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Refurbishment and Testing of the 1970's Era LASS Solenoid Coils for JLab's Hall D

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JLab refurbished the LASS*, 1.85 m bore Solenoid, consisting of four superconducting coils to act as the principal analysis magnet for nuclear physics in the newly constructed, Hall D at Jefferson Lab. The coils, built in 1971 at Stanford Linier Accelerator Center and used a second time at the MEGA Experiment** at Los Alamos, had electrical shorts and leaks to the insulating vacuum along with deteriorated superinsulation & instrumentation. Root cause diagnosis of the problems and the repair methods are described along with the measures used to qualify the vessels and piping within the Laboratory's Pressure Safety Program (mandated by 10CFR851). The extraordinary refrigerator operational methods used to utilize the obsolete cryogenic apparatus gathered for the off-line, single coil tests are described.

* The LASS Spectrometer, SLAC-Report-298, April 1986
** http://link.aps.org/doi/10.1103/PhysRevD.65.112002

Fabrication and Test of 4-m Long Nb_3Sn Quadrupole Coil Made of RRP-114/127 Strand

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Fermilab is collaborating with LBNL and BNL (US-LARP collaboration) to develop a large-aperture Nb_3Sn superconducting quadrupole for the Large Hadron Collider (LHC) luminosity upgrade. Several two-layer quadrupole models of the 1-meter and 3.4-meter length with 90mm apertures have been fabricated and tested by the US-LARP collaboration. High-Jc RRP-54/61 strand was used for nearly all models. Large flux jumps typical for this strand due to the large sub-element diameter limited magnet quench performance at temperatures below 2.5-3K. This paper summarizes the fabrication and test by Fermilab of LQM01, a long quadrupole coil test structure (quadrupole mirror) with the first 3.4m quadrupole coil made of more stable RRP-114/127 strand. The coil and structure are fully instrumented with voltage taps, full bridge strain gauges and strip heaters to monitor preload, thermal properties and quench behavior. Measurements during fabrication are reported, including preload during the yoke welding process. Testing is done at 4.5K, 1.9K and a range of intermediate temperatures. The test results include magnet strain and quench performance during training, as well as quench studies of current ramp rate and temperature dependence from 1.9K to 4.5K.

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Cryogenic System Design of 11 GeV/c Super High Momentum Spectrometer Superconducting Magnets at Jefferson Lab

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The design of the cryogenic system for the 11 GeV/c Super High Momentum Spectrometer will be presented. Details of the cryogenic system operation, control system, cryogenic transfer line, heat exchanger, cryogenic control reservoirs, and pressure piping will be summarized. The programmable logic controller (PLC) used to operate the cryogenic system and the control design philosophy of PLC will be discussed. A description of the cryogenic transfer line and cryogenic control reservoirs will be given. The unique challenges and approaches employed to ensure that the design follows and meets the requirements of the ASME Pressure Vessel Code and Pressure Piping Code guidelines will be discussed. Elastic-plastic stress analysis of the cryogenic control reservoirs and thermal stress analysis of liquid helium piping have been conducted and summaries of analysis results will be presented. Cryogenic system performance will be studied also.

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Mu2e Production Solenoid Cryostat Conceptual Design

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Mu2e is a muon-to-electron conversion experiment being designed by an international collaboration of more than 65 scientists and engineers from more than 20 research institutions for installation at Fermilab. The experiment is comprised of three large superconducting solenoid magnet systems, production solenoid (PS), transport solenoid (TS) and detector solenoid (DS). A 25 kW, 8 GeV proton beam strikes a target located in the PS creating muons from the decay of secondary particles. These muons are then focused in the PS and the resultant muon beam is transported through the TS towards the DS. The production solenoid presents a unique set of design challenges as the result of high radiation doses, stringent magnetic field requirements, and large structural forces. This paper describes the conceptual design of the PS cryostat and will include discussions of the vacuum vessel, thermal shield, multi-layer insulation, cooling system, cryogenic piping, and suspension system.

Conceptual Design of the Fermilab Mu2e Production Solenoid Cold Mass

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The Muon-to-Electron conversion experiment (Mu2e), under development at Fermilab, seeks to detect direct muon to electron conversion to provide evidence for a process violating muon and electron lepton number conservation that cannot be explained by the Standard Model of particle physics.

The Mu2e magnet system consists of three large superconducting solenoid systems. The first in the chain of magnets is the Production Solenoid (PS) that houses the pion production target. The role of the PS in Mu2e is to collect and focus pions, generated in interactions of an 8-GeV proton beam with the gold target, and muons from pion decays by supplying a peak axial field of more than 5 T and an axial field gradient of approximately 1 T/m within a 1.5 m warm bore.

This paper describes the conceptual design of the PS cold mass that includes superconducting coils and the coil support structures. In order to fulfill the physics requirements, the peak magnetic field in the coil approaches 6 T, creating large Lorentz forces in the coil that require a careful choice of structural materials. The magnetic and structural analyses are presented along with the motivations driving the material choices.

Radiation from the production target creates a number of added challenges, including degradation of the insulation, reduction of RRR in the cable stabilizer, and heat deposition in the coil. The main radiation factors and their influence on the particular design solutions are discussed as well.

Cryostat design and development for a superconducting undulator for the APS

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The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) is planning an upgrade project that includes the implementation of superconducting undulator insertion devices. A development program is underway to build, test, and operate a prototype device in the storage ring. We present the overall design concept including superconducting magnet structure, cryocooler-based cooling system, and cryostat as well as a status report on the R&D program. Results of cryocooler performance characterization using a model magnet in a test cryostat are described.

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Performance of helium recondenser for quadrapole magnet cryostat

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A superferric superconducting quadrapole doublet magnet cryostat is currently under fabrication at our institute. This cryostat will be located far off from the existing cryogenic distribution facility and hence the cryostat design is done based on the cooling capacities provided by a two stage GM cryo cooler. Cryocooler 1st stage cooling power will be used to cool the copper shield to 60 K and HTS leads and the second stage cooling power will be used to recycle the cold helium gas through a liquid helium recondenser heat exchanger apart from the radiation load from 60K shield and instrumentation wiring.
A helium recondenser with a surface area of 0.15 m^2 in a compact volume has been designed, fabricated and tested. To have maximum enhanced area per unit volume fin like straight grooves were cut into a OFHC copper block deep down. A detailed thermal analysis of the recondensor has been carried out both theoretically and experimentally. Lhe production rate achieved was 1.1 liter per day (lpd) and the measured refrigeration capacity in the setup was maximum 2.26 watt at an equilibrium pressure of ~56537 Pa inside the refrigeration chamber. Also study was conducted to measure the recondensation capacity at various input power in liquid helium against the stabilised chamber pressure and at the same time temperature at various points was measured. This paper will discuss the design aspect of the heat exchanger, and the performance w.r.t. refrigeration capacity at various pressure and temperature.

Experimental studies on thermal behavior of indigenously development of 6 Tesla cryogen-free superconducting magnet system

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A 6 T cryogen-free superconducting NbTi magnet system (CFMS) has been designed, constructed and tested for basic studies of material science in high magnetic field. The CFMS has a vertical Φ 50mm clear room temperature working bore. A two-stage GM-cryocooler has been used to cool the thermal radiation shield, hybrid current leads and the NbTi magnet. The magnet was charged from zero to 6T at energizing current 102 A in less than 20 minutes. The outer surface temperature of magnet temperature reached from 3.3K at zero current to 3.9K at 102A current. The thermal linkage between cold head and magnet greatly influences the excitation rate and the stability of the magnet. Based on the thermal analysis for the magnet system, an experimental study has been carried out on the thermal behavior of the magnet during operation. The stability has been studied with different thermal links (flexible and semi-rigid). Some novel technique has been used for connecting the HTS leads to the NbTi at to reduce both electrical and thermal contact resistance at the 2nd stage of cryocooler. This paper briefly describes the design, development of the system and results of the different experimental studies on thermal behavior of CFMS.

Thermal design of an Nb_3Sn high field accelerator magnet

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Within the framework of the European project EuCARD, an Nb_3Sn high field accelerator magnet is under design to serve as a test bed for future high field accelerator magnets and to upgrade the vertical CERN Fresca cable test facility. This block coil type magnet will be operated at 1.9 K and 4.2 K and is designed to produce about 15 T at 1.9 K and 13 T at 4.2 K. A numerical 2D thermal model was developed to determinate the temperature margin of the coil in working conditions and the cool-down scenario. The temperature margin, which is ΔT_{max} = 6.1 K at 1.9 K and ΔT_{max} = 3.8 K at 4.2 K, was investigated in steady state condition with the AC losses due to filed ramp rate as input heat generation. Several cool-down scenarios were examined in order to minimize the temperature difference and therefore reducing the mechanical constraints within the structure. The paper presents the numerical model, the assumptions taken for the calculations and several results of the simulation for the cool-down and temperature distribution due to several cases of field ramp rate.

Study of thermal radiation shields for the ILC cryomodule

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The baseline cryomodule design of the International Linear Collider (ILC), developed from the design of the DESY-III cryomodule, includes two stages of radiation shield intercepts at 5K and 40K. As part of the design studies for the ILC, a cost-benefit analysis of the thermal performances of the radiation shields in conjunction with the costs of the initial construction and the accelerator operation is being completed. The thermal performance of the shields has been evaluated by using experimental results from a 6-m long KEK-STF cryomodule test and FEM calculations, and the results are used as benchmarks on the thermal model of ILC 12-m cryomodule. As the proposal for a modified design of the ILC cryomodule, the thermal model with one stage of the thermal shield has been studied. As part of the design optimization in these studies, the cooling schemes of the thermal shields and the thermal intercepts are modified from those of the present module design shown in the ILC reference design report (1). In this paper, we will report these technical studies with a comparison between the thermal models of one or two thermal shields.

(1) ILC Reference Design Report, http://www.linearcollider.org, Vol.3 (Accelerator), (2007), III-165-169.

Design and development of a new srf cavity cryomodule for the ATLAS Intensity Upgrade

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The ATLAS heavy ion linac at Argonne National Laboratory is planning an intensity upgrade that includes the development and implementation of a new cryomodule containing four superconducting solenoids and seven quarter-wave drift-tube-loaded superconducting rf cavities. The rf cavities extend the state of the art for this class of structure and feature stainless steel liquid helium containment vessels. The cryomodule design is a further evolution of techniques recently implemented in a previous upgrade. We provide a status report on the construction effort and describe the vacuum vessel, thermal shield, cold mass support and alignment, and other subsystems including couplers and tuners. Cavity mechanical design is also reviewed.

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The study of microstructure and texture of the hydroformed Nb tube for SRF cavities

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Hydroforming is a promising technique for seamless fabrication of SRF cavities. In principle, it should eliminate a multitude of EB weld seams, with the potential for higher cavity fabrication productivity rates, and thus hopefully reduced full system cost. However, the method requires further investigation before it can be applied practically. First, the deformation during hydroforming highly depends on the microstructure and texture of the Nb tube, which is itself determined by the process of tube fabrication. Additionally, tube is more difficult to obtain than sheet. In this work we study the deformation of Nb tubes made from sheet via both FEM modeling and experiment to evaluate the influence of the welded area on tube deformation. First, FEM was used to examine the behavior of the Cu and Nb pipes under pressure, under condition modeling the experiment. This was followed up by experimental bulge tests performed on Cu and Nb pipes nominally 1.5 inches OD and 8 inches in length. The pipes were inserted into collars with a central region unconstrained and hydrostatic pressure was applied in order to bulge out the central region. Experimental and FEM model results are then compared.

Measurement of the dielectric properties of high-purity sapphire at 1.865 GHz from 2-10 Kelvin

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A dielectric test cavity was designed and tested to measure the microwave dielectric properties of ultrapure sapphire at cryogenic temperatures. Measurements were performed by placing a large cylindrical crystal of ultrapure sapphire in a Nb superconducting cavity operating in the TE_{01} mode at 1.865 GHz. The dielectric constant, heat capacity, and loss tangent were all calculated using experimental data and RF modeling software. The motivation for these measurements was to determine if such a sapphire could be used as a dielectric lens to focus the magnetic field onto a sample wafer in a high field wafer test cavity. The measured properties have been used to finalize the design of the wafer test cavity.

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Mechanical polishing for extremely smooth SRF cavities and cavity coatings

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Superconducting radio-frequency (SRF) cavities made from pure niobium typically require polishing of the interior surfaces to a smooth finish to improve the maximum accelerating electric field that can be attained and to remove any sharp protrusions that lead to field emission. Typically this is performed in two steps, a bulk removal step during which 100 to 200 μm thickness of metal is removed from the interior surface, and a final polishing step during which the surface roughness is reduced. For example, the roughness expressed as an average over a 1 mm scan length, R_a, can be reduced below 0.1 μm. Recent work has replaced commonly used acid etching or electropolishing with mechanical processes, such as centrifugal barrel polishing or tumbling, to perform the bulk removal step, resulting in cavity performance comparable to that obtained by the more hazardous acid-based processing. Very recently, work at Fermilab developed methods for fine polishing using a mechanical apparatus, which resulted in SRF cavity surfaces smoother than those attained by standard electropolishing routes. Some aspects of this work will be presented. Importantly, emerging technologies to apply conformal coatings to cavities, such as atomic layer deposition, or to apply niobium films with high purity, such as those produced by metal-plasma deposition, become more effective when R_a is less than the coating thickness (typically < 0.1 μm). Prospects for completely acid-free processing and new processing routes that utilize coating techniques enabled by mechanical fine polishing will be described.

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High-RRR thin-films of Nb produced using energetic condensation from a coaxial, rotating vacuum arc plasma (CED^{TM})

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We have recently demonstrated unprecedentedly high values of RRR (up to 542) in thin-films of pure Nb deposited on a-plane sapphire and MgO crystal substrates. The Nb films were grown using a vacuum arc plasma struck between a reactor grade Nb cathode rod (RRR~30) and a coaxial, semi-transparent Mo mesh anode, with a heated substrate placed just outside it. The substrates were pre-heated for several hours prior to deposition at different temperatures. Low pre-heat temperatures (<300^{o}C) and deposition temperatures (<300^{o}C) give low RRR (<50) films, whereas higher pre-heat (700^{o}C) and coating temperatures (500^{o}C) give RRR=214 on a-sapphire and RRR=542 on MgO. XRD (Bragg-Brentano scans and Pole figures), EBSD and SIMS data reveal several features: (1) on a-sapphire, higher temperatures show better 3D registry for epitaxial growth of Nb; the crystal structure evolves from textured, polycrystalline (with twins) to single-crystal; (2) on MgO, there is a transition from {110} planes to {100} as the temperature is increased beyond 500^{o}C. The dramatic increase in RRR (from ~10 at <300^{o}C to ~500 at >600^{o}C) is correlated with better epitaxial crystal structure in both a-sapphire and MgO substrate grown films. However, the SIMS data reveal that the most important requirement for high-RRR Nb films on either substrate is the reduction of impurities in the film, especially hydrogen. The hydrogen content in the MgO grown films is 10^{3} times lower than in bulk Nb tested as a reference from SRF cavity grade Nb! This astonishing result has potential implications for SRF accelerators. Coating bulk Nb cavities with an MgO layer followed by our CED^{TM} deposited Nb films, might create superior SRF cavities that would avoid Q-slope and operate at higher peak fields.This research was supported by Department of Energy grants DE-SC0004994 and DE-FG02-08ER85162

New injector cryostat-module based on 3 GHz SRF cavities for the S-DALINAC*

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Since 1991 the superconducting Darmstadt linear accelerator S-DALINAC provides an electron beam of up to 130 MeV for nuclear and astrophysical experiments. The accelerator consists of an injector and four main linac cryostats, where the superconducting 3 GHz cavities are operated in a liquid helium bath at 2K.
For the injector upgrade program, the RF power delivered to the beam had to be increased from 500 W to 2 kW. Therefore, the coaxial power couplers have to be replaced by new waveguide couplers. Consequently, modifications to the cryostat-module and had become necessary.
We review on the design of the module and some interesting features, described the production steps of major components give details on the tuning of our 20-cell cavities. Also a report on recent measurements of new components and diagnostics in our 2 K test cryostat will be given.

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New design of the current lead heat exchanger

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The better the heat transfer between the copper section of the current lead and the coolant (helium or nitrogen), the lower is the needed coolant flow. To obtain a good heat transfer a certain amount of pressure drop has to be available for the coolant flow. So one has to look for a geometry of the heat exchanger channels, which combines high heat transfer with minimum pressure drop. One such geometry is the flow between parallel flat plates with small distance. This can be realized by machining deep narrow channels into the outer surface of the copper cylinder, which wind helically around a solid central section of the copper cylinder. This design principle allows to vary the number of channels, channel width and depth as well as the thickness of the separating fins. Thus it is possible to optimize the detailed parameters of the geometry of the heat exchanger for each individual application. This type of heat exchanger can be used for current leads in any gravitational orientation, i.e. horizontal or with the cold end down or up.

Design & Development of 10 KA high Tc superconducting current leads

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A 10kA High Temperature Superconducting (HTS) Current Lead has been designed for the first time to develop indigenously to reduce the operation cost of refrigeration power. The lead is designed to operate with liquid nitrogen. The HTS part of 10 kA lead consists of 62 stacks cylindrically arranged on a stainless steel tube. Each stack is composed of two Di-BSCCO tapes soldered throughout the length. The conventional part is a heat exchanger made of braided cable to have high heat transfer efficiency. Each part is electro-thermally analyzed to improve the reliability of operation. High Tc module is designed with almost negligible perpendicular self-field on the tapes to optimize the cost. The detail design description of the lead along with several electro-thermal and magneto-static analyses, fabrication technologies and test plans will be presented.

Dr.D.P.Ivanov suggestions are highly acknowledged.

Compact 8-lead unit for the SC correction coils of the Super-KEKB IR magnet system

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In the proposed Super-KEKB interaction region (IR) magnet system 52 superconducting (SC) correction coils were designed to perform some specific functions with the current of about 50 A. To energize these coils, 104 current leads will be mounted in the cryostats where the stringent spatial constraint and the cryogenic operation require the compact and optimum design. Therefore 8 leads (4 pairs) of the current leads were designed to be assembled as one unit of integration. The 8 vapor cooled current leads consists of two different cross sections for the current and helium vapor. To equalize the temperature profile of the individual leads under the different current coils some copper blocks were placed between leads. The structures had been simulated by finite element model (FEM). In the cold test, the 8 leads were operated in the normal mode and responsed safely to some transient situation. This paper will present the thermal and electrical comparison between the experimental results and calculation. The test on the transient mode and copper anchor effect will also be discussed in this paper.

Evaluation of turbo-Brayton cycle for cooling current leads: Integrated current lead/heat exchanger†

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We investigate the optimization of turbo-Brayton cycles for cooling current leads. Simple models of single stage current lead, two-stage current lead and two stage current lead coupled with a double stage turbo-Brayton cycle have been used to provide understanding about the issues and the tradeoffs. In addition, we discuss the possibility of using the heat exchanger in the turbo-Brayton system as the current lead.

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Current distribution and re-distribution in HTS cables made from 2nd generation tapes†

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The current redistribution in cables made from 2nd generation HTS tapes is investigated in carpet-stack cables as well as helically wound, multiple layer cables. In the carpet stack geometry tapes are placed next to each other to build up a cable. In the helically wound cables, tapes are placed on a cylindrical surfaces inclined with respect to the main axis of the cable. The incline angle of the layers can be adjusted to obtain good current distribution among the layers. Current redistribution in HTS cables is complex because the built-in insulation layer in each tape prevents effective current transfer between tapes. A method of shunting the tapes using periodically distributed superconducting bridges is investigated to improve the current transfer in carpet-stack cables. We also calculate the mutual inductance between different tapes in a cable. The time constants for current transfer are calculated under different assumptions. The effective time constant for current redistribution in the case of a normal zone is then calculated. Power dissipation during current redistribution is evaluated and compared with typical values for the cryostat heat load. We show that shunting tapes using distributed superconducting bridges is an attractive method to achieve uniform current distribution in a HTS cable. The solution is flexible, and the performance of the system can be optimized by changing the width of shunt and/or the distance between shunts.

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Superconducting Link Bus Design for the Accelerator Project for Upgrade of LHC

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The Accelerator Project for Upgrade of LHC (APUL) is a U.S. project participating in and contributing to CERN's Large Hadron Collider (LHC) upgrade program. Fermi National Accelerator Laboratory in collaboration with Brookhaven National Laboratory is developing sub-systems for the upgrade of the LHC final focus magnet systems. Part of the upgrade calls for various lengths of superconducting power transmission lines known as SC Links, which are up to 100m long. The SC Link electrically connects the current leads in the Distribution Feed Boxes to the interaction region magnets. The SC Link is an extension of the magnet bus housed within a cryostat. The present concept for the bus consists of 22 power cables, 4 x 13kA, 2 x 7kA, 8 x 2.5kA and 8 x 0.6kA bundled into one bus. Different cable and strand possibilities were considered for the bus design including Rutherford cable. The Rutherford cable bus design potentially would have required splices at each sharp elbow in the SC Link. The advantage of the round bus design is that splices are only required at each end of the bus during installation at CERN. The round bus is very flexible and is suitable for pulling through the cryostat. Development of the round bus prototype and of 2 splice designs is described in this paper. Magnetic analysis and mechanical test results of the 13kA cable and splices are presented.

Optimization of Peltier current lead for applied superconducting systems with the optimum combination of cryo-stages

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One of the key technologies to solve the energy problems in the world is a superconducting (SC) system because of highly effective properties of zero direct current (DC) resistance on saving energy. Therefore, many applications have been proposed and, among them, SC transmission lines were also examined in several countries. We have developed SC DC transmission lines of 20 m and 200 m for the working trial systems. And we have studied the high performance cryogenics for the reduction of heat leak, which are highly required for the actual competitive applications. For example, high performance terminal systems are the key technology for the small applications such as internet data centers, as the conduction heat leak on the current lead has the large effect on the system performance. Thus, we have studied Peltier current lead (PCL) as the high performance current lead for the SC applications, including gas cooled systems. On the other hand, we should consider about the performance of cryo-cooler for the system optimization, where the coefficient of performance (COP) of cryo-coolers generally becomes large at the higher working temperature. In this context, the effective cooling of the coolant and current lead itself can open the new optimization scheme to enhance the system performance. We will consider about the multi-stages configurations for PCL and discuss about such advanced current lead designs for applied SC systems.

We acknowledge Dr Hiroshi Fujiwara for his support on the construction of 200 m superconducting facilities of CASER-2 and also Ministry of Education, Culture, Sports, Science and Technology as “Collaboration with Local Communities” Project for Private Universities for the support on 20 m ones (CASER-1).

A current lead test facility for the cryogenic test of the W7-X and JT-60SA HTS-current leads

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The Karlsruhe Institute of Technology (KIT) is responsible for the design, construction and test of 16 high temperature superconductor (HTS) current leads for the stellarator Wendelstein 7-X (W7-X) which is presently under construction at the Greifswald branch of the Max-Planck-Institute for Plasma Physics. In the framework of the Broader Approach Activities, KIT is also responsible for design, construction and test of further 26 HTS current leads for the tokamak project JT-60SA. The new current lead test facility Karlsruhe (CuLTKa) exclusively for HTS current lead testing is presently under construction in parallel to the running tests of W7-X prototype HTS current leads in the adapted TOSKA facility. CuLTKa will be integrated in the existing infrastructure of the Institute for Technical Physics (ITEP) and is designed to be able to test the HTS current leads for W7-X in upside down orientation as well as the JT-60SA current leads in normal orientation. CuLTKa will allow an optimization of test frequency to handle the tests of the W7-X current leads and the 26 current leads for JT-60SA with nominal current up to 26 kA in time. The cryogenic layout of CuLTKa will be described.

Cryogenic lifetime tests on a commercial epoxy resin high voltage bushing

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High-temperature superconducting (HTS) power devices operating in liquid nitrogen require high-voltage bushings to carry the current from the superconducting windings to the room temperature grid connections. Oak Ridge National Laboratory is collaborating with Waukesha Electric Systems, SuperPower, and Southern California Edison to develop and demonstrate an HTS utility power transformer. Previous dielectric high voltage tests in support of this program have been carried out in test cryostats with commercial epoxy resin bushings from Electro Composites Inc. (ECI), in Boisbriand, Canada. Though the bushings performed well in these short-term tests, their long-term operation at high voltage in liquid nitrogen needs to be verified for use on the utility grid. Long-term tests are being carried out on a sample 28-kV-class ECI bushing. The bushing has a monolithic cast, cycloaliphatic resin body and is fire- and shatter-resistant. The test cryostat is located in an interlocked cage and is energized at 25 kV ac around the clock during the week. Liquid nitrogen is transferred twice a day. Partial discharge, capacitance, and power factor tests are periodically performed to check for deviations from factory values. At present, several hundred hours have been accumulated with no changes in these parameters. The tests are scheduled to run for four to six months.

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Miniature pulse tube cooler at 100Hz

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Cryocoolers are often used in applications where small size and mass are needed. Especially for some certain kind of Dewar, the dimension of cold finger is limited strictly. The diameter of regenerator can be decreased but the cooling capacity is decreased meanwhile. On the other hand, to diminish the cold finger length, increasing the operating frequency is an effective method. At higher frequency the gas oscillates in less volume, so the length requisite for regenerator can be reduced, as well as the pulse tube. However, high frequency leaves the working gas less time to transfer heat with the regenerator mesh.

In this paper, a prototype of 100Hz miniature pulse tube cooler is developed. The dimension of regenerator is optimized by REGEN3.3. Phase angle and mass flow rate expected at the cold end are gained by a well-designed inertance tube, which is optimized by DeltaEC. The phase shift angle and mass flow rate is also experimentally measured at the cold end of the pulse tube cooler.

An in-line prototype of miniature pulse tube cooler is manufactured firstly. The outer diameter of the regenerator is 7.8mm. The cooling capacity of 1W@80K is gained by about 30W PV power input. A coaxial prototype with a cold finger of 9mm diameter is developed on the basis of the in-line one, whose length of pulse tube is even reduced. And the cooling capacity of 2W@80K is gained. The coaxial type PTC is more comfortable for coupling with other apparatus.

Acknowledgement: this paper is supported by the National Natural Science Fundation (No. 51006112).

Study on new type of pulse tube cooler precooled sorption Joule-Thomson cooler for Liquid Helium Temperature Range

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To meet the development of international space cryocooler technology, which requires long-life, large cooling power, ultra low temperature and light microminiature cooler, we have developed high frequency Pulse Tube Cooler (PTC) /sorption J-T hybrid cooler. The cold head and regenerator of the two-stage coaxial PTC provide cooling source for the J-T cooler. This cooler has no moving parts and is therefore essentially vibration-free and suitable for space mission. We have replaced the traditional four sorption cells with new cells that contain a new high-density activated carbon, which leads to an efficiency improvement and contact construction. The heat coupling combination is further discussed between the regenerator and the cold head of the PTC with the J-T sorption cooler. In order to improve the performance of PTC precooled, reduce the cooling power loss of PTC and increase the cooling efficiency of J-T cooler, we will analyze the effects of cooling power and cooling temperature of the J-T cooler, which are caused by the temperature variations of cold head and regenerator of high frequency PTC. This research will provide theoretical reference for the development of microminiature space cooler of liquid helium temperature range.

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Development and experimental results on 15 K pulse tube

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Futures space mission such as IXO would benefit from a pulse tube cooler providing several hundreds of milliwatts of cooling power at 15 K for the pre cooling of a Joule Thomson loop. Our team, in partnership with Air Liquide and Thales Cryogenics BV is involved in the development of such a product in the framework of an ESA contract. The goal is the development of an engineering model of a 3 stage pulse tube. Our approach is based on multistage pulse tube linked together with thermal linked. This modular approach allows for more flexibility in the mechanical design with keeping a high thermal efficiency. Our first experimental results with performances below 15 K are described. A preliminary architecture for a 3 stage pulse tube reaching 15 K is presented.

Investigations on the interaction between high frequency pulse tube cold fingers and their driving compressors

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The pulse tube cold finger adopting a linear compressor as the driving source has been proven to be an enabling cooler technology which guarantees the high reliability, low-noise and long life. It is well known that the dynamic parameters of a compressor produce a great impact on thermodynamic performance of the pulse tube cold finger. However, the experiments in our laboratory show that the geometrical and operating parameters of the pulse tube also have evident counteractions on the compressor performance. Of all the influencing factors, the phase-shifting components and the thermal characteristics in the heat exchangers exert the greatest impact on the driving compressor. The theoretical and experimental investigations on the interaction between the pulse tube and the compressor have been conducted on a series of high frequency pulse tube cryocoolers (PTCs) operating at 30-150K. The general principles have been summarized and the results will have important meaning in the design and optimization of high frequency PTCs.

Raytheon Low-Temperature RSP2 Cryocooler Design, Fabrication and Test

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The Low-Temperature Raytheon Stirling / Pulse Tube 2-stage ("LT-RSP2") hybrid cryocooler is a long-life, robust machine designed to operate efficiently at second stage temperatures below 12 K with a nominal capacity of several hundred milliwatts. An oscillating or steady-flow third stage is not required with this cryocooler, and design features have been included to allow for fine active vibration control. While some aspects of the expander warm-end mechanical design are carryovers from the existing High Capacity RSP2, the compressor module and expander cold head have been substantially optimized for increased efficiency and capacity at low cryogenic temperatures. The LT-RSP2 design was finalized in mid-2009, with piece-part fabrication taking place in late 2009 and early 2010. Assembly and initial testing in an ambient benchtop configuration occurred in 2010/2011. Major aspects of the mechanical and thermodynamic design will be presented in this paper, including information regarding the final operating point, performance, and packaging details. Results from the fabrication, assembly, and testing will be discussed, as will observations regarding the achieved system performance. Future testing and design enhancement plans will be discussed as well.

Dynamic Analysis of a Free Piston Free Displacer Split Stirling Cryocooler with pressure losses

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Free piston free displacer cryocoolers in the small capacity miniature range, used for cooling infrared sensors, have a long operating life without maintenance. The miniature Stirling cryocooler driven by linear motor does not have fixed amplitude of motion as in the case of crank driven system. The amplitude depends upon the cooler and the motor characteristics. Therefore, it becomes necessary to analyze dynamics of the cryocooler and the motor characteristics coupled together. The bounce space of the Free piston free displacer Stirling cryocooler has mainly been considered to be at the same mean pressure throughout the cycle and the variation in the pressure due to the movement of the piston in the bounce space are neglected. The variations, however small, can affect the performance of the cryocooler. It acts as a pneumatic spring. This paper shows the complete dynamics and thermodynamics of the free piston free displacer miniature cryocooler including the pressure loss due to the flow through the regenerator and the variation of the pressure in the bounce space.

The advantages of using a digital temperature controller in a miniature Stirling Cryogenic refrigerator for Infrared Imagers
Scope on K527 Sine Controller

S. Ninburg, U. Maimon - Ricor Cryogenic and Vacuum Systems

ABSTRACT

Modern Infra-Red (IR) night-vision thermal imagers for reconnaissance, surveillance, recognition and targeting rely mostly on Stirling-cycle cryogenic refrigerators thanks to their high thermodynamic efficiency. Traditionally, linear cryogenic refrigerators comprised analog temperature controllers for controlling the cold-tip temperature and controlling the desire frequency. These controllers usually consist operational amplifiers, comparators, resistors and capacitors. The fine-tuning of the pre-set cold-tip temperature and the desire cooler frequency where achieved by setting potentiometers to a certain resistance.

It is known that potentiometers are affected by environmental temperature variations, continuous exposure to extreme temperatures, and aging. Another aspect of using a potentiometer is the difficulty for the customer to change the pre-set cold tip temperature and frequency.

Using potentiometer to reach wide operation set point temperature means potentiometer with high resistance with less accuracy, means less accuracy set point.

Even without the use of potentiometers, the accuracy and stability of the analog components are not sufficient for the increasing requirements of advanced IR detectors at various environmental temperatures, loads, and input voltages.

Moreover, manufacturers of cryogenic refrigerators could improve the reliability and traceability of their products by adding various functions to the controllers.

A digital temperature controller that is based on a highly integrated flash MCU could serve both goals: improve the accuracy of the cold-tip temperature and accuracy of the desire frequency, and provide with extra features aimed at improving the functionality and reliability of the refrigerators.

This paper describes the various functions and advantages of the K527 Sine digital temperature controller that was developed in RICOR Vacuum and Cryogenic Systems.

Experimental investigation on complete pool boiling curve of methane under 0.3MPa pressure

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As a clean energy source, nature gas utilization is booming worldwide. Compared with its gas phase, the liquefied natural gas (LNG) is important in the worldwide natural gas trade because of its compact volume in the cases of oversea transport and huge amount storage. Methane is the key component of nature gas. So it is of great significance to study methane's boiling heat transfer behavior for LNG facilities developments. Up to date, there are few studies on the methane's pool boiling heat transfer. The authors have carried out experimental measurement of methane's nucleate pool boiling in our previous work. However, there is no open published data on the film boiling heat transfer of methane. The whole pool boiling behavior, especially the critical boiling point and the film pool boiling data are of great importance when dealing with the LNG facility accidents.

The object of this work is to measure the complete pool boiling heat transfer coefficients for methane under 0.3MPa, including the rarely reported data of the critical boiling and the film boiling heat transfer. In this study, a new visualization apparatus was designed and built to obtain the boiling heat transfer coefficients of methane from nucleate boiling to film boiling. Boiling takes place on the upper end surface of an oxygen free copper cylinder. With the experimental apparatus, heat transfer coefficients in pool boiling were measured for methane under the saturated conditions. At each measuring condition, experiments are repeated at least three times to make sure that the boiling data are creditable. The uncertainties of the experiment were also analyzed in details.

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Experimental investigation on two phase frictional pressure drop of methane in a horizontal tube

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The natural refrigerants are suitable selections for some cryogenic systems because they have good environmental criteria, and for some of them, high thermodynamic performances. Hydrocarbons belong to the group of natural refrigerants. Methane is an often-used component in mixture refrigerants, and the key component of nature gas. Therefore, it is of great significance to study methane's Frictional Pressure Drop behavior for new Cooling Systems and LNG facilities developments. Up to now, few experimental researches about the characteristics of Two Phase Frictional Pressure Drop of Methane can be found in publications.

An experimental investigation of two phase frictional pressure drop behavior of methane has been carried out at pressures from 0.3 to 0.6 MPa in a smooth horizontal tube. The test section is a horizontal smooth tube with a 6 mm ID and 1860 mm in length. The major objective of this work was to measure two-phase pressure drops over the vapor quality range from 0 to 1. Different experimental parameters' influence on the frictional pressure drop was analyzed. Comparison measurements of the two-phase frictional pressure drops at different operation conditions have been made at a particular set of test variables. The experimental two-phase frictional pressure drop results of methane are compared with such correlations as Friedel, Chisholm, Bandel and Müller-Steinhagen and Heck.

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Transient heat transfer from a horizontal flat plate in a pool of liquid hydrogen

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In designing a superconducting magnet cooled by liquid hydrogen, knowledge of transient heat transfer as well as steady-state one is necessary. However, there have been very small number of experimental data and little is known on the transient heat transfer. In this work, transient heat transfer caused by exponentially increasing heat input $(Q = Q_0 \exp(t/\tau))$ to a flat plate in liquid hydrogen was measured under saturated and subcooled conditions at pressures from 0.1 to 0.7 MPa. The exponential period τ was varied from 8 ms to 8 s. The flat plate heater used was made of SUS316, 5 mm in width, 60 mm in length and 0.5 mm in thickness. The test heater was supported horizontally with its width direction vertical. The average temperature of the heater was measured by a resistance thermometry by using a double bridge circuit including the plate as a branch. Transient heat transfer before the inception of boiling for the exponential period shorter than 100 ms was expressed well by the transient conduction heat transfer without movement of liquid. Incipient boiling heat flux and temperature, and critical heat flux were higher for shorter period. No direct transition from non-boiling to film-boiling, such as first found for transient heat transfer in a pool of liquid nitrogen, was observed for liquid hydrogen.

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DNB heat flux in forced flow of subcooled liquid hydrogen under pressures

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Forced flow heat transfers of liquid hydrogen through a vertical tube with the diameter, *d*, of 6.0 mm and length of 100 mm were measured at pressures of 0.4, 0.7 and 1.1 MPa for various inlet temperatures and flow velocities. The heat fluxes at the inception of boiling and the departure from nucleate boiling (DNB) heat fluxes were higher for higher flow velocity and larger subcooling. The DNB heat fluxes under subcooled condition were very weakly dependent on pressure. The effect of tube diameter and subcooling on the DNB heat flux was clarified. New correlation of the saturated and the subcooled DNB heat flux was presented based on the experimental data..

Nucleate pool boiling heat transfer characteristics of tetrafluoromethane and methane binary mixtures

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Low temperature mixed-refrigerant Joule-Thomson refrigerator (MJTR) is one of the high-efficiency refrigeration technologies suitable for 80~230 K refrigeration applications. Most of these mixed-refrigerants used in MJTRs contain hydrocarbon, fluorocarbon and nitrogen. Among these, tetrafluoromethane (FC14) and methane (HC50) are two popularly used components. The further study on these MJTRs makes it important to obtain the heat transfer data of these mixtures. Up to date, there are few studies on pool boiling heat transfer behaviors of HC50, FC14 especially their binary mixtures in the open published articles. The object of this work is to obtain the nucleate pool boiling heat transfer coefficients for HC50 and FC14 mixture at different concentrations.

The present measurements were carried out with an existing experimental apparatus used in our former work. Boiling takes place on the upper end surface of an oxygen free copper cylinder. With the experimental apparatus, heat transfer coefficients in nucleate pool boiling were measured for HC50 and FC14 mixture under the saturated conditions at pressure of 0.3 MPa. Series of experiments were carried out at a wide range of heat fluxes from 40 kW m^{-2} to 150 kW m^{-2} and various mixture concentrations. At each measuring condition, experiments are repeated at least three times to make sure that the boiling data are creditable. The uncertainties of the experiment are also analyzed in details. Based on the measured data and the pure components characteristics, the mixture effects on boiling heat transfer coefficients are deeply discussed. Experimental data is also compared with some existing correlations.

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Status of Cryogenic System for Spallation Neutron Source's Superconducting Radiofrequency Test Facility at Oak Ridge National Lab

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Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL) is building an independent cryogenic system for its Superconducting Radiofrequency Test Facility (SRFTF). The scope of the system is to support the SNS cryomodule test and cavity test at 2-K (using vacuum pump) and 4.5K for the maintenance purpose and Power Upgrade Project of SNS, and to provide the part of the cooling power needed to backup the current CHL to keep Linac at 4.5-K during CHL maintenance period in the future. The system is constructed in multiple phases. The first phase is to construct an independent 4K helium refrigeration system with helium Dewar and distribution box as load interface. It is schedule to be commissioned in 2012. Here we report the concept design of the system and the status of the first phase of this project.

Specification and Design of a 2 K Helium System for Cryomodule and Cavity Tests at FRIB

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Abstract

The Facility for Rare Isotope Beams (FRIB) will be a new User Facility for Nuclear Science. The facility is funded by the Department of Energy (DOE) Office of Science and Michigan State University (MSU) and will be constructed on the campus of MSU. The main accelerator for the FRIB project will be a superconducting linac constructed of 52 crymodules, housing 344 superconducting radio frequency (SRF) cavities. Of the 52 superconducting cryomodules, 35 must be operated at superfluid helium temperatures of 2 K with the remaining operating at 4.5K. During FRIB fabrication, and prior to the commissioning of the FRIB cryoplant, all cavities and cryomodules (both operating at 4.5 and 2K) must be tested as part of the FRIB quality assurance program. To meet the requirements of FRIB production, upgrades to the existing SRF infrastructure at the National Superconducting Cyclotron Lab (NSCL) must be designed and commissioned. These upgrades include: two additional test Dewars, a FRIB cryomodule testing bay, and a cryogenic system capable of supporting the 2K cryogenic load, including subatmospheric pumps, heat exchangers, and JT valves. Transfer lines connecting these new additions will also be designed and fabricated. This paper describes these new systems and show that they will meet FRIB requirements as well as maintaining flexibility for future changes.

Test stands for testing serial XFEL accelerator modules

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The European X-rays Free Electron Laser (XFEL) project is presently under construction at DESY, Hamburg, Germany. The XFEL linear accelerator will consist of about 100 accelerator modules. Each accelerator module is 12 meters long and contains eight superconducting 9 cell cavities and one superconducting magnet package. All superconducting components are cooled by helium II at 2 K. The assembled accelerator modules will have to be qualified before being installed in the XFEL accelerator. All serial XFEL accelerator modules will be tested at three test stands in the Accelerator Module Test Facility (AMTF) at DESY. The test stands will also be intended for optional spot tests of completed cavities. The test stands will be designed, manufactured, delivered to DESY and put into operation by Budker Institute of Nuclear Physics, Novosibirsk, Russia.

This paper describes layout of the test stands within AMTF, their mechanical and cryogenic designs, test program and schedule.

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SRF Cavity Testing Status and Operational Experience

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The cryogenic system at the Meson Detector Building (MDB) has now supported over four years of testing of fully assembled SRF cavities. The Horizontal Test Stand (HTS) has tested single, fully dressed 1.3 GHz and 3.9 GHz cavities at 2.0 K as final qualification prior to their installation into accelerator-ready cryomodules. The MDB cryogenic system has been expanded to support an additional cavity test area, the High Intensity Neutrino Source (HINS) test area, for 325 MHz single-spoke resonators. The HINS test area currently supports 4.5 K operations for research and development of the spoke cavities with tuner and coupler. The test area addition required the design and installation of a new cryogenic transfer line extension to reach this second test area and to allow for independent operations of either cavity test system. The cryogenic performance and operational experiences of both cavity test areas, operating individually or simultaneously, will be discussed. The cryogenic system general reliability and operational improvements will be discussed. Future plans for the MDB test area include lowering the HINS test temperature to 2 K and adding an additional Horizontal Test Stand (HTS-2).

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FERMILAB SRF CRYOMODULE OPERATIONAL EXPERIENCE

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Fermi National Accelerator Laboratory has constructed a superconducting 1.3 GHz cryomodule test facility located at the New Muon Lab building. The facility will be used for testing and validating cryomodule designs as well as support systems. The cryogenic infrastructure consists of two Tevatron style standalone refrigerators, cryogenic distribution system as well as an ambient temperature pumping system to achieve 2K operations with supporting purification systems. A single Type III plus 1.3 GHz cryomodule was installed, cooled and tested. Design constraints of the cryomodule required that the cryomodule individual circuits be cooled at predetermined rates. These constraints required special design solutions to achieve. This paper describes the initial cooldown and operational experience of a 1.3 GHz cryomodule using the New Muon Lab cryogenic system.

[1]Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

Conceptual Design of a Multiple-function Cryogenic System for Superconducting Devices in SSRF

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Three 500MHz superconducting RF cavities operating at 1.5 MV each are applied to the Shanghai Synchrotron Radiation Facility in order to provide accelerating voltage and sufficient RF power to make up for any power losses through synchrotron light. A cryogenic plant with cooling capacity of 650 W at 4.5 K was built for the SRF cavities. There will be more than 60 beam lines to be installed in the SSRF ring, and almost half of them will be based on insertion devices such as wigglers and mini-gap undulators. The superconducting insertion devices have been under development for the SSRF since 2009 because of advantages such as they can provide higher fields at a given period and provide users with expanded spectral range and with good overlap of harmonics. Consequently, a set of new cryogenic system with cooling capacity of at least 500 W at 4.5 K is proposed to be designed and constructed, which will be not only used for testing and operating the future SC insertion devices in the SSRF, but also for the off-line performance test for the development of the back-up 500MHz SRF cavity. Additionally, the new cryo-plant will be employed as the back-up of current 650 W refrigeration system to support normal operation of the on-line SRF cavities in case of any failure. This paper presents the conceptual design for the multiple-function cryogenic system in detail.

Experimental study on neon refrigeration system using commercial helium compressor

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In this study, we developed neon refrigeration system using commercial helium compressor which was originally designed for GM cryocooler. We performed this research as precedent study before developing neon refrigeration system for small-scale hydrogen liquefaction system. The developed system is based on precooled Linde-Hampson system with liquid nitrogen as precoolant. Design parameters of heat exchangers are determined from thermodynamic cycle analysis with operating pressure of 2 MPa and 0.4 MPa. Heat exchangers have concentric-tube exchanger configuration and orifice is used as Joule-Thompson expansion device. In experiments, pressure, temperature, mass flow rate and compressor input power are measured as charging pressure and heat load. With experimental results, the characteristics of heat exchanger, Joule-Thompson expansion and refrigeration system are discussed. The developed neon refrigeration system shows the lowest temperature of 43.9 K.

Second-Law Analysis and Optimization of Reverse Brayton Cycles of Different Configurations for Cryogenic Applications

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Second-law and exergy analyses and optimization of four Reverse Brayton Refrigeration (RBR) cycle configurations: Conventional 1-stage cycle; Conventional 2-stage cycle; Conventional 1-stage cycle modified with intermediate cooling of the recuperator using an auxiliary cooler; and an integrated 2-stage RBR cycle are performed. The RBR cycles are analyzed for low pressure ratio applications as well as high pressure ratio applications using multistage compressors with intercooling. Analytical solutions for the conventional cycles are developed including thermal and fluid flow irreversibilities of the recuperators and all heat exchangers in addition to the irreversibilities of the compression and expansion processes. Analytical solutions are used to find the thermodynamic bounds for the performance of the cycles. Exergy flow diagrams of the cycles are developed and the effects of important system parameters on the performance of the RBR cycles are investigated. Second-law analysis and optimization of the cycles with intermediate cooling of the recuperator, considering the cooling temperature and the recuperator effectiveness and pressure drop of the recuparator, are included in the analysis. The effect of the second-law efficiency of the auxiliary cooler on the total system efficiency is presented.

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

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The Air Force Research Laboratory (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 31,000 hours to the TRW 6020 which has been operating for more than 95,000 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.

L-3 CE Stirling-cycle Cooler Reliability Growth Update

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L-3 CE has in place a continuous effort to evaluate and improve the lifetime of its cryocooler products. This effort includes analysis of both lab environment reliability tests and field data from shipped units. The purpose of this paper is to outline L-3 CE's life testing methodology and provide reliability data for L-3 CE cryocoolers, specifically for the 0.6-Watt Cooler (Model B602), 1.0-Watt Reduced Size, Weight, and Power (RSWAP) Cooler (Model B610), and the 1.5-Watt Cooler (Model B1500). Cooler performance characteristics such as cooldown time, refrigeration capacity, and input power are monitored throughout the life of the cooler. The data presented here updates previously reported data. Field data for the 1.0-Watt Cooler (Model B1000) is also presented.

Experimental Study of AMR Cycle for Hydrogen Magnetic Refrigeration

For upcoming the hydrogen society, there are several technological key issues such as hydrogen generation, liquefaction, storage and transportation. Magnetic refrigeration systems based on the magnetocaloric effect involve intrinsically higher energy efficiency than conventional refrigeration systems at cryogenic temperatures, so they attract the attention as hydrogen liquefaction method.

We are buildingan active magnetic regenerative (AMR) test apparatus whichwill cool the hydrogen gas from 77K to the liquid hydrogen temperature 20K as a pre-cooling cycle of hydrogen magnetic refrigeration. In this system, we newly designed an external gas displacer system witch transfer the heat from AMR test bed. This external displacer is placed in the cryogenic temperature and expected to be more efficient because of less heat leaks. Various kinds of magnetic materials and higher magnetic fields > 5 T will be tested.

The performance comparison of Oxford and Triangle flexure bearings

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Abstract: Flexure bearings are widely used in linear compressor for its high radial stiffness and long life working hour. In this paper, the Finite Element Method (FEM) is employed to analysis the characteristics of Oxford and triangle flexure bearing. Through changing the load, the thickness and the width of the spring arm, the two kinds of plate spring solved separately, and the results of stress and displacement contour plots are shown by FEM calculation. In order to avoid the resonance frequency of compressor, the modal analysis is employed to discuss natural frequency of the flexure bearings. The characteristics calculated by numerical process fit well with the experimental results. Under the same basic structure, the triangle flexure bearing could provide larger radial/axial stiffness ratio and higher nature frequency, which is conductive to the lightweight of the entire cryocooler system.

Keywords: Flexure Bearings FEM method Stiffness Nature Frequency Fatigue limit

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Comparison of 1d and 2d flow numerical analysis applied to two stage pulse tube cryocooler

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In the recent years, for several applications such as cooling of sensors, super conducting magnets, cryo-pumping etc., there are worldwide efforts to replace cooling with liquid helium by cooling with closed cycle cryocoolers. The internal working processes in pulse tube cryocoolers are quite complex due to unsteady, oscillating compressible gas flow in the pulse tube. Although, considerable theoretical studies have been carried out, as on date, phenomena occurring in pulse tube are still to be understood. Three different numerical models namely isothermal model, adiabatic model and energy equation model which are based on the assumption of one-dimensional flow are compared with CFD model based on two dimensional flow approaches to analyze a two stage pulse tube cryocooler. The various experimental parameters have been incorporated in the models to carry out the analysis. The various losses of the pulse tube cryocooler are being calculated separately and incorporated into the models. The numerical results are compared with the experimental results obtained for a two stage pulse tube cryocooler for validation.

Key words: Cryocoolers, Numerical models, 2D flow, CFD

Cryogenic Control Valves – VELAN SAS

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VELAN SAS, a French Company located in Lyon, is one of the key suppliers of engineered valves for nuclear , LNG and cryogenic applications. The success of our company is based on our feedback, our technological expertise, the quality and reliability of our products.
VELAN SAS nuclear valves are specifically designed to equip the Reactor Coolant System and other systems of the nuclear island and its annexes. More than 300,000 nuclear valves have been manufactured over the past 40 years and are in operation on 380 NPPs around the world.
In cryogenics, VELAN SAS expertise and know-how are acknowledged throughout the world with more than 8,000 valves in operation on LNG receiving terminals, LNG tankers, LNG liquefaction plants and rocket launching pads..
Regarding the LHC project in Geneva for CERN, VELAN SAS developed and supplied more than 2000 cryogenic valves to control liquid helium in the superconductor magnets cooling systems and nearly 500 Safety Relief Cryogenic Valves, called Quench valves. The function of these very specific valves is to protect the superfluid helium enclosures of superconducting magnet resulting from resistive transitions (Quench phenomenon) as well as some of the cryogenic lines (QRL).
To meet required severe performances, VELAN SAS initiated cooperation with the Laboratories of CEA at Grenoble (SBT) to finalize the valves used for Very Low Temperatures and of CEA at Saclay for specific superconducting applications.
These valves ensure a good tightness at very low temperature (superfluid helium @ 1.8K) and are set at different opening pressures from 17 to 22 bar. They can automatically open to release overpressure in less than 10ms and can also be manually operated by electrical signal.
Optimisation of flow area and shape design allows large flow coefficients and linear opening/closing curves conform to CERN requirements.
The choice of materials and design allows this valve to withstand surrounding radiations in the tunnel and to ensure low heat in-leaks from ambient temperature to superfluid bath.
The SRV development has shown the know-how and the adaptation capability of VELAN SAS on the cryogenic market and placed the company as a key player of very low temperature valves.

Vacuum Load-Locked TES-Based Alpha Particle Spectrometer

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We are developing an alpha-particle spectrometer based on Superconducting Transition Edge Sensors (TES) for isotopic analysis of trace quantities of radioactive materials relevant to nuclear safeguards and forensics. Conventional analysis is a time-consuming, multi-day process involving wet chemistry followed by alpha counting and then mass spectrometry. In contrast, TES sensors easily resolve elemental and isotopic line overlaps, potentially reducing analysis times to two days. Such sensors have already demonstrated a resolution of 1 keV out of 5 MeV, a factor of 10 higher than conventional detectors. Since alpha-particles do not penetrate solids, sources must be located in the cryostat's vacuum space in close proximity to the detectors. To avoid the time and inconvenience of cycling the cryostat between 100 mK and 300 K, a load-lock system is being developed for rapid source insertion while maintaining vacuum and low temperatures. The load-lock is built into a standard pulse-tube cooled ADR cryostat, and utilizes heat switches at 60 K and 3 K for cooling the sources. Shutters at 60K and 3K open during source loading and then close during measurement to minimize parasitic radiation loads. Sources are mounted at 3 K to avoid the mechanical complexity of mating to the ADR platform. This paper describes the design and results of preliminary tests.

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A liquid nitrogen cryostat used for the cryogenic cooling of Ti:sapphire in laser system

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Ti:sapphire (Ti:Al2O3) laser oscillators and amplifiers are the important sources for ultra fast applications because they can deliver ultra short, widely tunable pulses and high pulse energies at various repetition rates. However the power scaling of high-average-power lasers is often constrained by the thermo-optic distortions effects due to the absorbed heat in the lasing medium. As a solution cryogenic cooling of Ti:sapphire is often used since the thermal properties of Ti:sapphire will be dramatically improved at low temperatures. Recently the cryogenic cooling of Ti:sapphire by liquid nitrogen was successfully applied to a laser amplifier with 100W of pump power in Technical Institute of Physics and Chemistry in China. This paper gives a brief description about the design of a liquid nitrogen cryostat used to cool the Ti:sapphire crystal. The crystal and cryostat assembly is housed in a vacuum chamber which has Brewster-angle windows for the laser propagation. A thermal mechanical analysis for the Ti:sapphire crystal has been performed and the manufacture of the cryostat have been completed and have passed cooling tests.

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Coupled Non-Uniform bi-SQUID: A Numerical Investigation

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This work investigates through numerical simulations a novel device that improves dynamic range and linearity. The standard DC SQUID can increase in linearity by adding a third junction, changing to a device knows as the bi-SQUID. It is known that the dynamic range can increase by connecting SQUIDs in series, and it has been shown that non-uniformity in the loops sizes in arrays of SQUIDs can produce a unique 'anti"-peak at the zero magnetic flux (device know as a SQIF). Thus, combining these ideas we can improve the dynamic range and design a highly linear device with a unique 'anti'-peak. Hence, this device can be referred to as a bi-SQIF or non-uniform bi-SQUID. Results have shown that the maximum voltage swing increase proportional to N, where N is the number of loops connected in series. The spur free dynamic range also improves as N increases, which is directly related to the linearity of the device. Therefore, we have designed a device which can lead to improvements in low noise amplifier (LNA), in turn, would increase link margins, and affect the entire communication system. Other application included unmanned aerial vehicles (UAVs), where size, weight and power are limited; the bi-SQUID array would allow use of practical 'electrically small' antennas that provide acceptable gain, and mine detection.

Investigation of Cryogenic De-Sublimation Approach to CO_2 Removal

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GE, Sustainable Energy Solutions (SES), and Air Liquide are developing a new technology for CO_2 removal from the combustion flue gas stream. The technology is based on lowering temperature of the flue gas stream to -119 ^oC at which solid CO_2 is formed. The solid CO_2 is separated from the gas stream, compressed, and then converted to supercritical liquid at 150 atm for sequestration. The process produces a nearly pure, pressurized CO_2 stream and a nearly CO_2-free nitrogen-rich stream from stationary power flue gases. The process also has the potential to remove SO_2 and NO_x. Unlike in the competing monoethanolamine (MEA) based process, the analyzed technology does not involve heat cycling of large volumes of material, produces CO_2 of high purity, and includes compression of solid CO_2 instead of low pressure CO_2 gas. As a result of these advantages, the analyzed "CO_2 Freeze" technology promises to be more cost effective than the MEA technology.

Two investigated approaches for cryogenic CO_2 capture included the utilization of external cooling (referred to as External Cooling Loop process or ECL process) and the compression of flue gas followed by its cooling via expansion (Compressed Flue Gas process or CFG process). In both approaches solid CO_2 and cold gas (mostly N_2 with small amount of O_2) formed at the back end of the process are used at the process front end to pre-cool flue gas to increase process energy efficiency. Evaluation of the ECL and CFG processes included 1) Aspen modeling to size process streams, balance energy fluxes, and estimate energy penalty for CO_2 capture and 2) economic analysis to estimate LCOE increase as a result of carbon capture. All results are scaled to a power plant with a nominal net output of 550 MWe to enable comparison with previous work completed on MEA technology.

Analysis has shown that both investigated concepts have lower energy penalty compared to the baseline amine (MEA) process with the CFG process having almost 45% less penalty. The CFG process appears to be more cost effective than the ECL process and can potentially meet the US DOE target of $< 35\%$ increase in cost of energy services with 90% CO_2 capture. Predicted cost of CO_2 capture using CFG approach is \$23/t of CO_2, a 50% decrease in comparison with the amine technology. Cost of CO_2 avoidance is about \$29/t of CO_2.

Development of a Collins-Type Cryocooler Floating Piston Control Algorithm

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A multi-stage Collins-type cryocooler is under development for zero-boil-off storage of liquid hydrogen and oxygen fuel in space. Each stage utilizes a novel floating piston design for the working fluid expansion similar to the design described by Chaudhry [2006, Cryogenic Engineering Conference (CEC)] and Segado [2010, CEC]. The piston floats between a cold volume, where the working fluid is expanded, and a warm volume. The piston's motion is controlled by opening and closing valves connecting several reservoirs at various pressures to the warm volume. The reservoirs must be maintained at steady pressures between the high and low system pressure in order to achieve a high efficiency during the expansion of the working fluid. In this work, a numerical, quasi-steady thermodynamic model is developed for the piston cycle. The model reveals the pressures required in each reservoir for the system to operate in the steady state. In past prototype systems, maintaining the reservoirs at the desired pressures has proven to be difficult. It is hypothesized that this is due to mass flow past the piston (in the gap between the piston and cylinder wall) during each cycle, as well as the losses associated with the pressure reservoir valve timing and geometry. As a result, the model described in this work is extended to investigate these loss mechanisms and the previously unknown effect they have on the steady state reservoir pressures. From this, a control algorithm to maintain the desired steady state reservoir pressures is discussed.

Comparison of Sage and CFD models of a diaphragm pressure wave generator

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Industrial Research Ltd has been developing a low-cost diaphragm pressure wave generator for refrigerators since 2005. To quickly design and optimize a refrigerator based on a diaphragm pressure wave generator, one-dimensional analysis plays a very important role. However, due to great cross-section change between the pressure wave generator and the heat exchanger, one-dimensional design code can't give fairly accurate results without adjusting empirical heat transfer and friction coefficients. Therefore, multi-dimensional analysis is needed to verify one-dimensional results and determine empirical coefficients. In our previous work, a two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model was developed to simulate oscillating fluid flow and heat transfer in a diaphragm pressure wave generator and validated by a series of validation experiments. In this study, the validation experiments were modelled using Sage commercial code. Results obtained from the Sage model were compared with those from CFD simulations and validation experiments. We present the results to assist to determine the empirical heat transfer coefficients in Sage for the cases with great cross-section change between a pressure wave generator and a heat exchanger.

Key words: Pressure wave generator; CFD; Sage; Heat transfer

Evaluation of mechanical losses in a linear motor pressure wave generator

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The net PV power delivered by the Pressure Wave Generator (PWG) should be known for the design of the Pulse tube refrigerator (PTR). This requires the estimation of the electrical and mechanical losses in the PWG. The shaft power (input power-copper and iron losses) is available to generate the acoustic power, a part of which is further reduced due to mechanical losses. The mechanical losses consist of Pressure losses and Flow losses. The Pressure losses arise due to leakage through the piston – cylinder clearance (blow-by) and irreversible heat transfer within the PWG. The Flow losses are due to the pressure drops within the intrinsic flow channels of the PWG and the transfer lines. In this work, we evaluate the mechanical losses in an indigenously developed PWG with a maximum swept volume of 2 cc. Measurements are made at Helium fill pressures (1.5-2.5 MPa) and for the operating frequencies of 70, 80 and 90 Hz. The pressure losses decrease with increasing frequency and decreasing fill pressure. On the contrary, the flow losses decrease with decreasing frequency and increasing fill pressure. The Pressure losses are segregated into blow-by and irreversible heat transfer losses by measuring the pressure history at the piston back side. This study indicates that the Pressure losses are significantly higher than the flow losses when the PWG is connected to an experimental PTR.

Analytical modeling of draining process of multi tank containing cryogenic liquid for space applications

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Drainage of multiple cryogenic tank configuration of space vehicle could lead to a possible unequal tank empting process. This differential tank draining may result in draining one tank quicker than others that can cause significant center of gravity (CG) shift. The CG shift can lead to mission abort or a catastrophic failure conditions. To investigate the differential cryogenic tank draining process, two analytical models were developed. Generalized Fluid Flow Simulation Program (GFSSP) was utilized for the first model. The GFSSP is a fluid system analyzer developed at Marshall Space Flight Center. The second model was based on the Ring methodology. A sensitivity analysis was carried out to evaluate parameters that influence the differential tank draining. The parameters were: 1) Difference in the feed-line resistances; 2) Unbalance ullage pressure during the draining process; 3) Difference in initial tank fill levels. The models descriptions and the results for liquid hydrogen and liquid oxygen applications will be presented in the final paper.

Testing and analytical modeling for purging process of a cryogenic line

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The purging operations for cryogenic main propulsion systems of upper stage are usually carried out for the following cases: 1) Purging of the Fill/Drain line after completion of propellant loading. This operation allows the removal of residual propellant mass; and 2) Purging of the Feed/Drain line if the mission is scrubbed. The lines would be purged by connections to a ground high-pressure gas storage source. The flowrate of purge gas should be regulated such that the pressure in the line will not exceed the required maximum allowable value. Exceeding the maximum allowable pressure may lead to structural damage in the line. To gain confidence in analytical models of the purge process, a test series was conducted. The test article, a 20-cm incline line, was filled with liquid hydrogen and then purged with gaseous helium (GHe). The influences of GHe flowrates and initial temperatures were evaluated. The Generalized Fluid System Simulation Program, an in-house general-purpose computer program for flow network analysis, was utilized to model and simulate the testing. The test procedures, modeling descriptions, and the results will be presented in the final paper.

Adsorption of Oxygen onto Zeolites at Pressures up to 15 MPa

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For NASA applications, high-pressure oxygen is an integral part of portable life support systems (PLSSs) for Extravehicular Activities (EVAs), some fuel cell systems and potential In Situ Resource Utilization (ISRU) systems. There are program needs for new high-pressure oxygen generation systems on the International Space Station (to enable EVAs after the Shuttle is retired), Lunar Lander (to use lower pressure cryogenic tanks as a source of high pressure oxygen for EVAs) and Lunar Habitat (to generate and store high pressure oxygen for extended periods of time). One of the candidate technologies for producing high-pressure oxygen, temperature swing adsorption (TSA) compression, offers many advantages but has a low technology readiness level. Evaluation of technical feasibility and safety issues, and specification of operating parameters of the compressor require the availability of fundamental equilibrium adsorption data. A cryogenic, high-pressure volumetric equilibrium adsorption apparatus has been developed at Ames Research Center to facilitate collection of the needed data. The apparatus incorporates cryogenic and vacuum surrounds, and a high-pressure oxygen circuit. In this paper, low-temperature equilibrium isotherms of oxygen on various sorbent materials are presented. Conceptual designs of a TSA system for this application are presented as well.

Spacecraft Propulsion Research Facility

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The National Aeronautics and Space Association (NASA) Glenn Research Center (GRC) Plum Brook Station (PBS) Spacecraft Propulsion Research Facility, commonly referred to as B-2, is NASA's third largest thermal vacuum facility. It is the largest designed to store and transfer large quantities of liquid hydrogen and liquid oxygen, and is perfectly suited to support developmental testing of upper stage chemical propulsion systems as well as fully integrated stages. The facility is also capable of providing thermal-vacuum simulation services to support testing of large lightweight structures, Cryogenic Fluid Management (CFM) systems, electric propulsion test programs, and other In-Space propulsion programs.

In 2006, with anticipation to meeting NASA's future needs for thermal vacuum upper-stage engine testing as well as those of commercial and international customers, B-2 undertook a systematic, phased approach to revitalize all major facility subsystems and ancillary infrastructure equipment. To date this refurbishment includes the vacuum chamber, all vacuum systems, propellant and pressurant systems, control and data acquisition systems, and numerous facility support systems. The B-2 revitalization project aims to reduce the cost of maintenance and test operations through unique design and operational concepts, providing highly reliable and available subsystems leading to quality data with known uncertainties and minimized test costs for customers.

A recently completed integrated system test demonstrated the refurbished thermal vacuum capabilities of the facility. The test used the modernized data acquisition and control system to monitor the facility during pump down of the vacuum chamber, operation of the liquid nitrogen heat sink (cold wall) and the infrared lamp array. A vacuum level of 7×10^{-6} Pa (5×10^{-8} torr) was achieved. The heat sink provided a uniform temperature environment of approximately -196°C (-320°F) along the entire inner surface of the vacuum chamber. The recently rebuilt and modernized infrared lamp array produced a nominal heat flux of 1400 W/m^2 at a chamber radius of 6.7 m (22 ft) and along 11m (36 ft) of the chamber's cylindrical interior. With the lamp array and heat sink operating simultaneously, the thermal systems produced a heat flux pattern simulating radiation to space on one surface and solar exposure on the other surface. The data acquired matched pretest predictions and demonstrated system functionality. The chamber has a vertical entry that can accommodate test articles approximately 6.7 m (22 ft) diameter and up to a vertical height of 15.8 m (52 ft).

This paper will discuss capabilities of the B-2 test facility and revitalizations efforts performed to date as well as plans for future work. Also included are results of the recent integrated systems test demonstrating the success of the revitalization effort.

Catalytic Pressurization of Liquid Hydrogen Fuel Tanks for Unmanned Aerial Vehicles

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As the use and applications of Unmanned Aerial Vehicles (UAV) expand, a lighter weight fuel allowing for longer duration flights has become the primary limiting factor in the advancement of these vehicles. To extend the operational envelope of UAV, onboard condensed hydrogen storage for missions exceeding seven days is necessary. Currently, large spherical liquid hydrogen tanks that are pressurized with external helium tanks are utilized for this purpose. However, the mass and size of the fuel storage tank and fuel pressurization system significantly limit the maximum payload of UAV. In an effort to alleviate these issues, this paper investigates the technological feasibility of orthohydrogen-parahydrogen catalysis as a method of fuel pressurization. Typical pressurization requirements for takeoff, cruise, and landing are reviewed. A preliminary system design is presented and analyzed from a heat transfer perspective. The feasibility of this method to pressurize fuel tanks filled with hydrogen slush is also discussed.

Hydrogen fuel storage on electric powered VTOL Personal Aircraft Vehicle (PAV)

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For decades, the “hydrogen economy research” has been seeking the “magic bullet” solution to the practical storage of hydrogen. DOE’s“Freedom Car” initiative aggressively funded research in cryogenic H2 distribution, high pressure vehicletanking, and nano-carbon absorbers. Current speculation is that an efficient, safe, reliable, and inexpensive method to store 1-100 gigjoules of H2 is not yet available to replace petroleum based vehicle propulsion. Ourfeasibility study suggests a highly integrated designapproach to: generation, storage and use of H2, whichmay permit storageweight% efficiencies greater than 10%. Initially, thestorage tank is unique to a Personal Aircraft Vehicle (PAV) and/or Unmanned Aerial Vehicle (UAV), and is made possible by compositeMLI/aerogel/bubble insulation techniques, pulse tube cryo-cooling, and carbon absorbers operating at 77K-100K. The ultra-light aircraft generates its own hydrogenas a fuel to later power this new design for electric powered VTOLs. Unique are:1)vehicle’s mission(UAV-aerial surveillance), 2) ultra-light tank manufacturing methods, 3)integration of: electrolyzer, fuel-cell,motor, thruster, 4) closed circuit liquid nitrogen refrigeration. For such a craft to manage its fuel, and fly, total computer control is necessary and recently made possible.

Optimization of Thermal Insulation Systems Comprised of MLI and Fiberglass Materials

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Cryogenic vacuum insulation systems, with proper materials selection and execution, can offer the highest levels of thermal performance for vessels, piping, and cold apparatus. Materials of interest include micro-fiberglass, multilayer insulation (MLI), and composite arrangements. Insulation research test cryostats using liquid nitrogen boil-off calorimetry techniques were used in the investigation of the thermal performance and optimization approaches for composite MLI and fiberglass systems. Detailed thermal conductivity test data for the low-density fiberglass material are also presented. The testing included actual-use boundary temperatures as well as a representative installation configuration for cryogenic storage tanks. The testing was performed over a wide range of vacuum pressures to determine heat leakage rates corresponding to a number of different field applications. The test data are compared with other thermal conductivity data for low-density fiberglass materials. Analyses of these data show the importance of material specifications, installation methods, and test conditions for each particular application.

Measurements of multi layer insulation with variable cold temperature

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Multilayer insulation (MLI) is commonly used in most cryogenic devices such as LHe-cryostats or storage vessels. Typically performance measurements of such MLI insulations are carried out using bath calorimeter cryostats. Inherent to all this devices is a fixed cold temperature at the boiling point of the particular cryogenic liquid. A recent approach for cryogenic pressure vessels covers a broad temperature range, i.e. hydrogen storage in supercritical state between 20 K and ambient temperature. Thus, a new calorimeter cryostat has been designed at TU Dresden to meet these requirements. The design as a flow cryostat allows the measurement of the thermal performance with variable cold temperature between 20 K and 300 K. It can be operated in vertical as well as in horizontal orientation. The insulation material is wrapped around a nearly isothermal cylinder which is held at the desired temperature by a cooling fluid. Preferably LHe respectively helium cold gas is used. Several design features reduce undesired parasitic drags. It is reported about the design and the equipment of this cryostat plus first operational experiences.

Development of an experimental set up for the study of adsorption characteristics of activated carbon and other porous materials down to 4.2 K.

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The knowledge of accurate performance characteristics of porous materials is an essential need for the selection of suitable sorbent materials for use in cryosorption devices. The temperature range between 5 K and 20 K is foreseen to be useful in order to exploit the cryosorption mechanisms in cryopumping systems for nuclear fusion. But such experimental data at cryogenic temperatures are very scarce in the open literature, especially at temperature levels other than liquid nitrogen. Hence, an experimental set up has been developed to measure the adsorption characteristics of porous materials under variable cryogenic temperatures (5 K to 100 K). This is based on the commercially available micropore-analyser coupled to a closed helium cycle two-stage Gifford McMahon Cryocooler, which allows the sample to reach temperatures down to 4.2K. The sample port is coupled to the Cryocooler through a heat switch. To obtain sample temperatures in the range from 5 K to 100 K, the heat switch is used to isolate the sample port from the Cryocooler cold end. The sample temperature can now be varied without affecting the performance of the Cryocooler. The above setup enables studies of adsorption characteristics over a wide range of pressures, from ambient down to 10^{-4} Pa. The paper describes the details of the set up and presents the preliminary experimental results of sorption data on different gases (helium, nitrogen) for activated carbon.

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Wrapped Multilayer Insulation for Cryogenic Piping

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Many cryogenic systems require thermal insulation on piping and tubing containing cryogenic fluids. The lowest heat leak is typically achieved with conventional multilayer insulation (MLI) wrapped around the tubing and contained in a vacuum. However, because of the inherent insulation compression and its effect on conventional MLI with netting spacers, MLI performance on piping and tubing is four to ten times worse than MLI on a cryogenic tank or flat surface. Wrapped MLI (wMLI) is a high performance multilayer insulation designed for cryogenic piping that uses an innovative discrete spacer technology to control layer spacing/density and reduce heat leak. We report on the initial development of wMLI and its demonstration as a feasible technology. The wMLI design was determined in models to provide four times better thermal insulation than spiral wrapped conventional MLI on cryogenic piping. A wMLI prototype was built and had a measured heat leak 27% of the heat leak of conventional MLI insulating tubing at 77 Kelvin. Plans for continued development of this insulation are also discussed.

Heat Shields: Materials and Cost Considerations

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Heat shields reduce the operating cost of a system by intercepting radiated heat that would otherwise add to the load on the low-temperature stage of the system. Recent fluctuations in the cost of helium have made the use of effective heat shields all the more critical to the cost effective operation of liquid helium systems. Heat shields come in many forms; they may be completely passive; relying on a low emissivity for effective operation, or they may be actively cooled by helium vapor, an intermediate stage of a refrigerator or by liquid nitrogen. For actively cooled heat shields a high thermal conductivity as well as a low emissivity is desirable. Structural considerations, such as the need to support the cold stage of the system, as well as space limitations may also factor in to heat shield design. Heat shields have traditionally been fabricated from copper and aluminum, when the highest possible thermal conductivity is required, and to a lesser extent from stainless steel. These materials have very different mechanical properties, are assembled with different fabrication techniques and have very different costs. In this paper we examine heat shield design options over a range of conditions and compare the costs of different materials and design options.

Thermal property of insulation material for HTS power cable

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The thermal property of insulation material is essential in developing a high temperature superconductor (HTS) power cable operating at around liquid nitrogen temperature. Unlike metallic materials, nonmetallic materials have a high thermal resistance; therefore, accurate estimate of the heat flow is difficult in the case of nonmetallic materials. The objective of the present work is to develop a precise instrument for measuring the thermal conductivity of insulating materials over a temperature range of 30 K to approximately the room temperature by using a cryocooler. The thermal conductivity of Teflon is measured and the accuracy confirmation is carried out by comparing exist data. In addition, the experimental results of thermal conductivity for polypropylene laminated paper (PPLP) are presented and the method of estimation for specific heat by solving one-dimensional heat diffusion equation is also discussed.

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Apparatus to Measure the Apparent Thermal Conductivity of Multilayer Insulation (MLI)

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The design of a concentric cylinder calorimeter for measuring the apparent thermal conductivity of MLI blankets is presented. Unlike similar devices, where a liquid cryogen is used to control the cold boundary temperature and the cryogen boil-off rate is used to obtain the heat transfer through blanket; the design presented in this paper utilizes mechanical refrigerators to control the boundary temperatures. This approach ensures two unique features of the apparatus. First, the use of cryocoolers enables the user to set the boundary temperatures anywhere within the operating range of the refrigerators and therefore permitting a range of temperature differences with the measurement. The other unique feature is that the total heat transfer through the blanket is obtained by measuring the temperature difference along a cold cylinder support rod of known thermal conductivity. To determine the absolute thermal conductivity, a calibration is needed to eliminate the temperature related effects on the support rod. The results from the calibration and preliminary data on MLI samples will be presented.

Thermal Conductivity of Spray-On Foam Insulations for Aerospace Applications

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A guarded-hot-plate apparatus[1] has been developed to measure the thermal conductivity of spray-on foam insulations (SOFI) at temperatures ranging from 30 K to 300 K. The foams tested include: NCFI 24-124, a polyurethane foam used on the External Tanks of the Space Shuttle Program, and a separate polyurethane foam which is being considered for future use on the Ares vehicles. The foams were tested first using air at ambient pressure as a residual gas, then evacuated and tested once more. The thermal conductivity of these samples was compared to that of samples which have been subjected to conditions similar to those experienced by the foam while on the launch pad at Kennedy Space Center. To mimic the condition experienced on the launch pad, an apparatus was built to enclose the foam sample in a warm, humid space while the other side of the sample is exposed to liquid nitrogen. The thermal conductivity data obtained was also compared to data found in the literature.

1. Barrios, M., Van Sciver, S.W., “An Apparatus to Measure Thermal Conductivity of Spray-On Foam Insulation,” *Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference*, Vol. 55 (2010).

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An approach for measuring the thermal conductivity of the actual foamed insulated pipe transporting liquid nitrogen

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Thermal conductivity of three foamed pipes has been tested for development of liquid nitrogen transmission pipelines. By establishing a function between evaporation rate and thermal conductivity, we obtain effective thermal conductivity without destroying pipes. The comparison between our test and sample-test shows that this test device is reliable and could be a standard test bench for checking insulation property of the actual foamed pipes transporting liquid nitrogen. Principle, system design, experimental results and effect factors of the test are presented in this paper.

CRYOGENIC PIPING FIELD JOINT CRYOPUMPING TESTING

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For long installations, vacuum jacketed piping often comes in 40 foot sections that are butt welded together in the field. A short can is then welded over the bare pipe connection to allow for insulation to be protected from the environment. Traditionally, the field joint is insulated with multilayer insulation and a vacuum is pulled on the can to minimize heat leak through the bare section and prevent frost from forming on the pipe section. The vacuum jacketed lines for the Ares I mobile launch platform were to be a combined 2000 feet long, with 60+ pipe sections and field joint cans. Historically, Kennedy Space Center has drilled a hole in the long sections to create a common vacuum with the field joint can to minimize maintenance on the vacuum jacketed piping by halving the number of pump-out ports. However, this effort looked at ways to use a passive system that didn't require a vacuum, but may cryopump to create its own vacuum when cold but remain at atmospheric pressure when warm. Various forms of aerogel, multilayer insulations, and combinations thereof were tested in several different gasses to determine the best method of insulating the field joint while minimizing maintenance and thermal losses using liquid nitrogen. A combination was found to have similar thermal performance to the traditional MLI at a cryopumped condition while eliminating the need for maintenance.