among cryocoolers. Double-inlet type pulse tube refrigerators are popular in GM type pulse tube refrigerators.
Experiments and numerical simulations are carried on to investigate the double-inlet characters GM type pulse tube refrigerators. Two parallel-placed needle valves with opposite flow direction named double-valve configuration, instead of single double-inlet valve, are used in our experiment to reduce the DC flow.The lowest cold end temperature of 18K has been obtained while the refrigerator is driven by compressor of 6 kW power. Moreover, a numerical model is made to analyze the characters of double-inlet refrigerators. The simulation results show the temperature field and velocity field of pulse tube with and without the double-inlet.

C1-D-02 Numerical simulation of Double-inlet GM type Pulse Tube Refrigerators

*B.Y. Du, **L.W. Yang**, J.H. Cai, J.T. Liang, Technical Institute of Physics and Chemistry, Chinese Academic of Sciences.*

Pulse tube refrigerators have demonstrated many advantages with respect to temperature stability, vibration, reliability and lifetime among cryocoolers. Double-inlet type pulse tube refrigerators are popular in GM type pulse tube refrigerators. The mass flow rate through the double-inlet is caused by the pressure drop through the regenerator, which improves the performance of pulse tube refrigerator. However, single double-inlet valve may introduce DC flow in refrigerator, which deteriorates the performance of pulse tube refrigerator, so it is crucial to control the DC flow.
Experiments and numerical simulations are carried on to investigate the double-inlet characters GM type pulse tube refrigerators. Two parallel-placed needle valves with opposite flow direction named double-valve configuration, instead of single double-inlet valve, are used in our experiment to reduce the DC flow.The lowest cold end temperature of 18K has been obtained while the refrigerator is driven by compressor of 6 kW power. Moreover, a numerical model is made to analyze the characters of double-inlet refrigerators. The simulation results show the temperature field and velocity field of pulse tube with and without the double-inlet.

Double-inlet is a key factor for a double-inlet type pulse tube refrigerators. It is important to understand the characters of double-inlet. Deep research on characters of double-inlet will be very helpful to reveal the mechanics of pulse tube refrigerator.
This work is supported by Natural Sciences Foundation of China (50206025).

C1-D-03 Experimental Studies on a Two-Stage Pulse Tube Cryocooler Reaching 3.3 K
***S. Kasthurirengan**, G. Srinivasa, G.S. Karthik, Centre for Cryogenic Technology, Dept. of Physics, Indian Institute of Science; K.P. Ramesh, Dept. of Physics, Indian Institute of Science; K.A. Shafi, TKM College of Engineering, Kollam, Kerala, India.*
A two stage Pulse Tube Cryocooler is designed and fabricated, which reaches no load temperatures of 3.3 K in the second stage and ~60 K in the first stage respectively. The system provides a refrigeration power of ~ 250mW at 5 K in the second stage. Stainless steel meshes (size 200) and lead (Pb) granules are used as first stage regenerator materials and combinations of Pb with Er_3Ni or Pb with $HoCu_2$ are used as second stage regenerator materials. The system operates at 1.8 Hz using an indigenous rotary valve along with a 6 kW water-cooled Helium compressor.
Studies conducted by varying the dimensions of Pulse Tubes and regenerators for the first and second stages show that pulse tube dimensions are more critical to the performance of the Cryocooler than those of the regenerators. Experimental studies show that the optimum volume ratio of Pb to Er_3Ni or $HoCu_2$ (in the second stage) should be ~ 3:2 for the best performance of the Cryocooler. Further, systems with $HoCu_2$ performed better than those with Er_3Ni. Pulse Tube Cryocoolers performed better when operated with anti-parallel double inlet valves than when operated with other DC flow arrangements.
Theoretical analysis of the above two-stage Pulse Tube Cryocooler system has been carried out using a simple isothermal model. The experimentally measured cooling powers are in close agreement with the theoretical predictions.
Financial support for the study has come from the Council of Scientific and Industrial Research, New Delhi, India.

C1-D-04 A buffered rotary valve system of GM-type pulse tube refrigerator
***G. Hwang**, J. Jung, S. Jeong, KAIST.*
In a GM or a GM-type PTR (Pulse Tube Refrigerator), considerable amount of helium flow is produced during the pressure transition periods from high to low values or vice versa. In a conventional rotary valve system, however, this kind of helium in- and out-flow which are supplied directly from the helium compressor does not contribute to the actual refrigeration power. We devised a buffered rotary valve system in order to reduce such an unnecessary helium flow from the compressor. In a buffered rotary valve system, pressurizing and depressurizing flow is not solely supplied by the compressor but also provided by a buffer volume. Theoretically, half of the transition flow can be alleviated in the compressor with a single buffer. The aim of the buffered rotary valve system is to use a compressor more effectively and make the expansion process in PTR more efficient. In this paper, the buffered rotary valve system is introduced at the first time, fully described with simple thermodynamic analysis, and also investigated experimentally to show its performance increase.
This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

C1-D-05 An experimental study of the G-M type two-Stage Pulse Tube Cryocooler for cryopump
***S.J. Park**, Y.J. Hong, H.B. Kim, Korea Institute of Machinery & Materials; S.J. Lee, Hyunmin Laboratory.*
The pulse tube cryocooler, which has no moving parts at its cold section, is attractive in obtaining higher reliability, simpler construction, and lower vibration than any other small cryocoolers. Korea Institute of Machinery & Materials(KIMM) has developed G-M type and Stirling type pulse tube cryocooler since 1992. The developments in KIMM on the pulse tube cryocooler systems have focused primarily on refrigeration capacity, efficiency and performance reliability as well as mechanical reliability. The purpose of this study is to provide reliable, efficient and long life cryocoolers for cooling systems in cryopump and other applications. The G-M type two-stage pulse tube cryocooler consists of a helium compressor, a pulse tube, regenerator, orifice, double inlet valve, a buffer (reservoir) volume and vacuum chamber. This paper describes the two-stage pulse tube cryocoolers designed for cooling arrays of the cryopump and their performance characteristics.

C1-D-06 Optimization of two stage pulse tube refrigerator for the integrated current lead system
***R. Maekawa**, S. Takami, A. Okada, T. Mito, National Institute for Fusion Science; Y. Matsubara, KEK; M. Konno, Fuji Electric Systems Co.; A. Tomioka, Fuji Electric Advanced Technology Co.; T. Imayoshi, H. Hayashi, Kyusyu Electric Power Co..*
The integrated current lead system, consists of a copper lead, a High Temperature Superconductor and two stage pulse tube refrigerator, has been developed for Superconducting Magnetic Energy Storage (SMES) system. A two-stage pulse tube refrigerator, series connected arrangement, was designed to satisfy the requirements for the integrated current lead system. Operation of the first stage refrigerator is four-valve method, while the second stage utilizes a double inlet method. This arrangement ensures the compactness of the current lead system. Refrigeration process of two-stage pulse tube refrigerator has been investigated to validate the conceptual design and finalize the current lead system development.
This work is supported by the NEDO under the contract of "Superconducting Power Network Control Technology Development" and by NIFS under ULAA114. The authors wish to acknowlege H. Ohkubo at Suzuki Shokan Co. for his support.

C1-D-07 Damping of Intrinsic Temperature Oscillations in a 4 K Pulse Tube Cooler by Means of Rare Earth Plates
*G. Thummes, L.M. Qiu, M. Dietrich, **K. Allweins**, University of Giessen.*
Regenerative cryocoolers, such as GM-coolers and pulse tube coolers, show oscillations of the refrigeration temperature that result from the periodic expansion of the working fluid (helium). In case of cryogen-free operation of sensitive superconducting devices the temperature oscillations can be rather disturbing because of the associated variation of the critical current and gap voltage. The oscillations can be damped by increasing the thermal mass attached to the cold end of the cooler. For cooling near 4 K it is impractical to employ normal metals for this purpose as in this case the specific heat of helium greatly exceeds that of normal metals. Here we report on the damping of temperature oscillations by making use of the high specific heat of rare-earth alloys, such as ErNi. Tests were performed on two types of in-house made 4 K pulse tube coolers with input powers of 6 kW and 1.7 kW. The damping is accomplished by ErNi-plates of different thickness that were installed between the cold end of the 4 K stage and the device mounting platform. E.g., with a 3.6 mm thick ErNi-plate (mass: 55 g) the temperature oscillation at 3.5 K was reduced by a factor of 18 from 90 mK to 5 mK in the 1.7 kW-system. The thermal resistance of the plate was 9 K/W, which was sufficiently low to successfully operate an AC Josephson voltage standard near 4 K by this set-up.
This work has been supported in part by the German BMBF (FKZ 13N8410). L.M. Qiu (permanent address: Zhejiang University, Hangzhou 310027, P.R. China) thanks the DAAD for a fellowship.

C1-E Superconducting RF Cavities and Cryosystems - I

C1-E-01 Superconducting Radiofrequency Separator Cryogenic System

*A. Ageyev, **S. Kozub**, A. Orlov, S. Zintchenko, Institute for High Energy Physics.*

Institute for High Energy Physics (Protvino, Russia) develops new channel of U-70 accelerator. Important part of the channel is RF superconducting kaon separator which consists of two niobium cavities cooled by superfluid helium at 1.8 K. The cryogenic and vacuum system description, test results and planned improvements are presented.

C1-E-02 Compact He II cooling system for superconducting cavities

***T. Kuriyama**, M. Takahashi, N. Kakutani, T. Ota, K. Nakayama, Toshiba Corporation; E. Kako, S. Noguchi, M. Ono, K. Saito, S. Shishido, Y. Yamazaki, KEK, High Energy Accelerator Research Organization.*

The paper describes a compact He II cooling system for superconducting cavities. The cooling system is mainly comprised of a vacuum vessel, 77K liquid nitrogen bath, a He I bath, a He II bath, a evacuation pump, a single stage GM cryocooler for 77K bath and a 4 K GM cryocooler. Superfluid helium is generated and refilled in the HeII bath via a heat exchanger and a JT valve by operating the evacuation pump. The refrigeration capacity attained was more than 10 W @ 1.8 K. The cooling system was connected with a single cavity vessel and a circulation loop. A superconducting cavity was immersed in the vessel. He II was supplied to the cavity vessel from the cooling system and evaporated helium gas was returned to it. The high electric field was successfully obtained by the superconducting cavity operation.

C1-E-03 Superconducting Radio-Frequency Modules Test Facility Operating Experience

***A. Klebaner**, R. Bossert, B. DeGraff, C. Darve, A. Martinez, L. Pei, W. Soyars, J.C. Theilacker, Fermilab.*

Fermilab is heavily engaged and making strong technical contributions to the superconducting radio-frequency research and development program (SCRF R&D). Four major SCRF test areas are being constructed to enable vertical and horizontal cavity testing, as well as cryomodule testing. The existing Fermilab cryogenic infrastructure has been modified to service Fermilab SCRF R&D needs. The first stage of the project has been successfully completed, which allows for distribution of cryogens for a single cavity cryomodule using the existing Cryogenic Test Facility (CTF) that houses three Tevatron satellite refrigerators. The cooling capacity available for cryomodule testing at MDB results from the liquefaction capacity of CTF cryogenic system. The cryogenic system for a single 9-cell cryomodule is currently operational. The paper describes the status, challenges and operational experience of the initial phase of the project.

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C1-E-04 Microwave response of a cylindrical cavity made of bulk MgB2 superconductor

*A. Agliolo Gallitto, G. Bonsignore, M. Bonura, M. Li Vigni, University of Palermo, Dipartimento di Scienze Fisiche e Astronomiche; **G. Giunchi**, EDISON SpA R & D; Yu. A. Nefyodiv, Institute of Solid State Physics, RAS.*

We report on the microwave properties of a resonant cylindrical cavity made of bulk MgB_2 superconductor, produced by Reactive Liquid Mg Infiltration process [1]. The resonant cavity has been characterized by measuring its frequency response in the range 5 – 13 GHz by an hp-8719D Network Analyzer. Among the various modes, two of them have shown the highest quality factors; they correspond to the TE_011 and TE_012 modes. At room temperature, and with the cavity filled by helium gas, the resonant frequencies of these modes are f_011 = 9.79 GHz and f_012 = 11.54 GHz. At T=4.2 K, without liquid helium inside the cavity, the unloaded quality factors are Q_011 = 220000 and Q_012 = 190000; both maintain values of the order of 100000 up to about 30 K and decrease by a factor 20 when the superconductor goes to the normal state (at T=38.5 K) [2]. The values of the surface resistance at 9.79 GHz as a function of the temperature, deduced from the Q measurements, agree quite well with those independently measured, by the hot-finger cavity perturbation at 9.4 GHz, in a small sample of MgB_2 extracted from the same specimen from which the cavity has been obtained.

[1] G. Giunchi, G. Ripamonti, T. Cavallin, E. Bassani, Cryogenics 46 (2006) 237.
[2] G. Giunchi, A. Agliolo Gallitto, G. Bonsignore, M. Bonura, M. Li Vigni, submitted to Supercond. Sci.Technol., cond-mat/0612159.

C1-E-05 Simulation of the impact of the Kapitza resistance at grain-grain boundaries on Niobium superconducting cavities

***J. Amrit**, Q. Li, LIMSI - CNRS.*

We examine the influence of the Kapitza resistance at grain-grain boundaries on the thermal behaviour of superconducting cavities made of polycrystalline Niobium. Calculations are performed for different grain sizes. The results indicate that a non-uniform size distribution of grains leads to an inhomogeneous temperature repartition in the cavity walls. Also, the importance of the grain-grain Kapitza resistance, compared to the Kapitza resistance at the niobium/helium interface, is revealed for the first time.

C1-F Thermal Insulation Systems - I

C1-F-01 Design Tool for Cryogenic Thermal Insulation Systems

***J.A. Demko**, Oak Ridge National Laboratory; J.E. Fesmire, NASA Kennedy Space Center; S.D. Augustynowicz, Sierra Lobo Inc..*

Thermal isolation of low temperature systems from ambient is a constant issue faced by practitioners of cryogenics. For energy-efficient systems and processes to be realized, thermal insulation must be considered as an integrated system, not merely an add-on element. A design tool to determine the performance of insulation systems for comparative trade-off studies of different available material options was developed. The approach is to apply thermal analysis to standard shapes (plane walls, cylinders, spheres) that are relatively simple to characterize with a one dimensional analytical or numerical model. The user describes the system hot and cold boundary geometry and the operating environment. Basic outputs such as heat load and temperature profiles are determined. The user can select from a built-in insulation material database or input user defined materials. Existing information combined with the new experimental thermal conductivity data produced by the Cryogenics Test Laboratory for cryogenic and vacuum environments, including high vacuum, soft vacuum, and no vacuum, is planned for incorporation. Materials include multilayer insulation, aerogel blankets, aerogel bulk-fill, foams, powders, composites, and other constructions. Results of the design tool are provided for some sample applications.

Funding was provided by the NASA Space Operations Mission Directorate under the Internal Research and Development project Technologies to Increase Reliability of Thermal Insulation Systems.

C1-F-02 Cryogenic Thermal Performance Testing of Bulk-Fill and Aerogel Insulation Materials

***B.E. Scholtens**, J.E. Fesmire, J.P. Sass, NASA KSC; S.D. Augustynowicz, K.W. Heckle, Sierra Lobo, Inc.*

The research testing and demonstration of new bulk-fill materials for cryogenic thermal insulation systems was performed by the Cryogenics Test Laboratory at NASA Kennedy Space Center. Thermal conductivity testing under actual-use cryogenic conditions is a key to understanding the total system performance encompassing engineering, economics, and materials factors. A number of bulk fill insulation materials, including aerogel beads, glass bubbles, and perlite powder, were tested using a new cylindrical cryostat. Boundary temperatures for the liquid nitrogen boil-off method were typically 293 K and 77 K. Tests were performed as a function of vacuum pressure level from high vacuum to no vacuum conditions. Results are compared with other complementary test methods in the range of 300 K to 10 K. Various testing techniques are shown to be required to obtain a complete understanding of the operating performance of a material and to establish a basis for answers to design engineering questions.

C1-F-03 Multilauer Insulation for Atlas

***S. Kozub**, K. Polkovnikov, A. Hartchenko, Institute for High Energy Physics.*

Multilayer insulation consists of aluminized mylar and mylar cloth spacer for ATLAS (LHC) was manufactured and tested at Institute for High Energy Physics (Protvino, Russia). The paper presents description of facility for the multilayer insulation test as well as results of gassing in vacuum rate and heat leakage measurements for the insulation.

C1-F-04 Testing of a Vacuum Insulated Flexible Line With Flowing Liquid Nitrogen During the Loss of Insulating Vacuum

***J.A. Demko**, M.J. Gouge, R.C. Duckworth, Oak Ridge National Laboratory; M. Roden, Southwire Co..*

Long length vacuum insulated lines are used to carry flowing liquid nitrogen in several high temperature superconducting cable projects. An important, but rare, failure scenario is the abrupt or catastrophic loss of the thermal insulating vacuum producing a rapid increase in heat transfer to the liquid nitrogen stream. In this investigation, a vacuum superinsulated 3 inch by 5 inch NPS is subjected to an abrupt loss of vacuum in order to measure the response of a flowing liquid nitrogen stream and the temperature response of the cryostat. The measured outlet stream temperature has a slight peak shortly after the loss of vacuum incident and drops to a steady state value. The heat loads measured before and after the vacuum loss event are reported. Some measurements of the temperatures in the multi-layer superinsulation are also discussed.

Research sponsored by the U.S. Department of Energy - Office of Electricity Delivery and Energy Reliability, Superconductivity Program for Electric Power Systems under contract DE-AC05-00OR22725 with Oak Ridge National Laboratory, managed and operated by UT-Battelle, LLC.

C1-F-05 Radiation heat measurement on thermally isolated double-pipe for DC superconducting power transmission

***M. Hamabe**, S. Yamaguchi, Chubu University; A. Ninomiya, Seikei University; Y. Ishiguro, S. Kusaka, JFE Steel Corporation.*

Multilayer insulation (MLI) is a strong tool to reduce the radiation heat and is widely used for the cryogenic systems. However, the use of the MLI leads to a huge increase of the surface area in vacuum; it takes extremely long time to reach a satisfactory vacuum for the thermal isolation, or the nitrogen gas flushing is needed several times. We have started the experiment by using the test bench of the DC superconducting (DC-SC) power cable in Chubu University. Since the DC-SC power cable is free from the AC losses, the acceptable radiation heat can be higher for this cable than the AC-SC power cable. Therefore, we are studying the possibility of the radiation shield without the MLI. The vacuum pumping process and the radiation heat are measured for the thermally isolated double-pipes (of the same size as those for the DC-SC PT cable) with the various surfaces. While the radiation heat for the liquid-nitrogen-filled double-pipe with the MLI radiation shield was 1/100 of that with the bare stainless steel surface, the reachable vacuum pressure with the MLI was 10 times poorer than that with the bare surface. We will also discuss a novel and convenient radiation shielding method for the different surface processes in this work.

C1-F-06 Low temperature heat transfer properties of electrical insulation for the Next European Dipole

***J. Polinski**, B. Baudouy, CEA Saclay; S. Canfer, G. Ellwood, RAL.*

The heat transfer properties of the electrical multilayer insulations of the Next European dipole has been tested under various conditions at low temperature. The electrical insulation is made of E-glass fibre with a plain weave and RAL epoxy system 227 (DGEBF epoxy resin and DETD aromatic hardener). The samples have been tested in superfluid helium where heat is applied perpendicularly to the fibres between 1.6 K to 2.1 K and their thermal conductivity, longitudinal to the fibres, had been also measured at low temperature below 77 K.

This work was supported in part by the European Community–Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395).

C1-F-07 Flexible Aerogel Composites for Cryogenic Insulation

*R. Trifu, R. Begag, G. Gould, O. Evans, **S. White**, Aspen Aerogels, Inc..*

Low-density, flexible aerogel composites offer a variety of performance advantages over other insulation materials for cryogenic insulation applications, particularly Multi-Layer Insulation (MLI). These advantages include reduced weight, increased durability, lower total costs, and dramatic improvements in lead-times required for fabrication / installation of the insulation with equal thermal performance. Additionally, large error bars often associated with the thermal modeling of MLI can be eliminated with the use of aerogel composites. These low density aerogel composites have been found to be compatible with sensitive space sensors. Outgassing data along with encapsulation concepts for the aerogel composites will be discussed. A 'higher' density aerogel composite for insulating liquid oxygen transfer lines and storage containers will also be presented.

Tuesday, 07/17/07 Oral
10:30am - 12:00pm

C1-G He II Transfer and Fluid Mechanics - I

C1-G-01 PIV Measurement Result of Superfluid He II Thermal Counterflow Jet

***M. Murakami**, T. Takakoshi, University of Tsukuba.*

We have attempted the application of PIV (Particle Image Velocimetry) technique to the measurement of superfluid helium thermo-fluid dynamic phenomena. Micro solid H-D particles were used as tracer particles that are nearly neutrally buoyant in superfluid helium. We have succeeded in the production of neutrally buoyant H-D particles with adequate particle size distribution and number density in He II for PIV measurements in the temperature range between 1.80 K and 2.17 K that is wider than that in our previous PIV experiment. The thermal counter flow jet that flows out from the straight jet nozzle into an open quiescent He II space is measured by applying the PIV technique with the image data analysis based on the cross-correlation method. Two-dimensional velocity field on a plane including the jet axis is obtained in the downstream jet region including the vicinity of the jet nozzle exit. The data are averaged to extract the mean velocity distribution. We obtained some systematic data on the spatial variation of the distribution of the average axial velocity component, and on the temperature dependence of the axial velocity near the jet exit in that temperature range. The dependency of the data on the temperature and the heat flux is compared with both the theoretical prediction and the previous LDV (Laser Doppler Velocimeter) measurement data.

C1-G-02 PIV measurements of He II flow in a horizontal channel

***T. Xu**, S.W. Van Sciver, National High Magnetic Field Laboratory, Florida State University.*

He II single phase forced flow and thermal counterflow in a horizontal channel have been investigated using the Particle Image Velocimetry (PIV) technique. The experimental channel used in this research is 3.5 meter long with a 20 mm X 20 mm square shape cross-section. We use solid H2, D2 and solid H2/D2 particles as tracers for the PIV measurements. The tracer particles are generated during the experiment by freezing the injected seeding gas in the channel. We measure the velocity field of He II in both flows. The results are compared with theoretical calculations. The effect of the different type of particles on the PIV measurements is also discussed in this paper.

This work is supported by U.S. Department of Energy-Division of High Energy Physics.

C1-G-03 Visualization study of phase transition caused by heating of He II in two-dimensional narrow channel

***S. Takada**, M. Murakami, Tsukuba University; N. Kimura, KEK; H. Kobayashi, Institute of Quantum Science, Nihon University.*

A visualization study was carried out by shadowgraph method for a number of phase transitions of He II in a two-dimensional narrow channel. The experiment was focused on the visual observation of phase transition interface of three types. The first is the vapor-liquid (He II) interface indicating the onset of film boiling, of which propagation could be observed. The second is the He I- He II interface, which is very important to recognize the onset of film boiling in subcooled He II. The third is the superheated He I- He II interface that indicate occurrence of superheated He I- He II interface in the superheated state. The detailed observation of this interface would be of great help to reveal the dynamic behavior of it that was originally discovered from the temperature measurement by H. Kobayashi et. al..[1]

These visualization experiments were conducted using the Claudet-type cryostat equipped with two optical windows. The visualization system was set based on the shadowgraph method. The behavior of phase transition interface was observed using a high speed camera. We succeed in taking pictures to indicate the appearance of these interfaces with aid of image processing technique to enhance S/N ratio.

[1]: Kobayashi H., Yagi K., Takeda K., Fukaya M., Takahashi M. and Ashimori T., Proceedings of ICEC 21 (2007), in press

The present study was carried out partly by the support of the Grand-in Aid for Scientific Research from the Japan Society for the Promotion of Science.

C1-G-04 Investigation of transient heat transfer in porous media in He II

***H. Allain**, B. Baudouy, CEA.*

An experimental set up was designed and built in order to study the transient heat transfer regimes of superfluid helium through porous media. Tests have been performed on different porous media samples, which differ by their thickness, their porosity and their average pore size diameter. Temperature has been measured across porous media from 1.4 K to 2.1 K in saturated superfluid helium. A step heat flux is applied for a given bath temperature and the evolution of temperature has been measured across the porous media. Results, representing the evolution of the temperature in time for a given heat flux, are presented and analyzed by using the energy equation for He II in the Gorter-Mellink regime. The effects of the properties of porous media are also discussed.

C1-G-06 Experimental tests of the HVBK equations for He II

***H.A. SNYDER**, University of Colorado at Boulder.*

We generally accept the HVBK equations as those governing the motion of He II. The simplest test of these equations, that involves all the terms, is the calculation of the onset of instability of rotating Couette flow. Linear perturbation methods and difference methods using the full nonlinear equations show that the critical Reynold`s number, and the wave number of the instability rapidly approach zero as the temperature drops below the lambda point. For a narrow gap the wave length becomes longer than practical test instruments at about 2.07 K. As the gap increases, theory concludes that the approach to zero is more rapid. The experimental data agree well with the calculations near the lambda point when the test apparatus is sufficiently long. However, several investigators report unexplained breaks in the slope of torque data and second sound attenuation data at much lower temperatures. Nonlinear analysis predicts that the onset is not strongly affected by the aspect ratio for a narrow gap. I reanalyzed my second sound attenuation data for a wide gap at 1.63 K in detail in an attempt to understand the discrepancy. We resolve the identification of the various second sound modes by a direct acoustic approach. We report the slopes of each mode. We suggest several causes of the breaks in slope and test them against the data.

C1-H Regenerator Performance

C1-H-01 Calculated Regenerator Performance at 4 K with Helium-4 and Helium-3

***R. Radebaugh**, Y. Huang, A. O`Gallagher, J. Gary, National Institute of Standards and Technology.*

For regenerative cryocoolers operating with the cold end near 4 K the helium-4 working fluid no longer behaves as an ideal gas. As a result, the losses in the regenerator, given by the time-averaged enthalpy flux, are increased and are strong functions of the operating pressure and temperature. Helium-3, with its lower boiling point, behaves somewhat closer to an ideal gas in this low temperature range and can reduce the losses in 4 K regenerators. An analytical model is used to find the fluid properties that strongly influence the regenerator losses as well as the gross refrigeration power. Numerical modeling of regenerator performance at 4 K with helium-3 working fluid has now been made possible by the incorporation of the thermodynamic and transport properties of helium-3 into the latest NIST regenerator model, known as REGEN3.3. With this model we show how the use of helium-3 in place of helium-4 can improve the performance of 4 K regenerative cryocoolers. The effects of operating pressure, warm-end temperature, and frequency on regenerators with helium-4 and helium-3 are investigated and compared. The results are used to find optimum operating conditions. The frequency range investigated varies from 1 Hz to 30 Hz, with particular emphasis on the higher frequencies. The majority of the studies are for a regenerator matrix of packed spheres. The effect of the matrix heat capacity is also investigated.

Funding from the Office of Naval Research is acknowledged

C1-H-02 Application of Novel Regenerator Material Within a Coaxial Two-Stage Pulse Tube Refrigerator

***T. Koettig**, F. Richter, R. Nawrodt, M. Thuerk, P. Seidel, Friedrich-Schiller-University Jena.*

We have developed a lead-based regenerator material which is suitable for working temperatures below 20 K. This material can be used as a substitute for the state of the art materials used today within very low-temperature regenerators. This high efficient regenerator matrix combines technological advantages with the possibility to vary the thermodynamic and flow characteristics over a wide range, continuously. Hence, our self-made electroplated screen material is compared with standard regenerator materials (commercially available woven screens and packed spheres). The gap between matrix porosities of standard screens around 0.65 and the porosity of packed spheres with 0.38 is stepwise investigated regarding the pressure drop and heat transfer characteristic. The design parameters and the influencing variables to optimise the regenerator performance will be discussed. The utility of the shop-made lead coated regenerator material is demonstrated in a coaxial two-staged pulse tube refrigerator with working temperatures below 7 K.

C1-H-03 The Impact of Uncertainties Associated with Regenerator Closure Parameters on the Predicted Performance of Pulse Tube and Stirling Cryocoolers

***J.S. Cha**, W.M. Clearman, S.M. Ghiaasiaan, P.V. Desai, G.W. Woodruff School of Mechanical Engineering Georgia Institute of Technology.*

Recent investigations have shown that computational fluid dynamics (CFD) techniques can be used for modeling the entire pulse tube (PTR) and Stirling cryocooler systems. However, the results of CFD simulations can be trusted only if they are based on correct closure relations. The hydrodynamic and heat transfer parameters associated with regenerators are among the most important and poorly-understood closure relations for these cryocooler systems. In this investigation the impact of uncertainties associated with flow resistance parameters, as well as solid-fluid heat transfer coefficients, on the performance of PTR and Stirling cryocoolers is examined using CFD simulations. This objective is achieved by performing simulations where reference PTR and Stirling cryocooler systems operating in steady-periodic conditions are modeled in their entirety. The effects of uncertainties in the regenerator closure parameters on the cryocoolers performance parameters, as well as their key local hydrodynamic and heat transport processes, are quantified by the parametric variation of the aforementioned regenerator closure parameters.

C1-H-04 New Thermoacoustic Model, New Measurement Principle and Experimental Results of Flowing and Heat Transfer Characteristics of Regenerator

***Y.Y. Chen**, Graduate University of Chinese Academy of Sciences; E.C. Luo, Technical Institute of Physics and Chemistry, CAS; W. Dai, Technical Institute of Physics and Chemistry,CAS.*

Regenerators play key role in oscillating-flow cryocoolers or thermoacoustic heat engine systems. However, their flowing and heat transfer mechanism is still not well understood. In this paper, the authors present a new methodology for studying flowing and heat transfer characteristics of the oscillating flow regenerator. First we will present a new thermoacoustic model for oscillating-flow regenerator. In the model, the local flow and heat transfer performance of the regenerator can be characterized by its equivalent thermoacoustic viscous and thermal functions, and a dimensionless local averaged temperature gradient. Then, we present a simple acoustical method and experimental system to get the functions. Here, pressure measurements and velocity measurements by hot wire anemometry were performed with different screen-packed regenerators to obtain the two functions. With the two measured functions, local flowing friction factor and heat transfer coefficient within the regenerators where mean temperature gradient exists can be predicted. Finally, local flowing and heat transfer coefficients are summarized with several dimensionless groups for general and convenient using.

This work was supported by the Natural Science Foundation of China(Grant No.50625620)

C1-H-05 Longitudinal Hydraulic Resistance Parameters of Cryocooler and Stirling Regenerators in Periodic Flow

***J.S. Cha**, S.M. Ghiaasiaan, P.V. Desai, G.W. Woodruff School of Mechanical Engineering Georgia Institute of Technology.*

The results of an on going research program aimed at the measurement and correlation of anisotropic hydrodynamic parameters of widely-used cryocooler regenerator fillers are presented. The hydrodynamic parameters associated with longitudinal steady-periodic flow are addressed in this paper. An experimental apparatus consisting of a cylindrical test section packed with regenerator fillers is used for the measurement of axial permeability and Forchheimer coefficients, with pure helium as the working fluid.The regenerator fillers that are tested include stainless steel 400-mesh screens with 69.2% and 62% porosity, stainless steel 325-mesh screens with 69.2% and 62% porosity, stainless steel 400-mesh sintered filler with 62% porosity, and stainless steel sintered foam metal with 56% porosity. The test section is connected to a Stirling type compressor on one end and to a constant volume chamber on the other end. The instrumentation includes piezoelectric pressure transducers at both ends of the regenerator. For each filler material, time histories of local pressures at both ends of the regenerator are measured under steady periodic conditions over a wide range of oscillation frequencies. A CFD assisted methodology is then used for the analysis and interpretation of the measured data. The permeability and Forchheimer parameter values obtained in this way are correlated in terms of the relevant dimensionless parameters.

C1-H-06 A new correlation of friction factor for oscillating flow regenerator operating at high frequencies

***Y.L. Ju**, Q.Q. Sheng, Shanghai Jiaotong University.*

Regenerator plays an important role on the performance of low-power cryocoolers, in particular at high operating frequencies. The ability to accurately predict the pressure drop and phase shift across the regenerator is directly related to the cooling capacity and efficiency of a cryocooler. Many works have revealed that the friction factors under unidirectional steady flow conditions are unsuccessful in predicting the flow characteristics of regenerators typically operating at oscillating flow and pulsating pressure conditions. Recent researches have been conducted, using both theoretical analyses and experimental measurements, either to correlate the conventional friction factor by introducing additional parameters or to develop new flow models to overcome the shortcoming of the steady-flow friction factor. However, validation and application of these results for cryocooler regenerators are still questionable because of the complex and randomly oriented matrix geometry of actual regenerators. In this paper, we will first summary typical experimental results and correlations on the friction factor of regenerators for different sizes of packed woven screens, at different frequencies, at room and cryogenic temperatures. The comparison of those friction factor data will then be presented to clarify the reason for their difference. Finally, a new correlation of friction factor for oscillating flow regenerator, in terms of two non-dimensional parameters, will be presented.

C1-I Cryogenic Cooling of High Temperature Superconducting Devices

C1-I-01 High Temperature Superconducting Degaussing - Cooling two HTS coils with one cryocooler for the Littoral Combat Ship

__B.K. Fitzpatrick__, J.T. Kephart, E.M. Golda, NAVSEA NSWCCD Philadelphia.

The concept of creating a high temperature superconducting degaussing system has previously been studied by the Navy and shown to provide significant weight savings over conventional copper based degaussing systems. Modeling efforts have shown that in a HTS Degaussing System for the Littoral Combat Ship the dominant costs are cryocoolers. In an effort to minimize the number of cryocoolers a two coil demonstrator cooled off of one cryocooler has been constructed at NAVSEA Philadelphia. The demonstration consists of two 72 foot long sections of flexible cryostat that are electrically isolated but connected in series through two junction boxes for gas flow. Within each cryostat section, 12 turns of HTS represent a vertical and horizontal degaussing coil. Use of Helium as the working fluid reduces safety impacts and allows higher current density in the HTS conductor. Testing of this two coil degaussing system includes characterizing the helium flow for a matrix of conditions including helium charge pressure and circulating fan speed. The results of helium flow characterization are presented in this paper.

C1-I-02 Thermal Fatigue Test Apparatus for Large Superconducting Coils

__J.T. Kephart__, B.K. Fitzpatrick, NAVSEA NSWCCD Philadelphia; J.C. Chen, Rowan University.

The Navy has a continued interest in the development of High Temperature Superconducting (HTS) to provide power dense, efficient propulsion and electrical power generation. These machines have large HTS rotor coils that will undergo many thermal cycles during the life of the ship. Thermally fatiguing tests for large coils is necessary to understand any degradation and life issues that could arise. NSWCCD has sponsored Rowan University to design and build a device that will assist in the thermal fatigue testing of superconducting coils. It was designed to be autonomous with programmable cool down and warm-up rates and varying temperatures from ambient temperature down to 77K. A typical test would include thermally cycling a coil a specified number of times, then performing a critical current test on the coil and repeating the test cycle as many times as desired. This paper introduces the thermal cycling test setup and presents preliminary calibration data.

C1-I-03 Flow Cooling of Superconducting Magnets for Spacecraft Applications

__A.J. Dietz__, W.E. Audette, M.D. Barton, Creare Inc.; W.S. Marshall, C.M. Rey, Tai-Yang Research Corporation; D.S. Winter, A.J. Petro, , NASA Johnson Space Center.

The development and testing of a flow cooling system for high-temperature superconducting (HTS) magnets is described. The system includes a turbo-Brayton cryocooler, a magnet thermal interface, and a magnet thermal isolation and support system. The target application is the Variable Specific Impulse Magnetoplasma Rocket (VASIMR). Turbo-Brayton coolers are well suited to such spacecraft applications, as they are compact, modular, lightweight, and efficient, with long maintenance-free lifetimes. Furthermore, the technology scales well to high-cooling capacities. The feasibility of using turbo-Brayton coolers in this application was proven in a design exercise in which existing cooler designs were scaled to provide cooling for the magnet sets required by 200 kW and 1 MW VASIMR engines. The performance of the concepts for the thermal interface and the thermal isolation and support system were measured in separate laboratory tests with a demonstration system built about a representative HTS magnet. Cooling for these tests was provided by a flow cooling loop comprising a compressor, recuperator and GM cryocooler, with the flow pressure, temperature, and mass flow rate selected to effectively simulate the turbo-Brayton operating condition. During system testing, the magnet was cooled below its design operating temperature of 35 K, and good thermal uniformity (<0.4 K) and low thermal loads (< 0.5 W) were demonstrated.

This work was funded by NASA under Contract NNJ05JA17C.

C1-I-04 Experimental Validation of Conduction Cooling of a Compact HTS Motor

J.E. Pienkos, __P.J. Masson__, C.A. Luongo, FSU-FAMU College of Engineering.

Previous modeling results show promise in utilizing conduction cooling to maintain cryogenic operating temperatures for a high power density, high temperature superconducting (HTS) motor. The motor is designed for aero-propulsion use where size and weight must be minimized. HTS components greatly increase the power density of the motor but must operate at the prescribed cryogenic temperature. The nature of this application, an aero-vehicle, lends to the simplicity of using a conduction cooling method. Conduction cooling is implemented in the inductor design by providing adequate heat transfer paths between a cryocooler head and the HTS elements in the motor. The non-conventional nature of the motor necessitates a two-step cooling system to achieve flux trapping in YBCO pellets. Experimental validation of the conduction cooling method was achieved by using a thermal mock-up of the HTS inductor. The mock-up inductor is constructed and tested under similar heat loads experienced during normal motor operation. The experiments are performed using a G-M cryocooler, cryostat, vacuum pump, and the mock-up inductor. Experimental results are shown, proving the viability of conduction cooling, and the overall feasibility of the compact HTS motor design for aero-propulsion.

This research was partially supported by the NASA Vehicle Systems Program and the Department of Defense Research and Engineering (DDR&E) division under the URETI on Aeropropulsion and Power.

C1-I-05 Novel cryogenic engineering solutions for the new Australian research reactor OPAL

__S. Olsen__, S. Kennedy, J. Schulz, R. Theiring, W. Lu, E. Gilbert, M. James, Bragg Institute.

In August 2006 the new 20MW low enriched uranium research reactor OPAL went critical. The reactor has 3 main functions, radiopharmaceutical production, silicon transmutation and neutron beam research. Commissioning on 7 neutron beam instruments began in December 2006.

A Cold Neutron Source, located inside the reactor, consists of a 20L liquid deuterium moderated source operating at 24K, 330kPa with a nominal refrigeration capacity of 5 kW and a peak neutron flux at 4.2meV. The Thermosiphon and Moderator Chamber are cooled by helium gas delivered at 19.8K cooled using the Brayton cycle. The helium is compressed by two 250kW compressors, with one a variable frequency drive to lower power consumption.

A 5 Tesla Bi-2223 horizontal field HTS magnet will be commissioned in mid 2007 for use on all the cold neutron instruments. The magnet is cooled by a pulse tube cryocooler operating at 20K. The magnet design allows for the neutron beam to pass both axially and transverse to the field. Samples will be mounted in a 4K to 800K GM cryofurnace, with the ability to apply an in-situ variable electric field.

A cryogen free 7.4 Tesla NbTi vertical field LTS magnet, which was commissioned in 2005 will be used on neutron diffraction instruments. It is cooled by a GM cryocooler operating at 4.2K. The sample is mounted in a 2nd GM cryocooler (4K-300K), with the ability to apply an in-situ variable electric field.

C1-J Pumps and Compressors

C1-J-01 Pressure Oscillator Losses at High Frequency and High Pressure

__P.E. Bradley__, M.A. Lewis, R. Radebaugh, National Institute of Standards and Technology; A. Veprik, Ricor Ltd, Cryogenic Vacuum Systems.

High frequencies show potential for reducing the size of both the pressure oscillator and cold head for a given cooling power while leading to a faster cool-down. Previously, we made comparisons of pressure oscillator efficiency employing a total loss method of subtracting internal thermodynamic losses from the PV power at the piston face for frequencies up to 70 Hz with mean pressures up to 2.5 MPa for a load optimized for around 45 Hz. In this paper we present similar comparisons for high frequency operation up to 120 Hz and high mean pressure up to 3.5 MPa for an appropriately optimized load. Both small and large pressure oscillators from 4 cm3 to 25 cm3 are evaluated for high frequency and high pressure operation. We discuss pressure and flow losses for the high frequency (120 Hz) and high pressure (3.5 MPa) operation compared with 30 to 60 Hz frequency and 2.0 to 2.5 MPa pressure operation. Pressure ratios ranged from 1.0 to 1.3. The overall compressor efficiency, the delivered PV power to a load divided by the electrical input power to the compressor is determined for the high frequency and high pressure operation as well.

C1-J-02 Screw Compressor Characteristics for Helium Refrigeration Systems

__P.N. Knudsen__, V. Ganni, Jefferson Lab.

The oil injected screw compressors have practically replaced all other types of compressors in modern helium refrigeration systems due to their large displacement capacity, minimal vibration, reliability and capability of handling helium`s high heat of compression.
At the present state of compressor system designs, half the input energy is lost in the compression system. Therefore it is important to understand the isothermal and volumetric efficiencies of these machines to help properly design these compression systems. This presentation summarizes three separate tests that have been conducted on Sullair compressors at the Superconducting Super-Collider Laboratory (SSCL) in 1993, Howden compressors at Jefferson Lab (JLab) in 2006 and Howden compressors at the Spallation Neutron Source (SNS) in 2006. Although the compressor pressure ratio and built-in volume ratio are the primary parameters affecting the efficiencies of the screw compressor proper, it is evident from these tests that the compressor skid design also strongly influences the overall efficiencies and performance of the compression system. This work is part of an ongoing task at JLab to understand the theoretical basis for these efficiencies and their loss mechanisms, as well as to implement practical solutions.

C1-J-03 Designing Liquid Cryogenic Systems for Use with Centrifugal Pumps

__J.E. Dillard__, W.D. Batton P.E., J.A. Busby Ph.D., J.W. Shull, M.R. Anderson, Barber-Nichols Inc.

A cryogenic system is a collection of interdependent components working together; therefore, proper system performance is dependent upon an understanding of each component’s relationship with other components in the system. This paper examines the relationship between centrifugal pumps and other components in liquid cryogenic systems during cool down and steady state operation.
Two common problems which affect liquid cryogenic systems are cavitation and cryogen vaporation; both can significantly decrease mass flow and adversely effect overall system performance. However, a system-based, rather than a component-based, design philosophy can help avoid these problems. Additionally, cool down and steady state operation are two equally important system modes. Excessively tight design margins based exclusively on steady state operational requirements can compromise a system’s ability to cool itself to its operating temperature.

C1-J-04 Experience with dry running vacuum pumps in helium service

__R. Arztmann__, Linde Kryotechnik AG.

A process vacuum system for helium using dry running vacuum pumps only was shop tested and installed in a refrigeration plant to serve cavities operating at 2K for a cryogenic storage ring.
The paper explains the joint development steps of Busch AG and Linde Kryotechnik AG to use dry running vacuum pumps for helium service at ambient temperature. A roots type booster pump followed by a non lube rotary screw pump provides very good performance in a helium vacuum pump system. Variable frequency drives on both pumps allow to adjust the pump characteristics to a wide range of operating parameters. Operation without friction of sealing elements in the compression space also of the screw pump promises extended maintenance intervals and virtually no wear on the rotors. The current plant operation at Max Plank Institute in Heidelberg, Germany Laboratory will provide additional experience for further applications.

C1-J-05 Thermal Design of a Superconducting Bearing with a Magnetic Journal at Room Temperature.

__X. Granados__, Q Lloberas, ICMAB-CSIC; J López, R Maynou, CEIB.

Interaction between permanent magnets and superconducting pellets provides a stable and durable way for bearing in both thrust and axial bearing. The axial symmetry of the magnetic field, and that of the inertia axis, allow achieving non-friction rotating coupling thus improving reliability and a simplification of the bearing design. The cooling requirement of the superconductors is a main concern because the life and the losses of the bearing are essentially the life and efficiency of the cooling system. In this work we present the thermal design of a passive thrust bearing with a room temperature magnetic journal and a plane superconducting stator. In this paper, we discuss the main points for optimization of the gap thermal isolation in order to achieve the minimum losses-stiffness ratio.

Tuesday, 07/17/07 Poster 1:30pm - 3:00pm

C1-K Low Temperature Superconducting Magnet Systems - I

C1-K-01 Leak-tight welding experience from the Industrial assembly of the LHC cryostats at CERN.

__V. Parma__, N. Bourcey, P. Campos, A. Mongelluzzo, A. Poncet, CERN; P. Limon, FNAL; G. Musso, SERCO.

The assembly of the approximately 1700 LHC ring cryostats at CERN involved extensive welding of cryogenic lines and vacuum vessels. More than 6 km of welding requiring leak tightness to a rate better than 1.10-9 mbar.l.s-1 on stainless steel and aluminium piping and envelopes was made, essentially by manual welding but also making use of orbital welding machines. In order to ensure the fulfillment of safety regulations of pressure vessels and to comply with the leak-tightness requirements of the vacuum systems of the machine, welds were executed according to high qualification standards and following a severe quality assurance plan. Leak detection by He mass spectrometry was extensively used. Neon leak detection was used successfully to locate leaks in the presence of helium backgrounds. The use of SF6 as a tracer gas with a sniffer was also tried.
This paper presents the quality assurance strategy adopted for welds and leak detection. It presents the statistics of non-conformities on welds and leaks detected throughout the entire production and the advances in the use of alternative leak detection methods in an industrial environment.

C1-K-03 Heat Exchanger Design Studies for an LHC Inner Triplet Upgrade

R. J. Rabehl, ***Y. Huang***, *Fermi National Accelerator Laboratory.*

A luminosity upgrade of the CERN Large Hadron Collider (LHC) is planned to coincide with the expected end of life of the existing inner triplet quadrupole magnets. The upgraded inner triplet will have much larger heat loads to be removed from the magnets by the cryogenics system. Within the framework of a design temperature profile, a number of design studies have been completed to investigate the required characteristics of a heat exchanger to transfer this heat from the pressurized He II bath to the saturated He II system. This paper presents limitations of the existing bayonet heat exchanger, required attributes of a heat exchanger external to the magnet cold mass, and required attributes of a heat exchanger internal to the magnet cold mass.

C1-K-04 High Intensity Neutrino Source Superconducting Solenoid Cryostat Design

T.M. Page, *T.H. Nicol, S. Feher, I. Terechkine, J. Tompkins, Fermi National Accelerator Laboratory.*

Fermi National Accelerator Laboratory (FNAL) is involved in the development of a 100 MeV superconducting linac. This linac is part of the High Intensity Neutrino Source (HINS) R&D Program. The initial beam acceleration in the front end section of the linac is achieved using room temperature spoke cavities, each of which is combined with a superconducting focusing solenoid. These solenoid magnets are cooled with liquid helium at 4.5K, operate at 250 A and have a maximum magnetic field strength of 7.5 T. The solenoid cryostat will house the helium vessel, suspension system, thermal shield, multilayer insulation, power leads, instrumentation, a vacuum vessel and cryogenic distribution lines. This paper discusses the requirements and detailed design of these superconducting solenoid cryostats.

C1-K-06 Development of new cooling system using GM/JT cryocoolers for the SKS magnet

K. Aoki, *T. Haruyama, Y. Makida, O. Araoka, K. Kasami, T. Takahashi, T. Nagae, Y. Kakiguchi, KEK; T. Orikasa, T. Kuriyama, TOSHIBA.*

The SKS (Superconducting Kaon Spectrometer) worked in the K6 beamline of the KEK 12-GeV PS for the study of nuclear physics from 1991 until 2006. After shutdown of the KEK 12-GeV PS, KEK and JAEA are constructing new accelerator facility J-PARC (Japan Proton Accelerator Research Complex) as a joint project. The SKS magnet, which is a large sector type superconducting magnet, is intended to be improved and used in the new Hadron Hall of the J-PARC. In our schedule, the magnet will be disassembled and improved from 2007 to 2008, and reassembled in early 2009. The new nuclear physics experiments at the J-PARC will start in the middle of 2009. The main change is to adopt a new cooling method using several GM/JT cryocoolers instead of an old 300W cold box. Recent improvement of the refrigeration power of the GM/JT cryocooler made this coolig method possible. Adopting this compact cooling methods also brings new possibilities to the spectrometer. One example is an easy maintenance. In this paper, we explain our project and describe our first result of the heat leak measurement test of a model port using a GM/JT cryocooler.

C1-L Low Temperature Superconducting Magnet Systems - II

C1-L-01 Characterization of the ENEA new concept joint for Cable-In-Conduit-Conductors

Aldo Di Zenobio, *Luigi Affinito, Ugo Besi Vetrella, Sandro Chiarelli, Antonio della Corte, Chiarasole Fiamozzi Zignani, Ferruccio Maierna, Giuseppe Messina, Luigi Muzzi, Matteo Napolitano, Luigi Reccia, Stefano Rueca, Simonetta Turtù, Rosario Viola, ENEA.*

In large superconducting magnets, joints connecting different conductor unit lengths are unavoidable and represent one of the main causes of dissipation due to their resistive behavior, as well as a key element in determining the distribution of transport current within the conductor section. A joint of new concept in shaking-hands configuration has been designed and patented by ENEA. It is based on the idea of cutting the last-but-one cabling stages of the two conductors to be joined at different lengths in a complementary way, matching the two ends. As a result, the cable original shape and size is maintained over the joint length. A detailed description of the joint design has been presented elsewhere. In this paper we describe the results of its experimental characterization, using both Nb3Sn and NbTi Cable-in-Conduit Conductors: some samples have been prepared using spare lengths of the new European Dipole conductor and some with an ITER sub-size NbTi cable. For all of them, we performed DC resistance measurements at sufficiently high current and AC losses characterization, both in straight or bent configurations. Moreover an interesting trial has been made, manufacturing a joint sample without removing the Ni coating from NbTi strand surfaces, in order to investigate its impact on the joint resistance.

C1-L-02 Freely Oriented Portable Superconducting Magnet

E.N. Schmierer, *C. Prenger, D. Hill, B. Charles, Los Alamos National Laboratory; G. Laughon, R. Efferson, American Magnetics Incorporated.*

A high-field LTS solenoidal magnet was developed that can be operated in any orientation relative to gravity and is portable. The design consists of several features that make it unique; 1) bulk liquid cryogen storage occurs in a separate dewar rather than as part of the magnet assembly, which allows for single-person transport due to its low weight and size, 2) vapor generated pressure circulates liquid cryogen to and from the magnet with flexible transfer lines allowing operation in any orientation, and 3) composite, low-conducting structural members are used to suspend the magnet and shield layers within the vacuum vessel that provide a robust low heat loss design. Cooling is provided to the magnet through fluid channels that are in thermal contact with the magnet. The overall design is presented and analysis for cooldown time and weight are discussed as well.

C1-L-03 Helium-Liquefaction by a Cryocooler in Closed-Loop Cooling System for 21 T FT-ICR Magnets

Y.S. Choi, *KBSI-NHMFL RCC; T.A. Painter, NHMFL; D.L. Kim, B.S. Lee, H.S. Yang, KBSI.*

An experiment of helium liquefaction using a two-stage pulse tube cryocooler is performed. The main objective of this study is to confirm the feasibility of our recently proposed cryogenic design for a 21 T FT-ICR superconducting magnet system by closed-loop cooling concept without any replenishment of cryogen. Since the cold surface of a cryocooler is very limited, a cylindrical copper fin is thermally anchored to the first and second stage coldheads in order to extend the available heat transfer surface. A heat exchanger tube is attached on the outer surface of each cylindrical fin and heat exchange occurs between tube and helium gas which is passing through the tube. The temperature distributions along the copper cylinder and heat exchanger are measured in steady state and compared with the numerical analysis. The effect of mass flow rate, inlet pressure of helium, and cooling capacity of cryocooler on the liquefaction rate is also investigated.

C1-L-04 Development of Cooling System for Cryogenic Preamplifier in FT-ICR Ion Trap

***Y.S. Choi**, KBSI-NHMFL RCC; D.L. Kim, M.C. Choi, H.S. Kim, J.S. Yoo, KBSI; T.A. Painter, NHMFL.*

The cooling system of cryogenic preamplifier is designed and fabricated for Fourier Transform Ion Cyclotron Resonance (FT-ICR) ion trap. A cryogenic preamplifier consisted of non-magnetic materials is thermally contact to the cooling medium which is passing through the flange maintaining high vacuum in the ion cell. At the other end, the cooling medium is thermally anchored to the coldhead of cryocooler or liquid helium reservoir. This cryogenic preamplifier is installed in 7 Tesla FT-ICR system. The temperature distribution along the cooling medium is measured for cool-down and steady state, and compared with the result of numerical analysis. The reduction of thermal noise is discussed in term of the temperature. The detail of flange for cooling medium withstanding severe thermal, mechanical and electrical operation is also described.

C1-L-05 Developmnet and Production of a Low Noise LHe4 Cryostat for use in High Magnetic Pulsed Fields

***P.F. Ruminer**, C.H. Mielke, J.B. Betts, National High Magnetic Field Lab, LANL.*

Pulsed Field Magnets, up to 100 Tesla, provide a valuable environment for materials studies.

The Magnets at NHMFL-LANL operate at 77K, have a 15mm bore and are powered by a 1.6MJ cap bank with pulses at up to 10KV at 16KA and a rise time of approximately 12mS. Sample data is taken in the mVolt range, 10 orders of magnitude less than the power in the magnet. Our He3 Fridges provide a 300mK sample space diameter of just over 6mm. Background noise produced by sample movement in the field, eddy current heating, field perturbation and temperature fluctuations can make these measurements very difficult. Conductive materials in close proximity to the magnet greatly add to this background noise. We have developed a new LHe4 cryostat that is quite robust and has drastically reduced the mass of material in this critical area, creating a much quieter and more stable data collection environment. In addition, we have made repairing of the tail section, in the case of Magnet failure, less expensive, faster and requiring less effort. The intention was also to increase the hold time in order to reduce He4 costs and increase the available data collection time each day. Since the NHMFL-LANL is a User Facility, this is all very important due to the often limited time our Users are able to spend at our Facility. In this poster I will present Cryostat design, noise data, temperature stability and LHe4 hold time data compared to previous designs.

C1-L-06 Fiber Bragg Grating Sensors for Measuring Temperature and Strain Simultaneously at Cryogenic Temperature

*R. Rajinikumar, Inst. of Technial Physics, Forschungszentrum Karlsruhe, Dept. of Mechanical Engg., Indian Inst. of Technology, Sensor System Technology, Univ. of Applied Sciences; M. Suesser, Institute of Technial Physics, Forschungszentrum Karlsruhe; K.G. Narayankhedkar, **M.D. Atrey**, Department of Mechanical Engineering, Indian Institute of Technology; G. Krieg, Sensor System Technology, University of Applied Sciences.*

We study the feasibility of employing fiber Bragg gratings (FBG) for measuring thermodynamics parameters of super conducting coils. The distributions of mechanical stress and temperature inside the coil are important for an optimized design. Standard sensors with electrical connections like resistance thermometer and strain gauges cannot be placed inside the coil. So it is impossible to access local stress and temperature data. The superimposed dual wavelength metallic recoated Bragg gratings, fabricated in one fiber at same location are better suited for this purpose. Coil temperature and stress will vary the gratings periods which can be read out with a tunable laser. The spectral position of the reflections may be correlated with the spatial position of the gratings, and the shift of the gratings' maximum reflection indicates the change of the gratings' period. This, in turn measures temperature and stress. The Simultaneous temperature and strain measurement response of an Indium metal coated FBG sensor is reported in this paper.

C1-M Aerospace Cryogenics

C1-M-01 Development of Cryogenic Loop Heat Pipe

***R. Karunanithi**, S. Jacob, D.S. Nadig, U. Behera, A.K. Sahoo, Centre for Cryogenic Technology, IISc.; G.S.V.L. Narasimham, Department of Mechanical Engineering, IISc; D. Kumar, Thermal Systems Group, ISAC, ISRO..*

The loop heat pipes (LHP) are different from conventional heat pipes, in that, the wick structure is required only in the evaporator section. Consequently, smooth wall tubing can be employed in the construction of the vapour and liquid lines, which avoid the significant liquid-flow losses. As it is confined to such a small length, very small pore size wicks can be used in applications with high thermal transport requirements and/or where the heat must be transported over a long distance against gravity. The diode nature of LHP is intrinsic. The design of a Cryogenic Loop Heat Pipes (CLHP) has to take care of supercritical nature of the working fluid at room temperature and take care of the self-priming of the heat pipe action at start-up. The research and development of a CLHP is presented in the paper. A mathematical modeling and FORTRAN program to solve and determine the parameters for various boundary conditions has been developed. The CLHP is designed to transfer 5W heat at 70K using nitrogen as working fluid. It will be a self priming type device which can operate against gravity with evaporator above the condenser as well as under microgravity condition. Its performance will be tested by coupling it with a home made pulse tube refrigerator. The design fabrication and performance of a cryogenic heat pipe with s.s. wick at the evaporator for a heat transfer of 5 W at 70 K will be described in the paper.

C1-M-02 Thermal Management Options for Cryogenic Propellant Tanks and Other Large Structures

***J.R. Feller**, L.J. Salerno, NASA-ARC; A. Kashani, B.P.M Helvensteijn, Atlas Scientific.*

Various thermal control options, both passive and active, enabling long-term storage of cryogenic propellants in zero boil-off (ZBO) or reduced boil-off (RBO) states, will be discussed. The primary focus will be on methods of active heat transfer from propellant tank walls or thermal shields, via enthalpy flow in large-scale distributed cooling networks, to a remotely located cryocooler cold head. While ZBO/RBO propellant storage is the only application explicitly addressed, the methods described would allow efficient cryogenic temperature control of other large or remote structures (e.g., sensor arrays). In addition to in-space design concepts and modeling results, the capabilities and potential applications of an experimental apparatus, constructed specifically to investigate the behavior of distributed cooling networks, will be described.

C1-M-03 Large-Scale Cryogenic Testing of Launch Vehicle Ground Systems at Kennedy Space Center

*E.W. Ernst, D.E. Taylor, J.P. Sass, NASA KSC; **D.A. Lobmeyer**, S.J. Sojourner, ASRC Aerospace; W.H. Hatfield, D.A. Rewinkel, Sierra Lobo, Inc..*

The development of a new launch vehicle to support NASA's future exploration plans requires significant redesign and upgrade of Kennedy Space Center's (KSC) launch pad and ground support equipment systems. In many cases, specialized test equipment and systems will be required to certify the function of the new system designs under simulated operational conditions, including propellant loading. This paper provides an overview of the cryogenic test infrastructure that is in place at KSC to conduct development and qualification testing that ranges from the component level to the integrated-system level. An overview of the major cryogenic test facilities will be provided, along with a detailed explanation of the technology focus area for each facility.

C1-M-04 Three Dimensional Transient Heat Transfer Modeling of Cryogenic Rocket Engine Thrust Chamber
B.T. Kuzhiveli*, National Institute of Technology Calicut; G.K. Kuruvilla, Liquid Propulsion Systems Centre ISRO.*
In a cryogenic engine thrust chamber making use of LH2-LOX combination, liquid hydrogen is passed through the regenerative channels to take care of the high energy combustion resulting out of close to three by fourth stoichiometric mixture ratio combustion. However the cryogenic cooling results in wide range of temperature distribution in the cross section and along the axis of the thrust chamber with respect to time and poses serious thermo-structural problems. In order to have an unnderstanding of temperature distribution, an accurate prediction of heat transfer characteristics for the complete spectrum of the thrust chamber with respect to time is necessary. The objective of this paper is to present transient thermal analysis with three dimensional approach which can provide transient temperature distribution along the axis and across the cross section during transient and steady state conditions for chill down and hot test. A computational model has been developed for the prediction of temperature distribution on the thrust chamber which could be suited for parametric studies and also for generating an optimum design for cryogenic rocket engines to recommend stable operation.

C1-M-05 Lox Separation Studies Using Cryogenic Vortex Tubes
S. Jacob*, P.J. Paul, R. Karunanithi, U. Behera, Indian Institute of Science.*
In-flight collection of air, pre-cooling, liquefaction and separation of liquid oxygen (LOX) are key technologies for futuristic launch vehicles. Vortex tube technology is one of the few promising technologies for this application. Significant work has been carried out at IISc Bangalore in developing cryogenic vortex tube technology for high purity LOX separation. Experimental studies have been conducted on temperature separation and LOX separation both for straight and conical vortex tubes by varying various parameters. Though straight vortex tubes are found to perform better for temperature separation, they are not suitable for LOX separation as compared to conical vortex tubes. Experiments have been conducted to study the influence of supply pressure and inlet temperature for conical vortex tubes of L/D of 10, 20, 25 and 30 to achieve high LOX purity and separation efficiency. Studies show that it is not possible to obtain both high LOX purity and high separation efficiency simultaneously in a single vortex tube. However, experimental results show that it is possible to achieve both high LOX purity and separation efficiency by staging of vortex tubes. LOX purity of 96% and separation efficiency of 73.5% has been achieved for second stage vortex tube supplied with pre-cooled air having 60% oxygen purity. LOX purity has been further increased to 97% by applying controlled heating power over liquid oxygen flowing discharge surface of vortex tube.

C1-M-06 Radiation Analysis of anti-Stokes fluorescent Cryocooler with Network-Matrix Method
B.T. Kuzhiveli*, National Institute of Technology Calicut ; S. Jacob, Indian Institute of Science Bangalore .*

Attaining cooling effect by using laser induced anti-Stokes florescence in solids appears to have several advantages over conventional mechanical systems and has been the topic of recent analysis and experimental work. Using anti-Stokes fluorescence phenomenon to remove heat from a glass by pumping it with laser light, stands as a pronouncing physical basis for solid state cooling. Cryocooling by fluorescence is a feasible solution for obtaining compactness and reliability. It has a distinct niche in the family of small capacity cryocoolers and is undergoing a revolutionary advance. In pursuit of developing laser induced anti-Stokes fluorescent cryocooler, it is required to develop numerical tools that support the thermal design and therefore a thorough analysis of radiation heat transfer mechanism within the cryocooler is necessary. The paper presents the details of numerical model developed for the cryocooler and the subsequent development of a computer program. The program has been used for the understanding of various heat transfer mechanisms in particular the radiation heat transfer and is being used for thermal design of components for an anti-Stokes fluorescent cryocooler.

The development of optical cryocooler is progressing at the Indian Institute of Science (I.I.Sc), Bangalore under the auspices of the Defense Research Development Organization (DRDO). The author is a consultant for thermal design of the optical cryocooler.

C1-M-07 Thermal Model for a Mars Instrument with Thermo-Electric Cooled Focal Plane: CCD Subsystem with Heat Switch
D.R. Ladner*, J.P. Martin, N-Science Corporation.*
The Mineral Identification and Composition Analyzer (MICA) is a miniature instrument that employs X-ray scattering and visual imaging to determine nondestructively the mineralogy of a rock sample in-situ. The CCD subsystem comprises the CCD focal plane, the thermoelectric cooler (TEC), the TEC heat sink, a passive heat switch, and the subsystem radiator. The TEC is used to hold the CCD focal plane at or below 208 K during instrument operation. The inclusion of the heat switch and TEC are found to significantly extend instrument observation times and to enable schedule flexibility during extreme Martian diurnal temperature excursions of atmosphere (175 - 255 K) and sky (130 - 200 K). The CCD Subsystem Model includes all parasitic and dissipative heat sources. The model incorporates logic that simulates heat switch operation to provide heat sink cool-down by night and isolation by day if a sufficient temperature difference exists between the radiator and the sink; the sink must not exceed 258 K. Model parameter variation allows the instrument designer to optimize the subsystem thermal parameters to minimize input power to the TEC and maximize instrument observation periods. This paper extends previous results to include all combinations of heat switch status, TEC status, and ambient environmental conditions. Recent imaging and X-ray diffraction and fluorescence test results of the MICA prototype instrument are discussed.

C1-M-08 Novel Optical Cooler with Thermoelectrically Cooled Radiation Shield
S. Jacob*, R. Karunanithi, K.S. Sangunni, K.T. Aruldasan, M. Venkateshan, Indian Institute of Science; B.T. Kuzhiveli, VICET; R. Srinivasan, Raman Research Institute.*
Optical cooling using laser induced anti-Stokes fluorescence in appropriate solid materials is a potential candidate for future cooler applications. They are characterized by positive features such as no vibration, no moving part, low mass, compact and maintenance free long life operation. The paper discusses the efforts made to develop an optical cooler by developing the appropriate materials technology of ZBLANP fluoride glass and also the development of the optical cooler cryostat. The novel feature of the design is the incorporation of a radiation shield cooled by a thermoelectric cooler, which enables to shield the optical cooler element from ambient radiation and also to mitigate the heating effect of the leaked fluorescent emission from dielectric coated cooler element surfaces. A nodal network thermal analysis has been carried out to optimize the thermal performance of the cooler. The paper describes design of the cryostat and the experimental work carried out.

C1-M-09 Development of a cryogen-free continuous ADR system for micro-gravity experiments.
K. Takahashi*, H. Nakagome, Chiba University; K. Kamiya, T. Numazawa, National Institute for Materials Science; P. Shirron, D. Wegel, NASA/GSFC.*
It has been widely recognized that ultra low-temperature environment is vital foundation to implement micro-gravity missions such as basic science and X-ray astronomy. In particular, TES(Transition Edge Sensor) type X-ray microcalorimeters, being planned for future science satellite missions in JAXA, NASA and ESA, requires a temperature of 100mK or less. Added to these, study on formation of solid helium facet as an example of basic science under micro-gravity also needs 100mK environment. For ground-based experiments, dilution refrigerators make use of the gravity, it is difficult for them to implement under micro-gravity environment. On this point, the ADR has advantage since it is independent of the gravity. In this study, we will report development of a cryogen-free continuous ADR originally developed by NASA/GSFC and its cooling application for airborne micro-gravity experiment planned by NIMS, GSFC and JAXA.

C1-M-10 Development of a Cryogenic Gate Valve with Robust Sealing

***W.H. Hatfield**, Sierra Lobo, Inc.; J.P. Sass, NASA KSC.*

A soft-seat cryogenic gate valve has been designed, fabricated, and demonstrated by the Cryogenics Test Laboratory at the Kennedy Space Center (KSC), featuring a robust sealing technology and a high Cv flow characteristic. The robust seat design incorporates a novel retracting seat-retaining disk to prevent soft-seat abrasive wear and damage on the valve body hard seat. Advanced materials were incorporated into the design, including porous sponge polytetrafluoroethylene (PTFE) for the seat material and titanium nitride coating for the 316 stainless-steel surfaces that are subject to wearing or galling. The valve is suitable for applications from ambient temperature down to liquid nitrogen temperature (77 K), with a seat leakage rate of less than 1 sccm per inch of valve diameter. The very low seat leakage, throttling capability, and high Cv flow characteristic of the valve make it suitable for block valve applications on standard to very large cryogenic storage tanks.

C1-M-11 Atmospheric Pressure Effects on Cryogenic Storage Tank Boiloff

***J.P. Sass**, C.R. Fortier, NASA KSC.*

The Cryogenics Test Laboratory at the Kennedy Space Center routinely uses cryostat test hardware to evaluate comparative and absolute thermal conductivities of a wide array of insulation systems. The test method is based on measurement of the flow rate of gas evolved as a result of evaporative boiloff of a cryogenic liquid. The gas flow rate typically stabilizes after a couple of hours to a couple of days, depending upon the test setup. The stable flow rate value is then used to calculate the thermal conductivity for the insulation system being tested. The latest set of identical cryostats, 1000-L spherical tanks, exhibited different behavior. On a macro level, the flow rate did stabilize after a couple of days; however, the stable flow rate was oscillatory, with peak-to-peak amplitude of up to 25% of the nominal value and a consistent period. The source of the oscillation has been traced to variations in atmospheric pressure caused by atmospheric tides similar to oceanic tides. This paper will present analysis of this phenomenon, including a calculation that explains why other cryostats are not affected by it.

C1-M-12 Cryocooler Prognostic Health Management System

*B. Penswick, Sest, Inc.; **A. Shaw**, Sest, Inc; C. Dodson, T. Roberts, Air Force Research Laboratory.*

High performance sensors are playing an increasingly important role in all aspects of all critical DoD missions. There is a family of sensors that operate with improved sensitivities if cooled to very low (cryogenic) temperatures. For these sensors a healthy and reliable mechanical refrigeration system (cryocooler) is required. The ability to accurately predict the "health" or remaining useful life of the cryocooler has significant benefits from the viewpoint of insuring that mission critical functions can be carried out with a high probability of success. The proposed paper provides an overview and approaches used for the development of a Cryocooler Prognostic Health Management System capable of assessing the cryocooler "health" from the viewpoint of the level of performance degradation and/or the potential for near term failure. Additionally, it quantifies the reliable remaining useful life of the cryocooler. While the proposed system is focused on the specific application to linear drive cryocoolers, especially for DoD, many of the attributes of the system can be applied to other specialized system hardware in both commercial and U.S. Government agency for situations where it is critical that all aspects of the hardware "health" and "remaining useful life" be fully understood. Several benefits of the health monitoring system are also described in the paper.

C1-N Large Scale Refrigerators and Liquefiers - I

C1-N-01 The on-site status of the KSTAR helium refrigeration system

***H.-S. Chang**, D.S. Park, J.J. Joo, K.W. Cho, Y.S. Kim, J.S. Bak, National Fusion Research Center; H.M. Kim, M.C. Cho, I.K. Kwon, Samsung Engineering and Construction Corporation; E. Fauve, J.-M. Bernhardt, P. Dauguet, J. Beauvisage, F. Andrieu, Air Liquide - Advanced Technologies Division; G.M. Gistau Baguer, Consultant - Biviers.*

Since the first "Cryogenic System Design Description" of the KSTAR helium refrigeration system (HRS) had been carried out in year 2000, many modifications and changes have been applied due to both system optimization and improved knowledge of the cold component of KSTAR. The present specification of the KSTAR HRS had been fixed during the "Design Clarification Meeting", beginning of year 2005. Consequent manufacturing of main equipments, such as compressor station (C/S), cold box (C/B), and distribution box (D/B) was completed by or under the supervision of Air Liquide (AL) DTA by the end of 2006. The major components of the C/S are 2 low and 2 high pressure compressor units and an oil removal system. The cooling power of the C/B at 4.5 K equivalent is 9 kW which is extracted by 6 AL turbo expanders. The D/B is a valve box housing 49 cryogenic valves, 2 supercritical helium circulators, 1 cold compressor, and 7 heat exchangers immersed in a 4 m3 liquid helium storage. The installation and commissioning of the KSTAR HRS is planned to be executed in year 2007.

In this proceeding, we will introduce the on-site installation and commissioning status of the KSTAR HRS. In addition, the final specification and design features of the HRS and the cooling schemes of the KSTAR cold components, which consist of superconducting (SC) magnets and corresponding structures, SC bus-lines, current leads, and thermal shields, will be presented.

C1-N-02 The JT60SA Cryoplant Current Design Status

***D. Henry**, P. Reynaud, J.-Y. Journeaux, J.-L. Maréchal, D. Balaguer, Ch. Roux, Département de Recherche sur la Fusion Contrôlée, Association ; F. Michel, P. Rousset, Département de Recherche Fondamentale sur la Matière Condensée, CEA/Grenoble, F-38000 Grenoble France.*

In the framework on the ITER Broader Approach, CEA is carrying out the procurement of the Cryogenic System to the JA-EU Satellite Tokamak JT60SA, which should be operated in Japan at JAEA, Naka since 2014. According to the Conceptual Design Review Report, JT60SA is to operate for periods of at least 6 months per years, with major shutdown periods in between for maintenance and further upgrades installation. For this operation scenario, the cryoplant and the cryodistribution have to cope with different heat loads which depend on the different JT60SA operating states. The cryoplant consists of two 4.5 K refrigerators and one 80 K helium loop coupled with an LN2 Pre-Cooler. These cryogenic subsystems have to operate simultaneously in order to remove the heat loads from the magnet, 80 K shields, divertor cryopumps and Pellet Injection System.

The first part of this study based on the Process Flow Diagram (PFD), presents the current design status of the JT60SA cryogenic system. The second part is dedicated to the analysis of the cryoplant normal operation modes including the regeneration mode of the divertor cryopumps.

Thanks to this analysis, the architecture of the present PFD is proposed in order to meet the technical specifications of the cryoplant with the JT60SA operation requirements.

C1-N-03 Performance Study for Cryogenic System at NSRRC

***H.H. Tsai**, F.Z. Hsiao, H.C. Li, S.H. Chang, W.S. Chiou, NSRRC.*

A new cryogenic system was installed on September of the year 2006 at NSRRC. So far, two superconducting magnets and one superconducting cavity for RF are cooled by one 450W liquid Helium system which had already been installed on the year 2002. The new system is planning to supply the liquid helium to five superconducting magnets and being a backup of the first one by transfer valve box. This paper presents the variation of parameters which were precooling temperature (from 87K to 105K), cold turbine outlet temperature (from 10K to 11.5K) and heating power to the stability of operation and liquefaction rate.

C1-N-04 Preliminary Commissioning of Cryogenic System of BES III

*Z.G Zong, **L. Zhang**, L.Q Liu, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences; S.P. Li, K. He, Institute of High Energy Physics, Chinese Academy of Sciences.*

A helium cryogenic system with cooling capacity of 500 W at 4.5 K was set up at Institute of High Energy Physics (IHEP), Chinese Academy of Sciences, Beijing. This helium refrigerating system is dedicated for the cooling of two interaction region quadrupole magnets (SCQ) and one detector solenoid magnet (SSM), which are the key devices of the upgrade project of Beijing Electron-Positron Collider (BEPC II). Commissioning of the cryogenic system with the detector magnet and SCQ magnets was carried out. This paper will present the overall status and some test results of the superconducting devices and cryogenic system during the commissioning. The fact that the cryogenic system stood the racket of the quench of SSM indicates the system is very robust.

C1-N-05 Performance of cold compressors in the sub-cooling system for LHD.

***H. Wakisaka**, S. Yoshinaga, T. Takahashi, N. Saji, Ishikawajima-Harima Heavy Industries Co., Ltd.; T. Mito, S. Imagawa, S. Hamaguchi, , National Institute for Fusion Science.*

To attempt the improvement of the cryogenic stability of helical coils in the Large Helical Device (LHD) of National Institute for Fusion Science(NIFS), the cooling system was upgraded with an additional pre-cooler. Two-stage cold compressors were adopted for this system to decompress the heat exchanger tank to 24 kPa as 3K sub-cooling system. The nominal flow rate is 15.9 g/s at the outlet condition of 120 kPa. The rotor of the compressor is supported by dynamic gas bearings and is driven by a variable-frequency motor that is located at the ambient temperature. These designs have the advantage of easy to maintenance and high reliability as a complete oil-free machine. 80 K gas cooled thermal shielding is adopted between the compressor impeller operating at 3.0 K and the ambient temperature part to decrease heat leak through the casing and shaft. This compressor is able to achieve high performance by adopting this structure and a high efficiency impeller. These cold compressors we re able to attain the nominal specification as the result of performance tests at NIFS.

C1-N-06 A Theoretical and Practicle Approach on 20K Brayton Refrigerator: KHNP WTRF Helium Refrigerator

***P. Briend**, E. Fauve, Advanced Technology Division - Air Liquide.*

The large 20K refrigerators designed for detritiation facilities or cold neutron source are commonly helium Brayton cycle machines. Beyond the apparently simple process, it is important to underline the weight of each component on the cycle efficiency. A thermodynamic and exergetic approach is of great help to design the system and analyse the deviations in operation. The WTRF/KHNP 30 kW@20K Helium Refrigerator that was commissioned in late 2006 illustrates the pertinence of this approach. The analysis of the deviation with expected results are explained through theoretical thermodynamical and exergetic balance. The focus on the main heat exchanger led to the right decision of an upgrading modification. The practical on site repair of the defaulted HX is illustrated and the final and successful performance test of the refrigerator coupled with the deuterium/tritium distillation is presented.

C1-N-07 Numerical simulation of the cryogenic system of BEPC II

*Z.G Zong, L.Q Liu, X.L Xiong, **L. Zhang**, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences.*

Cryogenic system of BEPC II with a total capacity of 1.0 kW at 4.5 K for cooling superconducting devices is being built at IHEP. Two sets of refrigerators with each capacity of 500 W at 4.5 K are adopted. In order to prepare for the commissioning of the cryogenic system, the refrigeration process was simulated and analyzed numerically. The simulation was conducted based on the latest engineering progresses and focusing on the steady state operation mode. The simulation results, such as the helium mass flow rates and pressure drops over the control valves of different cooling channels, thermodynamic parameters of each superconducting device, etc., are presented in this paper. Under considering the real heat loads, the powers of heaters of each device were figured out to realize the nominal operation modes.

C1-N-08 Dynamic simulation of an helium refrigerator.

***P. Roussel**, C. Deschildre, P. Bonnay, J.M. Poncet, F. Michel, A. Girard, CEA-Grenoble; A. Barraud, P. Briend, Laboratoire d`Automatisme de Grenoble; S.E. Sequeira, Air Liquide.*

A dynamic simulation of a large scale existing refrigerator has been performed using the industrial software HYSYS. This software is mainly used in chemical and refinery industries but is also able to cope with cryogenic fluids, as most cryogenic companies already use it in steady state mode for design purposes.
The first goal of our study has been to qualify the dynamic module of HYSYS and then to simulate our refrigerator. This refrigerator which is the 400W at 1.8K test facility at CEA-Grenoble, comprises all the typical equipments of large scale refrigerators: plate fins counter flow heat exchangers, centrifugal cold compressors, warm screw compressors, helium phase separators and cold turbine.
This dynamic simulation has helped for process control and regulation during normal operation. Existing control loops were taken into account in order to simulate the refrigerator behaviour with loads variations.
This paper presents, the model obtained using the HYSYS software and the results compared to experimental

C1-N-09 Understanding dynamic behavior of a large scale cryogenic plant

***R. Maekawa**, K. Ooba, T. Mito, National Institute for Fusion Science; M. Nobutoki, Taiyo Nippon Sanso Co.*

Development of Cryogenic Process REal-time SimulaTor (C-PREST) has been finalized to provide a platform to study refrigeration process simulation for the entire cryogenic system for the Large Helical Device (LHD). To understand dynamic behavior of the LHD cryogenic plant, the simulations have been carried out during the cooldown operation. Although LHD has three different cooling schemes, a pool boiling, a forced-flow supercritical helium cooling and a two-phase flow cooling, C-PREST simulates comparable results of LHD cooldown process. To validate the versatility of C-PREST, the heat pulse(s) were applied to the 20000 liters liquid helium reservoir of a helium refrigerator/liquefier. This paper describes operations of large cryogenic plant and discusses dynamic behavior of helium refrigerator/liquefier under various heat pulse inputs.

Tuesday, 07/17/07 Oral 3:00pm - 5:00pm

C1-O Stirling and Pulse Tube Capabilities Overview (Aerospace)

C1-O-01 Heritage Overview: 20 Years of Commercial Cryocooler Production for Space

*A.S. Gibson, **J.S. Reed**, EADS Astrium Limited.*

Space cryocooler production (formerly BAe and MMS) has spanned more than 2 decades. Industrialisation has taken the cryocooler from the laboratory to a proven space product. Over this period, Astrium have manufactured more than 50 Stirling coolers, 15 of which have flown. An historical review with lessons learned is presented.
Following transfer of the heritage design via Rutherford Appleton Laboratory (RAL), manufacturing began at Astrium on the first 80K Stirling coolers in 1986, with production of 2 development models (1 for ESA) and an EM unit. Following successes of Oxford/RAL coolers on ISAMS, ATSR-1 and ATSR-2, Astrium built standard 80K units for IMG-ADEOS(1996) and HTSSE-II(1997). 23 coolers of this type were built in 4 batches. A higher heat lift version (1991) led to the standard 50-80K product. These continue to fly in pairs on MOPITT(1999), MIPAS(2002), AATSR(2002), INTEGRAL(2002) and a military satellite (2004), with a single unit on ODIN(2001). Another pair is to be launched in 2007.
Industrialisation of a 2-stage RAL Stirling cooler design began in 1990 (ESA funded), to provide cooling from 20-50K. An EM was produced, followed by 3 QM units. In 2000, an improved 10K design (collaboration with RAL) was built for the US-Air Force Research Laboratory yielded a record temperature of 9.4K. Notably, development of this design has recently been re-initiated (ESA funding).
Astrium would like to acknowledge funding from ESA for industrialisation of cryocoolers.

C1-O-02 An Overview of the Performance and Maturity of Long Life Cryocoolers for Space Applications

***D.G. Curran**, S.W. Yuan, The Aerospace Corporation.*

A 2007 survey is made of long life cryocoolers involving Stirling, Pulse Tube, reverse Brayton, and Hybrid variants for space applications. A number of unit configuration types involving single and multi-temperature stages is included. The performance range varies from milliwatts of cooling at 4K to 10`s of watts at 150K. The objectives for this survey are to provide a hardware summary of available units from several U.S. manufacturers including the heritage and maturity level suitable for space use in payloads and instruments. Listed in the summary are life test and flight hours, environmental test levels, size, and electronics controller capabilities as well as load curves and specific power as a function of temperature.

C1-O-03 Endurance Evaluation of Long-Life Space Cryocoolers at AFRL- An Update

***J. Sutliff**, W. Scheirer, E. Pettyjohn, T. Roberts, AFRL/VSSS.*

The Air Force Research Lab (AFRL) in conjunction with various defense contractors has developed several long-life cryocooler designs. These cooler include the NGST HEC, the Raytheon PSC, the Ball 6020, and the Ball 35-60K. They represent different technologies including pulse tube and Stirling cycle. The coolers operating times range from the NGST HEC which has been running 28,000 hours to the TRW 6020 which has been operating for more that 69,000 hours. Endurance evaluation attempts to describe the long-life potential of these machines with a complete demonstration of these machines being 5-10 years of constant operational life in an environment designed to simulate the conditions of space. The testing hopes to show any wear out, fatigue, or electronic malfunction so that cryocoolers will continue to improve their long-life potential. Endurance testing also quantifies the performance degradation over time to help determine needs of future satellites. Data presented indicates that certain degradation patterns exist in these cryogenic refrigerators which will pose a challenge for their long term use in multi-year missions.

C1-O-04 Air Liquide Space Pulse Tube Cryocoolers

*T. Trollier, J. Tanchon, J. Buquet, **A. Ravex**, P. Crespi, Air Liquide Advanced Technology Division, AL/DTA, Sassenage, France.*

Thanks to important development efforts completed and partial ESA funding, AL/DTA is now in position to propose two Pulse Tube cooler systems in the 40-80K temperature range for coming Earth Observation missions such as MTG, Sentinel 3, etc… The two pulse tube coolers thermo-mechanical units are yet qualified against environmental constraints.
In addition to these two Pulse Tube cooler systems, a 20-50K multi-stage low temperature Pulse Tube cooler is currently under development for future Scientist Missions such as Xeus, Darwin, etc.. The paper presents the current status of each of the three thermo-mechanical units and associated cooler drive electronics.

C1-O-05 High Performance Pulse Tube Cryocoolers

***J.R. Olson**, P. Champagne, E. Roth, B. Evtimov, T.C. Nast, Lockheed Martin ATC.*

Lockheed Martin's Advanced Technology Center (LM-ATC) has been developing pulse tube cryocoolers for more than ten years. Recent innovations include successful testing of four-stage coldheads, no-load temperatures below 4 K, and the recent development of a high-efficiency compressor.
This paper discusses the predicted performance of single and multiple stage pulse tube coldheads driven by our new 5 kg "M5Midi" compressor, which is capable of 90% efficiency with 200W input power, and a maximum input power of 1000W. This compressor retains the simplicity of earlier LM-ATC compressors: it has a moving magnet and an external electrical coil, minimizing organics in the working gas and requiring no electrical penetrations through the pressure wall. Motor losses were minimized during design, resulting in a simple, easily-manufactured compressor with state-of-the-art motor efficiency.
The predicted cryocooler performance is presented as simple formulae, allowing an engineer to include the impact of a highly-optimized cryocooler into a full system analysis. Performance is given as a function of the heat rejection temperature and the cold tip temperature and cooling load. A discussion of the optimum number of coldhead stages will be given. We will also discuss a novel configuration where the compressor operates with no heat rejection, allowing very flimsy attachment to the satellite so as to minimize exported vibration.

C1-O-06 Ball Aerospace Hybrid Space Cryocoolers
***W. Gully**, D.S. Glaister, P. Hendershott, V. Kotsubo, E.D. Marquardt, Ball Aerospace & Technologies Corp..*
This paper describes the design, development, testing and performance at Ball Aerospace of a long life, hybrid (combination of Stirling and Joule-Thomson thermodynamic cycles) space cryocoolers. Hybrid coolers are synergistic combination of two thermodynamic cycles which combines advantages of each cycle to yield overall improved performance. Hybrid cooler performance advantages include: 1) load leveling of large heat loads, 2) remote cryogenic cooling with very low to negligible induced vibration and jitter, 3) very low redundant (off state) cooler penalties, 4) high power efficiency, especially at low temperatures, and 5) simplified system integration with capability to cross gimbals and no need for thermal straps or switches. Ball is currently developing hybrid coolers on several programs. The 35 K hybrid cooler provides 2.0 W at 35 K and 8.5 W at 85 K with an emphasis on load leveling of high transient heat loads and remote, low vibration cooling. The 10 K hybrid cooler provides 200 mW at 10 K, 700mW at 15 K, and 10.7 W at 85 K with an emphasis on power efficiency. In addition, Ball built and tested a complete hybrid cooler that met the requirements of the JWST Mid-Infrared Instrument (MIRI) cooler including providing 80 mW at 6 K and 100 mW at 18 K.

C1-O-07 Flight Qualified High Capacity Pulse Tube Cooler
***C. Jacob**, T. Nguyen, J. Raab, Northrop Grumman Space Technology.*
The High Capacity Cryocooler Flight Qualified Cryocooler (HCC Qual) is designed to provide large capacity cooling at 35K (2.3 Watts) and 85 K (14.3 Watts) for space applications which require cold focal planes and optics cooling. The HCC Qual is built upon the heritage of the High Capacity Cryocooler (HCC) with a coaxial cold head configuration. The coaxial configuration minimizes the cooler parasitic and offers superior cooler integration. Flight qualification of this cryocooler includes thermal performance mapping over a range of reject temperatures, launch vibration testing and thermal cycling testing. Acceptance test data will be presented.

C1-O-08 Raytheon Dual-Use Cryocooler Progress
***R.C. Hon**, C.S. Kirkconnell, Raytheon Space and Airborne Systems.*
Raytheon initiated development of the Dual-Use Cryocooler (DUC) as a way of bridging the gap between tactical and space cryocooler systems. The goal of the program is to produce a cryocooler system with 80% of the typical space system functionality at less than 20% of the typical cost. A single-stage pulse tube configuration was selected due to its inherently low complexity. The compressor module is a dual-opposed, self balanced design, making use of a flexure suspension and clearance gap scheme for long operational life. The drive electronics is based on a robust tactical design, modified for additional functionality and hardened against radiation typical of the space environment.
Development of the DUC system has progressed substantially over the past two years, including the design, build and testing of a brassboard thermo-mechanical unit (TMU). Demonstrated design simplification features and initial test results are presented. Significant progress was also made in terms of electronics development. Existing tactical assets were modified for use with the DUC, including the addition of separate drive circuits for each compressor motor. The software was modified to enable features not found in typical tactical systems such as first-order active vibration cancellation. The brassboard electronics test results are also presented.

C1-P Large Scale Refrigerators and Liquefiers - II

C1-P-01 Large scale helium liquefaction and considerations for site services for a plant located in Algeria
***P. Froehlich**, J.J. Clausen, Linde Kryotechnik AG.*
The large scale liquefaction of helium extracted from natural gas is depicted. Based on a block diagram the chain, starting with the pipeline downstream of the natural gas plant to the final storage of liquid helium is explained. Information will be provided about the recent experiences during installation and start-up of a bulk helium liquefaction plant located in Skikda, Algeria, including part load operation based on a reduced feed gas supply.
The local working and ambient conditions are described including challenging logistic problems like shipping and receiving of parts, qualified and semi-qualified subcontractors, basic provisions and tools at site, and precautions to sea water and ambient conditions.
Finally the differences in commissioning (technically and evaluation of time and work packages) to a European location and standards will be discussed.

C1-P-02 Status of the refrigeration plant for the Electrostatic
Cryogenic Storage Ring (CSR) at MPI-K in Heidelberg
*R. von Hahn, J. R. Crespo Lopez-Urrutia, H. Fadil, M. Grieser, K.-U. Kühnel, M. Lange, **D. A. Orlov**, R. Repnow, T. Sieber, D. Schwalm, J. Ullrich, A. Wolf, Max-Planck-Institute for Nuclear Physics; H. Quack, Ch. Haberstroh, Technische Universität Dresden; D. Zajfman, Weizmann Institute of Science.*
At the Max-Planck-Institute for Nuclear Physics in Heidelberg a next-generation electrostatic storage ring for atomic and molecular ion beams is under construction. In contrast to existing electrostatic storage rings our Cryogenic Storage Ring CSR will be cooled down to temperatures below 2 K. The low-temperature of the vacuum enclosure and all ion optical components decisively reduces the influence of the black-body radiation incident onto the stored particles such that only the lowest rotational levels of radiatively active molecular ions will be occupied. Moreover, due to the excellent vacuum of up to 10E-15 mbar highly charged (radioactive) ions or antiprotons can be stored with sufficient life times. A concept for the cooling of the storage ring has been developed and will soon be tested at a prototype with a length of 1/10 of the ring. A commercial refrigerator has been largely set up and is now in the commissioning phase. In this paper the refrigeration plant and first results of the test-operation will be presented.

C1-P-03 The CERN LHC Refrigeration System
***P. Dauguet**, G.M. Gistau-Baguer, P. Briend, B. Hilbert, E. Monneret, J.C. Villard, G. Marot, F. Delcayre, C. Mantileri, F. Hamber, J.C. Courty, P. Hirel, A. Cohu, H. Moussavi, Air Liquide.*
The LHC is the largest particle accelerator in the world. It is a superconducting machine over 27 kilometers. Its magnets and cavities require helium refrigeration and liquefaction in the temperature range 1.8 K to 300 K. This is the largest cryogenic system in the world regarding the needed cryogenic power : 144 kW equivalent power at 4.5 K.
The LHC cryogenic system is composed of 8 x 18 kW at 4.5 K refrigerators, 8 x 2.4 kW at 1.8 K refrigerators, 5 main valve boxes, more than 27 km of helium tranfer lines and around 300 service modules connecting the tranfer line to the magnet and cavity strings. Most of these components have been designed, manufactured, installed and started up by Air Liquide. Du to the huge size of the project, the engineering, construction and commissionning of the equipments have lasted for 8 years, from first order of equipments in 1998 to last commissionning in 2006. Specifications, architecture and design of the major components of the LHC Refrigeration System will be presented in the present paper.

C1-P-04 1.8 K refrigeration units for the LHC: conclusion of procurement phase and first operational experience

***G. Ferlin**, CERN.*

The cooling capacity below 2 K for the superconducting magnets of the Large Hadron Collider (LHC) is provided by eight refrigeration units of 2400 W at 1.8 K, each of them coupled to a 4.5 K refrigerator. After successful testing and acceptance of the pre-series units delivered by the two selected vendors, the 2 pre-series units and the 6 series units were installed in underground cavern at their final location. During the last two years, these 8 units were successfully tested at their installed capacity in a so-called “capacity check mode”. After a brief reminder of the pre-series commissioning tests results, a statement of the tests done at installed capacity for the eight units will be reported, with emphasis on the reproducibility of the results among the four units supplied by each vendor. Conclusion of the procurement phase will be drawn with the review of the critical points that have been solved. Finally this paper will report on the first operational experience of the units during the commissioning of the LHC sectors from January 2007 onwards.

C1-P-05 Design and Manufacturing of the KSTAR Tokamak Helium Refrigeration System

***P. Dauguet**, P. Briend, I. Abe, E. Fauve, J.M. Bernhardt, F. Andrieu, J. Beauvisage, Air Liquide.*

The KSTAR (Korean Superconducting Tokamak Advanced Research) project makes intensive use of superconducting magnets operated at 4.4 K. The cold components of KSTAR require forced flow of supercritical helium for magnets and structure, boiling liquid helium for current leads, and gaseous helium for thermal shields. A helium refrigeration system has been customed design for this project. The purpose of this paper is to give a brief overview of the proposed cryogenic system. The thermal loads specified to the refrigerator in the different operating modes of the KSTAR tokamak will be presented. This specification results in the definition of a design mode for the refrigerator. The design and construction of the resulting 9 kW at 4.5 K Helium Refrigeration System will be presented.

C1-P-06 Adopted methodology for cool-down of SST-1 superconducting magnet system: Operational experience with the helium refrigerator

*A.K. Sahu, **B. Sarkar**, P. Panchal, J. Tank, R. Bhattacharya, R. Panchal, V.L. Tanna, R. Patel, P. Shukla, J.C. Patel, M. Singh, D. Sonara, R. Sharma, R. Duggar, Y.C. Saxena, Institute for plasma research.*

The 1.3 kW @ 4.5 K helium refrigerator/liquefier (HRL) has been commissioned during year 2003 and since then the HRL is in operation for different experiments. The HRL has been operated with its different modes as per the functional requirements of the experiments. The recent experience of cooling down the magnet system (SCMS) of SST-1 with 16 nos. of toroidal field magnets and 9 nos. of poloidal field magnets has been unique. The cool-down experiment of the SCMS has been carried out under physical parameter constraints with not so appreciable vacuum inside the cryostat as well as uneven temperature distribution on the thermal shield at 80 K. Successful attempt has been made to cool the SCMS down to 4.5 K. The experience has been unique as new thermodynamic balance of the refrigerator had to be adjusted with the original boundary condition of the HRL. The enhanced capacity was achieved without any additional hardware. The control system of the HRL was tuned manually to achieve the stable thermodynamic balance, while keeping the turbine operating parameters at optimized condition. Extra mass flow rate requirement has been met by exploiting the margin available with the compressor station. The paper will describe the methodology adopted to modify the capacity of HRL with safety precaution and experience of SCMS cool down to 4.5 K. The operational experience along with control system of the HRL will be discussed.

C1-P-07 The Relativistic Heavy Ion Collider (RHIC) Cryogenic System at Brookhaven National Laboratory: Review of the Modifications and Upgrades since 2002 and Planned Improvements

***Y.R. Than**, J. Tuozzolo , Brookhaven National Laboratory; A. Sidi-Yekhlef, V. Ganni, P. Knudsen, D. Arenius, Thomas Jefferson National Accelerator Facility.*

An ongoing program at Brookhaven National Laboratory consists of improving the operational efficiency, reliability and stability of the cryogenic system which also resulted in improved beam quality of the Relativistic Heavy Ion Collider.

This paper presents a summary of the changes made over the four years and the proposed improvements for the future. The work was carried out in several phases by balancing the accelerator’s schedule of operation, time required for the modifications and budget constraints. The main changes include process control, oil removal, piping, elimination of the use of cold compressors, reduction in liquid storage, providing additional multi layer insulation on the in-use liquid helium reservoirs, and the addition of a load “wet” turbine and its associated heat exchangers at the low temperature end of the plant. Changes were also made to the cryogenic flow configuration to eliminate the use of the liquid helium circulators used to circulate the sub-cooled helium through the magnet loops. Future upgrades include the resizing of turbines 5 and 6 to increase their efficiencies.

The paper summarizes the work done to date and the progression of improvements after each upgrade phase, starting from the initial 9.3 MW power usage level to the present 6 MW and the expected level below 5 MW after the completion of the remaining improvements.

C1-P-08 An Overview of the Planned Jefferson Lab 12GeV 2.1 K Helium Refrigerator

***D. Arenius**, J. Creel, K. Dixon, V. Ganni, P. Knudsen, A. Sidi-Yekhlef, M. Wright, , Jefferson Laboratory.*

The US Department of Energy (DOE) has placed Jefferson Lab in Newport News, Virginia, on a path towards a major upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF). In April 2005, the DOE announced "critical decision zero" (CD-0) for the laboratory`s proposal to double the superconducting accelerator`s energy from 6 to 12 GeV, add a fourth experimental hall and upgrade equipment in the three existing halls. This step established the "mission need" and moves the upgrade into a formal project-definition phase. In February 2006, the DOE Office of Science approved “critical decision 1” (CD-1) status for the project.

Operating continuously since 1993, the Jefferson Lab’s current 2.1 K 4600W Central Helium Liquefier (CHL) capacity will be doubled to support the upgrade. An overview of the integration of the new proposed refrigeration system into CEBAF will be presented inclusive of planned work scope, current schedule plans and project status.

This work is supported under DOE Contract Number DE-AC05-06OR-23177

C1-Q MEMS Coolers

C1-Q-01 MicroMiniature Refrigeration

***W.A. Little**, MMR Technologies, Inc. and Stanford University, CA.*

The dramatic growth of industrial cryogenics in the past century has overshadowed the need for cryogenics on a smaller scale. Today, small scale, MEMS or microminiature refrigerators constitute a small part of the field, but one with a unique role to play, often in instrumentation. Key attributes of these coolers have proved to be their small size of course, very low noise, fast response, and low cost. The small size has made possible the integration of the instrument and the cooler, thus providing convenience to the end user. The fast response and low noise have made possible instruments of unique capabilities. We discuss some of these. Opportunities exist for the seamless integration of cryogenics in many other products. In order to succeed here though, a company needs to be more than a simple manufacturer of cryocoolers. Strength is needed in a broad range of disciplines, in materials science, electronics, software and documentation to name a few. In addition, to offset economies of scale, different fabrication technologies have had to be created, and others are needed. Some key elements remain to be developed before more widespread use of this technology will be seen. Better, low cost, manufacturable, miniature heat exchangers and regenerators are needed. Development of miniature or sub-miniature compressors to power the coolers could herald a new world of cooled devices analogous to the revolution created by fractional horsepower electric motors in the past fifty years. Opportunities abound!

C1-Q-02 Heat Transfer Efficiency of Kleemenko Cycle heat exchangers.

***W. A. Little**, MMR Technologies, Inc.*

During the past decade Kleemenko Cycle coolers have been developed to operate at temperatures between 180K and 70K using throttle expansion of multi-component refrigerants. They have demonstrated remarkable reliability – continuous, maintenance-free operation now approaching 100,000hrs, and the simplicity of their design and use of low cost components has kept their cost at a small fraction of that of any other cryocoolers. They have found markets in instrumentation, cooling of X-Ray detectors, in Office liquefiers, Automated Test Equipment, and other devices. However, little attention has been focused on optimizing the efficiency of these coolers. The problem has been the lack of an adequate understanding of the heat transfer of such multi-component mixtures to the walls of the heat exchanger, and to a lesser degree an understanding of the pressure drop along the exchangers. These factors have limited the ability to design more efficient, low cost exchangers needed for improved cryocooler performance. Recently we have made progress in this area allowing calculation of the heat transfer factors under the conditions of use of these exchangers, in reasonable agreement with experiment. We describe this work, discuss the potential improvements to be expected, and identify remaining issues.

I am indebted to my colleagues at MMR for comments and suggestions.

C1-Q-03 Micromachined Joule-Thomson coolers

*P.P.P.M. Lerou, **H.J.M. ter Brake**, H.V. Jansen, J.F. Burger, H.J. Holland, H. Rogalla, University of Twente.*

A MEMS-based Joule-Thomson cold stage was designed and prototypes were realized and tested. The cold stage consists of a stack of three glass wafers. In the top wafer, a high-pressure channel is etched that ends in a flow restriction with a height of typically 300 nm. An evaporator volume crosses the center wafer into the bottom wafer. This bottom wafer contains the low-pressure channel thus forming a counter-flow heat exchanger. A design aiming at a net cooling power of 10 mW at 96 K and operating with nitrogen as the working fluid was optimized based on the minimization of entropy production. The optimum cold finger measures 28 mm x 2.2 mm x 0.8 mm operating with a nitrogen flow of 1 mg/s at a high pressure of 80 bar and a low pressure of 6 bar. A batch of 14 prototype coolers was made in 8 different designs. Liquid nitrogen is collected in the evaporator, and since the low pressure is 6 bar, the temperature should be 96 K. However, because of thermal resistance between the bath and the thermocouple a temperature was measured of 105 K with a net cooling power of 5 mW. In the paper, the design and fabrication of the coolers will be discussed along with experimental results. A specific issue that will be addressed is the clogging of the restriction due to the deposition of ice crystals.

C1-Q-04 Performance of a MEMS Heat Exchanger for a Cryosurgical Probe

***M.J. White**, G.F. Nellis, S.A. Klein, Dept. of Mechanical Engineering, Univ. of Wisconsin-Madison; W. Zhu, Y.B. Gianchandani, Dept. of Mechanical Engineering, Univ. of Michigan-Ann Arbor; D.W. Hoch, Dept. of Mechanical Engineering, Univ. of North Carolina-Chapel Hill.*

This paper presents the experimental results of a 2nd generation Micro-Electro-Mechanical Systems (MEMS) heat exchanger that is a composite of silicon plates with micromachined flow passages interleaved with glass spacers. The MEMS heat exchanger was designed for use as the recuperative heat exchanger within the Joule-Thomson cycle used to energize a cryosurgical probe.
The experimental measurements are compared with the numerical predictions from a design model and also with experimental results obtained from a 1st generation MEMS heat exchanger. The 1st generation heat exchanger was unable to withstand the high pressure differences (1400 kPa) required by a J-T cryosurgical probe. The 2nd generation heat exchanger addresses these design deficiencies and exhibits superior thermal performance. Several prototypes of the 2nd generation heat exchanger have been manufactured and tested over a range of conditions.

This work was funded by the University of Michigan through a grant from the US National Institute of Health, NIH/NINBS R21 EB003349-01.

C1-Q-05 High Frequency Pressure Oscillator for Microcryocoolers

***S. Vanapalli**, Y. Zhao, R. Sanders, H.J.M. terBrake, M.C. Elwenspoek, MESA+ Institute of Nanotechnology, University of Twente.*

Regenerative type of microcryocoolers has to operate at higher frequencies compared to the typical operating frequency of Stirling or Pulse tube coolers owing to higher parasitic losses. Conventional linear motors used in pulse tube cryocoolers cannot be scaled down to frequencies of about 1 KHz due to increase in various losses. Piezo electric motor driven membrane type pressure oscillator provide an alternative choice in going to higher frequencies. In this paper we aim to present the design and operation of a piezo driven oscillator at frequencies of about 1 KHz and a filling pressure of 2.5 MPa. A pressure ratio of about 1.1 is achieved. Modelling of the pressure oscillator and comparison with experiments will also be presented.

STW-Dutch Technology Foundation for financial support

C1-Q-06 Piezo-Hydraulic Actuation for Driving High Frequency Miniature Split-Stirling Pulse Tube Cryocoolers

***I. Garaway**, G. Grossman, Technion - Israel Institute of Technology.*

In recent years piezoelectric actuation has been identified as a promising means of driving miniature Stirling devices. It supports miniaturization, has a high power to volume ratio, can operate at almost any frequency, good electrical to mechanical efficiencies, and potentially has a very long operating life. The major drawback of piezoelectric actuation, however, is the very small displacements that this physical phenomenon produces. This study shows that by employing valve-less hydraulic amplification, an oscillating pressure wave can be created that is sufficiently large to drive a high frequency miniature pulse tube cryocooler (as high as 350 Hz in our experiments, and perhaps higher). Beyond the direct benefits derived from using piezoelectric actuation there are further benefits derived from using the piezo-hydraulic arrangement with membranes. Due to the incompressibility of the hydraulic fluid the actuator may be separated from the main body of the cryocooler by relatively large distances with almost no detrimental effects, and the complete lack of rubbing parts in the power conversion processes makes this type of cryocooler extremely robust. The design and experimental device along with some test results will be presented.

C1-Q-07 Demonstration of a superconducting detector cooled by electron-tunneling refrigerators

***J.N. Ullom**, J.A. Beall, W.D. Duncan, F. Finkbeiner, G.C. Hilton, K.D. Irwin, D.R. Schmidt, L.R. Vale, NIST; N.A. Miller, G.C. O`Neil, NIST/University of Colorado Boulder; D.J. Benford, J.A. Chervenak, S.H. Moseley, R.F. Silverberg, NASA GSFC; T.C. Chen, Global Science and Technology.*

We have successfully cooled a Transition-Edge Sensor (TES) using thin-film, solid-state refrigerators based on Normal metal/Insulator/Superconductor (NIS) tunnel junctions. The cooling mechanism is the preferential tunneling of the highest energy (hottest) electrons through the biased NIS junctions. We describe the cooling performance, temperature noise, and energy resolution of the NIS-cooled TES. In particular, we show that the NIS refrigerators introduce no detectable noise in the TES operation. We also describe ongoing efforts to improve the cooling performance of NIS refrigerators and the ease with which they can be coupled to user-supplied payloads. NIS refrigerators can cool from temperatures near 0.3 K to below 0.1 K. The calculated power dissipation to cool 1,000 thin-film sensors is 1-10 microWatts. Combining a pumped He-3 system with NIS refrigerators provides a compact, lightweight alternative to adiabatic demagnetization refrigerators and dilution refrigerators.

Wednesday, 07/18/07 Plenary 8:00am - 9:00am

C2-A Wednesday Plenary Session

C2-A-01 The COBE Mission: How Cryogenics is Revolutionizing Astronomy and Astrophysics

***J. Mather**, NASA/Goddard Space Flight Center.*

The development of deep cooling for space science applications has enabled an extraordinary series of discoveries in astrophysics, ranging from infrared astronomy to X-ray astronomy and tests of general relativity to observations of the Big Bang itself. I will describe the instrument package and the cooling concepts used on the Cosmic Background Explorer satellite, and the scientific results that led to the Nobel Prize in Physics for 2006. The James Webb Space Telescope, now in preparation for launch in 2013, will use both radiative and active cooling to extend the science of the Hubble Space Telescope and the Spitzer Space Telescope. I will discuss the cooling concepts for these missions and others, and speculate on the future of cryogenics in space science.

Wednesday, 07/18/07 Oral 9:00am - 10:30am

C2-B He II Heat Transfer and Fluid Mechanics - II

C2-B-01 An experimental study of He II two-phase flow in a long horizontal pipe

*M. Takahashi, **T. Kuriyama**, T. Yazawa, I. Watanabe, K. Nakayama, Toshiba Corp.; Y. Ota, T. Okamura, Tokyo Tech.*

Superconductor cavities used in linear collider are cooled below 2K in superfluid helium to enhance the generated electric field. In some linear collider such as planned in the International Linear Collider project (ILC), the cryogenic system will have a considerably long horizontal pipe, more than hundred meters, in which two-phase superfluid helium flows. One of the key issue for the cryogenic design is the gradient of the liquid level in the pipe. It should be designed as small as possible to cause the dry-out at somewhere of the pipe. We have developed a test apparatus of He II two-phase flow in a long pipe. The apparatus is comprised mainly of a He II vessel, a two-phase flow pipe with 4 m in length and 32 mm in diameter, and some cavity vessels. Instead of cavities, electric heaters gave the thermal load. The gradient of the liquid level as a function of the load was measured by using two level meters. The experimental results were compared to numerical results.

C2-B-02 Experimental facility for comparison of high Reynolds number turbulence in both HeI and HeII : first results

***B. Rousset**, M. Bon Mardion, D. Communal, F. Daviaud, P. Diribarne, B. Durbrulle, A. Forgeas, A. Girard, P. Roussel, CEA; C. Baudet, Y. Gagne, P; Thibault, UJF; B. Castaing, ENS; B. Hebral, P. Roche, CNRS.*

Turbulence SuperFluid (TSF) project will use cryogenic liquid helium for the fundamental study of turbulent phenomena. For this purpose we have carried out an experiment of passive grid turbulence which is able to work in HeI as well as in HeII. The flow of liquid helium will be generated by a cold Barber and Nichols circulating pump, whereas helium flow temperature is kept constant by means of a heat exchanger immersed in a saturated bath, which mainly evacuates the heat due to friction.

This experiment will use the CEA Grenoble refrigerator (nominal capacity of 400 Watt at 1.8 K) to remove the heat due to pressures losses in this high Reynolds number experiment. In order to solve the Kolmogorov scale associated with such high flow local instrumentation (e.g. sub-micrometer anemometer) was developed. Use of this local and fragile instrumentation in a quasi industrial environment arises some difficulties we discussed here while the solutions adopted are also described.

Finally, first results obtained both in superfluid and in normal helium are presented. For this last case, a permanent mass flow rate of few hundreds of g/s was achieved.

C2-B-03 Pressure drop and heat transfer in He II forced flow through orifice plates

***H.J. Kim**, S.W. Van Sciver, FAMU-FSU College of Engineering / National High Magnetic Field Laboratory; S. Fuzier, National High Magnetic Field Laboratory.*

Forced flow superfluid helium (He II) through orifice plates at the high Reynolds number has been experimentally investigated. The flow of He II is generated with a bellows pump through a 1 m long, 73 mm inner diameter tubular channel containing three sizes of orifice plates: the ratios of orifice diameter to tube diameter are 10 %, 25 % and 50 %. The experimental channel is instrumented with eight thermometers, a film heater and two differential pressure transducers. Pressure drops in He II for adiabatic forced flow were measured across the orifice plates and compared with correlations for classical fluids at high Reynolds number. The temperature drops in He II forced flow in orifice plates were measured, and found to agree with the isenthalpic expansion. The heat generated by a film heater located three diameters upstream of the orifice plate generates counterflow in the He II resulting in local temperature in the vicinity of the orifice plates. These results are compared to predictions based on the two fluid model.

This work is supported by the Department of Energy, Division of High Energy Physics. Thanks to Scott Maier for technical assistance.

C2--B-04 Extraction of micron-sized particles from a He II bath

*M. Gnos, **S. Fuzier**, S.W. Van Sciver, NHMFL, Florida State University.*

Our laboratory is developing a new technique to separate micron and possibly submicron size particles by size using superfluid helium (He II). A heat current in the He II generates normal fluid flow which in turn drags particles of different sizes into different sections of an experimental channel immersed in a He II bath. In the present paper, we describe a technique developed to extract the particles from the separation channel while it is immersed in the helium bath. In situ extraction allows for a continuous process of separation without having to warm up the cryostat and disassemble the channel. A tube is inserted from the room temperature environment to the area in the channel collecting the particles to be extracted. This tube is closed at the bottom by a multibore tube cylinder and is pumped to a lower pressure that the helium bath. The pressure gradient through the multibore tubes creates a temperature gradient which drives the normal component of the He II and the particles into the tube. The particles can then be collected and extracted by pulling the tube out of the bath. We compare the performance of this device for extraction of polymer and hollow glass sphere particles of sizes varying between 1.7 and 12 micrometers.

Work supported by Oxford Instruments

C2-B-05 3-D Numerical Analysis for Heat Transfer from a Fat Plate in a Duct with Contractions Filled with Pressurized He II

*D. Doi, **Y. Shirai**, M. Shiotsu, Kyoto University.*

A computer code of three-dimensional heat transfer in superfluid helium named SUPER-3D was developed based on the two-fluid model. Critical heat fluxes (CHFs) on a flat plate located at one end of rectangular ducts having contractions with different rectangular open area were calculated by using the SUPER-3D for the liquid temperatures from 1.8 K to 2.1 K in pressurized He II. The analyses were made for the ducts with one contraction (Case A) and with two contractions (Case B). In case A, effects of the open mouth area, distance of the contraction from the flat plate and of the open mouth figure with the same area were clarified. The solutions of CHF for the various open mouth areas agreed well with the experimental data. In Case B, the solutions of CHF for the two contractions with the same open areas were affected by the combination of open mouth figures. It was found from the analysis that several vortices were generated around the contractions and played an important role in determining the CHF. Three dimensional analyses are necessary to evaluate the CHF accurately.

Wednesday, 07/18/07 Poster 9:00am - 10:30am

C2-C Stirling and Pulse Tube Components and Modeling (Aerospace)

C2-C-01 10K EM Pulse Tube Cooler

***C. Jacob**, T. Nguyen, R. Colbert, J. Raab, Northrop Grumman Space Technology.*

A 3 stage Engineering Model pulse tube cooler was built and tested for low temperature operations. The staged cooler uses the same compressor and parallel staging configuration for the 1st and 2nd stages previously employed in the Flight Qualified High Capacity Cryocooler (HCC Qual). Addition of the third stage extends the performance of this cooler to operating temperatures below 10K. The cooler performance at 10K has been characterized and test data will be presented.

C2-C-02 Numerical Study of Thermoacoustically-driven Pulse Tube Cooler
With Spring-Mass Resonators

*W. Dai, **Z. Wu**, S. Zhu, E. Luo, Technical Institute of Physics and Chemistry.*

Thermoacoustically-driven pulse tube cooler could be heat-driven and offer the advantages of being simple and highly reliable. Normal thermoacoustic engines with a long resonance tube to control the frequency face the problems of large thermoviscous dissipation, oversize and structural vibrations, etc, which is not good for practical small-scale applications. One solution is to use dual-opposed spring-mass resonator to replace the resonance tube, which could ensure the compact size, low vibration and remains to be simple on structure. This article uses the linear thermoacoustic theory to simulate such a configuration working at frequencies between 100~500Hz, which aims at small-scale cryogenic applications. The influence of spring-mass resonator parameters, operating conditions, coupling positions and other factors are studied.

This work is financially supported by National Natural Science Foundation with project number 50506031.

C2-C-03 Linear resonant moving magnet type motor for miniature pulse tube cryocooler

***B.T Kuzhiveli**, National Institute of Technology Calicut.*

More than past two decades, voice coil type moving coil linear motors have been in wide use for the
construction of various miniature cryocoolers. However they are haunted by its inherent life limiting problems such as rupture of lead wires, out gassing by the coil lamination etc. A recent tendency is to replace the moving coil type motor with moving magnet type motor for the compressor. Recent advances in miniature pulse tube cryocooler technology have made them surpass most of the miniature cryocoolers operating on other cooling cycles. The reasons attributed for this change are due to the advantages such as improved overall efficiencies, reduced number of moving parts, no vibration in cold head and suitability to use with moving magnet type motor etc. In this context splendid of scope exists for understanding new trade offs in technology of moving magnet type motor, design and evaluation of performance parameters and its comparison with moving coil type motor. A design methodology has been developed for the development of moving magnet and moving coil type linear motors. Computer code has been written down for motor optimisation and has been used for the design of motors.

C2-C-04 An aerospace miniature pulse tube cryocooler at 80K

*H.L. Chen, **L.W. Yang**, J.H. Cai, J.T. Liang, Y. Zhou, Technical Institute of Physics and Chemistry, CAS.*

An engineering model of a miniature pulse tube cryocooler is designed for space application. Coaxial configuration of the cold finger is convenient to connect with the aim element and improves integration. A series of jointing cooler products are manufactured and tested. The overall mass of the whole cooler system is around 3.5kg. The product coolers can provide 0.7W cooling capacity at 80K within 40W input electric power, while the experimental ones can proveide more than 0.8W cooling capacity. To make a product for space application, intense structure, light weight and small size are needed, so different materials and structures et al. decrease the cooling performance more or less. Reliability of the cooler working continously is tested. Also, the magnetic field of the compressor and anti-shake ability of the system has been examined.

C2-C-05 Investigation of a 500Hz heat-driven pulse tube cooler by using etched foil regenerator

*S.L. Zhu, Graduate University of Chinese Academy of Sciences; E.C. Luo, Technical Institute of Physics and Chemistry, CAS; **W. Dai**, Technical Institute of Physics and Chemistry,CAS.*

A thermoacoustically-driven high frequency pulse tube cooler has the advantage of being compact, which has good potential of using for aerospace cooling. This article presents a pulse tube cooler driven by a traveling-wave thermoacoustic engine with a working frequency around 500 Hz. As operating frequency increases, a traditional screen-packed regenerator is limited by the requirement of smaller wire diameter and higher mesh number of the screens. In this pulse tube cooler, however, we have used the etched foil regenerator instead of the screen-packed regenerator to decrease flowing loss, which shows more important impact on the global performance of the whole system when the operating frequency goes up to 500Hz. Experiments has been conducted to investigate the characteristics of the pulse tube, which includes the structure parameters of the novel regenerator and the operating parameters including mean pressure, inlet pressure ratio, inertance tube phase shifter. Numerical simulation results are also made and compared with the experiment results in the same condition.

This work was supported by the Natural Science Foundation of China(Grant No.50625620)

C2-C-06 Performance of a two stage Stirling cryocooler for space applications

*V.K. Bhojwani, M.D. Atrey, **S.L. Bapat**, Indian Institute of Technology Bombay, Mumbai, India; K.G. Narayankhedkar, Veermata Jijabai Technological Institute, Mumbai, India.*

A two-stage, split type Stirling cryocooler with capacity of 2 W at 100 K and 0.5 W at 50 K is designed. Second order cyclic analysis is used to decide the final geometry of the unit. The compressor with opposed pistons configuration is developed. Flexure stacks suspended piston and displacer are used. Moving coil linear motor is developed. Sensors are installed for measuring strokes of pistons and displacer; and pressure at the outlet of the compressor. 10 channel oscilloscope provides the variations of parameters. The load tests indicated that the cooling capacities are close to the design values. The power input for the compressor is 110 W as against 69 W predicted by the analysis. The experimental no load temperature for the stage I is observed to be close to the predicted temperature. Two identical expanders are developed to check the repeatability. For expander I, the temperatures attained for a load of 2 W on stage I and 0.5 W on stage II are 106 K and 74 K respectively with a power input of around 110 W. The corresponding values for expander II are 128 K, 66.7 K with a power input of 105.6 W.

The authors thank Indian Space Research Organisation for financial support.

C2-C-07 A model for the parametric analysis and optimization of inertance tube pulse tube refrigerators

***C Dodson**, A Razani, AFRL/VSSS-UNM; A Lopez, UNM/Sandia National labs; T Roberts, AFRL/VSSS.*

A first order model developed for the design analysis and optimization of Inertance Tube Pulse Tube Refrigerators (ITPTRs) is integrated with the code NIST REGEN 3.2 capable of modeling the regenerative heat exchangers used in ITPTRs. The model is based on the solution of simultaneous non-linear differential equations representing the inertance tube, an irreversibility parameter model for the pulse tube, and REGEN 3.2 to simulate the regenerator. The integration of REGEN 3.2 is accomplished by assuming a sinusoidal pressure wave at the cold side of regenerator. In this manner the computational power of REGEN 3.2 is conveniently used to reduce computational time required for parametric analysis and optimization of ITPTRs. The exergy flow and exergy destruction (irreversibility) of each component of ITPTRs is calculated and the effect of important system parameters on the second law efficiency of the refrigerators is presented.

C2-C-08 Reliability Growth of Stirling-Cycle Coolers at L-3 CE

*D.T. Kuo, **A.S. Loc**, Q.K. Phan, L-3 Communications - Cincinnati Electronics.*

L-3 Communication is conducting a reliability growth program to extend the life of tactical Stirling-cycle cryocoolers. The continuous product improvement processes consist of testing production coolers to failure, determining the root cause, incorporating improvements and verification. The most recent life test data for the 0.6-Watt Cooler (Model B600C), The 1.5-Watt Cooler (Model B1500E), and the Gas Bearing 1.0-Watt Cooler (Model GB1000E) are presented. From the life test data, sets of empirical constants are derived for life prediction, for any operating condition using the Watt-Hour approach. The data presented here extends the boundary of life data in previous papers from the authors.

C2-C-09 Performance Optimization of L-3 CE 0.6-Watt Linear Cooler

*D.T. Kuo, **A.S. Loc**, L-3 Communication - Cincinnati Electronics.*

Tactical FLIR are placing increasing demand for cryocoolers to deliver more performance without commensurate size and weight allowances. L-3 CE has re-optimized the design of its 0.6-Watt cooler to provide twice the refrigeration lift without significant changes to weight and size. This paper presents the performance characteristics of the re-optimized cooler model B610.

C2-D Large Scale Aerospace Test Facilities

C2-D-01 Large-Scale Test Facility for Advanced Cryogenic and Energy Technology Development

***W.H. Hatfield**, Sierra Lobo, Inc.; D.E. Taylor, J.P. Sass, NASA KSC.*

NASA has completed initial construction and verification testing of the Integrated Systems Test Facility (ISTF) Cryogenic Testbed. The ISTF is located at Complex 20 at Cape Canaveral Air Force Station, Florida. The remote and secure location is ideally suited for the following functions: (1) development testing of advanced cryogenic component technologies, (2) development testing of concepts and processes for entire ground support systems designed for servicing large launch vehicles, and (3) commercial-sector testing of cryogenic- and energy-related products and systems. The Cryogenic Testbed consists of modular fluid distribution piping and storage tanks for liquid oxygen/nitrogen (56,000 gal) and liquid hydrogen (66,000 gal). Storage tanks for liquid methane (41,000 gal) and Rocket Propellant 1 (37,000 gal) are also specified for the facility. A state-of-the-art blastproof test command and control center provides capability for remote operation, video surveillance, and data recording for all test areas.

C2-D-02 Cryogenic Propellant Tank Facility (K-SITE) at NASA`s Plum Brook Station

*J.A. Chambers, **D.E. Taylor**, J.M. Woytach, NASA GRC.*

The Cryogenic Propellant Tank Facility is multipurpose cryogenic and space simulation test facility. The 25 foot diameter test chamber has a 20 foot diameter door, removable LH2/LN2 cryogenic cold wall capable of simulating deep space temperatures down to 37deg R (-423deg F) and a unique hydraulic shaker system. The facility can provide vacuum to 10-6 torr without the cold wall and 10-8 torr with the cold wall in operation. An 800-gallon slush hydrogen batch production plant is also available. The facility's design and construction provides a safe environment for testing with high energy fluids. K-Site is ideally suited for performing a broad range of cryogenic experiments including performance testing of sensors and insulation systems, cryogenic storage tank boil-off and slosh tests, turbopump chill-down and start-up tests, Lunar surface simulation, and fuel cell development tests. The versatility of K-Site makes the possibilities almost endless. Build-up is supported by an on-site machine shop, rough build area and 40-foot high-bay immediately adjacent to the test chamber. A highly trained and competent technical staff is on-site to provide design, fabrication, installation and operations support. A large exclusion zone surrounding K-Site makes it ideal for high-risk propellant related programs.

C2-D-03 The Cryogenic Components Laboratory (CCL) at NASA`s Plum Brook Station

*J.A. Chambers, **D.E. Taylor**, J.M. Woytach, NASA GRC.*

The Cryogenic Components Laboratory is a new, state-of-the-art facility for research, development and qualification of cryogenic materials, components and systems. This facility provides systems and capabilities for cryogenic testing with liquid hydrogen, oxygen and nitrogen. These systems are highly re-configurable to meet a broad range of test requirements and parameters. A highly trained and competent technical staff is on-site to provide design, fabrication, installation and operations support. Run tank capacities and high gaseous nitrogen flow rates make the facilities well suited for cryogenic high-speed turbomachinery, bearing and seal testing. Large on-site storage capacities provide capability for extended run times. The facility's electrical design classification provides a safe environment for testing with high energy fluids. Liquid hydrogen and liquid oxygen densification skids capable of densifying propellants at rates up to 8 pounds-per-second are available. The state-of-the-art control room provides remote data acquisition and programmable logic control (PLC) for personnel and systems safety. The dual configuration design of the facility allows for build-up and operation of multiple simultaneous users. A large exclusion zone surrounding the CCL makes it ideal for high-risk propellant related programs.

C2-D-05 Large Cryogenic System for Space Environment Simulation

***H. Cho**, G.-W. Moon, H.-J. Seo, S.-H. Lee, S.-W. Choi, Korea Aerospace Research Institute.*

KARI (Korea Aerospace Research Institute)'s thermal vacuum chamber with 9 meters diameter and 10 meters depth was completed at the end of November 2006 being equipped with large cryogenic system for space environment. Cryogenic system enables a thermal shroud inside the vacuum chamber to be cooled down to 77 K with liquid nitrogen, which provides surrounding deep space environment for a satellite. This cryogenic system basically utilizing gravitational potential energy of stored liquid nitrogen in 10 meters height, is composed of phase separator, liquid nitrogen pump, cryogenic valve, vacuum jacketed pipes, liquid nitrogen exhaust system, and heated gaseous nitrogen purge system. Through several acceptance tests for the cryogenic system, it was verified that thermal shroud can be cooled from 295 K to 77 K within 30 minutes, temperature drift when the shroud is in steady condition is less than 2 K. Liquid nitrogen exhaust system and heated gaseous nitrogen purge system made an improvement for reducing of the time to increase the chilled shroud temperature up to ambient temperature, which could shorten the total satellite test duration. Test results and detail specifications of the cryogenic system including liquid nitrogen boil-off and consumption were described.

C2-D-06 The Development of the Cooling and Heating Device in the Test Facility for Space Tribological Simulation Experiment

***L.H. Gong**, X.D. Xu, R.J. Huang, L.F. Li, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences; X.J. Sun, W.M. Liu, Space Tribology Center, Lanzhou Institute of Chemical Physics,Chinese Academy of Sciences.*

The cooling and heating device in the test facility for space tribological experiment has been developed and tested. The device consists of a sample holder, a heater and an annular liquid nitrogen heat sink. The sample holder surrounded by a heater is located in the core of the heat sink. The holder, heater and heat sink, which almost have no any heat conduction among them, are closed in the high vacuum vessel (10E-7Pa). Therefor, the principle of the radiation heat transfer has been adopted for cooling and heating of the tribological sample because of the rotation of the sample holder which is connected to a long axes driven by the magnetic force. Some techniques have been introduced into the design in order to speed up the cool down rate of the sample, such as, the surface of the heater and the inside surface of the annular heat sink have been blacked and the special material and unique structure have been used for the axes of the sample holder.

Test results show that the highest heating temperature can be about 600K, and the lowest cooling temperature can reach around 130K. The cooling time is roughly two days. The sample temperature can be stabilized at any point with accuracy of 0.2K in the range of 130~600K. The heat transfer analysis, temperature control & display and test results of the cooling and heating device have been presented. And some considerations have been discussed to improve the slow cool down rate in the future.

C2-E Regenerators

C2-E-01 A Low-Temperature Regenerator Test Facility

***A. Kashani**, B.P.M. Helvensteijn, Atlas Scientific; J.R. Feller, L.J. Salerno, NASA-Ames Research Center; P. Kittel, Consultant.*

Testing regenerators presents an interesting challenge. When incorporated into a cryocooler, a regenerator is intimately coupled to the other components. It is difficult to isolate the performance of any single component. We have developed a low temperature test facility that separates the performance of the regenerator from the rest of the cryocooler. The purpose of the facility is the characterization of test regenerators using novel materials and/or geometries in temperature ranges down to 15 K. The test column consists of two regenerators stacked in series. The coldest stage regenerator is the device under test. The warmer stage regenerator consists of a stack of well-characterized material such as stainless-steel screen. A commercial cryocooler is used to cool the heat exchangers in the regenerator stack. The cryocooler is used to fix the temperatures at both ends of the test regenerator. Heaters on each cryocooler stage add the capability to vary the temperatures and allow measurement of the remaining cooling power, and thus, regenerator effectiveness. A linear compressor delivers an oscillating pressure to the the regenerator assembly. An inertance tube and reservoir provide the proper phase difference between mass flow and pressure. This phase shift, along with the imposed temperature differential, simulates the conditions the test regenerator might see when used in an actual cryocooler. This paper presents development details of the regenerator test facility.

C2-E-02 Hybrid Regenerator for Compact Stirling Cryocooler Design aspectes of a compact hybrid regenerator for pulse tube cryocooler application

B.T. Kuzhiveli, *National Inst. of Technology Calicut.*

A study has been conducted to find out the optimum configuration of regenerators to be used for miniature cryocoolers. Mesh sizes starting with 200 up to 400 with an interval of 50 have been sampled and performance estimation has been made. The study has been extended to determine the performance of a hybrid regenerator and its suitability to use in a cryocooler which can produce 5W at 80 K. A methodology has been developed to arrive at the appropriate mesh size and number of mesh to be used in the hybrid regenerator to go hand in hand with the available mass. Results are presented in the form of design charts for quick reference which could be helpful in the design of miniature regenerators.

C2-E-03 Dynamic characteristics of oscillating flow regenerators

H.L. Chen, ***L.W. Yang***, *J.H. Cai, J.T. Liang, Y. Zhou, Technical Institute of Physics and Chemistry, CAS.*

Regenerator is the most important component in a pulse-tube cryocooler. Because of oscillating flow, heat transfer and flow resistance in the regenerator are complex, and phase shifts between parameters affect the cooling performance evidently. Regenerator research is a fundamental work for cryocoolers. Experiments are performed to test regenerators of different size filled with different mesh number screens. Two fine hot-wire anemometers are used to measure the instantaneous velocities at the inlet and outlet of the regenerators, and the pressure waves are measured by piezoelectric pressure transducers at the same positions. The responding frequency of the measuring system is high enough.
In the past, we have performed experiments to study the oscillating flow at around 50Hz.In this paper, the system is driven by a thermoacoustic engine which generates a pressure wave at 300Hz. The two kinds of results are compared and analyzed.

C2-E-04 Analysis of Cryogenic Regenerator for Magnetic Refrigerator Applications

B.T. Kuzhiveli, *National Institute of Technology Calicut; R. Chahine, T.K Bose, Institut de recherche sur l'hydrogène, Université du Québec; C.B. Zimm, Astronautics Corporation of America.*

Magnetic refrigeration uses the temperature and field dependence of the entropy of specific magnetic materials to accomplish cooling. Because of the high efficiency of the magnetization and demagnetization processes and also because of the potential for excellent heat transfer between solid magnetic material and fluids, magnetic refrigerators may promise to have higher efficiency than existing gas cycle refrigerators. Many ground based and space borne applications could benefit significantly from the cost savings implied by efficiency. This paper deals with a basic computational model which could predict the temperature drop caused by the regenerator effect. It solves partial differential equations that describe fluid flow combined with heat transfer between fluid and solid regenerator particles. Temperature changes are calculated for discrete material segments at a number of time intervals over a complete operation cycle. A numerical step-by-step procedure to solve the differential equations describing the regenerative heat exchanger is set out and a computer program has been made to predict performance of the regenerator.

C2-E-05 Second-Law Analysis and Optimization of Regenerators Using REGEN 3.2

A.J. Lopez, *The Univ. of Nex Mexcio; Sandia Nat`l Laboratories; C. Dodson, A. Razani, The Univ. of New Mexico; Air Force Research Lab..*

In most Stirling and pulse tube refrigerators the regenerative heat exchanger is the major contributor to the irreversibility of the refrigerators. Exergy analysis is a convenient method to quantify the losses in regenerators. NIST Code REGEN 3.2 provides a powerful tool to quantify exergy flow in the regenerators to evaluate the exergy destruction (irreversibility) due to heat transfer and fluid friction. The effect of important parameters, with emphasis on the phase shift between the pressure and the mass flow rate at the cold side of regenerator, on the exergetic efficiency and the important components of exergy destruction in the regenerator is presented. The efficiency of the regenerator based on exergy analysis is compared to other methods of evaluating regenerator performance. The ability of the code to quantify the exergy flow and destruction at low temperatures where the ideal gas assumption is not applicable is discussed.

C2-E-06 Longitudinal Hydraulic Resistance Parameters of Cryocooler and Stirling Regenerators in Steady Flow

W.M. Clearman, *S.M. Ghiaasiaan, P.V. Desai, G.W. Woodruff School of Mechanical Engineering Georgia Institute of Technology.*

The results of an ongoing research program aimed at the measurement and correlation of anisotropic hydrodynamic parameters of widely-used cryocooler regenerator fillers are presented. The hydrodynamic parameters associated with steady, longitudinal flow are addressed in this paper. An experimental apparatus consisting of a cylindrical test section packed with regenerator fillers is used for the measurement of axial permeability and Forchheimer coefficients, with pure helium as the working fluid. The regenerator fillers that are tested include stainless steel 400-mesh screens with 69.2% and 62% porosity, stainless steel 325-mesh screens with 69.2% and 62% porosity, stainless steel 400-mesh sintered filler with 62% porosity, and stainless steel sintered foam metal with 56% porosity. The test section is subjected to a steady flow of helium at one end, and is open to the atmosphere at the other end. The instrumentation includes pressure transducers and a high-precision flow meter. For each filler material, time histories of local pressures at inlet to the regenerator are measured under steady flow conditions over a wide range of flow rates. A CFD assisted methodology is then used for the analysis and interpretation of the measured data. The permeability and Forchheimer parameter values obtained in this way are then correlated in terms of the relevant dimensionless parameters.

Wednesday, 07/18/07 Oral 10:30am - 11:45am

C2-G Low Temperature Superconducting Magnet Systems III

C2-G-01 ATLAS Superconducting Magnet System Status of Completion

***H.H.J. Ten Kate**, CERN.*

The superconducting magnet system of the ATLAS Detector at CERN comprises a Barrel Toroid, two End-Cap Toroids and a Central Solenoid and it provides the magnetic field for the muon- and inner detectors, respectively. The huge Barrel Toroid with outer dimensions of 25m length and 20m diameter is built up from 8 identical racetrack coils, each of them already unique in size. The coils are wound with an aluminium stabilised NbTi conductor and operate at 20.5kA at 3.9T peak magnetic field in the windings. The coils, in total 370 tons of cold mass, are conduction cooled at 4.8K by circulating forced flow helium in cooling tubes attached to the cold mass. The two End Cap Toroids are smaller sized, still 11m in diameter and 5m in height, essentially made with the same superconductor and operates also at 20.5kA. The Central Solenoid has dimensions of 2.4m diameter and 5.7m length. The stored energy of the magnet system is 1.5GJ at nominal current. After the successful on-surface acceptance tests, the 8 coils of the Barrel Toroid and the Solenoid were installed in the ATLAS cavern 100m underground. The magnets were successfully charged to full field in autumn 2006. The two End Cap Toroids were completed in spring 2007 and are taken into operation as well thereby completing this very challenging magnet system. The status of project in its nearly completed state as well as the first experience with testing and operation of the system in the underground cavern is reported.
This research is financed by the funding agencies and laboratories working together in the ATLAS Collaboration.

C2-G-02 Series-Produced Helium II Cryostats for the LHC Magnets: Technical Choices, Industrialization, Costs

***A. Poncet**, V. Parma, CERN AT-MCS.*

Assembled in 8 continuous segments of approximately 2.7 kms length each, the He II cryostats for the 1232 cryodipoles and 474 Short Straight Sections (SSS housing the quadrupoles) must fulfill tight technical requirements .They have been produced by industry in large series according to cost-effective industrial production methods to keep expenditure within the financial constraints of the project, and assembled under contract at CERN.
The specific technical requirements of the generic systems of the cryostat (vacuum, cryogenic, electrical distribution, magnet alignment) are briefly recalled, as well as the basic design choices leading to the definition of their components (vacuum vessels, thermal shielding, supporting systems, interconnection elements). Early in the design process emphasis was placed on the feasibility of manufacturing techniques adequate for large series production of components, optimal tooling for time-effective assembly methods, and reliable quality assurance systems.
An analytical review of the costs of the cryostats from component procurement to final assembly and tests is presented and compared with initial estimates, together with an appraisal of the results and lessons learned.

C2-G-04 Design, production and first commissioning results of the electrical feedboxes for the LHC

*A. Perin, A. Ballarino, V. Benda, A. Bouillot, S. Claudet, R. Folch, M. Genet, S. Koczorowski, L. Metral, J. Miles, L. Serio, Ph. Trilhe, R. van Weelderen, CERN; K. Polkovnikov, **V. Zhabitskiy**, IHEP, Russia.*

A total of 44 CERN-designed cryogenic electrical feedboxes are needed to power the LHC superconducting magnets. The feedboxes include more than 1000 superconducting circuits fed by high-temperature superconductor and conventional current leads with currents ranging from 120 A to 13 000 A. In addition to supplying the electrical current to the magnet circuits, they also ensure specific mechanical and cryogenic functions for the LHC. The paper focuses on the main design aspects and related production operations, and gives an overview of specific technologies employed. Results of the commissioning of the feedboxes in the first LHC sectors are presented.

C2-G-05 Quench Performance of Nb3Sn cos-theta coils made of 108/127 RRP Strands*

***R. Bossert**, G. Ambrosio, N. Andreev, E. Barzi, R. Carcagno, V.S. Kashikhin, V.V. Kashikhin, M. Lamm, F. Nobrega, I. Novitski, Yu. Pischalnikov, M. Tartaglia, D. Turrioni, R. Yamada, A.V. Zlobin, Fermilab.*

Fermilab is developing a new generation of high field accelerator magnets based on Nb3Sn shell-type coils and the wind-and-react technology. The high performance Nb3Sn strand produced by Oxford Superconducting Technology (OST) using the Restack Rod Process (RRP) is considered at present time as a baseline conductor for the model magnet R&D program. To improve the strand stability in the current and field range expected in magnet models, the number of sub-elements in the strand was increased by a factor of two (from 54 to 108), which resulted in a smaller effective filament size. The performance of the 1.0 mm strands of this design was extensively studied using virgin and deformed strand samples. Rutherford-type cables made of this strand were also tested using a superconducting transformer and small racetrack coils. Based on the positive results of strand and cable tests, two shell-type dipole coils were fabricated and tested using a magnetic mirror configuration. This paper describes the parameters of the 108/127 RRP strand and cables, and reports the results of strand, cable and coil testing.
**This work was supported by the U.S. Department of Energy*

C2-H Heat Transfer - I

C2-H-02 Thermal conductivity of subcooled liquid hydrogen

*T.M.F Charignon, D. Celik, NHMFL-Cryolab; A. Hemmati, **S.W. Van Sciver**, NHMFL-Cryolab .*

Here we present thermal conductivity measurements of subcooled equilibrium liquid hydrogen in the temperature range from 15 to 23 K and under pressures up to 1 MPa. The measurements have been done in a horizontal, guarded, flat-plates calorimeter. One dimensional heat transfer between the hot and the cold plates of the calorimeter is achieved by surrounding the calorimeter plates with two thermal guards. Capacitance measured between the calorimeter plates gives a precise and accurate gap value for the test cell. A two-stage Gifford-McMahon cryocooler provides the cooling power to the calorimeter. The absolute temperatures are monitored using platinum resistance thermometers calibrated against the saturated vapor-pressure line of equilibrium hydrogen. Results reported in this paper are compared to data published earlier. The density dependence of thermal conductivity is expected to be especially useful for subcooled hydrogen transport properties.
This research has been supported by NASA through the Research Initiative for Florida Universities under the grant NAG3-2751. We acknowledge technical support from Scott Maier.

C2-H-03 Viscous Energy Dissipation in Frozen Cryogens

***S.J. Meitner**, J.M. Pfotenhauer, M.R. Andraschko, University of Wisconsin-Madison.*

ITER is an international research and development project with the goal of demonstrating the feasibility of fusion power. The fuel for the ITER plasma is injected in the form of frozen deuterium pellets; the current injector design includes a batch extruder, cooled by liquid helium. A more advanced fuel system will produce deuterium pellets continuously using a twin-screw extruder, cooled by a cryocooler. One of the critical design parameters for the advanced system is the friction associated with the shearing planes of the frozen deuterium in the extruder; the friction determines the required screw torque as well as the cryocooler heat load.
An experiment has been designed to measure the energy dissipation associated with shearing frozen deuterium. Deuterium gas is cooled to its freezing point in the gap between a stationary outer cylinder and a rotating inner cylinder. The dissipation is measured mechanically and through calorimetric means. The experiment has also been used to measure dissipation in other cryogens (e.g., hydrogen and nitrogen) as a function of rotational velocity and temperature. This paper describes the design and construction of the experiment and presents measurements over a range of cryogens and test conditions.
This work is supported by the U.S. Department of Energy.

C2-H-04 Study on thermal diffusion in artificial air near the critical point

*A Nakano, **T Maeda**, AIST.*

AIR is absolutely essential for our everyday life and also very important in the field of industry. The major part of it is composed of nitrogen and oxygen. We investigated the soret effect in artificial air, which was nitrogen-oxygen binary mixture with the composition of 0.791 mole fraction of nitrogen and 0.209 mole fraction of oxygen near the critical point. In the case of the artificial air, the Max.-Condentherm (MC) temperature and the MC pressure are 131.532 K and 3.65187 MPa, respectively. The critical temperature and the critical pressure are slightly lower than the MC temperature and the MC pressure. We carried out the experiments by using a single stage two-chamber cell, which was divided by a porous diaphragm. We made a temperature difference between the two chambers. After an experiment had run for sufficient time to reach steady state, the concentration of oxygen in each chamber was measured by using a gas chromatograph. From the experiments, we observed that the thermal diffusion factor showed a strong drop near the critical point. The thermal diffusion ratio indicated negative and behaved as 3He-4He mixture. There has been no report that the thermal diffusion ratio of the nitrogen-oxygen system behaves just like the mixture of such substances. We discuss the thermal diffusion in the nitrogen-oxygen binary mixture near the critical point.

C2-H-05 Thermal Conductivity of Powder Insulations Below 80 K

***M.N. Barrios**, Y.S. Choi, S.W. Van Sciver, National High Magnetic Field Laboratory.*

The thermal conductivity of powder insulating materials was measured at average temperatures ranging from 30 K to 80 K. The measuring device consists of two closed, concentric cylinders which are suspended inside of a cryostat. The insulation being tested is filled into the annular space between the cylinders. A single stage Gifford-McMahon cryocooler is thermally anchored to the outer cylinder and used to cool the apparatus to a desired temperature range. A heater mounted on the inner cylinder generates uniform heat flux through the insulating material between the two cylinders. Fourier's law of heat conduction is used to relate the temperature difference between the two cylinders and heating power to a bulk effective thermal conductivity of the powder insulation. Data is collected for aerogel beads and glass bubbles at temperatures between 30 K and 80 K. Using the measured thermal conductivity, we obtain the temperature distribution in the powder insulation by solving the one-dimensional heat diffusion equation.
This research is supported by NASA-Kennedy Space Center under contract NAS1003006.

C2-H-06 Thermal Conductivity as a Function of Contact Pressure, Temperature, and Interface Material

***B.C. Jackson Sr.**, Everson Tesla Inc..*

The purpose of this study is to determine the thermal conductivity between two copper surfaces as a function of contact pressure and interface material at a range of cryogenic temperatures between 4K and 100K. The study differs from previous work in that it utilizes extended contact pressures and temperatures. This study is needed to enable researchers and members of industry to reach improved levels of joint performance required for the operation of novel and existing devices including superconducting magnet cryostats. The test apparatus utilizes a 2-Stage 4.2K GM cryocooler system in conjunction with load adjusting devices to accurately adjust the contact force between the cryocooler stages and the interface plates. Various types of material will be used between the two contact surfaces to make up for surface imperfections including Apezion-N grease and indium foil. A series of tests will be conducted at specified values of contact force and interface material type. Heat applied to the interface is continuously varied and the temperature measured. A family of curves will be constructed in order to determine the thermal conductivity as a function of contact pressure, temperature and interface material. The beneficial result of this study will be the economical construction of high performance low temperature interfaces.
David M. Rakos Co-Author

C2-I Aerospace Mission Cooling Systems

C2-I-01 The NICMOS Cooling System – 5 Years of Successful On-Orbit Operation

*F.X. Dolan, **M.V. Zagarola**, Creare Inc.; W.L. Swift, Consultant.*

The NICMOS Cooling System consists of a closed loop turbo-Brayton cryocooler coupled with a cryogenic circulator that provides refrigeration to the Near InfraRed Camera and Multi Object Spectrometer (NICMOS) on the Hubble Space Telescope (HST). The cryocooler rejects heat to space through a capillary pumped loop connected to radiators mounted on the side of the telescope. The system was deployed and integrated with NICMOS by astronauts during STS – 109 (Space Shuttle Columbia) in April 2002. It has operated continuously without performance degradation since that time, maintaining NICMOS detectors at a constant temperature of 77 K. Miniature, high-speed turbomachines are used in the cryocooler and the circulator loop to provide vibration-free, long-life operation. A small centrifugal compressor and miniature turboalternator are key elements of the closed loop cryocooler. A miniature cryogenic centrifugal circulator in a separate pressurized neon loop transports heat from the NICMOS instrument to the cryocooler interface heat exchanger. This paper describes the development of the system, including key operational features, ground and orbital tests prior to its on-orbit integration with NICMOS, and operational results during its five-year operational history on orbit.

C2-I-02 The first European turbo-Brayton cooler in-orbit: experience gained after one year in flight and future applications for space

***P. Crespi**, J. Guichard, Air Liquide; M.N. de Parolis, ESA; J. Chegancas, Astrium.*

In the frame of a contract granted by the European Space Agency and ASTRIUM, AIR LIQUIDE has developed the first European turbo-Brayton cooler for a space application. This cooler was successfully powered on in the International Space Station in July 2006 and has been running since then. This paper presents the design of the cooler and recalls the main milestones of the development/qualification process. The experience gained on the behaviour of the cooler during this one year of operation is presented. We also discuss the possibility to extend the on-orbit lifetime of the cooler from two years up to seven years. Finally, a survey of potential applications of turbo-Brayton coolers for space are presented, ranging from zero boil-off systems for future launchers to In-Situ Resource Utilization (ISRU) systems and focal plane unit cooling for astronomical satellites.

C2-I-03 Planck Passive Cooler Design, Test and Performance

***E. Gavila**, J.B. Riti, D. Valentini, Alcatel Alenia Space; C. Damasio, ESA.*

Planck Spacecraft, as part of the 4th cornerstone Herschel Planck ESA mission, is dedicated to the Cosmic Microwave Background mapping. Planck and Herschel satellites will be launched early 2008 on a single ARIANEV launcher and inserted into the Lagrange2 point of the Earth-Sun system. One of the main features of Planck lies in its cryogenic chain, made of a 60K passive cooler, a 20K H2 sorption cooler, a Joule Thomson 4K He4 cooler and finally a 0.1K He3He4 dilution cooler. Thermal aspects, and in particular those related to the Passive Cooler, drive in a large part the S/C architecture as well as its verification approach. The Passive Cooler is given contradictory tasks to cool large Telescope items and to locally heat sink active Coolers at 60K. The architecture achieving thermal requirements is a black painted open honeycomb surface insulated from the warm spacecraft by a set of angled shields opened to cold space. Detailed modelling was needed to support conception phase and to predict flight and test thermal behaviours. Mathematical model had furthermore to be populated by material properties data over the 300K-50K temperature range.

All analytical and design efforts, carried on the specimen and on a dedicated test facility, converged eventually to a satisfactory match between predictions and measurements, confirming both mathematical model reliability and Passive Cooler high performance.

C2-I-04 Mid InfraRed Instrument (MIRI) Cooler Subsystem Prototype Demonstration

***D. Durand**, R. Colbert, C. Jaco, M. Michaelian, T. Nguyen, M. Petach, J. Raab, , Northrop Grumman.*

The Cooler Subsystem for the Mid InfRared Instrument (MIRI) of the James Webb Space Telescope (JWST) features a 6 Kelvin Joule-Thomson (JT) cooler pre-cooled by a three-stage Pulse Tube (PT) cryocooler to provide 65 mW of cooling at the instrument. MIRI's 6 Kelvin cooling load, directly behind the primary mirror of JWST, is remote from the location of the compressors and pre-cooler. This distance, and the parasitic heat load on the refrigerant lines spanning it, is accommodated by the design. The effort during 2006 has focused on the demonstration of a MIRI Cooler prototype in the relevant environment, required to achieve Technology Readiness Level 6 (TRL 6) as defined by NASA. Performance when exposed to key aspects of the relevant environment, launch vibration and simulated thermal-vacuum during operation, will be discussed.

This work is funded by NASA and managed by the California Institute of Technology, Jet Propulsion Laboratory.

C2-I-05 ABI Active Cooler Subsystem

***S.W. Clark**, A.L. Hensley, S.R. Farringer, C.L. Bornkamp, P.G. Ramsey, ITT Space Systems.*

The Active Cooler Subsystem is responsible for providing cryogenic cooling of the focal planes of the Advanced Baseline Imager (ABI) instrument. Main components include primary/redundant two-stage pulse tube cryocoolers, flexible thermal straps, vacuum housing components and a flexible bellows.

This paper presents design, analysis, performance and test details of the ABI Active Cooler Subsystem. Each cryocooler incorporates an integral HEC pulse tube cooler and a remote coaxial cold head that are required to provide 2.27W of cooling at 53K and 5.14W of cooling at 183K. The structural performance of the four unique flexible aluminum foil thermal straps range from 0.15 to 5.0 N/mm of mechanical flexibility. The thermal conductance requirements of the thermal straps are 0.71 W/K @ 53K and 0.37 W/K at 183K. The vacuum housing, pseudo-kinematic mounts and related components provide structural support for on-orbit environments, survival of launch loads, CTE compliance, contamination control and ground bench testing. Test data will be included for several components including cryocooler vibration, cryocooler off-state thermal loads and thermal strap conductivity, vibration transmissibility and load deflection.

ITT leads the Advanced Baseline Imager (ABI) team as the prime contractor and has overall responsibility for the program development effort. ABI is a NASA administered contract.

C2-I-06 WISE Solid Hydrogen Cryostat Design Overview and Build Status

*L. Naes, Lockheed Martin Advanced Technology Center; **B. Lloyd**, Space Dynamics Laboratory; S. Schick, Practical Technology Solutions.*

The Wide-Field Infrared Survey Explorer (WISE) is a MIDEX mission that is being developed by the Jet Propulsion Laboratory (JPL) to address several of NASA's Astronomical Search of Origins (ASO) objectives. The WISE instrument, developed by the Space Dynamics Laboratory (SDL), includes a cryogenically-cooled telescope operating at < 13K, and four focal plane assemblies, two of which operate at 7.8K. Cooling of the instrument is accomplished by a dual-stage solid hydrogen cryostat that is developed by the Lockheed Martin Advanced Technology Center (LM-ATC).

This paper provides an overview of the WISE cryostat design and thermal support system along with a status of the flight system build.

C2-K Large Scale Refrigerators and Liquefiers - III

C2-K-01 Mal-distribution in a 20K Helium Refrigeration System Heat Exchanger

***J.A Crabtree**, Oak Ridge National Laboratory; G.N. Gottier, Cryo Technologies.*

The Hydrogen Moderator System at the Spallation Neutron Source utilizes a 7.5kW Helium Refrigerator to cool three circulating loops of supercritical hydrogen at a nominal temperature of 20K. When this system was originally commissioned, it was discovered that the refrigerator's capacity was not stable at design operating conditions. Contrary to conventional wisdom, the system appeared to operate more stably and sustained a higher capacity at a lower compressor suction pressure. When the suction pressure was increased to design conditions, the turbine outlet temperature would initially drop but the warm and cold end delta T's would substantially increase. The refrigeration capacity, as measured by the commissioning heater, would rise with increased suction pressure to a peak and then quickly dissipate. A number of common problems were investigated to no avail. At the outset, it was assumed that the stable conditions observed at the lower suction pressure would allow continuous operation at a reduced capacity. When the system was operated for a period of three weeks, however, it was discovered that the capacity actually slowly degrades with time. This degradation was easily documented by tracking the heater power as well as the heat exchanger's ever increasing delta T's. A number of diagnostic tests were performed that ultimately led to a modification of all of the heat exchanger's headers. A summary of the analyses, diagnosis, repair, and results are provided.

C2-K-02 Improvements of helium liquefaction/refrigeration plants and applications

***HP. Wilhelm**, K-H. Berdais, Th. Ungricht, Linde Kryotechnik AG.*

Design features of a new generation of helium liquefiers and refrigerators with liquefaction capacities ranging from 30 to 280 l/h LHe (respectively refrigeration capacities from 100 to 900 Watt @ 4.5K) are presented. The new generation shows an increased efficiency due to improved turbine and heat exchanger designs. Other benefits of the new design are shortened cool-down times, a very compact design and better flexibility and process control. The modular setup using standardized components covers a wide range of applications including refrigeration at different temperature levels or simultaneous liquefaction and refrigeration. The presentation will highlight the individual improvements in the design.

During the presentation the influence of certain parameters like power requirement and cold box inlet pressure in relation to the liquefaction and refrigeration capacities shall be shown and discussed.

C2-K-03 Evolution of the standard helium liquefier and refrigerator range designed by Air Liquide Advanced Technology Division, France

***A. Caillaud**, S. Crispel, V. Grabié, F. Delcayre, G. Aigouy, Air Liquide DTA.*

The standard helium liquefier and refrigerator range, called HELIAL and designed by Air Liquide DTA, has recently been upgraded in order to improve the efficiency of these machines. Indeed in the multi-range of markets requiring these cryogenic systems, (international laboratories, aerospace applications, synchrotrons, HTS applications...), the technological solution has to provide increasingly high performances. The new HELIAL Evolution range, equipped with very reliable DTA turbo-expanders, will constitute a highly efficient product for this wide application field. The optimizations, adaptations and results of the HELIAL Evolution series, doubling the performance for the same electrical consumption, will be presented.

C2-K-04 Cryocooler for Air Liquefaction Onboard Large Aircraft

***J.J. Breedlove**, P.J. Magari, Creare Inc.; G.W. Miller, Air Force Research Laboratory.*

Creare has developed a turbo-Brayton cryocooler designed to produce approximately 1 kW of refrigeration at 95 K. The cryocooler is intended to provide cryogenic cooling to an air separation system being developed for the Air Force to produce and store liquid oxygen and liquid nitrogen onboard large aircraft. The oxygen will be used for high-altitude breathing and medical evacuation operations, while the nitrogen will be used to inert the ullage space inside the fuel tanks. The cryocooler utilizes gas bearings in the turbomachines for long life without maintenance, which is a critical requirement for this application. The mass of a flight version of this cryocooler is expected to be around 270 kg, while the input power is expected to be approximately 25 kW. This paper describes the design and testing of the laboratory demonstration cryocooler that was constructed to demonstrate the feasibility of the approach. In the future, the cryocooler will be integrated and tested with a distillation column subsystem. Subsequent testing may also be performed in-flight on an Air Force transport aircraft.

C2-K-05 Process Study of Nominal 2 K Refrigeration Recovery

***P.N. Knudsen**, V. Ganni, Jefferson Lab.*

There is an increased interest in the nominal 2K helium refrigeration systems (below lambda) for test stands at the present time. This paper presents the process parameter choices and their influence on the system performance of various non-cold compressor configurations. This study is intended to facilitate the adoption of this process in conjunction with commercially available small 4.5K helium refrigerator systems. By way of an introduction, the efficiency of some commonly employed (but inefficient) 2 K process configurations are analyzed. Then the analyses of three nominal 2K refrigeration recovery process configurations utilizing a refrigeration recovery heat exchanger are presented. The effect of the process parameters, such as flow imbalance, heat exchanger size, supply pressure and 4.5K plant injection location are investigated so that the conditions yielding the maximum coefficient of performance can be determined.

C2-K-06 Recent progress in dynamic process simulations of cryogenic refrigerators

***A. Kuendig**, Linde Kryotechnik AG.*

At the CEC 2005 a paper with the title "Helium refrigerator design for pulsed heat load in Tokamaks" was presented. That paper highlighted the control requirements for cryogenic refrigerators to cope with the expected load variations of future nuclear fusion reactors. First dynamic computer simulations have been presented.
In the mean time, the computer program is enhanced and new series of process simulations are available. The new program considers not only the heat flows and the temperature variations within the heat exchangers, but also the variation of mass flow and pressure drops. The heat transfer numbers now are calculated in dependence of the flow speed and the gas properties. PI-controllers calculate the necessary position of specific valves for maintaining pressures, temperatures and the rotation speed of turbines.
The value of such a program is the tracing of difficult transient operating modes in the design phase of a refrigerator. The simulation further is helpful for testing control programs in absence of the real refrigerator and it enables to find optimal control parameters. Worth mentioning that such a program is applicable for the education of engineers and operators.

C2-K-07 Design of Subcooled Pressurized Cryogenic Systems

***G.E. McIntosh**, Cryogenic Technical Services, Inc..*

High temperature superconducting power lines and various beamline targets require cooling with subcooled, non-boiling cryogens in the pressure range from 5 to 15 Bar. In conventional closed-loop refrigerated systems this is accomplished by using a pressurized ballast cryogen dewar to maintain the desired pressure. Although consumption is modest, cryogen flows continuously from the ballast dewar and periodic replenishment is necessary. This paper describes an innovative refrigerated system which eliminates the ballast dewar and operates continuously without cryogen or gaseous make-up after the initial fill.

C2-K-08 The Cost of Helium Refrigerators and Coolers for Superconducting Devices as a Function of Cooling Power at 4.5 K

***M. A, Green**, Lawrence Berkeley National Laboratory.*

This paper is written in memory of Rod Byrns of the Lawrence Berkeley National Laboratory who died two years ago.
This paper is an update of papers written in 1991, 1997 by Rod Byrns and this author concerning estimating the cost of refrigeration for superconducting magnets and cavities. The actual costs of helium refrigerators and coolers (escalated to 2007 dollars) are plotted and compared to a correlation function. A correlation function between cost and refrigeration at 4.5 K and 1.8 K is given. The capital cost of larger refrigerators (greater than 50 W at 4.5 K) 1s plotted as a function of 4.5 K cooling. The cost of small coolers is also plotted as a function of refrigeration available at 4.5 K. An annual cost for refrigeration can also be estimated based on the refrigeration at 4.5 K or 1.8 K and the cost of electrical energy. A correlation function for estimating input power to the compressors to the refrigeration produced at 4.5 K and 1.8 K is also given.
This work was supported by the Office of Science, United States Department of Energy, under DOE contract DE-AC02-05CH11231.

C2-L Stirling and Pulse Tube Coolers, Development and Testing (Aerospace)

C2-L-01 Development Of A 4.5 K Pulse Tube Cryocooler For Superconducting Electronics

***Ted Nast** , Jeff Olson , Patrick Champagne , Jack Mix, Bobby Evtimov, Eric Roth , Andre Collaco , , Lockheed Martin Space Co.*

Lockheed Martin`s Advanced Technology Center is developing a four stage pulse tube to provide temperatures of 4.5 K for superconducting electronics to be used in a ground based communications system. We have developed prior 4 stage units which have operated down to 3.8K. The relatively high cooling loads for this program led us to a design which reduces the input power over prior systems. The design of the system includes a unique pulse tube approach using both Helium-3 and Helium 4 working gas in two separate compression spaces, which leads to enhanced power efficiency. The compressor is our standard moving magnet, clearance seal, flexure bearing system. This paper will present the experimental data and compare it with our prediction methods.
The system is compact, lightweight and reliable and utilizes our aerospace cooler technology to provide unlimited lifetime. The unit is an engineering model to demonstrate proof of concept. Follow on production for ground based communication systems is anticipated.
This work is subcontracted from HYPRES and is funded by the Army and the Navy

C2-L-02 Development and Space Flight Qualification of a Dual Stage 20K Stirling Cryocooler

M.G. Houston*, M. Brownhill, J.S. Reed, A.S. Gibson, EADS Astrium Limited.*

A two-stage Stirling cycle cooler has been developed for space applications to provide cooling below 20K. It was initially developed for the ESA Far Infrared Space Telescope (FIRST). The FIRST 20K cooler is the first dual-stage Stirling cryocooler to be developed under funding by ESA and has successfully passed a qualification readiness review in 2006.

The qualification model cooler has a 2-stage displacer with a helium working gas, compressed by dual-opposed pistons, and implements a momentum balancer unit attached to the displacer, to achieve low vibration characteristics for the system. This cooler builds on the success and heritage of the Astrium 50-80K Stirling cryocooler mechanisms. The cooler benefits from unparalleled space heritage, with a capability for high efficiency at low temperatures and ability to lift heat at 2 different temperatures. It is capable of providing in excess of 120mW heat lift at 20K at the cold stage, while providing 500mW heat lift at the mid-stage for an input power of <100W. This paper reports on the test results through qualification, including: performance characterisation, loadlines, demonstration of exported vibration, capability to withstand launch vibration, EMI and thermal vacuum testing.

Astrium would like to acknowledge the support of ESA in funding this work.

C2-L-03 20 K Coaxial Pulse Tube using Passive Cooling

I. Charles*, L. Golanski, A. Gauthier, A. Coynel, J.M. Duval, CEA/DSM/DRFMC/SBT.*

Development on low temperature high frequency pulse tube cooler is underway at CEA/SBT. For space applications, it is possible to use passive cooling available on numerous science mission to decrease the no load temperature and enhance the cooling power. Several in line configurations have been tested and temperature below 15 K has been achieved with 100 watts of mechanical power (PV power). An integrated coaxial configuration has been built and tested. The passive cooling is simulated by a GM cooler. The influence of the heat intercept temperature on the pulse tube performance is presented. The heat to be removed at the heat intercept as function of various parameters as heat intercept temperature, input power, load, is discussed.

C2-L-04 ABI Lifetest Cooler System

R. Colbert*, G Pruitt, T Nguyen, J Raab, Northrop grumman Space Technology.*

The Advanced Baseline Imager (ABI) Pulse Tube Cooler System is a two-stage pulse tube cooler for space applications. The cooler incorporates an integral HEC pulse tube cooler and a remote coaxial cold head. The two-stage cold head was designed to provide simultaneous large cooling power at 53 K and 183K.

This paper presents the data collected on the lifetest cooler during acceptance testing. Tests included thermal performance mapping at different heat rejection temperatures, cooler orientation relative to gravity and temperature stability tests. Designed for a 10-year life, the ABI coolers are required to provide 2.27W of cooling at 53K and 5.14W of cooling at 183K while rejecting to 300K with less than 143W input power to the compressor. The ABI lifetest cooler meets the cooling requirement at 53K while exceeding the requirements at the remote cold head (153K vs 183K) and compressor input power (125W vs 143W). The cooler meets both the short and long term temperature stability of 100mKp-p and 500mKp-p respectively.

"Northrop Grumman Space Technology is part of the ITT Advanced Baseline Imager (ABI) team. ITT leads the team as the prime contractor and has overall responsibility for the program development effort. ABI is a NASA administered contract.

C2-L-06 Ball Aerospace Advances in 35 K Cooling: The SB235E Cryocooler

J.S. Lock*, D.S. Glaister, W. Gully, P. Hendershott, V. Kotsubo, E.D. Marquardt, Ball Aerospace & Technologies Corp.*

This paper describes the design, development, testing and performance of the Ball Aerospace SB235E; long life, a 2-stage space cryocooler that has been optimized for 2 cooling loads. The SB235E model is a 2-stage coolers designed to provide simultaneous cooling at 35 K (typically for HgCdTe detectors) and 85 K (typically for optics). The SB235E is a higher capacity model derivative of the SB235. A unit has been built and tested and 2 more units are precoolers for a Stirling/Joule-Thomson (J-T) hybrid coolers under development at Ball Aerospace for the DoD 35 K High Capacity Variable Load Cryocooler program and for the 10 K Cryocooler program. Initial testing of the SB235E has shown performance of 2.49 W at 35 K and 10.3 W at 85 K for 202 W power. These data equate to Carnot efficiency of 0.222 or about twice that of other published space cryocooler data. Qualification testing has been completed including full performance mapping, vibration export verification, and vibration testing. Performance mapping with the cold-stage temperature varying from 20 K to 80 K and mid-stage temperatures varying from 85 K to 175 K are presented.

C2-L-07 Raytheon Stirling / Pulse Tube Hybrid Cryocooler Engineering Model

C.S. Kirkconnell*, R.C. Hon, M. Pillar, L. Bellis, T. Pollack, Raytheon Space and Airborne Systems.*

The first generation flight-design Stirling / pulse tube "hybrid" two-stage cryocooler has entered initial performance and environmental testing. The results of the testing are presented. Numerous improvements have been implemented as compared to the preceding brassboard versions to improve performance, extend life, and enhance launch survivability. This has largely been accomplished by incorporating successful flight-design features from the Raytheon Stirling one-stage cryocooler product line. These design improvements are described. In parallel with these mechanical cryocooler development efforts, a third generation electronics module is being developed that will support both Stirling / pulse tube and Stirling cryocoolers. Improvements relative to the second generation design relate to improved radiation hardness, reduced parts count, and improved vibration cancellation capability. Progress on the electronics is also presented.

C2-L-08 Multistage Stirling Cycle Refrigeration Characterization of the Northrup Grumman High Capacity Cooler- an Update

J. Sultiff*, T. Roberts, E. Pettyjohn, AFRL/VSSS.*

The characterization of a multistage Pulse Tube cycle refrigeration system has been performed on the Northrop Grumman High Capacity Cooler (NG HCC) cryocooler by the Air Force Research Laboratory. This cooler's design uses two pulse tube cold ends in parallel. The 85 K cold end is thermally strapped to the regenerator housing of the 35 K cold end in order to boost 35 K cooling capacity. The cooler was tailored to support long wave infrared (LWIR) HgCdTe focal plane arrays and their associated optical systems, but this particular refrigeration system can also support a variety of short or medium wave infrared sensing as well as high temperature superconducting electronics applications. The results are presented for both steady state and transient performance envelopes for this cooler on and off the design point of 2 Watts of cooling at 35 K and 17 Watts at 85 K. When it is off the design point the load is up to 15 Watts of cooling at 35 K and 50 Watts on the 85 K side. Testing off the design point will indicate the applicability of this cooler to other systems. These results are presented both as empirical data and as interpolating function estimates of the entire performance envelope.

C2-M Instrumentation

C2-M-01 Operation of Superconducting Digital Receiver Circuits on 2-Stage Gifford-McMahon Cryocooler

***R.J. Webber**, V. Dotsenko, A. Talalaevskii, R. Miller, J. Tang, D. Kirichenko, I. Vernik, P. Schevchenko, D. Gupta, O.A. Mukhanov, Hypres, Inc.*

We have demonstrated the full operation of digital RF receivers on a Hypres-designed cryostat, which couples a Nb-based superconducting Rapid Single Flux Quantum (RSFQ) chip to a commercially available 100 mW 4 Kelvin Gifford-McMahon cryocooler. The electrical performance at clock speeds in excess of 24 GHz is described as well as the design of the electrical interfaces with room temperature support electronics. The digital receiver chip is a 1cm x 1 cm chip comprising ~ 11,000 Josephson junctions. Within the cryostat there is the inevitable conflict between the need to minimize heat-leaks and the need to minimize dissipation in input-output leads. The measured cryogenic thermal and magnetic environments of the chip are discussed and their impact on performance. Reception and direct digital conversion of real signals in the HF-, VHF-, and X-bands including signals from military satellite antennae shows the potential of this system to replace large and power-hungry multiple analogue receivers.

This work was supported in part by the Office of Naval Research, the Army Small Business Innovation and Research Program and by the US Air Force

C2-M-02 Level-detected characteristics of MgB2 sensor for liquid hydrogen

***M. Takeda**, T. Akazawa, Y. Iwamoto, Kobe University; H. Kumakura, A. Matsumoto, H. Uematsu, C. Kazama, National Institute for Materials Science; H. Iwashita, I. Kodama, Y. Matsuno, Iwatani Industrial Gases Corporation.*

In order to establish the storage and transportation system for liquid hydrogen, it is important to develop a high sensitive liquid level meter. A superconductive MgB2 level meter is expected to be a new one. However, a research on the level-detected characteristics of the MgB2 sensor has not been sufficiently carried out. Thus the characteristics of the level sensor, which consists of a MgB2 wire (0.5 mm in diameter, 200 mm long) made by means of powder-in-tube method, an electrical heater, and voltage/current taps, were investigated by using the liquid hydrogen optical cryostat. The linearity, resolution, repeatability, and heater current dependence of the sensor reading with varying liquid levels are discussed.

This work was supported in part by Hyogo Prefecture (COE Program), Japan.

C2-M-03 Cryogenic Fiber Optic Sensors Based on Fiber Bragg Gratings

***P.R. Swinehart**, M. Maklad, S.S. Courts, Lake Shore Cryotronics, Inc.*

Fiber optic sensing has many favorable characteristics - a single fiber can be used to interrogate multiple sensors along the length of the fiber, fiber optic sensing is immune to electromagnetic noise and is inherently safe for combustible liquids and atmospheres. Previously, fiber optic sensors based on fiber Bragg gratings (FBGs) have been demonstrated for cryogenic use for both temperature and strain sensing, but often little data is supplied as to the reproducibility or unit-to-unit uniformity of these sensors. Lake Shore Cryotronics has manufactured fiber optic cryogenic temperature and strain sensors based on Bragg gratings using novel packaging techniques. The reproducibility and uniformity characteristics of the cryogenic strain sensor is reported for 295 K and 77K. The temperature response, reproducibility, and uniformity of wide range temperature sensors is reported from 20K to 480K.

C2-M-04 A Commercial Ruthenium Oxide Thermometer For Use to 10 mK

***S.S. Courts**, J.K. Krause, Lake Shore Cryotronics, Inc.*

The adoption of the PLTS-2000 has given the ultra low temperature community a recognized temperature scale with which to work. However, the defining instrument, the He-3 melting curve thermometer, is not well suited for transferring this scale. Primary thermometers are available for ultra low temperatures, namely nuclear orientation and noise thermometry, but they are statistical in nature and require long averaging times for a single measurement limiting their practical use. Resistance thermometers are easy to use, provide fast measurements allowing active feedback temperature control, and have extremely high sensitivities at ultra low temperatures allowing for microkelvin level control. However, resistance thermometry for use below 50 mK requires rethinking the standard packaging. Many common materials used in packaging cryogenic sensors limit the thermal connection to the sensor thus limiting the allowable excitation used for measurement. This research examines the use of a commercially available ruthenium oxide thick film chip resistor for thermometry to 10 mK. Data was acquired for sample sensors fabricated using two package styles. The temperature was measured using a Co-60 nuclear orientation thermometer in conjunction with PTB-calibrated germanium thermometers. Resistance as a function of temperature, self-heating and time response data are presented.

C2-M-05 The Effect of Small Helium Leaks into Low Temperature Systems

***J. Panek**, E. Canavan, M. DiPirro, J. Francis, S. Riall, P. Shirron, NASA.*

Recent experience with small helium leaks (<1e-10 sccs He) into the guard vacuums of two different low temperature (50 mK) systems at Goddard Space Flight Center is described. The flight cryostat for the X-Ray Spectrometer instrument and a ground test facility for infra-red detectors both suffered small leaks which were detected initially by means other than a standard helium mass-spectrometer leak detector. The unusual symptoms of the leaks (heat pulses detected with resistive thermometers) and the advanced leak checking techniques required to find them are detailed.

C2-M-06 A Novel Ge-on-GaAs Film Resistance Thermometer for Measurement of Low Temperatures in High Magnetic Fields

***V.F. Mitin**, V.V. Kholevchuk, V. Lashkaryov Institute of Semiconductor Physics, and "MicroSensor", Research & Production Company; N.S. Boltovets, State Enterprise “Research Institute ORION”.*

A new model of resistance thermometer for measurement of temperatures from 1.5 up to 300 K in high magnetic fields has been designed and characterized. It is based on Ge film on semi-insulating GaAs substrate. This model of Ge-on-GaAs film thermometer is characterized by high thermosensitivity and low magnetoresistance which results in small errors, (T(B)-T)/T, in thermometer reading when measuring in a magnetic field. (Here T is the temperature measured in zero field, and T(B) is that measured in magnetic field B.) The errors are less than 1% for magnetic fields up to 8 Tesla over the whole temperature range (from 1.5 up to 300 K). For some temperatures it is also possible to obtain (T(B)-T)/T less than 1% in the field of 10 Tesla.

This work was partially funded under the CRDF “First Steps to Market” Program, and Scientific Instruments Inc. (West Palm Beach, FL, USA), Contract no. UKE2-005062-KV-05.

Wednesday, 07/18/07 Poster 3:30pm - 5:00pm

C2-O Instrumentation - Large Scale Systems

C2-O-01 First Experience with the LHC Cryogenic Instrumentation

*N. Vauthier, Ch. Balle, J. Casas-Cubillos, G. Fernandez-Penacoba, E. Fortescue-Beck, P. Gomes, N. Jeanmonod, A. Lopez Lorente, **A. Suraci**, CERN.*

The LHC under construction at CERN will be the world's largest super-conducting accelerator and therefore makes massive use of cryogenic instruments. The cryogenic instrumentation mainly comprises sensors for temperature, pressure and level, as well as heaters and valve actuators. These instruments are installed in the tunnel and therefore have to withstand the LHC environment that imposes radiation-tolerant design and construction. Most of the instruments require individual calibration; some of them exhibit several variants as concerns measuring span; all relevant data are therefore stored in an Oracle® database. Those data are used for the various quality assurance procedures defined for installation and commissioning, as well as for generating tables used by the control system to configure automatically the input/output channels. This paper describes the commissioning of the sensors and the corresponding electronics, the first measurement results during the cool-down of one machine sector; it discusses topics that caused problems and the solutions found. Furthermore it also gives an overview of the different procedures covering final installation stages, testing and cool-down operations.

C2-O-02 Calibration of Cryogenic Thermometers for the LHC

*Chr. Balle, J. Casas-Cubillos, N. Vauthier, CERN; **J.P. Thermeau**, IPN, Orsay.*

7000 cryogenic temperature sensors of semi-conductor type covering the range from room temperature down to 1.6 K are installed on the LHC machine under construction. In order to meet the stringent requirements on temperature control of the super-conducting magnets, each single sensor needs to be calibrated individually. In the framework of a special contribution, IPN (Institut de Physique Nucléaire) in Orsay, France built up and operated a calibration facility with a throughput of 80 thermometers per week.

After reception from the manufacturer, the thermometer is assembled onto a support specific to the measurement environment, thermally cycled ten times and calibrated at least once from 1.6 to 300 K. The procedure for each of these interventions includes various measurements and the acquired data is recorded in an ORACLE®-database. Furthermore random calibrations on some samples are executed at CERN to crosscheck the coherence between the approximation data obtained by both IPN and CERN. In the range of 1.5 K to 30 K, the calibration apparatuses at IPN and CERN are traceable to standards maintained in a national metrological laboratory by using a set of rhodium-iron temperature sensors of metrological quality.

This paper presents the calibration procedure, the quality assurance applied, the results of the calibration campaigns and the return of experience gained.

C2-O-03 Radiation Requirements and Testing of Cryogenic Thermometers for the ILC

***J. Trenikhina**, Saratov State University; T. Barnett, University of Illinois; Yu.P. Filippov, Joint Institute for Nuclear Research; N. Mokhov, N. Nakao, A. Klebaner, K. Vaziri, Fermi National Accelerator Laboratory*; S. Korenev, J.C. Theilacker, Beams & Plasma Technologies.*

Large quantity of cryogenic temperature sensors will be used for operation of the International Linear Collider (ILC). Most of them will be subject to high radiation doses during the accelerator lifetime. Understanding of particle energy spectra, accumulated radiation dose in thermometers and its impact on performance are vital in establishing technical specification of cryogenic thermometry for the ILC. Realistic MARS15 computer simulations were performed to understand the ILC radiation environment. Simulation results were used to establish radiation dose requirements for commercially available cryogenic thermometers. Two types of thermometers, Cernox® and TVO, were calibrated prior to irradiation using different technique. The sensors were subjected then to up to 200 kGy electron beam irradiation with kinetic energy of 5 MeV, a representative of the situation at the ILC operation. A post-irradiation behavior of the sensors was studied. The paper describes the MARS15 model, simulation results, cryogenic test set-up, irradiation tests, and cryogenic test results.

**Work supported by the U.S. Department of Energy under contract No. DE-AC02-76CHO3000.*

C2-O-04 Instrumentation, data acquisition and controls for temperature measurement of cold surfaces at 4.5 K and 80 K of SST-1 machine

***P. Panchal**, D. Sonara, B. Sarkar, R. Bhattacharya, R. Panchal, R. Patel, J. Tank, M Singh, A.K. Sahu, Y.C. Saxena, Institute for Plasma Research.*

Two-temperature regimes have been envisaged for the SST-1 machine, 80 K on the thermal shield and 4.5 K of the superconducting magnet system. The aim of temperature measurement is two folds (i) to monitor the temperature distribution as well as process parameters (ii) to achieve controlled cool down from 300 K to 4.5 K and 80 K. Temperature sensors have been mounted on cold surfaces at strategic locations to ease the operation during cool down and steady state. Several techniques are employed for temperature measurement and control. Cernox sensors (Lakeshore make) and PT -102 have been used for the temperature measurement at 4.5 K and 80 K surfaces respectively. A data acquisition system (DAS) has been indigenously developed using 4-20 mA current loop transmitter, which provided better functioning than the commercially available one. The reliability of the transmitter card has been tested on-line for continuous operation for 3 months. The control functioning has been designed and developed using programmable logic controller with built-in support for calibration curve handling, failure alarm and 3-port isolation with direct interfacing of the transmitter card. The temperature data is obtained at the supervisory control and data acquisition of dedicated node. The developed DAS has been found to be very reliable and satisfactory. The paper will describe the details of the philosophy of the DAS and experience along with indigenously developed transmitter card.

C2-O-05 Thermal and electrical anchorage of superconducting devices into large facility superconducting magnets.

***B. Minetti**, R. Gerbaldo, G. Ghigo, L. Gozzelino, F. Laviano, G. Lopardo, E. Mezzetti, R. Cherubini, Dept of Physics - Politecnico Torino; A. Rovelli, INFN-LNS.*

In this paper the issue of exploiting the use of superconducting sensors with their extremely favourable radiation hardness and low noise properties at low temperatures is addressed with reference to other currently used sensor solutions. The major problem for an extensive use of superconductors as field and photon sensors was (until now) referred to the need of the sensors anchorage to cold fingers in cryocoolers. In large facilities such as e.g. LHC (CERN) environment, running at temperature lower then 4K, the problem is reduced to achieving technical solutions for thermal anchorage, shielded read-outs and space constraints. In the paper several solution are proposed on the basis of measurements and suitable tests in controlled ambient at the large I.N.F.N. irradiation facilities in LNL, (Legnaro- Padova, Italy) and LNS (Catania, Italy).

C2-O-06 Cryogenic Controls System for Fermilab's SRF Cavities Test Facility

***B. Norris**, R. Bossert, A. Klebaner, S. Lackey, A. Martinez, L. Pei, W. Soyars, V. Sirotenko, Fermi National Accelerator Laboratory.*

A new superconducting radio frequency (SRF) cavities test facility is now operational at Fermilab's Meson Detector Building (MDB). The facility is supplied cryogens from the Cryogenic Test Facility (CTF) located in a separate building 500 m away. The design incorporates ambient temperature pumping for super-fluid helium production, as well as three 0.6kW at 4.5K refrigerators, five screw compressors, a helium purifier, helium and nitrogen inventory, cryogenic distribution system, and a variety of test cryostats. To control and monitor the vastly distributed cryogenic system, a flexible scheme has been developed. Both commercial and experimental physics tools are used. APACS+, a process automation control system from Siemens-Moore, is at the heart of the design. APACS+ allows engineers to configure an ever evolving test facility while maintaining control over the plant and distribution system. APACS+ nodes at CTF and MDB are coupled by a fiber optic network. DirectLogic205 PLC's by KOYO are used as the field level interface to most I/O. The top layer of this system uses EPICS (Experimental Physics and Industrial Control System) as a SCADA/HMI. Utilities for graphical display, control loop setting, real time/historical plotting and alarming have been implemented by using the world-wide library of applications for EPICS. OPC client/server technology is used to bridge across each different platform.
This paper presents this design and its successful implementation.

C2-O-07 The assembly of the LHC Short Straight Sections cryostats at CERN: work organization, Quality Assurance and lessons learned.

***V. Parma**, N. Bourcey, P. Campos, R. Lopez, A. Poncet, CERN.*

After 4 years of activity, the assembly of the approximately 500 Short Straight Sections (SSS) for the LHC has come to an end at the beginning of 2007. This activity, which was initially foreseen in European industry, was in-sourced at CERN because of the insolvency of the prime contractor. While the quadrupole cold masses were produced in industry, the assembly within their cryostats was transferred to CERN and executed by an external company under a result-oriented contract. CERN procured cryostat components, set up a dedicated 2000 m2 assembly hall with all the specific assembly equipment and tooling and defined the assembly and testing procedures. The contractor took up responsibility for the timely execution within the required quality. A dedicated CERN production and quality assurance team was constituted. A specific quality assurance plan was set up involving 2 additional contractors responsible for weld inspections (more than 5 km of critical assembly welds) and the execution of about 2500 leak detection tests. This paper presents the organizational aspects of the activity and the experience gained throughout the production. The learning curves and statistics by type of non-conformities detected and general quality assurance aspects are presented and discussed. The main lessons learnt are summarized, in an attempt to draw some conclusions and guidelines which could be useful in making strategic choices for the cryostat assembly in future large-scale accelerators.

C2-P High Temperature Superconducting Devices

C2-P-01 Numerical Simulation of Pulsed Field Magnetization of Cryocooler-Cooled Bulk Superconductor

***Hiroyuki Ohsaki**, Sousuke Matsumura, Satoshi Kawamoto, Ryosuke Shiraishi, The University of Tokyo.*

RE-Ba-Cu-O bulk superconductors have strong flux pinning force and are expected to be used as a strong magnetic flux source. Magnetization is a very important technique to be studied for such application of bulk superconductors. In particular, pulsed field magnetization (PFM) is considered a useful method for magnetizing bulk superconductor because this method needs a more compact field-excitation system than the field cooling magnetization (FCM). Multi-pulse techniques have been also investigated experimentally for PFM to reach as high a trapped magnetic field as that obtained by FCM. Numerical analysis techniques are also quite important to perform such research subjects more effectively and clarify the physical phenomena.
We have studied the pulsed field magnetization of cryocooler-cooled bulk superconductor. A simulation tool based on the finite element method has been developed, and transient phenomena in electromagnetic and thermal conduction fields during pulsed field magnetization were analyzed. Bulk superconductor was modeled using an E-J relation based on a power law. Dependence of critical current density on flux density and temperature was taken into account. Approximate modeling of thermal conductivities and electric properties of the system components was carried out. The relation between PFM conditions and trapped magnetic field is discussed.

C2-P-02 Persistent magnetization of MgB2 cylinders induced by a pulsed field

***G. Giunchi**, E. Perini, EDISON SpA; T. Cavallin, CNR-IENI; R. Quarantiello, V. Cavaliere, A. Matrone, ANSALDO CRIS.*

High stable trapped fields in bulk superconductors can be useful applied in many electrotechnical applications. The HTS bulk materials can be magnetized applying constant magnetic fields or pulsed magnetization methods. Even if the pulse magnetization is far less effective than the DC magnetization in the trapping ability, it appears as the most friendly technique in practical devices. So we have studied the effects of the pulsed technique, applied to bulk MgB2 cylinders that are very promising devices in view of their easy manufacturing in large dimensions [1]. To this purpose we have used a copper solenoid to magnetize the MgB2 cylinder, both cylinder and solenoid conductively cooled between 10 and 25 K. This simple cryogenic arrangement can be representative of many more elaborate practical devices. Tailoring the applied pulsed field and the sequence repetition, we successfully magnetize cylinders of diameter of the order of 50 mm, to more that 0.5 T, in their centre, and the persistent magnetization is not affected by external perturbations. The parameters which regulate the trapping field performances are mainly related to the heat management of the MgB2 cylinder. This aspects is discussed and modelled with numerical computations and several assembling solutions of the magnetized cylinders are presented.

[1] G.Giunchi et al., Cryogenics 46, 237-242 (2006)

C2-P-04 Cryogenic design of the ALUHEAT project

I. Hiltunen*, A. Korpela, R. Mikkonen, J. Lehtonen, Tampere University of Technology; M. Runde, SINTEF Energy Research; N. Magnusson, SINTEF Energy Research ; G. Kalkowski, Fraunhofer IOF.*

In this paper, the cryostat design of the ALUHEAT project that aims to build a cryogen-free superconducting induction heater is presented in detail. Designing of the cryostat involves heat loss calculations, mechanical analysis and the optimization of current leads and cooling conditions. The system consists of two separate cryostats between of which the billet to be heated is located. Exceptionally short distance between the magnet and the cryostat wall, the large forces between the magnets in separate cryostats, and the rotation of the billet create application specific requirements that must be taken into account. Finite element analysis is used to design the cryostat to withstand both the vacuum and magnetic forces.
Finally, the thermal interface, the radiation shield and the magnet support are designed and all components assembled into the complete system.

C2-P-05 Introduction of the 35kV/90MVA Saturated Iron Core Type Superconducting Fault Current Limiter

Y. Xin*, W.Z. Gong, X.Y. Niu, B. Tian, Z.J. Cao, H.X. Xi, Y. Yang, J.Y. Zhang, X,M. Hu, H. Hong, A.L. Ren, Z.L. Chen, H.H. Li, B. Hou, X.C. Yang, Innopower Superconductor Cable Co..*

A 35kV/90MVA prototype saturated iron core type superconducting fault current limiter was developed and installed in a transmission network for testing and trial operation. This prototype is of many unique features, such as actively de-magnetizing the iron core when a fault takes place to enhance the limiting capacity, additional circuit for protecting the dc current supply and other components in the dc bias side, and a new concept in iron core design. These innovations overcome the shortcomings that the long-established design of a saturated iron core type superconducting fault current limiting device has, making this type of current limiter more reliable and efficient. For the 35kV/90MVA system, we plan to carry out a live-grid trial operation at Puji Substation of China Southern Power Grid for a long period of time. In this presentation, we will report the technical details of the system and the testing results we have got up to date.

C2-P-06 Modular concept for the cryopackaging design.

V.V. Borzenets*, SLAC; I.V. Borzenets, Duke Univ.*

Cryocooled devices and assemblies always involve two interfaces: the cryogenic interface which provides the required low temperatures, and the electronic interface which essentially provides the function of your device. A problem with all current systems is that these two interfaces are linked together. That means that in order to do any component replacement or electronics maintenance, the entire system has to be shut down and taken apart. This introduces extensive delays during system assembly and usage. More over, this rules out a system with easily interchangeable electronic components.
We propose a concept of modular packaging that will completely decouple the cryogenic/temperature control interface with the electronic interface. This will result in the ability to quickly remove and replace one interface without the need to shut down or disassemble the other. This means that the system will not only have reduced servicing time, but that the system will have the capability to do “cold swaps”. Conceptually, this would be achieved by having a separate vacuum space for the cryogenic interface as well as for each detachable electronic interface block. The thermal contact for all low temperature stages of the cryocooler with the electronics package will be achieved via properly matched thermal metal to metal contacts.

Wednesday, 07/18/07 Oral 5:00pm - 6:00pm

C2-R JT Coolers (Non-Aerospace)

C2-R-01 Fast Cool-Down J-T Cryocooler to 88K

N. Tzabar*, I. Lifshits, A. Kaplansky, Rafael Ltd..*

Fast cool-down is usually implemented with J-T cryocoolers which also enable low-cost and small-scale systems. In this paper, we describe an analysis for achieving cool-down time of a few seconds to 88K, using Argon as the main coolant, and at least 3 minutes of steady state cooling. It appears that according to system demands, cost reduction, reliability, and manufacturing considerations the use of Argon as a single coolant is more beneficial than precooling with another coolant, such as Krypton. The results were successfully verified against experimental data.

C2-R-02 Vibration Characterization and Reduction of a Joule-Thomson Cryocooler for a SQUID-Based Metal Detection System

G.J. De Groot*, CSIRO Industrial Physics, M.A. SANTIN, CSIRO Industrial Physics & Federal University of Santa Catarina, T. THIJSSEN, CSIRO Industrial Physics & University of Twente.*

Very sensitive high-temperature SQUID (Superconducting Quantum Interference Device) magnetometers are used for the detection of very small metal contaminants in food and other products. When the SQUIDs are cooled with liquid nitrogen, a detection sensitivity of 500 nAm2 in a 150 × 150 mm2 orifice is obtained [1]. However, when a commercial Joule-Thompson cryocooler was used, the sensitivity was reduced by a factor of 5 due to spurious magnetic signals [2].
In this study the emphasis is on understanding noise that may be created due to mechanical vibrations in the cryocooler cold head. The natural frequencies of the cryocooler cold head are modelled and two mechanisms of noise generation are considered and analysed. Calculations show that the noise created by vibrating dipoles in the cold head may create noise of 1 pT up to 20 pT in the frequency range of 10 to 50 Hz. The vibration characteristics of several parts of the cryocooler cold head assembly were determined with a laser vibrometer, a fluxgate magnetometer and through finite element simulations. Two natural frequencies of approximately 21 and 49 Hz are particularly noticeable and are also observed in the SQUID noise. Anti-vibration measures are introduced to reduce external vibrations.
Many thanks go out to Marcel Bick, David Tilbrook, Keith Leslie, Barry Martin, Lawrence Dickinson, Prem Narang and Emma Mitchell for their support and insights.

C2-R-03 Performance of a precooled J-T refrigerator operating with refrigerant mixtures

C.T. Sairam, ***G. Venkatarathnam****, Indian Institute of Technology Madras.*

Single stage J-T refrigerators operating with refrigerant mixtures are under development worldwide. Precooled J-T refrigerators operating with refrigerant mixtures were studies by Alexeev et.al for operation in 90-100 K temperature range [1-2].
In this paper we present the results obtained by us in a two stage J-T refrigerator. Mixtures of propane and ethane are used in the first stage, and mixtures of neon,nitrogen,methane, ethane and propane in the second stage. The refrigerator was tested in the temperature range 69-85 K. A heat load of 9W was met at a temperature of 77K with a power input of 1.4 kW. A heat load of 50W was met at a temperature of 100K with a power input of 1.1-1.3 kW. The performance of the refrigerator with different mixtures in the precooling stage and the main stage are described in this paper.

References

1.Alexeev, A., Ch. Haberstroh and H. Quack (1998) Further development of a mixed gas Joule-Thomson refrigerator. Advances in Cryogenic Engineering, 43B, 1667-1675.
2.Alexeev, A., Ch. Haberstroh and H. Quack (1999) Mixed Gas J-T Cryocooler with Precooling stage. Cryocoolers 10, 475-479.

C2-R-04 Open cycle Joule-Thomson cryocooling with prior sequential isentropic expansion

***B-Z. Maytal**, Rafael.*

The high pressure stream outlets a gas reservoir and expands through a loaded turbine prior to being fed into a Joule-Thomson (J-T) cryocooler. Due to the load and according to its extent, the gas drops its pressure through the turbine at a constant entropy process. On the one hand, the gas that inlets the J-T cryocooler is of lower pressure than without a turbine. This effect suppresses the integral isothermal J-T effect which is the specific cooling capacity of the stream. On the other hand, the isentropic expansion is accompanied by temperature reduction which elevates the specific cooling capacity. This effect dominates the former one thus consequently; the specific cooling capacity is enhanced even when the high pressure gas reservoir stays isothermal. The isentropic expansion is always accompanied by a temperature drop which is quite substantial. Therefore, the expanded very first cooled stream inletting the J-T cryocooler may significantly accelerates the cooldown process.. This beneficial performance of the serial arrangement of a turbine and a J-T cryocooler is analyzed and formulated for argon and nitrogen according to any loading policy as for instance, dropping the pressure at the turbine by a predetermined constant factor.

C2-S Superconducting Cables

C2-S_01 The Latest Status of A Long Term In-grid Operation in Albany HTS Cable Project

***H. Yumura**, T. Masuda, M. Watanabe, H. Takigawa, Y. Ashibe, H. Ito, M. Hirose, K. Sato, Sumitomo Electric, Industries, Ltd.*

The HTS cable system is expected to be a solution for improvement of the power grid, and three demonstration projects in the real grid have been carrying out in the United States. The Albany Cable Project, one of them, is to develop the 350 meters long HTS cable system with capacity of 34.5kV, 800A, connecting between two substations in National Grid Power Company`s grid.
A 320-meter and a 30-meter cable are installed into underground conduit and jointed each other at a vault. The cable was fabricated with Di-BSCCO wire total amount of 70km and has the structure of 3 cores-in-one cryostat. The cable installation of a 320-meter and a 30-meter section was completed successfully with using the same pulling method of a conventional cable. After cable installation, the joint and two terminations were assembled at the test site. After the initial cooling of the system, the completion tests such as the critical current, heat loss measurement and DC withstand voltage test were conducted successfully.
The in-grid operation was begun on 20th of July, 2006. And a long term in-gird operation has been progressed satisfactorily at unattended condition. In the Albany project, the 30-meter section is planed to be replaced to YBCO cable in this spring. The development of YBCO cable has been carried out by using SuperPower's YBCO coated conductors. This paper describes the latest status of the Albany cable project.

C2-S-02 Deveopment of YBCO Cable for Albany HTS Cable Project

***H. Yumura**, M. Ohya, Y. Ashibe, H. Ito, T. Masuda, K. Sato, Sumitomo Electric Industries, Ltd.*

The Albany Cable Project is to develop the 350 meters long HTS cable system with capacity of 34.5kV, 800A, connecting between two substations in National Grid Power Company`s grid.
In-grid operation with BSCCO HTS cable was begun on 20th of July, 2006, successfully. And a long term in-gird operation has been progressed satisfactorily at unattended condition. The BSCCO cable line consists of a 320-meter, a 30-meter cable, cable-to-cable splice in vault and two terminations. In the Albany project, the 30-meter section is planed to be replaced to YBCO cable in this spring. The development of YBCO cable has been carried out by using SuperPower's YBCO coated conductors. The YBCO sample core was fabricated and evaluated its electrical and mechanical properties in order to confirm the cable design. The critical current of conductor and shield were approx. 1.4 kA and 2.0 kA, respectively. They are almost same as design value considering with tape's Ic and the effect of magnetic field. The ac loss of the sample was 0.4 W/m/ph at 800 Arms of 60Hz. The fault current test, 23kA and38cycles, was conducted under open bath condition. The temperature rises at conductor and shield were almost same as the ones of BSCCO core, and no Ic degradation was found after the fault current test. This paper describes the detail of test results for YBCO sample core and design of YBCO cable for Albany Project.

C2-S-03 A Cooling System for Navy Degaussing Cables

***J. Yuan**, J. Maguire, D. Aized, A. Covel, American Superconductor Co.*

Degaussing cables are a vital part of today's military ships. Degaussing cables are utilized in most navy ships to reduce their magnetic signature, thereby making them much more difficult to be "seen" by magnetic sensors and by magnetically activated mines. Current degaussing systems consist of a series of field-generating loops and their installation involves running heavy copper cables around the perimeter of the ship's hull. High Temperature superconductor-based degaussing cables provide many benefits as a replacement for conventional, copper-based degaussing systems, including lighter weight, lower operating voltage, lower installation costs, higher energy efficiency and smaller size. In March 2006, AMSC announced that it had demonstrated the successful operation of the world's first full-scale HTS degaussing cable for military ships. The 40 meter long HTS degaussing cable produced 4100 Amp-turns with a significant decrease in operating voltage to less than 0.5 volts, or 1000 times lower than a comparable Amp-turn copper-based system. The system has been continuing running since March, 2006. This paper reviews the testing of the degaussing cable, along with a comparison between the simulation and experiments.

C2-S-04 Performance Test of Cooling System for KEPCO HTS Power Cable

***H.S. Yang**, D.L. Kim, B.S. Lee, Y.S. Choi, Korea Basic Science Institute; S.H. Sohn, J.H. Lim, Korea Electric Power Research Institute; H.S. Ryoo, S.D. Hwang, Korea Electrotechnology Research Institute.*

A cooling system for a 3-phase 100m HTS power cable with 22.9kV/1.25kA was installed and tested at KEPCO's Gochang power testing center in Korea. The system consists of a liquid nitrogen decompression cooling system with a cooling capacity of 3kW at 66K and a closed circulation system of subcooled liquid nitrogen. Several performance tests of the cable system with respect to the cooling such as heat load, AC loss and temperature stability, were performed at operating temperature of 66.4K. Thermal cycle test, cool-down to liquid nitrogen temperature and warm-up to room temperature, was also performed to investigate thermal cycle influences. The outline of the installed cooling system and performance test results are presented in this paper.

This research was supported in part by the Electric Power Industry Technology Evaluation & Planning office, Republic of Korea.

C2-T Thermoacoustics

C2-T-01 A thermoacoustically-driven two-stage pulse tube cryocooler operating below 20K by using a novel coupler

J.Y. Hu*, Graduate University of Chinese Academy of Sciences; E.C. Luo, Technical Institute of Physics and Chemistry, CAS; W. Dai, Technical Institute of Physics and Chemistry,CAS.*

In a heat-driven thermoacoustic cryocooler, the optimum working frequency of the pulse tube cooler is often below 50Hz and the pressure ratio is higher than 1.2. Meanwhile a typical thermoacoustic heat engine with moderate dimensions often can not meet the need of the cooler. So in our new heat-driven thermoacoustic cryocooler, a new coupling method was employed to decrease the frequency and improve the pressure ratio. First, a tube with a reservoir was used as an acoustic amplifier to connect the engine and the cooler. The acoustic amplifier can amplify the amplitude of pressure wave through it, and this allows the cooler to obtain higher pressure ratio than that in the engine itself. Secondly, an acoustic transparent but gas blocking membrane was installed between the engine and the cooler. Thus, the engine can use nitrogen as the working gas to work at low frequency; meanwhile, the cooler can still use helium to maintain its high refrigeration performance in cryogenic temperature range. Because of the new coupling method, the thermoacoustic engine worked at about 23.5Hz and the pressure ratio in the pulse tube cooler reached 1.27. Consequently, a lowest cooling temperature of the heat-driven thermoacoustic cryocooler reached 18.1K. This new heat-driven thermoacoustic cryocooler promises good application potential for thermoacoustic technology in the temperature of liquid hydrogen.
This work was supported by the Natural Science Foundation of China(Grant No.50506031 and No.50625620)

C2-T-02 Universal scaling law of inertance tube phase shifters

S.L. Zhu, Graduate University of Chinese Academy of Sciences; E.C. Luo, Technical Institute of Physics and Chemistry, CAS; ***Z.H. Wu****, W. Dai, Technical Institute of Physics and Chemistry,CAS.*

The inertance tube is a long thin tube that is now frequently used as phase shifters of pulse tube cryocoolers. However, previous works usually focused on specific operating case of an inertance tube, which make their conclusion lack of universal guidance for other peoples. Thus, developing a universal scaling law of the inertance tube shifter becomes the objective of this work. Because different pulse tube coolers need different inertance tube phase shifter which can be characterized by its acoustical power transmission and phase shifting capability. In other word, the acoustical power at the inlet of the inertance tube simply reflects the gross cooling capacity of the pulse tube cryocooler, and the phase angle at its inlet is required by the pulse tube cryocooler for efficient operation. To obtain the universal operating behavior of the inertance phase shifter, a series of dimensionless groups are needed, including dimensionless diameter, dimensionless length of the inertance tube, and dimensionless acoustical power. Two most typical cases of the inertance tube phase shifter configurations, infinite reservoir volume and zero reservoir volume are highlighted in modeling. Another unique feature of the work is that oscillating turbulent flow effect is incorporated to make the universal scaling law well describe practical operating behavior of the inertance tube shifter. Lots of figures are provided to quickly choose an optimal inertance tube phase shifter.
This work was supported by the Natural Science Foundation of China(Grant. No.50625620)

C2-T-03 Impedance Measurements of Inertance Tubes at High Frequency and Pressure

M.A. Lewis*, NIST.*

Previous comparisons between measured and calculated inertance tube impedance were made at frequencies below 70 Hz and average pressures below 3 MPa. In this paper we present results on similar comparisons for frequencies up to 120 Hz and average pressures up to 3.5 MPa. Measurements were made on inertance tubes from 1.0 mm to about 3.0 mm, as well as a double inlet arrangement. Pressure ratios were varied from 1.1 to 1.4, and acoustic powers up to about 100 W were used in these measurements. The higher frequencies have the potential of reducing the size of both the pressure oscillator and the cold finger for a given refrigeration power. The smaller cold finger also leads to faster cooldown. In these experiments flow at the entrance to the inertance tube was determined from measurements of the calibrated pressure drop across a stack of screens. The wide range of frequencies and acoustic powers covered in these measurements enable us to separate the effects of compliance and inertance in the comparisons with transmission line and thermoacoustic models.

Thursday, 07/19/07 Poster 9:00am - 10:30am

C3-B High Frequency Pulse Tube Pressure Wave Generators

C3-B-01 Investigation on the dynamic behavior of linear compressor in Stirling-type pulse tube refrigerator

J. Ko*, S. Jeong, KAIST.*

This paper describes the experimental study of the dynamic behavior of linear compressor in Stirling-type pulse tube refrigerator (PTR). The dynamic behavior of the piston is closely coupled with the hydraulic force of the gas and, therefore, directly influenced by the specific load condition of the pulse tube refrigerator. In the experiment, the frequency response of the pressure at each component, the cooling performance and the piston displacement are measured while the alternative current with the fixed magnitude is supplied to the cryocooler. The linear compressor in this study is originally designed for the Stirling cryocooler and its maximum input power is approximately 200 W. The pulse tube refrigerator is configured as in-line type and an inertance tube is incorporated as the phase control device in the pulse tube refrigerator near the resonant frequency. The pressure difference between both ends of the piston imposes the additional stiffness and the PV power at the compression space can be considered as the damping effect in the vibration system of the piston. From the experimental results, the effect of the gas force on the dynamic behavior of the piston is discussed. The dynamic relation among the input current, the displacement of the piston, the pulsating pressure and the cooling performance is also studied.
This work was supported by ETEP (Electric Power Industry Technology Evaluation and Planning) and KOSEF (Korea Science and Engineering Foundation).

C3-B-02 Development of a Compressor for a Miniature Pulse Tube Cryocooler of 2.5 W at 65 K for Telecommunication Applications

***N Matsumoto**, Y Yasukawa, K Ohshima, T Takeuchi, T Matsushita, Y Mizoguchi, Fuji Electric Systems Co., Ltd.*

Fuji Electric group has established main technologies for high reliability in some stirling cryocoolers for space satellite systems. We also have developed and started selling a miniature pulse tube cryocooler from 2 W to 3 W at 70 K with 100 W electric power input for any commercial applications. In development of a new compressor, we introduce a moving magnet to a driving system in order to achieve moreover compactness and higher efficiency, not a moving coil that is a conventional system with about 70% efficiency. And an Expander is adopted a coaxial pulse tube for compactness. This development is for cooling a high temperature superconductive device in a wireless telecommunication system. The compressor requires total compression work of 75 W with 90% efficiency and longer than 50,000 hour.

So far, the primary tests that a part of a moving magnet liner motor and a coaxial pulse tube have finished. As next phase, we have made a first stage prototype compressor used by the new liner motor, and then we have tested the new machine. This paper mainly describes the test results of the compressor.

A Japanese government institution, the Ministry of Public Management, Home affairs, Posts and Telecommunications

C3-B-03 High Frequency Nonmagnetic and Nonmetallic Pulse Tube Cryocooler for 80K

*Y.Q. Xun, **L.W. Yang**, J.H. Cai, J.T. Liang, Y. Zhou, Technical Institute of Physics and Chemistry of CAS.*

Many cryogenic apparatus, such as Superconducting Quantum Interference Devices (SQUIDs), are quite strict with the cold source for their sensitivity to the mechanical and magnetic vibrations. The high frequency pulse tube cryocooler (PTC) has considerable system advantages due to the reduction of induced electromagnetic disturbance and simple mechanism for having no moving part in the cold head. By using nonmagnetic and nonmetallic materials for main components, we are developing a high Frequency coaxial non-metallic and non-magnetic PTC system with lower vibrations and electromagnetic interferences to supply the low-noise cooling for highly magnetic flux sensitive high-Tc superconductoring electronics including high-Tc SQUIDs. A liner compressor is used to drive this version of PTC. With an input electric power of 35W and 42Hz operation frequency, this PTC has achieved a no-load temperature of 76.9K and provides a cooling power of 0.1W at 82K.

Research supported by National Natural Science Foundation of China. (Grant No.50476086)

C3-B-04 Experimental Investigation on Multi-bypass and Fixed Phase-shifter Comparison in Single-stage High Frequency Pulse Tube Cryocooler

*X.F. Hou, **L.W. Yang**, J.T. Liang, Y. Zhou, Technical Institute of Physics and Chemistry of CAS.*

A below 40K single-stage high-frequency pulse tube cryocooler(PTC) is introduced in this paper. At present, the lowest temperature of 34.22K with input power of 222W is reached. Four fixed phase shifter including inertance tube, inertance tube plus double inlet, inertance tube plus multi-bypass and inertance tube plus double inlet plus multi-bypass are compared by experiments. Experiments show that inertance tube plus double inlet plus multi-bypass is a best choice to apply very low temperature and inertance tube is a good choice to apply high temperature and large cooling power in single-stage high frequency PTC. And the experiments also show that multi-bypass plus nozzle can decrease the DC flow in PTC and increase the performance of PTC.

C3-B-05 Experimental demonstration of a Novel Heat Exchange Loop Used for Oscillating Flow Systems

*B. Gao, Technical Inst. of Physics and Chemistry, CAS; Graduate University of Chinese Academy of Sciences; **Z.H. Wu**, Technical Institute of Physics and Chemistry, CAS; W. Dai, E.C. Luo, Technical Institute of Physics and Chemistry,CAS.*

This paper proposed a non-resonant self-circulating heat exchanger which uses a pair of single-direction valves to transform oscillating flow into steady flow that allows the oscillating flow system's own working gas to go through a physically remote high-temperature or cold-temperature heat source. Unlike traditional oscillating flow heat exchangers, the length of non-resonant self-circulating heat exchanger is not limited by the peak-to-peak displacement. In addition, it is also different from the resonant self-circulating heat exchanger that needs a specific resonant length [G.Swift and S. Backhaus, A resonant, self-pumped, circulating thermoacoustic heat exchanger," Journal of the Acoustical Society of America 116, 2923-2938 (2004)]. This invention may lead to easy design and fabrication of heat exchangers for oscillating-flow refrigeration system with large capacity. To verify this idea, we have built an experimental system by incorporating such a heat exchanger into a pulse-tube type of Stirling refrigerator. Measurements of heat transfer of the heat exchanger under different operating conditions including pressure ratio, mean pressure, and operating frequency, etc. have been made. Our experiments have demonstrated its feasibility and great flexibility for practical applications.

This work was supported by the Natural Sciences Foundation of China(Grant. No.50625620).

C3-B-06 A low cost pressure wave generator using diaphragms

***A.J. Caughley**, Industrial Research Ltd; D. Haywood, Industrial Reserach Ltd; C. Wang, Cryomech.*

The high cost of Pressure Wave Generators (PWGs) is a major barrier to the more widespread use of high-efficiency pulse tube and Stirling cryocoolers. This paper describes the development and testing of a low-cost industrial-style PWG which employs metal diaphragms. The use of diaphragms removes the need for rubbing or clearance seals, and eliminates contamination problems by hermetically separating the gas circuit and the lubricated driving mechanism. The diaphragms also allow a conventional low-cost electric motor to be used as the power input device for the PWG, via a novel high-efficiency kinematic linkage. A first prototype of the diaphragm PWG produced approximately 3.3 kW of PV power with a measured electro-acoustic efficiency of 69%. Accelerated testing predicts a diaphragm life time in excess of 40,000 hours. An additional advantage of the use of diaphragms is the ability to directly cool the gas in the compression space. This eliminates or significantly reduces the requirement for an aftercooler, and further decreases the cost of the whole cryocooler system. A pulse tube cryocooler has been successfully run at Industrial Research Ltd to 59K with the diaphragm PWG and no aftercooler. Another pulse tube cryocooler with the diaphragm PWG is undergoing development at Cryomech, the results of which will be given in another presentation.

This programme was supported by the Foundation for Research, Science and Techology, New Zealand.

C3-C Heat Transfer - II

C3-C-01 Effect of Heated Perimeter on Forced Convection Heat Transfer of He I at a Supercritical Pressure

*D. Doi, **M. Shiotsu**, Y. Shirai, Kyoto University; K. Hama, Kyoto Unniversity.*

In designing a superconducting coil wound with CICC cooled by supercritical helium, accurate knowledge of heat transfer in forced flow of He I under supercritical pressure is necessary. However, there have been very small number of experimental data and little is known on the forced convection heat transfer under supercritical pressures. The authors experimentally studied the forced convection heat transfer from a flat plate located at a wall of a rectangular duct under a supercritical pressure, 2.8 atm and presented the heat transfer correlation including a parameter of (L/De) where L is the heater length and De is the equivalent diameter. As the perimeter of the duct was partially (about 1/4) heated in the experiment, to clarify the effect of heated ratio in the perimeter is necessary. In this work, a rectangular duct which had the same dimension as used in the previous work, 420 mm in length and 5 mm x 6 mm in inner cross section, was used. Two pairs of test plates all 5.5 mm in width were located face to face on opposite sides of the duct. Each pair having the same length of 20 mm and 80 mm, respectively, was connected in series electrically. Inlet temperature and flow velocity were varied from 2.2 to 6.5 K and 0.1 to 5.2 m/s. Comparison of the obtained Nusselt numbers with the former results with a single test pate showed clear effect of heated perimeter. Non-dimensional heat transfer equation including the effect was presented.

C3-C-02 Forced convection heat transfer of subcooled liquid nitrogen in horizontal tube

***H. Tatsumoto**, T. Kato, Japan Atomic Energy Agency; Y. Shirai, K. Hata, M. Shiotsu, Kyoto University.*

The knowledge of heat transfer in forced flow cryogenic hydrogen is important for the cooling design of hydrogen moderator systems for spallation neutron sources. However, there is few experimental data of the forced convection heat transfer of cryogenic hydrogen. In order to improve prediction of the heat transfer of the hydrogen, experimental research of forced convection heat transfer of subcooled nitrogen ranging from the pressures of 0.3 to 2.5 MPa was carried out as basic research. In this study, an experimental apparatus that could obtain forced flow without a pump was developed. The inlet temperatures were varied from 77 K to its saturated temperature. The flow velocities were varied from 0.1 to 5 m/s. A stainless steel tube with a diameter of 5.4 mm and the length of 100 mm was used as a heater. The heat transfer coefficients in non-boiling regime and the critical heat fluxes of nucleate boiling are higher for higher flow velocity and higher subcooling. Obtained Nusselt number (Nu) in non-boiling region is proportional to Reynolds number (Re) to the power of 0.7. With decreases in Re, Nu approached a constant value that corresponds to that in a pool of liquid nitrogen.

C3-C-03 Heat Transfer Characteristics of Slush Nitrogen in Turbulent Pipe Flows

***K. Ohira**, J. Ishimoto, Institute of Fluid Science, Tohoku University; T. Kura, Tohoku University.*

Slush fluid such as slush hydrogen and slush nitrogen is a two-phase (solid-liquid) single-component cryogenic fluid containing solid particles in liquid, so that its density and cooling capacity increase compared with liquid state fluid. This paper reports the experimental results of the forced convection heat transfer characteristics of slush nitrogen (63 K) flowing in a 15 mm internal diameter, 625 mm long, horizontal, copper pipe. Heat was supplied to the slush nitrogen by the heater wound around the pipe wall. The heat transfer coefficient was measured with the changes of the velocity and the solid fraction. The heat transfer correlation between the Nusselt number and Reynolds number was obtained and the differences between two-phase slush and one-phase liquid in heat transfer characteristics were clarified.

C3-C-04 Thermal conductivity measurement of thin film (Kapton and PPLP) in low temperature

***S. Yamaguchi**, M. Hamabe, H. Takahashi, Chubu University.*

One of power applications of high temperature superconductor (HTS) is AC power cable, and the design value of the insulation voltage is 30 to 160 kV in the present time. Thin film is used for electrical insulation of the cables, and the thermal resistance of the thin film should be low in order to keep low temperature of the HTS tape conductor. However, since the measurement of thin film thermal conductivity is not easy in low temperature, because the thermal resistance of the surface between the different materials must be considered, we proposed a new method to measure the thermal conductivity of thin film. We measured the thermal conductivity of Kapton sheet from the room temperature to 50 K, and get the good agreement of the previous data in the room temperature. Therefore, this method will be useful to measure the other different thin film materials. We also show the thermal conductivity of the PPLP (Polypropylene Laminated Paper) from the room temperature to 50 K.
This work is supported in part by "University-Industry Research Project for Private Universities matching fund" by subsidy from MEXT, Japan, 2005-2009.

C3-D Cryofuel Systems

C3-D-01 A method for low methane sources in MRC small scale CBM liquefaction plant

***H. Li**, L. Jia, Q. Yin, Q. Fan, G. Yang, X. Liu, W. Bai, F. Xu, Z. Ji, J. Cui, Institute of Cryogenics and Superconductivity Technology,Harbin Institute of Technology.*

Coalbed methane liquefiers in small scale, 5000 to 20000Nm3/d, play more and more important roles in Chinese LNG application plan. Most CBM sources contain 50% more methane and 50% less air. In order to make use of these low methane energy sources, a new full-scale separation system was designed and tested using mixed refrigerant cycle. A method of air discarding of low CBM sources in liquefying process is discussed in this paper.

C3-D-02 Economic Analysis of Mixed-refrigerant Cycle and Nitrogen Expander Cycle in Small Scale Natural Gas Liquefier

***Q.S. Yin**, H.Y. Li, Q.H. Fan, L.X. Jia, Institute of Cryogenics and Superconductivity Technology, Harbin Institute of Technology.*

Two types of natural gas liquefaction processes, mixed-refrigerant cycle and nitrogen expander cycle were simulated according to the applications in small scale LNG plants in China. Their processes parameters were optimized and compared. Their economic characteristics were analyzed. Although the mixed-refrigerant liquefaction process is more complicated than nitrogen expander cycle, its energy consumption is only 46% of the nitrogen expander cycle. The operation costs of mixed-refrigerant process are lower than those of nitrogen expander cycle, so the process is more competitive. Referenced the articles published, the energy consumption of the optimized mixed-refrigerant cycle reaches the level of propane precooled mixed-refrigerant process, which is usually used in the base load natural gas liquefaction factory and is the lowest in the mixed-refrigerant process. The process is comparatively simple, consumes less energy and has economic features. So the mixed-refrigerant process is the first choice when one develops small-scale natural gas liquefaction device.

C3-D-03 Scheme Design and Analysis on the Small-scale Biogas Liquefaction Cycle

***Q.H. Fan**, H.Y. Li, Q.S. Yin, L.X. Jia, Institute of Cryogenics and Superconductivity Technology CHarbin Institute of Technology, Harbin.*

The biogas has important practical significance in solving the energy crisis as a kind of clean, renewable biological energy of ground. As the large-scale concentratedness of the biogas is produced, the liquefaction of the biogas is extremely urgent in technical research in China. According to the characteristic of the biogas, on the basis of mature natural gas purification and liquefaction technology, this paper discussed the small-scale biogas liquefaction system of the double purposes to purification, liquefaction and recovery of liquefied CO2. This paper provides the liquefaction biogas plant process chart, and system analysis, and the effects on the key parameters. Finally, the thermal parameters of the liquefaction cycle are presented. The result provides guidelines for the design of the small-scale biogas liquefaction device.

C3-D-04 Membrane and Joule-Thomson cooler based natural gas liquefying system

*A. Piotrowska, **M. Chorowski**, Wroclaw University of Technology.*

The significance of liquid natural gas (LNG) as a fuel in transport and power engineering has increased significantly. The composition of natural gas is not stable and varies depending on the source. Prior to its use the gas should be purified, dehydrated, excess nitrogen should be removed and eventually helium recovered. The combination of the polymer membrane gas separation technology with Joule –Thomson closed cycle can be used as a combined purifying and liquefaction system of natural gas. The impurities can be separated on hollow fiber membrane and the purified gas can be liquefied with use of Joule-Thomson cooler supplied with gas mixture. This system is especially suitable for low capacity natural gas sources. A proper choice of gas mixture limits temperature difference in the heat exchanger. The paper presents thermodynamic analysis and optimization of the system.

C3-D-05 Development of a magnetic refrigerator for hydrogen liquefaction.

***S. Yoshioka**, H. Nakagome, Chiba University; K. Kamiya, T. Numazawa, National Institute for Materials Science; K. Matsumoto, Kanazawa University.*

To prepare for the arrival of the hydrogen society, great effort has been made on hydrogen liquefaction methods. Compared to conventional liquefaction systems using a Joule-Thomson valve, magnetic refrigeration for hydrogen liquefaction has great potential and its development is an urgent necessity. Magnetic refrigeration makes use of magnetocaloric effect, and is well known as an efficent method in principal because its cooling cycle can most closely follow the Carnot cycle with appropriate heat switches. A liquefaction principal of our magnetic refrigerator is based on thermo-siphon method, in which liquid hydrogen is condensed directly on the surface of magnetic refrigerants and drops downward. This paper reports recent progress on development of our magnetic refrigerator and ways to make it more efficient by examing design of magnetic refrigerants.

C3-E Large Scale Systems

C3-E-01 Performance of liquid xenon calorimeter cryogenic system for the MEG experiment

***T. Haruyama**, K. Kasami, KEK; H. Nishiguchi, S. Mihara, T. Mori, W. Otani, R. Sawada, T. Nishitani, The University of Tokyo.*

The rare muon decay physics experiment, so called mu-e-gamma (MEG) experiment, is almost ready at the Paul Scherer Institute in Zurich. To meet with extremely high sensitivity to catch gamma-ray, 800L of cryogenic liquid xenon is used as a main media in the calorimeter. 800 photo multipliers (PMT) are all immersed in liquid xenon for capturing scintilaton light in liqud. The total dissipation power of these PMTs is expected to be about 60 W at 165 K. The scintilation light with a wavelength of 174 nm is easily absorbed by residual water in the carolimeter, liquid xenon must be purified to the lebel of ppb water contents. This is achieved by using the cryogenic centrifugal pump and cold molecular shieves. The total heat load of the calorimeter is about 120 W, and the single pulse tube cryocooler compensates this heat load. It has a cooling power of 180 W at 165 K, developed at KEK and sofisticatedly manufactured at Iwatani Industrial Gas corp. The cryogenic system mainly consists of a cryocooler, a liquid pump and a 1000L dewar. In addition to the liquid purification, a pump and a dewar will be used for an emergency evacuation of large amount of liquid xenon. The paper describes successful initial performance test of each cryogenic components and total commissioning.

C3-E-02 Cryogenic Supply for the GERDA Experiment (70m3 LAr Dewar Tank)

***Ch. Haberstroh**, TU Dresden, Lehrstuhl fuer Kaelte- und Kryotech.*

In the GERDA experiment (GERmanium Detector Array for the search of neutrinoless double beta decay of 76Ge) germanium diodes are suspended in a superinsulated copper cryostat filled with liquid argon. The cold medium is required since the diodes have to be operated at low temperatures, furthermore for shielding against background radiation. In order to achieve acceptable radiation levels, a quantity of 70 m^3 LAr is needed, placed in a surrounding water tank. For the same reason the whole experiment will be placed in the underground laboratories in the Gran Sasso mountains, Italy. Project leader is the Max-Planck-Institute for Nuclear Physics, Heidelberg. In order to avoid any detrimental perturbation inside the dewar vessel, the LAr inventory in the main tank should be kept in subcooled state, at a working pressure of 1.2 bar absolute at the surface. At the TU Dresden an appropriate cryogenic arrangement was designed to match with all these requirements. Liquid nitrogen is used as on-hand cooling medium for a zero-boil-off system. Special care was taken to cope with the narrow temperature span between LAr boiling temperature and triple point. In the proposed solution a subcooler located close to the neck provides a stable LAr convection inside the main tank. The working pressure is adjusted by a controlled, slightly elevated temperature level at the liquid – vapor interface.

C3-E-03 The results of cooling test on HTS power cable of KEPCO

***J.H. Lim**, S.H. Sohn, S.D. Hwang, Korea Electric Power Research Institute; H.S. Yang, D.L. Kim, Korea Basic Science Institute; H.S. Ryoo, Korea Electrotechnology Research Institute.*

Due to the inherent characteristics of the superconductivity allowing large power transmission capability, many researches on the high temperature superconductivity (HTS) power cables have been carried out world widely. KEPCO (Korea Electric Power Corporation) had installed three phases, 22.9 kV, 1250 A, 50 MVA, and 100 m class HTS cable system at Gochang power test center of KEPCO. The HTS cable system of KEPCO consists of two terminations, HTS power cable, and cooling system. Decompression cooling system is chosen for operation characteristics of the HTS cable system because it has simple structure and is easier to maintain. Sub-cooled liquid nitrogen is used for coolant of the HTS power cable and operation temperature of the HTS cable at inlet position is from 66 K to 77 K. Circulation cooling tests at different temperatures was performed to investigate operating condition and heat loss at loading AC current was measured. The results of performance correlated with cooling test will be presented in this paper.

This work was supported in part by the Electric Power Industry Technology Evaluation & Planning office, Republic of Korea.

C3-E-04 Experimental studies on cryogenic system for 22.9 kV HTS cable system

*S. H. Sohn, **J. H. Lim**, S. D Hwang, Korea Electric Power Research Institute; H. S. Yang, D. L. Kim, Korea Basic Science Institute; H. S. Ryoo, Korea Electrotechnology Research Institute; C. D. Kim, LS Cable Ltd. ; D. H. Kim, S. K. Lee, LS Cable Ltd..*

In terms of high transmission capacity with lower voltage, a high temperature superconducting (HTS) cable system is very attractive challenge for power utilities. On the other hand, concomitant cryogenic system for the HTS cable system is one of the tantalizing problems in the operation. The reliability and maintainability of cryogenic system are the key issues to apply it to the real electric power grid. Korea Electric Power Corporation (KEPCO) is making an attempt to verify the applicability of the HTS cable system to promote the efficiency of electric power industry. Since May 2006, 22.9 kV, 50 MVA, 3-phase, 100 m class HTS cable system with an open refrigeration cooling system has been operated at Gochang test yard of KEPCO. Concurrently, another HTS cable verification test with the same electrical specification and hybrid cooling system has been carried out by LS cable Ltd in close proximity with KEPCO's HTS cable system within Gochang test yard. Two GM crycooler, a Stirling cryocooler and a pulse tube cryocooler were included in LS HTS cable cryogenic system. KEPCO is conducting the operation of the open refrigeration system by itself and the evaluation of the hybrid system of LS cable with the aspect of facility performance and usability. Various tests have been done to confirm the performance of HTS cable systems. This paper will compare the cryogenic performance of both HTS cable systems and discuss results related with cooling tests such as step response.
This work was supported in part by the Electric Power Industry Technology Evaluation & Planning office, Republic of Korea.

C3-E-05 Design of a Long-Distance Liquid Helium Transfer Line

*Ch. Wang, M.C. Lin, L.H. Chang, M.S. Yeh, M.H. Tsai, **H.H. Tsai**, National Synchrotron Radiation Research Center.*

Design of a 200-m multi-channel line is to be presented. Currently there are two 400-W liquid helium systems in Taiwan Light Source. One of them will serve only for SRF application soon, which requests only 120-W cooling capacity in normal operation. The spared capacity is considered to serve for the SRF test stand in another building 200-m away from the cold box and the 2000-L dewar. Thus a long transfer line must be constructed to transfer liquid helium from the 2000-L dewar to a 500-L dewar in SRF test area. One of the major concerns is to reduce the heat loss of this transfer line, while an effective cool-down of this transfer line is also considered. The challenges come from not only the limited cooling capacity of the existing refrigeration system, but also the pressure drop of the long distance transfer. A two-phase mathematical model is developed initially to estimate the liquid helium transfer feasibility. Major design considerations and solutions are presented and discussed herein.

C3-E-06 Thermal stress analysis for a transfer line of hydrogen moderator in J-PARC

***H. Tatsumoto**, M. Teshigawara, T. Aso, K. Ohtsu, F. Maekawa, T. Kato, Japan Atomic Energy Agency.*

The JAEA and KEK proceed with the construction of the Japan Proton Accelerator Research Complex (J-PARC). As one of the main experimental facilities in J-PARC, a spallation neutron source (JSNS) driven by proton beam power of 1 MW is constructed. In JSNS, cryogenic hydrogen at supercritical pressure is selected as a moderator. Three kinds of moderator, whose vessel is made of aluminum alloy, are installed to provide higher neutronic performance. The hydrogen transfer line with the length of about 4 m is adopted to supply cryogenic hydrogen to the moderator vessel. It consists of multiplex pipes such as cryogenic hydrogen supplying pipe, vacuum pipe, cryogenic hydrogen return pipe, vacuum pipe, helium blanket pipe, and pipe for cooling water. It is necessary to minimum the piping size in order to decrease the effect of radiation streaming. The piping should have some bend parts to reduce radiation streaming and have friction weld joints (aluminum alloy to stainless steal). Therefore, the piping design should have strict conditions and then we considered mechanical stress concentration, deformation, and, touching between the pipes due to the thermal shrinkage at the cryogenic hydrogen temperature. Then, the thermal stress and the thermal shrinkage of the transfer lines were analyzed by using computer code such as ABAQUS. The analysis results determined support locations to keep the thermal stress below allowable stress and also show no interference between each pipes.

C3-E-07 Cryogenic and vacuum technological aspects of the low-energy electrostatic Cryogenic Storage Ring

***D.A. Orlov**, M. Lange, H. Fadil, M. Froese, M. Grieser, R. von Hahn, V. Mallinger, T. Weber, A. Wolf, MPI-K; M. Rappaport, T. Sieber, Weizmann Institute of Science.*

A next generation, cryogenic electrostatic ion storage ring will be built at the MPI-K in Heidelberg. The machine will store beams with kinetic energies between 20 and 300 keV with a main focus on the study of molecular ion physics. Wall temperature of about 10 K is required to reduce black body radiation in order to obtain and to store molecular ions in their rotational ground states. The temperature of about 2 K will help to provide extremely low vacuum that will make it possible to reach the long beam storage times needed for the molecules to complete rotational cooling by the emission of infrared radiation. The cryostat was being designed to be bakeable up to 600 K to reach 10^{-12} mbar vacuum range at room temperature and to obtain extremely low vacuum (less than 1000 molecules per cubic centimeter) at a wall temperature of 2 K.
Despite a strong link of cryogenic and vacuum techniques, in the most cases cryogenic materials and instrumentation can not survive a high-temperature bakeout which is typically required for UHV systems. To test cryogenic and vacuum technological aspects of the CSR we are building a prototype. The first results and status of the current work with the prototype will be presented.

C3-F High Temperature Superconducting Current Leads

C3-F-01 Vapor cooled current leads in BEPCII

***Q.J. Xu**, Institute of High Energy Physics(IHEP), Chinese Academy of Sciences(CAS); C.L. Yi, H.S. Chen, H. Yang, J.G. Hu, Z.A. Zhu, W.G. Li, S.P. Li, C. Zhang, K. He, R. Ge, M.J. Sang, J. Gao, IHEP,CAS; L.Q. Liu, Technical Institute of Physics and Chemistry(TIPC),CAS; L. Zhang, TIPC, CAS.*

In the upgrade project of Beijing Electron and Positron Collider(BEPCII), Two kinds of superconducting magnets were adopted. One is the Beijing Spectrometer III (BESIII) detector magnet, the other is the quadrupole(SCQ) magnet. The operating currents of them are 3400A, 1100A,600A,130A and 60A respectively. Thirteen pairs of Vapor cooled current leads(VCCL) were designed and fabricated for these magnets. The paper presents the detail of the design, fabrication and the test results of these VCCL.

C3-F-02 Performance of Heat Exchanger Models in Upside-Down Orientation for the Use in HTS Current Leads for W7-X

R. Lietzow, *R. Heller , H. Neumann , Forschungszentrum Karlsruhe.*

The sc magnet system of the W7-X stellarator requires 7 pairs of current leads designed for a maximum current of 18.2 kA. The Forschungszentrum Karlsruhe is responsible for the construction, manufacturing and performance test of the current leads. Special design feature is the installation of the current leads in upside-down orientation, i.e., the low temperature end of the current lead is at the top and the room temperature end at the bottom side leading to the problem of free convection inside the heat exchanger (HEX) due to density gradients of the helium between 4.5 K and 300 K (factor 500, p = 0.15 MPa). The occurrence of free convection leads to a reduced performance of the HEX and results in a higher mass flow rate required for the operation of the current leads. To overcome the problem it was decided to use HTS material in the temperature range between 4.5 K and 60 K. The current lead can then be cooled with 50 K helium. The main reasons for choosing 50 K are: 50 K helium is available at a higher pressure level from the refrigerator and the density gradient between 50 K and 300 K is drastically reduced (factor 6, p = 0.6 MPa). This will reduce the problem of free convection.

In the paper the performance of HEX mock-ups built of different HEX types will be described. The tests were performed with helium cooling of various temperatures in normal and upside-down orientation. These results were used to select the HEX type for the W7-X current leads.

C3-F-03 Using High Temperature Superconducting Leads in a Magnetic Field

M. A, Green, *Lawrence Berkeley National Laboratory; H. Witte, Oxford University.*

HTS leads are increasingly used on superconducting magnets. In most cases either the magnet is iron shielded or the magnet is actively shielded so that the stray field at HTS leads is low. There are magnets where the HTS leads must be located in a magnetic field. The two general types of HTS leads that are commercially available are either leads fabricated from bulk HTS materials or leads fabricated from oriented HTS materials that have one or two planes of favorable current density. HTS leads have been fabricated from a variety of HTS materials. This paper will discuss how two or three types of leads are affected by magnetic field. The performance of a HTS leads is determined by the high temperature end of the lead. The protection of HTS leads from quenching becomes an important consideration. Examples of HTS leads in a magnetic field are shown muon ionization experiment (MICE) magnets.

This work was supported by the Office of Science, United States Department of Energy, under DOE contract DE-AC02-05CH11231

C3-F-04 Implementation of HTSC leads for research cryostats

Y. Shiroyanagi, *G. Gopalakrishnan, S. An, D. Ko, T. J. Gramila, Ohio State University.*

Although the advantage of HTSC wires have been proven both in high current applications and in the presence of active cryocoolers, their implementation in liquid Helium research cryostats has not been as successful. A central difficulty involves the need to establish a specific temperature at the warm end of the HTSC wire, which is inside the neck of the dewar where temperatures are generally not well known. A novel approach to heat sinking of magnet leads[1] has enabled detailed numerical modeling of the magnet lead system, including the cooling capability of the exiting Helium gas. This approach has permitted the incorporation of HTSC leads into He research cryostats, while ensuring they remain cold enough to superconduct. The overall structure of magnet lead system including the HTSC wires, its relevant design features, and our characterization of the system will be presented.

[1] A Novel Approach for Magnet Leads: submitted to JLTP.

Thursday, 07/19/07 Oral 10:30am - 11:45am

C3-G Low Temperature Superconducting Magnet Systems - IV

C3-G-01 CFD Modeling of ITER Cable-in-Conduit Superconductors. PART V: Combined Momentum and Heat Transfer in a Spiral Rib-Roughened Pipe

R. Zanino, *Politecnico di Torino; S. Giors, Varian s.p.a.*

Dual-channel cable-in-conduit conductors (CICC) are used in the present design of superconducting magnets for the International Thermonuclear Experimental Reactor (ITER). Supercritical helium coolant flows both in the annular cable region, and in the central channel, delimited by a (perforated) spiral. As the CICC axial/transverse size ratio is typically ~ 100, 1D (axial) models are customarily used for the CICC, but they require constitutive relations for the transverse fluxes. A novel approach, based on Computational Fluid Dynamics (CFD), was recently proposed [1], [2] to understand the complex transverse thermal-hydraulic processes in an ITER CICC. A 3D CFD tool, the commercial FLUENT code, was used to compute the friction factor F in spiral rib-roughened pipes, mimicking the central channel of an ITER CICC. The results where validated against compact heat exchanger and ITER-relevant experiments. That analysis is extended here to the problem of combined heat/momentum transfer. The model is first validated against 2D and 3D data from compact heat exchangers and then applied to the analysis of central channel-like geometries relevant for ITER CICC, contributing to a better understanding of the role of geometric parameters to optimize both F and the Nusselt number (Nu). The question of the applicability of the Colburn analogy between F and Nu is also analyzed.

[1]R. Zanino, et al., Adv. Cryo. Eng. 51 (2006) 1009.
[2]R. Zanino, et al., Fus. Eng. Des. 81 (2006) 2605.

C3-G-02 Stability analysis of the ITER TF coil conductor

L. Savoldi Richard, ***R. Zanino***, *Dipartimento di Energetica, Politecnico.*

The stability analysis of the International Thermonuclear Experimental Reactor (ITER). Toroidal Field (TF) coil Nb3Sn conductor is performed using the Mithrandir code [1]. The most critical conductor in the winding pack, as well as the most critical location along it, is identified by the Vincenta code analysis, which also provides the initial and boundary conditions for the stability analysis. Two different disturbances are considered: one short in space and time (1 cm, 1 ms), simulating a disturbance of mechanical nature, the other longer (3 m, 100 ms) corresponding to AC losses (plasma disruption). Both disturbances are applied to the superconducting (SC) cable at end-of-burn (EOB) in the reference ITER inductive operation scenario. Using this approach, the Mithrandir analysis can be restricted to the most critical conductor, using a much finer grid than Vincenta, in order to capture the details of normal zone initiation and possible recovery to SC state. The computed results, in terms of minimum quench energy, are compared to the design values. Since the results are strongly influenced by the choice of the heat transfer coefficient between strands and helium as expected, this effect has been also parametrically investigated.

[1] R.Zanino, S.DePalo and L.Bottura,

C3-G-03 Design of the KATRIN source cryostat

***S. Grohmann**, H. Neumann, Forschungszentrum Karlsruhe.*

The KATRIN experiment will measure the mass of electron antineutrinos with a sensitivity of 0.2 eV/c^2, based on the precise measurement of the tritium beta spectrum. A key component is the Windowless Gaseous Tritium Source – WGTS, which will deliver 10^11 beta decay electrons per second. The WGTS consists in its centre of a 10 m long beam tube (BT) that is operated at 30 K, and that is surrounded by a series of sc solenoids. Molecular T2 is injected in the BT through a central injection chamber and pumped at either end. The T2 density profile must have a stability of 0.001 in order to limit the systematic errors, yielding stringent requirements on the BT temperature homogeneity and stability of ±30 mK and ±30 mK/h, respectively. This shall be achieved with a design, where the radiation heat load is almost entirely absorbed by LN2 and He coolers on the pumping chambers connected to the BT ends. The BT itself will be cooled with saturated Ne that is evaporating from a quasi-stationary liquid level in evaporator tubes, which are attached to either side of the BT and which are part of a thermosiphon. Starting from a functional description, we shall explain the cryogenic design of the sc magnet cryostat that features 12 fluid circuits with 6 cryogenic fluids. Beside the magnet cooling, we shall focus on the layout of the BT cooling system, as well as on the preparations for a full-scale demonstrator test.

C3-G-05 Superconductive Undulators, a new source for brilliant synchrotron radiation

***R. Rossmanith**, S. Casalbuoni, B. Kostka, Research Center Karlsruhe, Germany; A. Bernhard, University of Karlsruhe, Germany.*

After years of development, superconducting undulators slowly become a better alternative to conventional permanent magnet undulators. Superconducting undulators have higher fields and are more flexible than permanent magnet undulators. The Research Center Karlsruhe is a pioneer in this development and built and tested the first superconductive undulator in a storage ring (ANKA). The tests were so successful that a program to further developments was initiated. The results of the tests and the next steps in the development are presented in this paper.

C3-H Non-Aerospace Coolers

C3-H-01 Dry Dilution Refrigerator with High Cooling Capacity

***K. Uhlig**, WMI.*

We present the construction concept and cooling capacity measurements of a 3,4He dilution refrigerator which was precooled by a commercial pulse tube refrigerator. No cryogens are needed for the operation of this type of cryostat. The condensation of the helium mash was done in an integrated Joule-Thomson circuit which was part of the dilution unit. The composition of the dilution unit was standard, but its components (still, heat exchangers, mixing chamber) were designed for high 3He flow. For thermometry, calibrated RuO chip resistance thermometers were available.
In order to condense the mixture before an experiment, the fridge was operated like a Joule-Thomson liquefier with a relatively high inlet pressure (4 bar), where the liquid fraction of the circulating 3,4He mixture was accumulated in the dilution unit. The condensation took about 2 hours, and after 2 more hours of running the temperature of the mixing chamber approached its minimum temperature of 10 mK. The maximum flow rate of the fridge was 650 µmol/s, and the refrigeration capacity of the mixing chamber was 450 µW @ 100mK. High cooling capacity, ease of operation and reliability distinguish this type of millikelvibn cooler.

C3-H-02 Research of Application of a New-type of Magnetic Refrigerant to Active Magnetic Regenerative Refrigeration

***A.T. Saito**, S. Kaji, T. Kobayashi, Toshiba Corporation; S. Kito, S. Uchimoto, K. Kamiya, H. Nakagome, , Chiba University.*

Magnetic refrigeration technique based on the magnetocaloric effect (MCE) has received much attention as a potential alternative to conventional gas-expansion cooling techniques. The new concept of the active magnetic regeneration (AMR) cycle of refrigeration, the development of high-performance permanent magnet, and the proposal of a new type of high-performance magnetic refrigerants have all been accomplished in recent years. These technical innovations make it possible to realize magnetic refrigeration over an extensive temperature range from cryogenic temperature to room temperature using permanent magnets. We succeeded in preparing spherical particles of high-performance magnetic refrigerants. This paper will present a guide of the application of a new type of high-performance magnetic refrigerants which exhibit large MCEs especially in low magnetic field to the AMR refrigeration using permanent magnets, in terms of MCE, heat regeneration and heat exchange between refrigerants and heat transfer fluid. It will be shown the physical properties of a new type of magnetic refrigerants, and shown a result of simulation of the AMR cycle operation as well as experimental results of an AMR cycle operation.

C3-H-03 Cryogenic Testing of an Active Magnetic Regenerative Refrigerator

***A. Rowe**, A Tura, B. MacDonald, P. Francescutti, University of Victoria.*

Active magnetic regenerative (AMR) refrigeration cycles have been proposed as a means of creating compact and efficient devices for refrigeration. An interesting application is the development of a cooling stage for a hydrogen liquefier operating in the range of 80-20 K. An AMR test apparatus has been developed for testing magnetic regenerators at temperatures ranging from room-temperature to 20 K. Near 300 K, no-load temperature spans over 80 K have been produced using regenerators composed of two different magnetocaloric materials. Modifications to the apparatus have been performed to allow testing at cryogenic temperatures. Initial tests near 80 K using magnetic fields of 5 T are presented using an AMR composed of Gd5Si0.33Ge3.67. In addition, design characteristics of the test apparatus, problems encountered, and suggestions for improving experimental results are discussed.

The financial support of Natural Resources Canada, CFI, BCKDF, and the Natural Sciences and Engineering Research Council of Canada is greatly appreciated.

C3-H-04 The Use of Small Coolers in a Magnetic Field

***M. A, Green**, Lawrence Berkeley National Laboratory; H. Witte, Oxford University.*

Small 4 K coolers are increasingly used to cool superconducting magnets. These coolers are usually used with HTS leads. In most cases, either the magnet has an iron shield or the magnet is actively shielded so that the stray field where the cooler is located is low. There are instances when the cooler must be in a magnetic field. There are two types of coolers that are commercially available to cool superconducting magnets. These coolers are either GM coolers or pulse tube coolers. Since these coolers are different, their sensitivity to magnetic fields is also different. This paper will discuss how the two types of
coolers are affected by the stray magnetic field. Strategies for using coolers on magnets which generate stray magnetic fields are discussed. Examples of coolers in a magnetic field are shown in the magnets for the muon ionization experiment (MICE).

This work was supported by the Office of Science, United States Department of Energy, under DOE contract DE-AC02-05CH11231.

C3-H-05 Performance of Helium Circulation System 1 (HCS1)

T. Takeda*, M. Okamoto, K. Atsuda, A. Kobayashi, K. Katagiri, Univ. of Tokyo.*

We have developed a system to collect evaporated helium gas, to cool it down to liquid and to return it into a FRP dewar for MEG (Magnetoencephalography) using two GM cryocoolers without delivering any disturbing noises to the MEG. The key idea is to utilize relatively high temperature helium gas (about 40K) cooled by the first stage of the GM cryocoolers to get rid of invading heat to the dewar, but not to use liquid helium directly to keep the dewar cooled down. The gas is fed at the neck tube of the dewar. The evaporated helium gas in the dewar is collected swiftly while it is in the low temperature (about 8K) and is returned to liquid without using much energy.
A transfer tube that passes the liquid helium, the low temperature helium gas (about 8K) and the relatively high temperature helium gas has been developed to accomplish the above idea. A refiner to collect the contaminating gases such as oxygen and nitrogen effectively by freezing the gases is developed. It has an electric heater to remove the frozen contamination in the form of gases into the air. A gas flow controller is also developed, which automatically control the heater to cleanup the contamination. The magnetic, vibrational and acoustic noises are attenuated to be low enough for MEG measurements. The system can circulate at least 35.5 litters of evaporated liquid helium per day and usable at least for one year without any maintenance.

C3-H-06 Design Parameters for Cryogenic Thermosyphons

H. Timinger*, B. David, R. Eckart, J. Overweg, Philips Research Europe-Hamburg.*

Cryogenic thermosyphons are the thermal conductors of choice for a variety of applications like e.g. conduction-cooled superconducting devices. They exhibit a small effective thermal resistance at small cross-sections. A careful design, however, is crucial to ensure sufficient heat transport for all possible heat loads. The aim of this work is to obtain experimental results on the effective thermal resistance dependent on the length, the cross-sectional area, and the working fluid fill level of a thermosyphon for different heat loads. For the experiments, a modular thermosyphon was designed with 4 different adiabatic tubes of length [cm]/cross-sectional area [sqcm] 10/0.8, 10/3.14, 30/0.8, and 30/3.14, which can be mounted between condenser and evaporator. The thermosyphon was operated with different fill-levels of either nitrogen or neon and different heat loads. The thermal resistance between condenser and evaporator was determined, dependent on the design parameters mentioned above. Additionally, the useful temperature range of operation was determined for nitrogen and neon. The results of the experiments are summarized in diagrams and provide useful reference data for the design of cryogenic thermosyphons.

C3-I Fluid Mechanics - II

C3-I-01 Surface oscillation of liquid nitrogen induced by step reduction of gravity acceleration

M. Stief*, M.E. Dreyer, ZARM – Univ. of Bremen - Germany.*

For space application, which involve the handling of cryogenic liquids e.g. liquid hydrogen or oxygen, the concern of free surface behavior upon change of acceleration level arises. With reduction of gravity acceleration hydrostatic loose there dominance and the free surface and therefore the motion of liquids is dominated by capillary forces. So far the characteristics of the fluid motion subjected to a sudden reduction of gravity acceleration has been mostly investigated with conventional storable liquids. Because cryogenic liquids have different characteristics, these results provide only limited estimations for considered space applications. To overcome this knowledge gap experiments with liquid nitrogen inside partly filled right circular cylinder have been performed at the droptower in Bremen, which provides 4.7s of very low gravity acceleration level and a steep transition from 1g to 0g. The oscillation of the free surface where optically observed by video system during microgravity and processed for detection of the motion of the center location of the free surface and contact line of the liquid at the cylinder wall.

The funding of the research project by the German Aerospace Center (DLR) under grant numbers 50JR0011 and 50WM0241 is gratefully acknowledged.

C3-I-02 Pressure drop of cable-in-conduit conductors with different void fraction

C. Marinucci, ***P. Bruzzone****, F. Staehli, EPFL, CRPP Fusion Technology; L. Bottura, CERN, AT Dept..*

Pressure drop cable-in-conduit conductors (CICC) was measured at CRPP. The conductors are single channel CICC's with different void fraction in the range 38 to 28 %. Several conductor samples are investigated and tested in SULTAN by supercritical helium and in a room temperature facility by pressurized water. In particular, experiments are performed on samples at different degree of compaction, measuring the void fraction after each compression step. In this way it is possible to assess the friction factor of the cable bundle as a function of the void fraction. The reduction of the experimental data to obtain the friction factor as a function of Reynolds number is performed by (a) established methods using the correlation proposed by Katheder and (b) a new porous media analogy model. We discuss the results and in particular the comparison of these two methods of correlation.

C3-I-03 Flow of Saturated Liquid Nitrogen through Micro-Scale Orifices

T.A. Jankowski*, E.N. Schmierer, F.C. Prenger, S.P. Ashworth, Los Alamos National Laboratory.*

The flow of saturated liquid nitrogen through micro-scale orifices has been characterized experimentally. Measurements of pressure drop and flow rate were made with liquid nitrogen flowing through orifices ranging in diameter from 35 micron to 250 micron, with orifice length to diameter ratios ranging from 2 to 15. The design of the experimental apparatus, the instrumentation used, and the experimental uncertainties are presented. Difficulties with clogging of the micro-scale orifices and with obtaining repeatable and reliable results at cryogenic temperatures are discussed. Finally, experimental results are shown to agree with previous investigations of flow through micro-scale orifices using room temperature refrigerants.

C3-I-04 A Rotating Heat Pipe for Cooling of Superconducting Machines

T.A. Jankowski*, F.C. Prenger, E.N. Schmierer, Los Alamos National Laboratory; A. Razani, The University of New Mexico.*

A curved rotating heat pipe for use in superconducting motor and generator applications is introduced here. A numerical model of the curved rotating heat pipe [1], which has been validated with room temperature experiments, is used to predict the performance of rotating heat pipes using cryogenic working fluids. Heat pipe model results are compared to results for a single-phase gas-cooled refrigeration system in typical superconducting generators and motors. The nearly isothermal operation of the heat pipe is shown to reduce the temperature gradients seen by the superconducting coil compared to the forced flow gas system. Furthermore, because of the passive nature of the heat pipe operation, the heat pipe concept may be advantageous when considering the overall refrigeration system. Finally, because of their modular nature, the use of multiple heat pipes provides redundancy in the cooling system.

[1] T. A. Jankowski, "Numerical and Experimental Investigations of a Rotating Heat Pipe," Ph.D. Dissertation, The University of New Mexico, 2007.

C3-K Thermal Insulation Systems - II

C3-K-01 Vacuum-Insulated, Flexible Cryostats for Long HTS Cables: Requirements, Status and Prospects

M.J. Gouge*, J.A. Demko, ORNL; J.F. Maguire, AMSC; M.L. Roden, Southwire Company; C.S. Weber, SuperPower, Inc..*

Several high temperature superconducting (HTS) cable demonstration projects have begun operation on the electric grid in the last year with the liquid nitrogen-cooled cable contained in one or more vacuum-insulated, flexible cryostats with lengths up to 600 meters. These grid demonstration projects are prototypes of the anticipated commercial market which will require superconducting cable lengths in the multiple kilometer range with the vacuum-jacketed cryostats in underground ducts providing acceptable thermal insulation for decades. The current state-of-the art for flexible cryostats (installation constraints, heat loads with a good and degraded vacuum, impact of cable bends, getter lifetime and reliability) is discussed. Further development needed to meet the challenging commercial HTS cable application is outlined.

Research sponsored by the U.S. Department of Energy - Office of Electricity Delivery and Energy Reliability, Superconductivity Program for Electric Power Systems under contract DE-AC05-00OR22725 with Oak Ridge National Laboratory, managed and operated by UT-Battelle, LLC.

C3-K-02 Heat Flow Measurement and Analysis of Thermal Vacuum Insulation

C. Laa*, C. Hirschl, J. Stipsitz, Austrian Aerospace GmbH.*

A new kind of calorimeter has been developed to obtain specific material parameters needed for the analysis of thermal vacuum insulation. A detailed description of the measuring device and the measurement results will be given in this paper.
This calorimeter facility allows to measure the heat flow through the insulation under vacuum conditions in a wide temperature range from liquid nitrogen to ambient. Both boundary temperatures can be chosen within this range. The insulation can be characterized at high vacuum or under degraded vacuum, the latter using helium or nitrogen gas. The mechanisms of heat transfer have been investigated, namely infrared radiation between the reflective layers of the insulation and conduction through the interleaving spacer material. A mathematical description of the heat flow through the insulation has been derived. Based on this the heat flow for a typical insulation material has been calculated by finite element analysis by use of the software tool ANSYS. Such a transient calculation is needed to determine the time to reach thermal equilibrium, which is mandatory for a proper interpretation and evaluation of the measurement.
The new insulation measurement results combined with the proposed type of analysis can be applied to better understand the thermal behavior of any kind of cryogenic system.

C3-K-03 Robust Multilayer Insulation for Cryogenic Systems

J.E. Fesmire*, B.E. Scholtens, NASA KSC; S.D. Augustynowicz, Sierra Lobo, Inc..*

New requirements for thermal insulation include robust multilayer insulation (MLI) systems that work for a range of environments from high vacuum to no vacuum. Improved MLI systems must be simple to install and maintain while meeting the life-cycle cost and thermal performance objectives. Performance of MLI systems in actual use has been shown to be much worse than the ideal case. Industry products using robust MLI can benefit from improved cost-efficiency and system safety. Spacecraft that must store cryogens during all mission phases, including orbital/lunar service (high vacuum) and ground launch operations (no vacuum) are planned. Future cryogenic spacecraft for the soft vacuum environment of Mars are also envisioned. Novel materials have been developed to operate as excellent thermal insulators at vacuum levels that are much less stringent than the absolute high vacuum requirement of current MLI systems. One such robust system, Layered Composite Insulation (LCI), has been developed at the Cryogenics Test Laboratory of NASA Kennedy Space Center. The experimental testing and development of LCI is the focus of this paper. Compared to MLI under cryogenic conditions, LCI thermal performance is shown to be six times better at soft vacuum and similar at high vacuum. The apparent thermal conductivity (k-value) and heat flux data for LCI systems are compared with other MLI systems.

C3-K-04 Synthesis on the multilayer cryogenic vacuum insulation modelling and measurements

M. Chorowski*, J. Polinski, Wroclaw University of Technology.*

A thermodynamic approach towards insulation systems in cryogenic engineering is proposed. A mathematical model of the heat transfer through multilayer insulation (MLI) has been developed and experimentally verified. The model comprises both physical and engineering parameters determining the MLI performance and enables a complex optimisation of the insulation system including the choice of the insulation location in a vacuum space. The model takes into account an interstitial (interlayer) gas pressure and a shield – spacer thermal contact resistance variation with the MLI layer density. The paper presents the discussion of MLI performance in different conditions and provides comparison of computation results with experimental reference data. The optimisation of the insulation for different boundary conditions is analysed and concluded.

C3-K-05 Thermal Performance Comparison of Glass Microsphere and Perlite Insulation Systems for Liquid Hydrogen Storage Tanks

J.P. Sass*, J.E. Fesmire, D.L. Morris, NASA KSC; Z.F. Nagy, S.D. Augustynowicz, Sierra Lobo, Inc.; S.J. Sojourner, ASRC Aerospace.*

A technology demonstration test project was conducted by the Cryogenics Test Laboratory at the Kennedy Space Center (KSC) to provide comparative thermal performance data for glass microsphere and perlite insulation for liquid hydrogen tank applications. Two identical 1/15th scale versions of the 850,000 gallon spherical liquid hydrogen tanks at Launch Complex 39 at KSC were custom designed and built to serve as test articles for this test project. Evaporative (boil-off) calorimeter test protocols, including liquid hydrogen and liquid nitrogen, were established to provide tank test conditions characteristic of the large storage tanks that support the Space Shuttle launch operations. This paper provides comparative thermal performance test results for glass microspheres and perlite for a wide range of conditions. Limited results for aerogel insulation material are also included. Aerogel-based insulation systems are targeted for non-evacuated liquid oxygen tank applications due to cost and performance parameters. Thermal performance as a function of cryogenic commodity (hydrogen and nitrogen), vacuum pressure, insulation fill level, tank liquid level, and thermal cycles will be presented.

Funding was provided by the NASA Space Operations Mission Directorate under the Internal Research and Development project New Materials and Technologies for Cost-Efficient Storage and Transfer of Cryogens.

C3-K-06 Cost-Efficient Storage of Cryogens

J.E. Fesmire*, J.P. Sass, D.L. Morris, NASA KSC; Z.F. Nagy, S.D. Augustynowicz, Sierra Lobo, Inc.; S.J. Sojourner, ASRC Aerospace.*

NASA's critical cryogenic infrastructure that supports launch vehicle operations and propulsion testing is reaching an age where major refurbishment will soon be required. A key element of this infrastructure is the insulation in large double-walled cryogenic storage tanks, for which perlite has been the insulation material of choice for decades. New materials are now available that can provide improved thermal and mechanical performance. An internal research and development project investigated the application of new bulk-fill insulation materials and associated technology upgrades to advance the overall efficiency of cryogenic storage tanks. Technical, safety and affordability data were produced to support NASA program decisions on the benefits and risks of using the alternative insulation materials, including glass microspheres and aerogel beads. Work was divided into three areas: material testing (thermal conductivity and physical characterization), tank demonstration testing (liquid nitrogen and liquid hydrogen), and system studies (thermal modeling, economic analysis, and insulation changeout). The research work presents a more cost-effective solution for large-scale cryogenic storage worldwide, new cryogenic test equipment and methods, and a pathway for mass-efficient storage and transfer of cryogens on the Moon and Mars.

Funding was provided by the NASA Space Operations Mission Directorate under the Internal Research and Development project New Materials and Technologies for Cost-Efficient Storage and Transfer of Cryogens.

C3-L Accelerator Cryogenics

C3-L-01 Cooldown of the first sector of the Large Hadron Collider: comparison between mathematical model and measurements

L. Liu, Chinese Academy of Sciences; G. Riddone, ***L. Tavian****, CERN.*

The first LHC sector (3.3-km long) will be cooled down for the first time from room temperature to 1.8 K at the beginning of the year 2007. For this cool-down, the mass-flow distribution of each cell has been optimized using a mathematical model developed to establish reference set-points. In this paper, the measured evolution of temperatures, pressures, mass-flow rates of helium in each cell of the machine as well as in the cryogenic distribution line will be presented and compared with the simulation results obtained from the previous mathematical model. Possible discrepancies between measurements and calculation will be also analyzed for improving the mathematical model.

C3-L-02 Commissioning the cryogenic system of the first LHC sectors

F. Millet, S. Claudet, G. Ferlin, P. Gomes, S. Junker, G. Riddone, M. Soubiran, L. Tavian, B. Vullierme, ***U. Wagner****, CERN; L. Ronayette, L. Serio, CNRS.*

The LHC machine, composed of eight sectors with superconducting magnets and cavities requires a complex cryogenic system providing high cooling capacities (equivalent to 18 kW at 4.5 K and 2.4 kW at 1.8 K per sector produced in large cold boxes and distributed via 3.3-km cryogenic transfer lines). After individual reception tests of the cryogenic subsystems (cryogen storages, refrigerators, cryogenic transfer lines and distribution boxes) performed since 2000, the commissioning of the cryogenic system of the first LHC sectors is under way since November 2006.
After a brief description of the LHC cryogenic system and its specificities, the commissioning will be reported detailing the preparation phase (pressure and leak tests, conditioning and flushing), the cool-down or warm-up sequences including the handling of cryogenic fluids and finally the powering phase of magnets and cavities. Preliminary conclusions of the commissioning of the first LHC sectors will be drawn with the review of the critical points solved or still pending. Finally this paper will report on the first operation experience of the LHC cryogenic system in perspective of the commissioning of the remaining LHC sectors and the beam injection test.

C3-L-03 Validation and Performance of the LHC Cryogenic System Through Commissioning of the First Sectors

L. Serio*, CERN.*

The cryogenic system for the Large Hadron Collider accelerator is presently in its final phase of commissioning at nominal operating conditions. The refrigeration capacity for the LHC is produced using eight large cryogenic plants and eight 1.8 K refrigeration units installed on five technical sites. Machine cryogenic equipments are installed in a 26.7 km circumference ring deep underground tunnel and are maintained at their nominal operating conditions via a distribution system consisting of transfer lines, cold interconnection boxes at each technical site and a cryogenic distribution line.
The functional analysis of the whole system during all operating conditions was established and validated during the first sectors tests in order to maximize the system availability and minimize the operation cost. The analysis, operating modes, main failure scenarios, results and performances of the cryogenic system are presented.

C3-L-04 Thermal test of the cryogenic distribution line of the first complete sector of the Large Hadron Collider

K. Brodzinski, S. Claudet, J. Fydrych, F. Millet, G. Riddone, L. Serio, M. Strychalski, ***L. Tavian****, CERN; M. Chorowski, Wroclaw University of Technology.*

The first of the eight sectors of the Large Hadron Collider (LHC) has been completely installed in the underground tunnel and connected to its cryogenic distribution line (QRL). The QRL will distribute the gaseous and supercritical helium along the 3.3-km long sector. In the so-called service modules the supercritical helium is sub-cooled and then expanded to produce saturated 1.8 K superfluid helium This helium is used as cryogenic refrigerant for the accelerator superconducting magnets already immersed in a superfluid helium bath at 1.9 K.
One of the next milestones, after the successful thermo-mechanical validation of the QRL alone, carried out in 2005, is the hardware commissioning of first complete sector of the LHC. One of the main issues of this commissioning is the heat inleak measurements to the different circuits located in the QRL as well as in the LHC machine. The paper describes the applied heat inleak measurement methodology, its accuracy and error estimation, as well as presents the main results of the measured heat inleaks at the different temperature levels. The measured heat inleaks will be also compared to the results obtained from the test of the QRL alone.

C3-M Pulse Tube Theory and Models

C3-M-01 Performance Limits of 3He in Pulse Tube Cryocoolers

P. Kittel*, Consultant.*

The enthalpy, entropy, and exergy flows of the real gas effects of 4He in ideal pulse tube cryocoolers have been described previously. Huang, et. al, have recently developed a computer program for the thermophysical properties of 3He. This paper uses this model to describe how the thermodynamic flows are affected by real gas phenomena of 3He in ideal pulse tube cryocoolers.
Frequently such descriptions take an energy-centric view, concentrating on the first law of thermodynamics, the conservation of energy. This approach can result in a complex description of the cooler in terms of energy and enthalpy flows.
An alternative is to take an entropy-centric approach. Closely related to this is the exergy-centric approach. These descriptions concentrate on the second law of thermodynamics, the generation of entropy or the destruction of exergy.
Both the energy-centric and exergy/entropy-centric approaches make use of both the laws of thermodynamics and both approaches give equivalent descriptions of a cryocooler. However, the latter approach can be more useful as it can yield a simpler description, one that emphasizes loss mechanisms.
This paper applies the second law approach to pulse tube cryocoolers. The non-ideal gas effects of 3He in Pulse Tube cryocoolers are discussed and compared to similar effects from 4He.

This work was funded through University Affiliated Research Center (UARC) Subcontract P0228861. The UARC is managed by the University of California, Santa Cruz under NASA Ames Research Center Contract NAS2-03144.

C3-M-02 Design for a Miniature Pulse Tube Cryocooler Operating at 150Hz

***Z. Gan**, NIST; Cryogenics Lab., Zheijiang Univ.; R. Radebaugh, M.A. Lewis, P.E. Bradley, NIST; A. Veprik, NIST; Ricor, Cryogenic and Vacuum Systems.*

Recent research shows that a pulse tube cryocooler successfully operating at 120Hz achieved 50K with high efficiency at 80K. That shows cryocoolers can operate at very high frequency and not be limited to about 60Hz. There are many benefits of high frequency operation, such as fast cooldown, less temperature oscillation at the cold head and small size. But, simply increasing the operating frequency leads to large losses in the regenerator. Based on the numerical calculations with REGEN 3.2 developed by NIST, it shows efficient regenerator operation at high frequencies is possible only with high charging pressure above 2.5MPa and with very small hydraulic diameters and lengths. For commercially available compressors, we have designed a pulse tube cryocooler as small as possible while maintaining adiabatic conditions in the pulse tube. The length¡äinner diameter of pulse tube and regenerator are 27mm¡ä1.96mm and 27mm¡ä4.39mm respectively. This paper presents a design for pulse tube cryocooler operating at 80K with a charging pressure of 5MPa at 150 Hz with the pressure ratio at the cold end of 1.30.

C3-M-03 Modeling and Experiments on Fast Cooldown of a 120 Hz Pulse Tube Cryocooler

***S. Vanapalli**, H.J.M. terBrake, MESA+ Institute of Nanotechnology, Univeristy of Twente; M. Lewis, R. Radebaugh, NIST, Boulder, CO, 80305; G. Zhihua, 3Cryogenics Lab, Zheijiang University, Hangzhou & NIST, Boulder, CO 80305.*

The high frequency operation of a pulse tube cryocooler leads to reduced regenerator volume, which results in a reduced heat capacity and a faster cooldown time. A pulse tube cryocooler operating at a frequency of 120 Hz and a filling pressure of 3.5 MPa achieved a no-load temperature of 50 K and a cooldown time of 11 minutes. The cooling power at 80 K is about 3.35 W with a cooldown time of about 5.5 minutes. The back ground losses were about 0.9 W. This very fast cooldown is very attractive to many applications. In this study we present an analytical model relating various parameters such as regenerator volume, frequency of operation, thermal load and cooldown time. A comparison is also done between the analytical model, REGEN3.2 numerical calculations and experiments.

STW-Dutch Technology Foundation for the financial support

C3-M-04 Approximate Design Method for Single Stage Pulse Tube Refrigerators

***John Pfotenhauer**, University of Wisconsin - Madison.*

An approximate method is presented for the design of a single stage, Stirling-type pulse tube refrigerator. The design method begins from a defined cooling power, operating temperature, average and dynamic pressure, and frequency. Using a combination of phasor analysis, approximate correlations derived from extensive use of REGEN3.2, a few ‘rules of thumb,’ and available models for inertance tubes, a process is presented to define appropriate geometries for the regenerator, pulse tube and inertance tube components. In addition, specifications for the acoustic power and phase between the pressure and flow required from the compressor are defined. The process enables an appreciation of the primary physical parameters operating within the pulse tube refrigerator, but relies on approximate values for the combined loss mechanisms. The defined geometries can provide both a useful starting point, and a sanity check, for more sophisticated design methodologies. A comparison of the model results with the performance of existing pulse tube refrigerators is included.

C3-M-05 Two-dimensional model analysis for the pulse tube of rotating pulse tube refrigerator

***J. Choi**, S. Jung, KAIST.*

The objective of this paper is to investigate the rotational effect on the Stirling type pulse tube refrigerator which is to be used as an on-board cooling system for superconducting rotor. The two-dimensional analysis model is applied to study thermohydraulic behavior of oscillating flow in the rotating pulse tube.

Two dimensional differential equations for the viscous compressible flow in a pulse tube are solved for limited case of very small expansion parameter. In the first order analysis, the enthalpy flow which is directly related to the refrigeration power is calculated. The result of the first order analysis shows that the net enthalpy flow in the pulse tube slightly decreases with the rotation. In the second order analysis, the steady components of the second order variables are calculated on the bases of the first order solutions and the effects of the rotation on the enthalpy flow loss due to the mass streaming are evaluated. The slow rotation of the pulse tube reduces the secondary steady flow, which decreases the streaming-driven enthalpy flow loss. As the rotating speed however, surpasses a certain value, the secondary steady flow is generated in the opposite direction, which results in the increase of the steady enthalpy flow loss again. In this paper, we also performed numerical simulation using a finite-volume method and compared the numerical results with the approximate solution of the differential equations.

This work was supported by a grant from Center for Applied Superconductivity Technology of the 21th Century Frontier R&D Program funded by the Ministry of Science and Technology, Republic of Korea.

C3-M-07 Optimal Pulse-Tube Design Using Computational Fluid Dynamics

***R.P. Taylor**, G.F. Nellis, S.A. Klein, University of Wisconsin.*

Over the past few decades, the pulse-tube cryocooler has been transformed from a curiosity to one of the most attractive systems for providing reliable cryogenic cooling; it is now used in aerospace, medical and superconductor applications. This technology development has been enabled by advances in the simulation tools that are available for regenerator, compressor, and inertance tube design. However, a dedicated design tool for the pulse-tube component in a pulse-tube cryocooler and the associated flow transitions between the pulse tube and the regenerator and the pulse tube and the inertance network has yet to be developed.

This paper describes the development of a two-dimensional, axisymmetric CFD model of the pulse-tube and its associated flow transitions operating under conditions that are consistent with a pulse-tube refrigerator. The model is implemented in the commercial CFD package FLUENT. The CFD simulations calculate and delineate the various loss mechanisms; these are reported as a percentage of the acoustic power at the cold end. A gross figure of merit (the pulse tube efficiency) is defined as the ratio of the useful cooling provided to the available acoustic power. The practical uses (e.g., determining an optimal geometric design) and limitations (e.g., the accuracy) of the model are discussed and initial optimization results of the CFD simulations are presented.

This work was supported by the Office of Naval Research under contract N00014-06-1-0007.

C3-N Aerospace Cryogen Storage

C3-N-01 Cryogenic Propellant Storage Analyses and Design Tool Evolved from In-Space Cryogenic Propellant Depot Project

***D.W. Plachta**, NASA GRC; J. Feller, NASA ARC; R. Christie, E. Carlberg, ASRC Aerospace.*

Lunar missions under consideration would benefit with incorporation of high specific impulse propellants, such as LH2 and LO2, in the propulsion systems provided associated cryogenic propellant storage boil-off mass were minimized. Concepts to do so were considered under the In-Space Cryogenic Propellant Depot Project. Specific to that was an investigation of cryocooler integration concepts for relatively large depot sized propellant tanks. One concept proved most promising—it moves heat efficiently to the cryocooler over long distances via a compressed helium loop. The analyses and designs for this were incorporated into a Cryogenic Analysis Tool. That design approach is explained and shown herein, as are the analytical trends that make it so promising.

C3-N-02 Optimized heat interception for cryogen tank support structure

***E.R. Canavan**, F.K. Miller, NASA – Goddard Space Flight Center.*

We consider means for using the cooling available in boil-off gas to intercept heat conducted through the support structure of a cryogen tank. A one-dimensional model of the structure coupled to a gas stream gives an analytical expression for heat leak in terms of flow rate for temperature independent properties and laminar flow. A numerical model has been developed for heat transfer on a thin cylindrical tube with an attached vent line. The model is used to determine the vent path layout that will minimize heat flow into the cryogen tank. The results are useful for a number of applications, but the one of interest in this study is the minimization of the boil-off in large cryopropellant tanks in low Earth and low lunar orbit.

C3-N-03 The Performance of Gas Filled Multilayer Insulation

***G. L. Mills**, V. Y. Kotsubo, Ball Aerospace and Technologies Corp..*

The NASA Exploration Program is currently planning to use combinations of liquid oxygen, methane and hydrogen for propulsion in future spacecraft for the human exploration of the Moon and Mars. This will require the efficient long term, on-orbit storage these cryogens. Multilayer insulation (MLI) will be critical to achieving the required thermal performance since it has much lower heat transfer than any other insulation when used in a vacuum. However, the size and mass constraints of these propulsion systems will not allow a vacuum shell to be used to provide the vacuum during ground hold and launch. An effective solution is to purge the MLI during ground hold with an inert gas which is then vented during ascent and on-orbit. In this paper, we report on experimental tests and modeling that we have done on MLI used to insulate a cryogenic tank. These include measurements of the heat transfer of gas filled insulation, evacuated insulation and during the transition in between. The water vapor pressure of the MLI and its effect on the thermal performance was also measured.

C3-N-04 Development of Cryogenic Composite Over-Wrapped Pressure Vessels

***T. DeLay**, NASA/MSFC; J. Patterson, HyPerComp Engineering; J. Schneider, Mississippi State University.*

There have been recent changes in the needs of helium pressurant tanks and in propellant tanks for new launch vehicles that have the requirement to function at cryogenic temperatures. Cryogenic propellants are needed for the upper-stage for NASA's new ARES-1 vehicle concept, which also has the requirement for 5,000 psi pressurant tanks to be located in the liquid hydrogen tank of a LOX/LH2 common bulkhead tank. There is a similar need for cryogenic propellant tanks for the developing commercial launch business and for alternate fuel ventures to transport liquefied natural gas and hydrogen. In all of these cases it is important to know how the materials perform at cryogenic temperatures in order to minimize weight and to ensure safety and reliability. A multi-year collaborative effort has made considerable progress in this venture. This effort involved the simultaneous development of tank designs, test methods and material formulations. Many COPV's have been tested at cryogenic conditions and are supported by cryogenic material tests of candidate fiber and resin systems formulated specifically for cryogenic applications. This comprehensive approach is also being expanded to addressing issues with impact damage tolerance and material degradation due to environmental factors.

C3-N-05 Testing the Effects of Helium Pressurant on Thermodynamic Vent System Performance with Liquid Hydrogen

***R. H. Flachbart**, A. Hedayat, S. Nelson, S. P. Tucker, NASA - Marshall Space Flight Center; L. J. Hastings, Alpha Technology Inc..*

In support of the development of a micro-gravity pressure control capability for liquid hydrogen, testing was conducted at the Marshall Space Flight Center using the Multipurpose Hydrogen Test Bed (MHTB) to evaluate the effects of helium pressurant on the performance of a spray bar thermodynamic vent system (TVS). Fourteen days of testing were performed in August – September 2005, with an ambient heat leak of about 70-80 watts and tank fill levels of 90%, 50%, and 25%. The TVS successfully controlled the tank pressure within a +/- 3.45 kPa (+/- 0.5 psi) band with various helium concentration levels in the ullage. Relative to pressure control with an "all hydrogen" ullage, the helium presence resulted in 10 to 30 per cent longer pressure reduction durations, depending on the fill level, during the mixing/venting phase of the control cycle. Testing was also conducted to evaluate thermodynamic venting without the mixer operating, first with liquid then with vapor at the recirculation line inlet. Although ullage stratification was present, the ullage pressure was successfully controlled without the mixer operating. Thus, if vapor surrounded the pump inlet in reduced gravity, the ullage pressure can still be controlled by venting through the TVS Joule Thomson valve and heat exchanger. It was evident that the spray bar configuration, which extended almost the entire length of the tank, enabled significant thermal energy removal from the ullage even without the mixer operating.

C3-N-06 Analyzing the Use of Gaseous Helium as a Pressurant with Cryogenic Propellants with Thermodynamic Venting System Modelling and Test Data

***A. Hedayat**, S.L. Nelson, R.H. Flachbart, D.J. Vermilion, S.P. Tucker, NASA-MSFC; L.J. Hastings, Alpha Technology, Inc..*

Cryogenic propellants are candidate propellants for NASA's Lunar and Mars exploration programs. To provide adequate mass flow to the system's engines and/or to prevent feed system cavitation, gaseous helium (GHe) is frequently considered as a pressurant. Also during low gravity operations, a Thermodynamic Venting System (TVS) concept is expected to maintain tank pressure without propellant resettling. Therefore, a series of tests were conducted at the Marshall Space Flight Center to evaluate the effects of GHe pressurant on pressure control performance of a TVS with liquid nitrogen, hydrogen, and methane. The TVS utilized in this effort consists of a recirculation pump, Joule-Thomson (J-T) expansion valve, and a parallel flow concentric tube heat exchanger combined with a longitudinal spray bar. Using a small amount of liquid extracted by the pump and passing it though the J-T valve, then through the heat exchanger, thermal energy is periodically extracted from the bulk liquid and ullage thereby enabling pressure control. The test bed set up provided thermal conditioning under both vacuum and ambient environments. Transient one-dimensional analytical models of the TVS are used to predict the ullage and bulk liquid pressures and temperatures. Details of predictions and comparisons with test data will be presented in the final paper.

C3-N-07 Screen Channel Liquid Acquisition Device Testing using Liquid Methane

***J.M. Jurns**, J.D. Gaby, ASRC Aerospace Inc.; S.A. Sinacore, J.B. McQuillen, NASA Glenn Research Center.*

Liquid acquisition devices (LADs) can be utilized within a propellant tank in space to deliver single-phase liquid to the engine in low gravity. One type of liquid acquisition device is a screened gallery whereby a fine mesh screen acts as a "bubble filter" and prevents the gas bubbles from passing through until a crucial pressure differential condition across the screen, called the bubble point, is reached. This paper presents data for LAD bubble point data in liquid methane (LCH4) for stainless steel Dutch Twill Screens with mesh sizes of 325x2300 and 200x1400. Data is presented for both saturated and sub-cooled LCH4, and is compared with predicted values. These tests represent the first known non-proprietary effort to collect LAD data in LCH4.

C3-N-08 Numerical Modeling of Propellant Boil-Off in a Cryogenic Storage Tank

***A.K. Majumdar**, NASA MSFC; T.E. Steadman, J.L. Maroney, Sverdrup; J.P. Sass, J.E. Fesmire, NASA KSC.*

A numerical model to predict boil-off of stored propellant in large spherical cryogenic tanks has been developed. Accurate prediction of tank boil-off rates for different thermal insulation systems was the goal of this collaboration effort. The Generalized Fluid System Simulation Program, integrating flow analysis and conjugate heat transfer for solving complex fluid system problems, was used to create the model. Calculation of tank boil-off rate requires simultaneous simulation of heat transfer processes among liquid propellant, vapor ullage space, and tank structure. The reference tank for the boil-off model was the 850,000 gallon liquid hydrogen tank at Launch Complex 39B (LC-39B) at Kennedy Space Center, which is under study for future infrastructure improvements to support the Constellation program. The methodology employed in the numerical model was validated using a sub-scale model and tank. Experimental test data from a 1/15th scale version of the LC-39B tank using both liquid hydrogen and liquid nitrogen were used to anchor the analytical predictions of the sub-scale model. Favorable correlations between sub-scale model and experimental test data have provided confidence in full-scale tank boil-off predictions. These methods are now being used in the preliminary design for other cases including future launch vehicles.

Funding was provided by the NASA Space Operations Mission Directorate under the Internal Research and Development project New Materials and Technologies for Cost-Efficient Storage and Transfer of Cryogens.

C3-O Aerospace Mission Concepts

C3-O-01 ST9 Large Space Telescope: A Proposed Mission to Validate the New Paradigm in Low Temperature Cooling

***M. DiPirro**, D. Muheim, J. Tuttle, K. Walyus, NASA/GSFC; P. Cleveland, Energy Solutions International; D. Durand, NGST; A. Klavins, D. Tennerelli, J. Tolomeo, LMMSC; C. Paine, NASA/JPL.*

NASA's New Millennium Program has sponsored 5 studies for space missions to advance space science related technologies. One of these studies, the ST9-Large Space Telescope (LST) will demonstrate cooling to 4 to 6 K by passive radiation and an active cooler rather than the previous method of stored cryogens. Stored cryogen systems are not practical for the larger and longer duration missions of the future. Passive radiation is accomplished through the use of a deployable, multilayer sunshield which has the property of reflecting radiation perpendicular to it while emitting radiation parallel to the layers. Such a shield is already under development for the James Webb Space Telescope (JWST). The JWST shield effectively attenuates solar and Earth radiation and thermal radiation and conduction from the spacecraft by three orders of magnitude, producing an inner layer temperature of 90 K. LST will take this technology several steps further. By incorporating two stages of active cooling the LST shield will attenuate the warm surroundings by 6 orders of magnitude producing a shield with an inner layer at 20 K and a cold base plate for a future telescope to below 6 K. This talk will summarize the material properties tests, thermal and structural analyses, component level test beds, plans for ground verification through the use of subscale thermal tests, and mission operations planned for ST9 LST.

C3-O-02 An Analysis of the Cryogenic Environments for the Xeus Mission

***J.S. Reed**, P. D'Arrigo , M-C. Perkinson , K. Geelen , EADS Astrium Ltd.; I. Hepburn , C. Brockley-Blatt , Mullard Space Science Laboratory; T. Bradshaw , L. Duband , Rutherford Appleton Laboratory.*

The X-ray Evolving Universe Spectroscopy (XEUS), mission is a candidate for the ESA Cosmic Vision 2015-2025 plan, following XMM-Newton and Chandra. The presently proposed system consists of two Mirror and Detector spacecraft, flying 35m apart at L2. The Detector Spacecraft model payload consists of a passively cooled wide-field camera at 200K, and one of two narrow-field instruments at 300mK and 50mK. As the mission lifetime is 5 years, with a 10 year goal, long-life closed cycle cooling systems will be required. Hence, XEUS will be one of the most complex observatories ever flown, with state-of-the-art cryogenic systems. Under contract to ESA, Astrium has worked with MSSL, RAL, and CEA-SBT, to propose a payload design capable of meeting the demanding requirements. Our baseline consists of a double stage ADR at 50mK, and a helium sorption cooler at 300mK. Each system will be pre-cooled by a closed cycle J-T system, similar to Planck, at 2.5K or 4K, which itself will be pre-cooled by a two-stage Stirling cycle cooler, at 15K or 18K. This paper describes the mission, and discusses the cryogenic architecture.

C3-O-03 USAF Cryogenic Thermal Management System Needs

***T. Roberts**, F. Roush, Air Force Research Laboratory.*

The Air Force Research Laboratory (AFRL) Space Vehicles Directorate actively pursues cryogenic refrigeration system and system integration technology research to support the research needs of the Air Force, Missile Defense Agency, and Department of Defense. This effort not only takes into consideration the specific cryogenic support requirements of payload components such as infrared sensors, but also seeks to minimize the system impact on payload and spacecraft operations in terms of power and mass budgets or jitter producing vibration. These general thermal management needs of missions supporting Air Force space operations are discussed with respect to the technology portfolio funded by AFRL in order to meet these future requirements. Specific strengths and weaknesses of the current state of technology are also compared to these needs.

C3-O-04 Cryogenic System Challenges for Lightweight Superconducting Magnet and Power Systems

C.E. Oberly, *G.L. Rhoads, Air Force Research Laboratory.*

Significant savings in weight and volume for operational military systems can be gained by employing high temperature superconducting (HTS) magnets for electrical power equipment operating at both very high and power frequency. The demands on a cryogenic system are significantly reduced as temperature rises from 4.2K to 77K, but military operational challenges remain. While the weight, volume and electrical power requirements for HTS systems can be reduced by orders of magnitude at 77K, the cryogenic system remains as a deterrent to quick implementation of HTS technology. Military readiness and field operations do not permit optimal, continuously cooled, cryogenic systems. Extreme ambient temperatures drive commercial refrigerators out of their performance envelope. Rapid cooldown requirements in the range of 1 to 4 hours are difficult to meet with a lightweight refrigerator coupled to a sizeable HTS cold mass. Liquid heat transport systems are penalized by makeup gas in remote field operations where many cooldowns from ambient are required. Multiple rapid cooldowns creat thermomechanical stresses on the new HTS magnet and power systems that have not yet been fully explored. Several examples of HTS military magnet and power systems are explored and compared to provide insight into the need for future cryogenic systems for challenging military systems. New refrigeration approaches are discussed to meet the future demands of military systems.

This work has been supported by the Air Force Research Laboratory and the Air Force Office of Aerospace Research.

C3-P Novel Cryostats

C3-P-01 Subcooled Liquid Oxygen Cryostat for Magneto-Archimedes Particle Separation by Density*

D.K. Hilton, *D. Celik, S.W. Van Sciver, NHMFL/FSU.*

An instrument for the separation of particles by density (sorting) is being developed that uses the magneto-archimedes effect in liquid oxygen. With liquid oxygen strongly paramagnetic, the magneto-archimedes effect is an extension of diamagnetic levitation. The instrument will be able to separate ensembles of particles from 100 µm to 100 nm in size, and vertically map or mechanically deliver the separated particles. The instrument requires a column of liquid oxygen that is nearly isothermal, free of thermal convection, subcooled to prevent nucleate boiling, and supported against the strong magnetic field used. Thus, the unique cryostat design that meets these requirements is described. It consists in part of a column of liquid nitrogen below for cooling the liquid oxygen, with the liquid oxygen pressurized with helium gas to prevent nucleate boiling.

**Research supported by IHRP Grant No. 5057.*

C3-P-02 Novel Integration of a 6T Cryogen-Free Magneto-Optical System with a Variable Temperature Sample Using a Single Cryocooler

A.B. Berryhill, *D.M. Coffey, Cryomagnetics, Inc..*

Cryomagnetics` new “C-Mag Optical” Magneto-Optic Property Measurement System is a versatile materials and device characterization system that allows the researcher to simultaneously control the applied magnetic field and temperature of a sample while studying its electrical and optic properties. The system integrates a totally liquid cryogen-free 6T superconducting split-pair magnet with a variable temperature sample space, both cooled using a single 4.2K pulse tube refrigerator. To avoid warming the magnet when operating a sample at elevated temperatures, a novel heat switch was developed. The heat switch allows the sample temperature to be varied from <10K to 325K while maintaining the magnet at 4.2K or below. In this paper, the design and performance of the overall magnet system and the heat switch will be presented. New concepts for the next generation system will also be discussed.

C3-P-03 Low vibration closed-cycle cryostat for cryogenic scanning probe microscopy

M. Janotta *, A. Kueng , C. Boedefeld , attocube systems AG; M. Buehler , J. Hoehne , VeriCold Technologies GmbH.*

Low temperature scanning probe techniques as e.g. confocal microscopy are methods of major interest with regard to research fields ranging from material and surface science to single molecule spectroscopy. Conventional instrumental set-ups involve the usage of expensive liquid helium and have, in earlier days, suffered from the lack of coarse positioning units at these temperatures.
We present a highly flexible scanning probe microscope (SPM) system combined with a pulse-tube based closed-cycle cooler. Furthermore, the principle of the implemented nanopositioning units which are based on the slip-stick principle will be discussed shortly. The complete cryogenic microscopic system enables plug-and-play high resolution SPM measurements at 4 K without the need of liquid helium. The cryostat has been specially adapted for very low vibrations as required for all scanning probe applications. Furthermore, extremely short cool down times of less than 2 hours for standard samples can be achieved. Various exemplary results of cryogenic confocal microscopy are shown which demonstrate its ultra-high stability at low temperature while at the same time very high optical resolution is provided. Furthermore, projected applications for AFM measurements in combination with the presented cooling system will be reported.
The merge of the 4 K closed-cycle cryostat with SPM techniques makes this product line unique in the field of cryogenic, liquid helium free, analytical instruments.

C3-P-04 Performance Studies of a Batch Type Cryofreezer with Precooler

R.M Khadatkar, *G.H.Raisoni College of Engineering; S.C. Pattanayak, Indian Institute of Technology, Kharagpur.*

A batch type, top door open cryofreezer having two chambers of 28.274 liters each, using LN2 as coolant has been designed and developed. To increase the heat transfer rate around the food products, variable speed axial fans of 1/40 H.P and 1600 rpm are used inside the chambers. ASCO made cryogenic solenoid valves supported by a temperature sensor and cut-off circuit are used to control the LN2 flow. The liquid cycle alternates between the two chambers making one chamber as freezer and other chamber as precooler at desirable setpoint temperature. This minimizes the handling of frozen and precooled samples during freezing process. The exit cold GN2 is effectively utilized to precool the samples, which reduces the LN2 consumption for freezing.
The heat inleak to the chambers by conduction, convection and radiation from the surrounding is calculated as 61.5 Watts and the experimentally determined as 69.5 Watts. It is observed that 0.05 kg/min is the optimum flow rate of LN2 for cooldown the chambers at minimum time. The chamber-1 when uses the LN2, reaches the lowest achievable temperature of 125.6K within 125 min and chamber-2 when uses cold GN2, reaches 213.1K in 110 min cooled from ambient condition at 0.05 kg/min, LN2 flow rate.
Empirical equation of the best-fit curve on the basis of experimental results, are derived to predict the cooldown time, LN2 requirement for different setpoint temperatures and varying flow rates.

Keywords: Cryogenic freezing, LN2.

C3-Q High Frequency Pulse Tube Coolers

C3-Q-01 Numerical simulation of a three-stage high-frequency Stirling-type pulse tube cryocooler for 4K operation

***J.Y. Hu**, Graduate University of Chinese Academy of Sciences; Z.W. Wu, E.C. Luo, W. Dai, Technical Institute of Physics and Chemistry, CAS.*

The thermoacoustically driven two-stage pulse tube cooler recently has already reached a lowest temperature of about 18K in our lab. In order to further decrease the cooling temperature to 4K, we are developing a three-stage Stirling-type pulse tube cooler working at about 25Hz. Thermoacoustic theory is a powerful tool for understanding the working mechanism of many regenerative cryocoolers. Thus, this theory will be employed to simulate the three-stage pulse tube cryocooler in this paper. As we know, in high frequency pulse tube cryocoolers, the main losses come from their regenerators. So the structure parameters and thermal properties of the regenerators must be carefully designed and considered. Some special materials and flow structures for the regenerators with lower resistance and high heat capacity were tested in this cooler numerically. Besides this, the dimensions of the regenerators and the pulse tubes were also optimized to get proper phase relationship between the velocity and pressure waves. According to our simulation result, when the input pressure ratio is about 1.25, the first and second stage cold tips can respectively work at about 65K and 20K, and a lowest cooling temperature of the third stage may reach about 4K.

This work was supported by the Natural Sciences Foundation of China(Grant No.50625620)

C3-Q-02 Development and research of pulse tube refrigerators at CAS in China

***L. Yang**, J. Liang, Z. Yuan, Technical Institute of Physical and Chemistry of CAS.*

This paper gives the review of pulse tube research in the past several years at Technical Institute of Physical and Chemistry, former Cryogenic Lab.

One main work is to develop high frequency high efficiency PTC to satisfy the application at 80K temperature scope. Four different sizes coaxial PTCs have been developed: One is miniature version PTC to provide cooling of 0.1-1W/80K, in this work, we have the PTC of outside diameter of 6mm prototype. Another miniature version PTC is to provide 0.3-1.5W/80K cooling power. The small version PTC is to provide 0.5W-3W/80K cooling power, while the large version PTC is to provide 2W-10W/80K cooling power. These works covers most of the requirements at 80K temperature scope in China.

Another work is to develop high frequency high efficiency PTC to satisfy the application at below 50K temperature scope. One is to develop single stage PTC that could reach below 30K. Multi-stage high frequency pulse tube refrigerator was also our interest for potential application and a 16K two-stage PTC is available.

We are developing non-mental high frequency PTCs also. Our target is to acquire low temperature at low input power, for example 0.1W/80K with 20W input.

We are also developing single stage low frequency pulse tube for 20-40K application.

Besides the PTCs aims for practical application, we are also do research on numerical simulation and oscillating flow research experiment. This will also be reported.

This work is supported by Natural Sciences Foundation of China (50206025, 50476086).

C3-Q-03 High Frequency Miniature Reservoir-less Pulse Tube Cryocooler

***I Garaway**, G Grossman, Technion - Israel Institute of Technology.*

A miniature high frequency reservoir-less pulse tube cryocooler has been designed and tested in our laboratory. The cryocooler having a regenerator length of 12.0 mm and an overall volume of 2.3cc (excluding the compressor) reached a low temperature of 151K. This study shows that it is possible to miniaturize a pulse tube cryocooler to very short regenerator length by implementing a few basic principles: Most importantly, higher operating frequencies at small tidal displacements with increased helium fill pressures. This study also shows that as the operating frequency of a miniature cryocooler increases, the reservoir becomes less necessary as a phase shifting device. At higher frequencies and smaller inertance tube geometries the impedance and capacitance of the inertance tube itself takes over the phase shifting task. This study shows that in a high frequency (greater than 250Hz) system the volume of such an inertance tube can be decreased to values of less than 1cc. An outline of the design and modeling principles will be presented along with some details of the experimental apparatus and testing procedures.

C3-Q-04 Development of a low cost high frequency pulse tube cryocooler

***C. Wang**, Cryomech, Inc.; A. Caughley, D. Haywood, Industrial Research Ltd.*

In cooperation with Industrial Research Ltd (IRL), Cryomech, Inc. is developing a low cost high frequency pulse tube cryocooler. The valveless compressor, developed by IRL, employs two S.S. diaphragms and novel kinematics driven mechanism. The pulse tube cold head has co-axial configuration and is separated from the compressor by 1.5m. The diaphragm compressor and co-axial pulse tube cold head ensure low cost on the manufacturing. The design is also user friendly for integration. The preliminary tests demonstrate encouraging results of the system. It has a bottom temperature of 40 K and over 100W at 80K for 3.6kW power input. The design goal is to have a cooling capacity of 200W at 80K. The improvement of the pulse tube cryocooler is undergoing. The details of the design, development and performance will be presented in the conference.

Friday, 07/20/07 Plenary 8:00am - 9:00am

C4-A Friday Plenary Session

C4-A-01 Overview of the Liquefied Natural Gas (LNG) Industry

***R.T. Rogers**, AGL Resources.*

The presentation will include an overview of the different types of LNG Plants, from the small Satellite LNG Plants to the large Import or Base Load LNG Terminals. The talk will also present information about AGL Resources` LNG Operations, as AGL Resources is the largest LNG Peak Shaving Operator in the Southeast United States. The presentation will also include a demonstration of the characteristics of LNG as well as address the phenomenon of LNG Tank Rollover.

Friday, 07/20/07 Oral 9:15am - 10:45am

C4-B Superconducting RF Cavities and Cryosystems - II

C4-B-01 ILC Cryogenic Systems Reference Design

***T. Peterson**, M. Geynisman, A. Klebaner, J. Theilacker, Fermilab; V. Parma, L. Tavian, CERN.*

A Global Design Effort began in 2005 to study a TeV scale electron-positron linear accelerator based on superconducting radio-frequency (RF) technology, called the International Linear Collider (ILC). In early 2007, the design effort culminated in a reference design for the ILC, closely based on the earlier TESLA design. The ILC will consist of two 250 GeV linacs, which provide positron-electron collisions for high energy physics research. The particle beams will be accelerated to their final energy in superconducting niobium RF cavities operating at 2 Kelvin. At a length of about 12 km each, the main linacs will be the largest cryogenic systems in the ILC. Positron and electron sources, damping rings, and beam delivery systems will also have a large number and variety of other superconducting RF cavities and magnets, which require cooling at liquid helium temperatures. Ten large cryogenic plants with 2 Kelvin refrigeration are envisioned to cool the main linac and the electron and positron sources. Three smaller cryogenic plants will cool the damping rings and beam delivery system components predominately at 4.5 K. This paper describes the cryogenic systems concepts for the ILC.

C4-B-02 Installation and Commissioning of the Superconducting RF Linac Cryomodules for the ERLP

***A.R. Goulden**, R. Bate, CCLRC Daresbury Laboratory UK; R.K. Buckley, S.M. Pattalwar, CCLRC Daresbury Labpratory UK.*

An Energy Recovery Linac Prototype (ERLP) is currently being constructed at Daresbury Laboratory (UK), to promote the necessary skills in science & technology, particularly in photocathode electron gun and Super Conducting RF, to enable the construction of a fourth generation light source, based on energy recovery linacs-4GLS [1]. The ERLP uses two identical cryomodules, one as a booster cavity accelerating the beam to 8.5 MeV, the other as a linac module in the re-circulating loop with an energy gain of 24.5 MeV. Each module consists of two nine cell cavities operating at a frequency of 1.3GHz and a temperature of 2K. As there is no energy recovery in the booster it requires a peak power of 53kW; whereas the linac module only requires 8kW. The RF power is supplied by 4 IOTs. The maximum heat load or the cooling power required in the Super Conducting RF system is 180W at 2K and is achieved in two stages: a LN2 pre-cooled Linde TCF050 liquefier produces liquid helium at 4.5K, followed by a 2K cold box consisting of a JT valve, recuperator and an external room temperature vacuum pumping system.
This presentation reports the experience gained during, installation, commissioning and the initial operation of the cryomodules.

C4-B-03 Initial Operating Experience for the ISAC-II SC-Linac at TRIUMF

***I. Sekachev**, W. Andersson, R. Laxdal, G. Stanford, TRIUMF.*

A first stage of the heavy ion superconducting linac cryogenic system comprising a 500W LHe refrigerator and distribution system has been installed and started operation at TRIUMF. The early experience with the cryogenic systems including data of the thermal loads and refrigerator performance will be presented.

C4-B-04 Operation of the Superconducting Linac at the Spallation Neutron Source.*

***I. E. Campisi**, F. Casagrande, M. Crofford, M. Howell, Y. Kang, S. H. Kim, Z. Kursun, P. Ladd, D. Stout, W. Strong, ORNL/SNS; M.S. Champion, FNAL.*

At the Spallation Neutron Source, the first fully operational pulsed superconducting linac has been active for about two years. During this period, stable beam operation at 4.4 K has been achieved with beam for repetition rates up to 15 Hz. Lower temperatures have been occasionally attained to study conditions required to support full beam power delivery, which requires 60 Hz RF and beam pulses of 1 millisecond. A large amount of data has been collected on the pulsed behavior of cavities and cryomodules at various repetition rates and at various temperatures. This experience will be of great value in determining future optimizations of SNS as well in guiding in the design and operation of future pulsed superconducting linacs.
This paper describes the details of the cryogenic system and RF properties of the SNS superconducting linac.

**SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy*

C4-B-05 Cryogenic Infrastructure for Fermilab's ILC Vertical Cavity Test Facility

*R. Carcagno, C. Ginsburg, Y. Huang, **B. Norris**, J. Ozelis, T. Peterson, R. Rabehl, C. Sylvester, M. Wong, Fermi National Accelerator Laboratory.*

Fermilab is building a Vertical Cavity Test Facility (VCTF) to provide for R&D and pre-production testing of bare 9-cell, 1.3 GHz superconducting RF (SRF) cavities for the International Linear Collider (ILC) program. This facility is located in the existing Industrial Building 1 (IB1) where the Magnet Test Facility (MTF) also resides. Helium and nitrogen cryogenics are shared between the VCTF and MTF including the existing 1500W @ 4.5K helium refrigerator with vacuum pumping for super-fluid operation (125 W capacity at 2K).
The VCTF is being constructed in multiple phases. The first phase is scheduled for completion in mid 2007, and includes modifications to the IB1 cryogenic infrastructure to allow helium cooling to be directed to either the VCTF or MTF as scheduling demands require. At this stage, the VCTF consists of one Vertical Test Stand (VTS) cryostat for the testing of one cavity in a 2 K helium bath.
Planning is underway to provide a total of three Vertical Test Stands at VCTF, each capable of accommodating two cavities. Cryogenic infrastructure improvements necessary to support these additional VCTF test stands include a dedicated ambient temperature vacuum pump, a new helium purification skid, and the addition of helium gas storage.
This paper describes the system design and initial cryogenic operation results for the first VCTF phase, and outlines future cryogenic infrastructure upgrade plans for expanding to three Vertical Test Stands.

C4-B-06 European XFEL-Linac Two-Phase Helium II Flow Simulations

*V. Gubarev, **B. Petersen**, D. Sellmann, DESY; Y. Xiang, GSI.*

The superconducting 1.3-GHz niobium cavities of the XFEL linear accelerator will be cooled in a bath of liquid helium II at a temperature of 2K. The liquid helium II supply of the 1.7-km long linac is subdivided in sections of 150m length. In these sections a two phase flow of helium II liquid and corresponding vapor occurs. A stable stratified smooth helium flow has to be maintained for the RF operation of the cavities, to avoid any microphonic effects. A computer code has been developed to simulate the two phase flow in the XFEL-linac. The flow characteristics at different cryogenic loads and tube dimensions have been calculated. The results are shown and the consequences for the design of the XFEL-cryomodules are discussed.

C4-C Aerospace Components

C4-C-01 Developments on Vibration Free Sorption Cooling

J.F. Burger, R.J. Meijer, H.J. Holland, ***H.J.M. ter Brake****, University of Twente; A. Sirbi, ESA-ESTEC.*

At the University of Twente, a breadboard 4.5 K sorption cooler was developed under an ESA-TRP contract. It has no moving parts and, therefore, is essentially vibration-free. Moreover, it has the potential of a very long life. This cooler is a favorite option for missions such as ESA's Darwin mission, which is a future space interferometer consisting of a few free flying telescopes and a central beam combiner. Because of the optics involved, hardly any vibration can be tolerated.
The cooler consists of a hydrogen stage cooling from 80K to 14.5K and a helium stage establishing 10mW at 4.5K. Both stages use micro-porous activated carbon as the adsorption material. The two cooler stages need 8W of input power and are heat sunk at two passive radiators at temperatures of about 50 and 80K. We developed and built a demonstrator of the helium stage. In the paper, the design, realization and tests of this demonstrator cooler will be reviewed. Following this review, we will describe further developments on improved carbon cells and sub-components such as passive check valves. Furthermore, trends will be presented that consider the use of other working fluids at different temperature ranges.

C4-C-03 Cryogenic Quad-redundant Thermal Switch

B. C. Thompson*, B. Lloyd, Space Dynamics Laboratory; S. H. Schick, Practical Technology Solutions Inc.; L. Li, Utah State University.*

A Quad-Redundant Thermal Switch (QRTS) for the James Webb Space Telescope has been successfully designed, fabricated, and tested at the Space Dynamics Laboratory (SDL). A flight-like prototype successfully passed thermal and structural qualification tests in a representative space environment and achieved Technology Readiness Level 6. The QRTS serves as a high thermal conductance, high reliability thermal connect / disconnect between heat sources and sinks. The switch consists of an all metallic core switch construction packaged in a cross-strapped quad-redundant configuration. Actuation of the switch is based on differential thermal expansion. The four individual switches are passively closed over the entire operational range and actuated open by applying heat to the actuation rods. Key qualification tests included: robust characterization of thermal closed and open performance from 32 to 313K; and a full suite of vibration testing (sine, random, and sine burst). This paper presents an overview of the QRTS functionality, thermal and structural qualification tests, and resulting switch performance.
Thanks to D. S. Hansen and K. N. Johnson from Space Dynamics Laboratory and S. Glazer from GSFC. Funding for this project was provided by GSFC.

C4-C-04 High Specific Power Motors in LN2 and LH2

G.V. Brown*, J.J. Trudell, NASA Glenn Research Center; R.H. Jansen, University of Toledo.*

Low winding resistance and high thermal conductivity in LN2 and LH2 allow electric machine windings to be cooled only at end turns to preserve slot space for conductor and insulation. End turn layers, shaped into heat exchangers, provide large heat transfer area and flow channels for nucleate boiling and excellent cooling. Joule heat is rejected outside the magnetically active region with low temperature rise. The result is very high specific power. "Self-finned" coils in LN2 show rms current density 10 times that typical at room temperature. A 12/8 switched-reluctance motor of 18 lb electromagnetic (EM) weight, with such coils, produced 7.9 kW/lb-EM in one second tests at 20 krpm, at an rms current sustainable at steady state in uninstalled coils. If the motor can be supplied with LN2 and cleared of GN2 bubbles at steady state, the specific power will exceed that of any other motor or generator, including superconducting machines. On future LH2-fueled aircraft this type motor would use fuel for cooling before the fuel is burned. End-cooled coils would perform even better in LH2 than in LN2 because of further increases in electrical and thermal conductivity. Coils could be longer, carry more current without thermal runaway and make less boil-off gas. Measurements, analysis and motor performance will be presented.

C4-D Stirling and Pulse Tube Performance Enhancement and Modeling

C4-D-01 A new Mini Pulse Tube Cryocooler with a heat interceptor

Ph. Gully*, I. Charles, CEA-Grenoble/SBT; R. Briet, CNES-Toulouse.*

An experimental study of a coaxial mini Pulse Tube Cryocooler is presented. First various rejection temperatures for the pulse tube warm end and the compressor foot have been investigated. It is shown that the rejection temperature at the warm side of the Pulse Tube is a key parameter and that the heat sink of the cooler can be located only at this point. Heat repartition between the pulse tube and the compressor as a function of the rejection temperatures is discussed.
The coaxial mini pulse tube cooler has been equipped with a heat interceptor in order to take advantage of passive intermediate free cooling available for some space missions. The heat interceptor is a simple copper collar mounted on the half warm side of the regenerator tube. It is shown that this concept allows boosting the cryocooler performances with a small associated passive radiator thermally linked to the interceptor. As an example, a 0.05m2 radiator allows to increase the cooling power at 80K from 1.5 to 2 W. Performances obtained for different heat interceptor positions are presented and discussed.
Thanks to SBT experimental team for its help and CNES for its financial support

C4-D-02 A thermoacoustically-driven micro-miniature pulse tube cooler operating with high frequency of 300 to 500Hz

G.Y. Yu*, S.L. Zhu, Graduate University of Chinese Academy of Sciences; E.C. Luo, Technical Institute of Physics and Chemistry, CAS; W. Dai, Technical Institute of Physics and Chemistry,CAS.*

High frequency thermoacoustic cryocooler system is quite attractive to small-capacity cryogenic applications such as for aerospace cooling. Recently, a no-load temperature of 95K and 79.6K have been obtained on a 300Hz pulse tube cooler driven by a standing-wave thermoacoustic engine with 750W and 1750W heating powers in our lab, respectively. However, the standing-wave thermoacoustic engine is intrinsically irreversible, which limits the global thermal efficiency of the system. Aimed for a cooling power of about half Watts at 80K with a higher thermal efficiency, a high frequency thermoacoustic-Stirling heat engine was designed to drive a pulse tube cooler in the work to be presented here. Ideas such as tapered resonator, acoustic amplifier tube and half wavelength inertance tube phase shifter (without reservoir) are used to effectively suppress the harmonic modes, amplify the acoustic pressure wave available to the pulse tube cooler and provide desired acoustic impedance for the pulse tube cooler, respectively. Influence of average pressure, heating power, mesh size and coupling mechanism are given in detail. Up to now, a lowest temperature of 129K has been obtained on the system with 3.93MPa helium gas, 309Hz working frequency and 400W heat input. Numerical simulations based on the linear thermoacoustic theory have also been done for comparison with experimental results, which shows reasonable agreement. Further optimization work is being under way.
This work was supported by the Natural Sciences Foundation of China(Grant No.50625620)

C4-D-03 An Innovative Inertance Device for Pulse Tube Cryocoolers

Sidney Yuan*, David Curran, Aerospace Corp.*

The theory behind a Pulse Tube Cryocooler is very similar to that of a Stirling cooler with the motion of the displacer replaced by that of the gas piston. Some of the best performance of the Pulse Tube coolers matches that of the Stirling refrigerator. Obviously, the importance of the phase shift mechanism in a Pulse Tube cannot be overemphasized. In this paper, an innovative inertance phase-shift device is described. The performance of this invention has been validated by analysis using the SAGE software. This invention offer tremendous benefit over the traditional phase shift devices used in Pulse Tubes.

C4-D-04 Multistage Pulse Tube Refrigeration Performance Mapping of the Lockheed Martin RAMOS Engineering Model Cryocooler

W.D. Scheirer, *T.P. Roberts, Air Force Research Laboratory.*

The performance mapping of a multistage pulse tube refrigeration system has been performed on the Lockheed Martin Russian-American Observational Satellite (RAMOS) engineering model cryocooler by the Air Force Research Laboratory. The cryocooler consists of a two-stage pulse tube coldhead driven by a linear flexure-bearing compressor. The coldhead and compressor are separated by a transfer line of up to one meter. The RAMOS cryocooler is designed to deliver 0.75 W of cooling at 75K and 6 W of cooling at 130K. Characterization test results include performance mapping at rejection temperatures from 275K to 325K, drive frequency variation effects from 39 Hz – 65 Hz, as well as results for both steady state and transient performance envelopes. The effects of varying operational conditions on the transfer line's non-isothermal behavior will also be presented.

C4-D-05 Design and Performance Optimisation of a Coaxial Pulse Tube Cooler

W. van de Groep, *J. Mullie, T. Benschop, F. van Wordragen, THALES Cryogenics B.V..*

Since 2005 Thales Cryogenics has been producing coaxial pulse tube coolers under CEA license for applications that are very sensitive for mechanical vibrations and require a long lifetime.
In order to optimise the existing baseline design of the coaxial pulse tube Thales Cryogenics has been working on several of the critical elements inside the pulse tube. This optimisation should lead to a wider application of these pulse tube coolers into high-end civil applications.
This paper describes the work carried out on the optimisation of the heat exchangers at the cold tip, the warm-end and the buffer including irreversible heat losses caused by disruptions of the gas flow. Moreover, the heat exchange of warm end gas to the surroundings has been investigated. Also, the impact on cool downtime and the sensitivity to internal contamination has been tested.
Results will enable a design optimisation of the whole range of coaxial pulse tube coolers, varying from 1 and 4W at 80K to pulse tube coolers of more than 12W cooling power at 80K.
In this paper, test result, trade-off's and benefits of the new design will be discussed and evaluated.

C4-D-06 Fast Response Temperature Measurements in Stirling Cycle Cryocooler Components

K, Kar, *University of Auckland; M.W. Dadd, P. Bailey, C.R. Stone, University of Oxford.*

One reason that heat transfer processes are not well understood is the difficulty of obtaining reliable temperature measurements when gas temperatures vary rapidly. In the work described here gas temperatures have been measured using a fine wire resistance thermometer with a 3.8 micron active sensor. The equipment represented the basic elements of a cryocooler: a clearance seal linear compressor and a wire mesh regenerator. Both were operated close to ambient temperature, with gas temperatures being measured close to the regenerator.
The test rig was run at different volume ratios, frequencies (8–50 Hz), gases and filling pressures (1–26 bar). The waveforms of the gas temperature were found to vary dramatically for differing flow regimes.
The results suggested that the thermometer was measuring the temperatures of two distinct volumes of gas, and that the gas must remain stratified in the compression space. A flow transition was identified from the cycle-by-cycle variations in temperature. The critical Reynolds number was determined to be 9.6–11. At the critical condition, the temperature was so unstable that fluctuations up to 250 Hz were observed. A series of validation tests have confirmed that the observed temperatures were not artifacts.
This work was sponsored by the Air Force Office of Scientific Research, Air Force Material Command, USAF, under grant number FA8655-06-1-3071.

C4-D-07 Optimal Control Strategies for a Rectified Continuous
Flow Loop Interfaced with a Distributed Load

H.M. Skye, *G.F. Nellis, S.A. Klein, University of Wisconsin - Madison.*

Distributed loads are frequently encountered in large deployable structures used in space applications such as optical mirrors and focal plane electronics. An innovative mechanism for providing distributed cooling is an oscillatory pulse-tube cryocooler that is integrated with a fluid rectification system consisting of check-valves and buffer volumes in order to extract a small amount of continuous flow. This continuous flow allows relatively large loads to be accepted over a long distance. An additional advantage of the rectified system is that ability to provide rapid and precise temperature control via modulation of the flow rate in the flow loop. This paper investigates this latter capability of the rectifying interface, the ability to control the temperature of a distributed load under the influence of various thermal disturbances. Temperature regulation is enabled using a temperature feedback control of a throttle valve placed in the loop. The control parameters are selected to meet temperature regulation specifications, including maximum temperature deviation and settling time in response to a step change in distributed load. The predicted and measured controlled transient behaviors are compared in order to demonstrate the temperature control capability.
This work was supported by the Missile Defense Agency through the Air Force Research Laboratory, and by the National Space Grant College and Fellowship Program and the Wisconsin Space Grant Consortium. The technical assistance of Atlas Scientific is gratefully acknowledged.

C4-D-08 Performance Prediction of PTR for Different Pressure Waveforms

S. Desai, C.K. Pithawala College of Engineering, Surat, Gujarat, India; K.P. Desai, ***H.B. Naik***, *S.V. National Institute of Technology, Surat, Gujarat, India; M.D. Atrey, Indian Institute of Technology Bombay, Mumbai, India.*

Many researchers have shown that the performance of the PTR depends significantly on the pressure waveforms generated by the rotary valve in a G-M type PTR. Some literature has shown this effect experimentally for various waveforms. The design of the rotary valve therefore is very critical in order to generate an optimum pressure waveform. However, if the optimum waveform for obtaining maximum cooling power is known, it will help the valve design significantly. In view of this, the valve design would be improved significantly if the performance of the PTR could be predicted with reasonable accuracy for any pressure waveform. The present paper aims at developing a procedure to generate such predictions of the PTR performance for different pressure waveforms. This will help to determine an optimum pressure waveform for a given PTR configuration and will be useful in a significant way for the design of the rotary valve.
An isothermal model of the PTR has been developed for various operational modes viz, Basic, OPTR, DIPTR, and has been validated with experimental results. The model is then extended to predict the PTR performance for various pressure waveforms. The experimental data, available in literature in the form of different pressure waves for a given PTR configuration, has then been analyzed. A comparison between the experimental results and the model predictions has been presented.

C4-E Cryosystems for Fusion

C4-E-01 Cryogenics for Fusion

***P. Dauguet**, G.M. Gistau-Baguer, M. Bonneton, J.C. Boissin, E. Fauve, J.M. Bernhardt, J. Beauvisage, F. Andrieu, Air Liquide.*

Fusion of Hydrogen to produce energy is one of the technology under study to meet the mankind raising need in energy and as a substitute to fossile fuels for the future. This technology is under investigation for more than 20 years already, with, for example, the former construction of experimental reactors Tore Supra, DIII-D and JET. With the construction of ITER to start, the next step to "fusion for energy" will be done. In these projects, an extensive use of cryogenic systems are requested. Air Liquide has been involved as cryogenic partner in most of former and presently constructed fusion reactors. In the present paper, a review of the cryogenic systems we delivered to Tore Supra, JET, IPR and KSTAR will be presented.

C4-E-02 Investigation of a test loop for the cooling system of the ITER TF coil under pulsed heat load

***B. Rousset**, A. Girard, J.M. Poncet, P. Roussel, M. Sanmarti, CEA; V. Kalinin, ITER; S. Maze, AREVA; D. Murdoch, EFDA.*

The CEA is involved in the design of the cooling scheme of the future ITER tokomak. Pulsed operation of ITER will result in heat load variations which refrigerators have difficulty to deal with. A load smoothing device has been proposed by the ITER team which needs to be validated. To do this, a scaled-down experiment (similitude) was proposed and studied in the framework of an EFDA sub-task. This paper presents the test loop dimensioning and then preliminary design for constructing the mock-up.

The choice of the relevant design criteria had to be defined so as to obtain in fine a geometric ratio for similitude. We chose to conserve the fluid properties (pressure and temperature) as well as the time allocated for the different scenarios. The similitude ratio then relates to the heat loads involved for the model and ITER. It is shown that this ratio is then applicable for the mass flowrates and also the different volumes (heat exchanger, pipes, …) existing on ITER and on the future mock-up.

Once the similitude ratio had been established, the circuit was simplified (influence of gravity was ignored and several parallel pipes were replaced by an equivalent pipe) while keeping the objective of the study, i.e. validating smoothing of the pulsed load. Some 3D views corresponding to this preliminary study are presented in this paper.

C4-E-03 Design, analysis and test concept for prototype cryo-line of ITER

***B. Sarkar**, H. Vaghela, N. Shah, S. Badgujar, R. Bhattacharya, Ch. Chakrapani, Institute for Plasma Research.*

The ITER cryo-distribution and cryo-line is a part of the in-kind supply for India. The design of the systems is in progress. The topology of torus and neutral beam cryo-line is defined as six process pipes along with thermal shield at 80 K and outer vacuum jacket. In order to develop confidence in the concept as well as to establish the high level of engineering and manufacturing technology, a prototype testing has been proposed. The prototype test will be carried out on 1:1 model in terms of dimension. However, the mass flow rate of the supercritical helium at 4.5 K and gaseous helium at 80 K, will be on a 1:10 scale. The prototype cryo-line has been designed and analyzed for thermal, structural and hydraulic parameters. The prototype will simulate the major integrities and technical issues of the cryo-line. The objective of this prototype test is to verify mechanical behavior due to thermal stress & pressure force, thermal and hydraulic performances. The concept of test facility has been realized along with the P& I diagram, instrumentation, controls, data acquisition and 80 K helium generation with warm compressors, primary and secondary heat exchangers. The test set up consists of supply and receiver valve boxes and interfacing hardware. The test will also qualify the analysis tools being used and the deviations. The paper will discuss the design concept, methodology for analysis and approximations, as well as the test facility.

Sincere acknowledgement to E. Tada, V. Kalinin

C4-E-04 Design of the NIF Cryogenic Target System

***C.R. Gibson**, General Atomics; B.J. Haid, T.N. Malsbury, M.D. Vergino, Lawrence Livermore National Laboratory.*

The National Ignition Facility (NIF), with its 192 beamlines focused on a tiny target, is the world's largest laser project. The mission of the NIF is to produce high-energy-density conditions and, ultimately, to demonstrate fusion ignition through a process called Inertial Confinement Fusion. Although many different target designs have been proposed, they all include a spherical capsule ~3 mm in diameter filled with a mixture of deuterium and tritium (DT). All target designs require that the DT is in the form of a solid layer, and hence the target temperature must be ~18 K at shot time.

The purpose of the NIF Cryogenic Target System (CTS) is to field cryogenic targets on the NIF. It is designed to cool the targets to solidify the DT fuel. Once the DT has formed a smooth layer, the target is transported to the center of the NIF Target Chamber and shot. The cooling for the CTS is provided by a Gifford-McMahon two-stage cryocooler. The use of a mechanical cryocooler instead of liquid helium does impose design challenges in the area of target temperature stability (+/- 2 mK) and target mechanical stability (+/- 6.8 micron).

The NIF Cryogenic Target System has completed the Final Design phase and a prototype of the cryogenic subsystem has been tested. The first CTS production unit is now being fabricated and assembled. This paper will present the system design and test results with an emphasis on cryogenic design challenges and solutions proposed to meet those challenges.

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C4-E-05 Performance of upgraded cooling system for LHD helical coils

***S. Hamaguchi**, S. Imagawa, T. Obana, N. Yanagi, S. Moriuchi, H. Sekiguchi, K. Oba, T. Mito, O. Motojima, National Institute for Fusion Science; T. Okamura, Tokyo Institute of Technology; T. Senba, Hitachi, Ltd.; S. Yoshinaga, H. Wakisaka, Ishikawajima-Harima Heavy Industries Co., Ltd..*

Helical coils of the Large Helical Device (LHD) are large scale superconducting magnets for heliotron plasma experiments. The helical coils had been cooled by saturated helium at 4.4 K, 120 kPa until 2005. An upgrade of the cooling system was carried out in 2006 in order to improve the cryogenic stability of the helical coils and then it has been possible to supply the coils with subcooled helium at 3.2 K, 120 kPa. A designed mass flow of the supplied subcooled helium is 50 g/s. The subcooled helium is generated at a heat exchanger in a saturated helium bath. A series of two centrifugal cold compressors with gas foil bearing is utilized to lower the helium pressure in the bath. The supplied helium temperature is regulated by rotation speed of the cold compressors and power of a heater in the bath. The mass flow of the supplied helium is also controlled by ten heaters at the outlet above the coils. In the present study, the performance of the cooling system has been investigated. Although the designed mass flow of the subcooled helium at 3.2 K could be supplied to the coils stably, the estimated temperature of the coils was higher than expected one. The maximum mass flow of the subcooled helium at 3.2 K was 60 g/s due to the cooling capacity of the cold compressors. In this case, the average temperature of the coils is expected to be lowered to 3.5 K, which is the designed temperature of the coils after the upgrade.