ICC 20

Burlington, VT · June 18-21, 2018

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WELCOME

On behalf of the ICC 20 Organizing and Program Committees, we welcome you to the 20th International Cryocooler Conference (ICC 20) being held June 18–21, 2018 in Burlington Vermont, USA. The ICC is held every other year and is the preeminent international conference on the development and usage of cryocoolers. It attracts international participants from all continents representing academia, government laboratories, and industry.

At this meeting you will have the opportunity to learn of the latest developments in cryocooler technology and to discuss these developments with authors from around the world. We will have three full days of oral and poster presentations. To assure that you will not miss any of the presentations, the program has been arranged so that there are no parallel sessions. As a participant you will receive a copy of the proceedings, ***Cryocoolers 20***, approximately six months after the conference, which includes copies of the papers presented at ICC 20. These papers are peer reviewed by the session chairs to assure the quality of the proceedings.

Attendees at ICC 20 include: educators and students, particularly those interested in cryogenics and/or thermal management, cryogenic component manufacturers and suppliers; mechanical, electrical, and software engineers engaged in cryocooler design, manufacture and sales; system engineers responsible for selecting and/or integrating cryocoolers; and commercial and government cryocooler users.

We are very pleased to host ICC20 in beautiful Burlington, Vermont on the serene and picturesque grounds of the Hilton Burlington. Shopping, dining, entertainment and sightseeing options abound close by, throughout the city.

Please join us for our Welcome Reception on Monday, June 18th from 6:00 PM to 9:00 PM in the *Seasons of the Lake Room* at the Hilton Burlington.

The ICC 20 Conference Dinner Cruise will be held on Wednesday evening, June 20th from 6:00 PM to 9:00 PM aboard the *Spirit of the Ethan Allen* cruise ship, in Burlington.

We hope you will find the conference interesting, the venue enjoyable and your time well spent. Welcome to Burlington and ICC 20!

Mark Zagarola
Conference Chairman
Weibo Chen
Conference Co-Chairmen

Jeff Olson
Program Chair
Elaine M. Lim
Deputy Program Chair

CONFERENCE OVERVIEW

The biennial International Cryocooler Conference is the premier international forum for the presentation, discussion, and dissemination of the latest research and development activities related to all aspects of cryogenic cooling. Program topics include developments in commercial, military and space cryocoolers of all types, sizes and temperature ranges as well as recent technology advances in the coolers and the instruments and devices that they cool.

The 20th International Cryocooler Conference (ICC 20) will take place on June 18–21, 2018 at the Hilton Burlington in Burlington, Vermont.

The Conference begins with an ice breaking Welcome Reception on Monday evening, June 18th at 6:00 PM in the *Seasons of the Lake* room at the Hilton Burlington. The Technical Program commences at 8:30 AM on Tuesday, June 19th. Approximately 86 papers will be presented in both oral and poster formats during the ensuing three days, concluding on Thursday afternoon, June 21st at 3:30 PM. The papers are being presented in consecutive Oral and Poster Sessions. For your convenience, a complete overview of the Conference Schedule is provided both on the back cover and on the website.

REGISTRATION

Registration will be held in the Montpelier Room on Monday, Tuesday, Wednesday, and Thursday. All attendees must register.

The onsite registration fee is $800, which includes the Technical Program, all of the Social Program events and provided meals, conference materials, and the Conference Proceedings, which will be mailed to each participant approximately 6 months after the event. Companion guest tickets to the Conference Cruise/Dinner are available for an additional fee of $85.

Payments to ICC 20 must be in U.S. currency by credit card. Purchase orders will not be accepted. Registration is available online at www.cryocooler.org and onsite at the conference at the Registration Desk.

Oral Presenters please submit the electronic versions of your viewgraphs and papers at the time of registration. Poster presenters please submit your electronic version and hard copy versions of the paper at the time of registration; hold on to your poster presentation so that you can put it up prior to your poster session. Your thumb drive or CD/DVD will be returned to you after successful loading of your documents on the conference computers.

Onsite registration hours and locations are as follows:

Monday, June 18:	1:00 PM – 6:00 PM	Montpelier Room
Tuesday, June 19:	7:00 AM – 4:00 PM	Montpelier Room
Wednesday, June 20:	7:00 AM – 2:00 PM	Montpelier Room
Thursday, June 21:	7:00 AM – 12:00 PM	Montpelier Room

WELCOME RECEPTION and CONFERENCE DINNER

The Welcome Reception will be held in the *Seasons of the Lake* room at the Hilton Burlington on Monday evening, June 18th from 6:00 PM to 9:00 PM. A variety of appetizers, finger foods, desserts and beverages will be served. You will also be supplied with two drink tickets that can be used for soft drinks, wine and beer from the bar. Additional beverages and mixed drinks will be available at the cash bar. This will give us time to unwind after travel, make new friends, catch up with old friends and get settled.

On Wednesday evening, June 20th from 6:00 PM to 9:00 PM, a scenic dinner cruise awaits you at the *Spirit of the Ethan Allen* cruise ship. Buffet dinner will be served in the enclosed and fully climate controlled dining area.

You will also be supplied with two drink tickets that can be used for soft drinks, wine and beer from the bar. Additional beverages and mixed drinks will be available at a cash bar. Additional banquet guest tickets are available for $85 each. Guest tickets can be purchased prior to the event when registering online or at the onsite registration desk.

The Ethan Allen Cruise Ship is located within walking distance of the hotel (0.2 miles).

CONFERENCE MEALS

In addition to the Welcome Reception and Dinner Cruise, your registration includes a light breakfast each morning (Tuesday through Thursday) between 7:00–8:00 AM in the Pre-Function Room (outside the Adirondack Ballroom) prior to the day’s start of the Technical Program. Mid-morning and mid-afternoon refreshments will be provided in the Pre-Function Room during the day at breaks and coincident with Poster sessions.

All Session Chairs are invited to the Session Chair Breakfast Meeting at 7:00 AM on Tuesday, June 19th in the *Vermont Room*. This will be the only Session Chair Breakfast Meeting for the conference so please try to attend. The Program Chair and Editors will address a number of topics including how the sessions will run, the collection of papers, the review process of the papers and other pertinent information.

You will be on your own for lunch. The 1 hour and 45-minute conference lunch break should provide adequate time for lunch. There is a restaurant at the Hilton *(Mounted Cat)* with lake views from both the interior dining room and exterior patio. The Mounted Cat utilizes many materials indigenous to Vermont. There are also endless dining options within walking distance of the hotel, including several located at the Church Street Marketplace, where you will enjoy exquisite dining, endless shopping, and exciting entertainment.

BURLINGTON, VERMONT

The city of Burlington is located on the shores of beautiful Lake Champlain, and offers many opportunities for arts and entertainment, sightseeing, and outdoor recreation. Major airline service is available. Downtown shops and restaurants line the walking mall along the Church Street Marketplace. The city is also home to the University of Vermont. The nearby Shelburne Museum houses American folk and decorative art in a collection of historic buildings.

Area Websites of Interest:

Lake Champlain Chamber of Commerce: http://www.vermont.org/see-and-do

Church Street Marketplace: https://www.churchstmarketplace.com/calendar

http://www3.hilton.com/resources/media/hi/BTTVTHF/en_US/pdf/en_BTTVTHF_3DMap_April_2015.pdf

BURLINGTON WEATHER

During the month of June, the average high temperature is 76°F (24°C) and the average low temperature is 55°F (13°C).

BURLINGTON HILTON

(www3.hilton.com/en/hotels/vermont/hilton-burlington-BTTVTHF)

Situated on the waterfront, Hilton Burlington offers expansive views of the scenic Lake Champlain and the picturesque Adirondacks. With its convenient location, on-site amenities and substantial event space, our hotel has something for everyone. Our hotel is minutes from Burlington International Airport and Interstate 89. We are easily accessible by land or air and 90 minutes from Montreal. Explore the area's many attractions and activities including a scenic lake cruise on The Spirit of Ethan Allen and Burlington Segway Tours.

Amenities and features include guest room Wi-Fi, indoor pool, whirlpool, and fitness room. ICC 20 guests

For those who do arrive by car, the rate for overnight guests is $15.00 per night.

Upon arrival, you will receive a blue parking voucher which will allow in and out access for the duration of your stay.

The Hilton hotel offers shuttle service from 6am–10pm to/from the Burlington International Airport. The shuttle does not run on a continuous loop. Conference attendees will need to call the shuttle directly (1-802-658-6500) upon landing to request a pick-up. When you need to head back to the airport from the hotel, you can sign up at the front desk. The shuttle will leave at the top of every hour. The shuttle is used specifically for airport runs and pick-ups; however, if the bellmen are available, they will be able to shuttle guests to and from Church Street.

Have an extra day or two before or after the conference? Take in the local sites, such as the Shelburne Museum, Church Street Marketplace, Flynn Center for the Performing Arts, Echo Lake Aquarium & Science Center, or stroll along the beautiful Lake Champlain waterfront.

TRANSPORTATION

DRIVING DIRECTIONS from BURLINGTON INTERNATIONAL AIRPORT www.btv.aero) (~4 miles or 6.5 km)

Directions: Start going North on Airport Cir towards Airport Drive. Turn right onto Airport Drive. Take the first left on White Street (.84 miles). Turn right onto Williston Road/US-2W (1.72 miles). Stay straight to go onto Main Street (.65 miles). Turn right onto Battery Street. Hilton Burlington will be on the left.

TAXI, HOTEL SHUTTLE, PUBLIC TRANSPORTATION

The Hilton Burlington does offer free shuttle service to/from the airport. To schedule a pick-up at the airport, call the hotel shuttle directly at 802-658-6500. When departing to the airport, guests can sign up at the hotel front desk for a departure shuttle. There are low cost options for getting to and from the airport if you choose not to rent a car. Taxi cabs are available to and from the airport for this short distance for approximately $13.00 USD.

Green Mountain Transit offers local public transportation as well. To view a full schedule, visit:

http://ridegmt.com

AUTHOR / PRESENTER INFORMATION

INSTRUCTIONS for POSTER PRESENTERS

Poster sessions will be held in Salon D of the Adirondack Ballroom on Tuesday at 2:45 PM, on Wednesday at 9:30 AM, and on Thursday at 9:45 AM. Presenters are expected to only attend to their poster during their respective session. We encourage all poster session papers to be posted before the start of the day's first session or during lunch and request that they be removed by 5:00 PM. Posters not removed in a timely manner may be held at the registration desk for a while, but will be discarded at the end of the conference Thursday afternoon.

Each poster presenter will be provided with a poster board with a mounting area 96" (0.91m) wide by 48" (1.22 m) high. The poster boards have a foam core or corkboard surface and papers must be affixed with pushpins or velcro, which will be provided. Only pushpins may be used to attach materials to the poster boards. This should also enable you to have a small box or cup to hold business cards for those who would like to have an electronic version of your paper emailed to them.

Poster material must be readable from a distance of six feet (2 meters). Lettering in text and figures should be at least 0.25" (6 mm) high; the poster title should be in letters at least 1" (25 mm) high. The poster paper number will be mounted by Conference personnel at the top of each poster board, outside of your mounting area.

INSTRUCTIONS for ORAL PRESENTERS

Oral sessions will be held in Salons A-C of the Adirondack Ballroom. Each oral presenter is permitted 15 minutes. You should arrange your talk so that your presentation lasts 12 to13 minutes, with 2 to 3 minutes available for questions. You are expected to notify the session chair of your presence 10 minutes before the start of the session so that he/she knows that you are present. There will be no rearrangement of papers within an oral session to accommodate absences or cancellations. The time that you have been assigned within the oral session is fixed. Please inform your session chair if you must withdraw your paper from the program on site at the conference.

All oral presenters are required to submit an electronic version of their presentation by the close of the Registration Table of the day prior to their presentation. Presentations must be submitted in Microsoft Power Point format (but may be saved as a PDF). It is strongly recommended that presenters save their Power Point presentations with True Type fonts attached. Acceptable media include CD, DVD and USB flash drive. All presentations will be scanned for any viruses and subsequently loaded on an appropriate computer for the following day's presentations. All sessions will be equipped with an LCD projector, a computer, and a screen. Presenters are not allowed to use their own personal laptops. The laptops are not equipped to accommodate audio sound.

Mac computers will NOT be available in any of the sessions. Authors using a Mac platform will need to ensure that their files operate compatibly in the PC environment.

Authors are strongly encouraged to bring to their session an additional electronic copy for added security against unanticipated software/hardware anomalies.

If a presenter has failed to submit his/her presentation by the close of the Registration Table of the day prior to their presentation, they may be required to present their paper without accompanying viewgraphs. Papers not presented either as a poster or an oral presentation will not be published in ***Cryocoolers 20***.

INSTRUCTIONS for PAPER SUBMISSION

Authors must submit their manuscripts to conference registration/publications staff in the Publications Room, located in the Montpelier room by 5:00 PM on Monday, June 18th. Please bring the following:

- An electronic version of Oral Presentation on a CD, DVD or flash drive
- An electronic version of Paper on a CD, DVD or flash drive
- One print-ready hard copy
- Three additional hard copies for use by the technical reviewers
- Signed Copyright Release Form

Technical papers for each session will be distributed to the respective session chairs by the registration/publications staff for peer review prior to publication in the conference proceedings, ***Cryocoolers 20***. A timely review and return of the marked up papers and the paper review form will help shorten the publication time of the proceedings. Hard copy review forms will be included with each session paper, and a fill-in review form is also available in the cryocooler website. (www.cryocooler.org/papers/papers/).

TECHNICAL PROGRAM

The Technical Program for the 20th ICC is organized into 11 oral sessions and 6 poster sessions containing approximately 87 papers. The conference will begin in the Adirondack Ballroom on Tuesday, June 19th at 8:30 AM with introductory remarks and instructions by the ICC 20 Organizing Committee by the conference chairman. The first Oral session will begin immediately after. The technical sessions will begin at 8:00 AM on Wednesday, June 20th and on Thursday June 21st. The conference ends at 3:30 PM on Thursday, June 21st.

The 6 poster sessions will provide an excellent opportunity for close personal interaction with authors of these specialized topical subjects. The poster sessions will coincide with the morning or afternoon refreshment breaks.

INTERNET ACCESS

Wi-Fi is available in Guest Rooms, and throughout the hotel. Meeting/Guest Room passcode is “Hiltonwifi2018”.

ABOUT THIS ABSTRACT BOOK

This Abstract Book is arranged in order of presentation of the papers. This is illustrated on the proceeding page with the Days, Times, Session Names, Session Numbers and Session Chairs. The following Table of Contents and the Abstracts are also arranged in the same chronological order.

This Abstract Book is also posted online at www.cryocoolerorg.wildapricot.org.

TECHNICAL PROGRAM / SESSION CHAIRS

Tuesday, June 19, 2018					
Start	**End**		**Session #**	**Chair 1**	**Chair 2**
8:30	8:45	**Welcome to the Conference – Chair**			
8:45	10:15	**Aerospace Cryocoolers I**	TO1	Tonny Benchtop	Weibo Chen
10:15	10:30	**Break**			
10:30	12:00	**Advanced Cryocooler Components**	TO2	Keisuke Shinozaki	Marcel ter Brake
12:00	1:45	**Lunch**			
1:45	2:45	**Brayton and Sorption Cryocoolers**	TO3	Fons De Waele	Thomas Prouve
2:45	4:00	**Stirling/PT/Hybrid Cryocoolers**	TP1	Julien Tanchon	Vince Loung
2:45	4:00	**Miniaturization of Cryocoolers**	TP2	Jennifer Detlor	Nir Tzabar
4:00	5:15	**Very Low Temperature Cryocoolers**	TO4	Sylvain Martin	Ravi Bains

Wednesday, June 20, 2018					
Start	**End**		**Session #**	**Chair 1**	**Chair 2**
8:00	9:30	**Applications I**	WO5	Carl Kirkconnell	Ingo Rühlich
9:30	10:45	**Advanced Cryocooler Components**	WP3	Akihiro Nagata	Ali Kashani
9:30	10:45	**Commercial and Laboratory Cryocoolers**	WP4	Paul Bailey	Chao Wang
10:45	12:00	**Advanced Analysis and Modeling Techniques**	WO6	Mostafa G	Tanh Nguyen
12:00	1:45	**Lunch**			
1:45	2:15	**Cryocooler Electronics**	WO7	Jeff Raab	Dean Johnson
2:15	4:00	**Stirling/PT/Hybrid Cryocoolers**	WO8	Peter Kittel	Andrew Gibson

Thursday, June 21, 2018					
Start	**End**		**Session #**	**Chair 1**	**Chair 2**
8:15	9:45	**Commercial and Laboratory Cryocoolers**	THO9	Ted Conrad	Phil Spoor
9:45	11:00	**Advanced Analysis and Modeling Techniques**	THP5	Ray Radebaugh	Ryan Taylor
9:45	11:00	**Very Low Temperature Cryocoolers**	THP6	Lionel Duband	Peter Shirron
11:00	12:00	**Aerospace Cryocoolers II**	THO10	Thierry Trollier	Martin Crook
12:00	1:45	**Lunch**			
1:45	3:30	**Applications II**	THO11	Jennifer Marquardt	Thierry Tirolien

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TRL6 Qualification of Northrop Grumman Micro Cooler [TO1-1]

T. Nguyen, J. Russo, D. Chi, L. Abelson

Northrop Grumman Aerospace Systems, Redondo Beach, California, 90278 USA

The Northrop Grumman (NG) space micro pulse tube cooler is a split configuration cooler incorporating a coaxial cold head connected via a transfer line to a vibrationally balanced back to back linear flexure bearing compressor. Scaled from the TRL 9 HEC cryocooler and designed for > 10 year operation with no performance change, the 1.1 kg mechanical cooler incorporates a very efficient pulse tube cold head over a range of temperatures above 40 K.

This paper reports the results of the Technology Readiness Level (TRL) 6 qualification of the NG microcooler. The microcooler was subjected to launch vibration and thermal cycling conditions appropriate to space as well as tactical applications. The cooler performance was also characterized over a wide range of reject temperatures and input powers to demonstrate its suitability to a wide range of missions and applications.

Qualification Test Results for the TIRS-2 Cryocooler [TO1-2]

E. Marquardt[1], R. Taylor[1], J. Marquardt[1]
T. Meunch[2]

[1]Ball Aerospace, Boulder, CO 80301, USA
[2] NASA Goddard Space Flight Center, Greenbelt 20771, MD, USA

Ball Aerospace has completed qualification testing of its flight Stirling-cycle cryocooler for the Goddard TIRS-2 (Thermal Infrared Sensor) instrument slated to fly on the Landsat 9 in December 2020. The TIRS-2 thermo-mechanical unit (TMU) is a two-stage Stirling cryocooler that underwent minor modifications from TIRS-1 to increase its manufacturability and to incorporate lessons learned during the TIRS-1 program. The TIRS-2 cryocooler control electronics (CCE) is a new electronics architecture developed on IRAD after TIRS-1 to modernize Ball's electronics approach. The TIRS-2 cryocooler has redundant control electronics with a switch between the CCEs and TMU making a highly reliable system. The cryocooler provides 1.6 W at 38 K and 9.95 W at 90 K using 205 W input power to the electronics. The TIRS-2 flight units have now been delivered to Goddard for instrument integration. Qualification test results are reported.

Characterization Testing of Lockheed Martin Micro1-2 Cryocoolers Optimized for 220 K Environment [TO1-3]

I. McKinley, D. Johnson, J. Rodriguez

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91125 USA

The Mapping Imaging Spectrometer for Europa (MISE) instrument on the planned Europa Clipper mission has baselined a Lockheed Martin “high power” Micro1-2 pulse tube cryocooler operating at 135 Hz with a 220 K heat rejection temperature. This paper describes the testing and results of two Lockheed Martin Micro1-2 coolers optimized for these conditions. The thermal performance of the microcoolers was measured in vacuum for heat reject temperatures between 220 and 230 K. The coolers were driven with a Chroma 61602 AC power source for input powers ranging from 5 to 40 W and drive frequency between 125 and 145 Hz. The optimal drive frequency was dependent on both input power and heat reject temperature. In addition, the exported forces and torques of the coolers were measured at 300 K heat rejection with the coolers driven by Iris Technology high-power low cost control electronics (HP-LCCE) for input powers ranging from 5 to 60 W and drive frequency between 120 and 160 Hz. The exported forces were dependent on both input power and drive frequency. Moreover, the following were measured on one of the coolers: DC and AC magnetic fields at various locations, the off-state conductance of the pulse tube, and the effect on performance of inclination angle of the pulse tube relative to gravity. Finally, one of the coolers was subjected to random vibration testing.

Demonstration of a 3 Stage Pulse Tube Cooler for Space Applications [TO1-4]

T. Prouvé[1], J.M. Duval[1], I. Charles[1], S. Martin[1], C. Daniel[2]

[1] University Grenoble Alpes, CEA INAC-SBT, 38000 Grenoble, France
[2]CNES Toulouse, 3100 Toulouse, France

Highly sensitive detectors, as used for the ATHENA/X-IFU « X-rays » instrument, require cooling down to 50 mK. To achieve this in a closed cycle cooling chain, offering a long mission life, mechanical coolers are used both to cool down thermal shields and to cool down the focal plane itself. CEA has been working on 15 K pulse tube coolers based on a single stage pulse tube precooled at different interface temperature. Most notably a 2 stage 15 K pulse tube based on an intercepted stage and a 80 K single stage pulse tube has reached TRL 6 in a partnership with Air Liquide and Thales Cryogenics. In addition CEA-SBT developed a TRL 6 model of a two stage coaxial pulse tube. This project was initiated under a CNES program and recently improved under an ESA project with Thales cryogenics and Absolut System. This two stage pulse tube can provide cooling at 80 K-120 K at the first stage and 20 K–80 K at the second stage. Currently CNES and CEA are funding the test of a 3 stage 15 K pulse tube cooler based on a double intercepted stage and CEA EM double stage cooler. For the ATHENA/X-IFU instrument, which includes several cryogenic shields, a 3 stage pulse tube cooler may improve the overall cryochain design in particular in regards to redundancy aspects. In this paper we describe the X-IFU relevant experimental coupling of the two stage pulse tube with an intercepted low temperature pulse tube, making it an efficient 3-stage cooler.

Spacecraft Cryogenic Developments and Perspectives at the European Space Agency [TO1-5]

T. Tirolien, M. Linder, M. Branco

European Space Agency (ESA-ESTEC), Noordwijk, The Netherlands

The year 2009 with the successful launch of Herschel/Planck was a significant milestone for Space Cryogenics in general and the European Cryogenic community in particular: Europe – in collaboration with American partners – successfully put in orbit and operated sub-Kelvin instruments cooled by sophisticated cryochains. It was not only an engineering achievement leading to the collect of invaluable scientific data, but also the culmination of almost 20 years of space cryogenic developments in the different institutes, companies and agencies in Europe. Since this turning point, space cryogenics Research and Development/Technology has never been so dynamic in Europe. The European Space Agency has been involved in over 80 activities ranging from PhD projects to qualification of new products. New satellites appeared with more and more stringent requirements (low vibration/vibration free, increasing cooling power, lower detectors temperature etc.). This paper will describe the recent and current developments in the field of Spacecraft cryogenics at ESA as well as the driving missions in the Earth Observation and Science domains. The whole range of temperature (from 50 mK to 200 K) and technologies (coolers, heat switches, energy storage units) will be addressed. The in-orbit performances of the cryogenic sub-system for Agency recently launched satellites (e.g. Sentinel 3) and the design and verification for cryogenic instruments currently in development (e.g. Meteosat 3rd Generation, Athena) will be touched upon. Finally, the paper will lay out the current outlook in terms of missions and needs in the domain of Cryogenics for spacecrafts.

Scaling Studies on a High-Frequency, Miniature Stirling Cryocooler [TO1-6]

C.S. Kirkconnell[1], A. Ghavami[2], S.M. Ghiaasiaan[2], M.V. Zagarola[3], W. Chen[3]

[1]West Coast Solutions, Huntington Beach, CA 92648, USA
[2]George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[3]Creare LLC, Hanover, NH 03755, USA

West Coast Solutions, the Georgia Tech Cryogenics Laboratory, and Creare are developing a family of small satellite cryocooler technologies to meet the growing demand for miniaturized, yet highly capable infrared payloads on satellite buses down to as a small as 3U. Previous papers by this team have described work on an 80 K, 200 mW Stirling cryocooler operating in excess of 200 Hz to meet a mass target of 150g. This work has continued with additional thermodynamic, electromagnetic, and fluid dynamic analyses, as well as more detailed solid modeling. Recent progress is presented. In addition, a variant of the 80 K design has been undertaken to optimize for significantly higher cooling capacity (2 W) at a somewhat higher temperature (110 K). Initial results indicate that the required scale up in size and capacity may motivate the implementation of different materials and manufacturing techniques to achieve optimum performance for these two significantly different operating points. Such tailoring would obviously come at the expense of increased nonrecurring engineering development costs, so careful analysis is appropriate to quantify the performance differences between the tailored approaches versus using a common architecture. The results of this study are presented.

ErPr Coated Regenerator for 30 K Stirling Cryocoolers [TO2-1]

W. Chen[1], M. Jaeger[1], Y. Kim[2], K. Wilson[2]

[1]Creare LLC, Hanover NH 03755, USA
[2] Sunpower® Inc., Athens, OH, 45701, USA

Many next-generation spaceborne electro-optical devices and emerging terrestrial superconducting devices need to be operated near 30 K and thus require efficient cooling at this temperature range. The thermal efficiency of current single-stage regenerative cryocoolers is largely hampered by the limited low heat capacity of regenerators at this low temperature range. To overcome this limitation, Creare has developed a reliable process to deposit a layer of ErPr coating on a regenerator matrix. The coating process has features to enhance the adhesion of the coating on the substrate and uniformity on the matrix elements. This paper first presents measured heat capacity and pressure drop of coated regenerators, and compares them with results for an uncoated regenerator. Next, the paper presents the enhanced performance of Sunpower Inc. cryocoolers that have incorporated the coated regenerator elements.

Joule-Thomson Microcryocooler Test Results [TO2-2]

J. Olson[1], E. Roth[1], M. Guzinski[1], A. Ruiz[1], C. Mangun[2], D. King[2], N. Hejmanowski[2], D. Carroll[2]

[1] Advanced Technology Center, Lockheed Martin Space, Palo Alto, CA 94304, USA
[2] CU Aerospace, Champaign, IL 61820 USA

Small closed-cycle Joule-Thomson cryocoolers offer certain advantages in packaging and heat rejection when compared with Stirling and pulse tube cryocoolers. This paper describes results of performance testing of a closed-cycle Joule-Thomson (JT) microcryocooler. The JT cooler is driven by a 200 gram JT micro compressor developed by Lockheed Martin and previously presented at ICC 19. The counterflow heat exchanger was produced by CU Aerospace in Champaign, IL, and is a novel anisotropic material consisting of a woven array of counterflowing microcapillaries and copper isothermalization wires. The microcapillaries are created using a novel sacrificial fiber method and encapsulated in an epoxy matrix using CU Aerospace's VascTech™ process, details of which are presented in this paper. Testing was performed with R14 gas, and with mixtures of R14 and nitrogen, with varying fill pressure and compressor power.

A Lightweight, High-Effectiveness Recuperator for Next-Generation Airborne Cryocoolers [TO2-3]

A. Niblick, J. Cox, M. Zagarola

Creare LLC, Hanover, NH 03755, USA

Next-generation turboelectric aircraft aim to decouple power generation from propulsion by using gas turbines, driving electric generators, connected to electric propulsion motors. The power density requirements for these electric machines can only be achieved with superconductors, which in turn require lightweight, high-capacity cryocoolers. However, current cryocooler technologies offer cooling capacities that are too low and masses that are too high to meet projected aircraft needs. For turbo-Brayton cryocoolers, the recuperative heat exchanger historically has been the largest and most massive component, and offers the most potential for size and weight reduction. Improvements may be achieved through the use of smaller flow passages; orthotropic core thermal resistance, to decrease resistance between flow streams and increase resistance from warm to cold ends; and lighter-weight materials. To this end, a recuperator that implements all such improvements has been developed. The recuperator core consists of a stack of copper-polyimide plates with miniature flow features for high stream-to-stream conductance. The plates are bonded together to produce a monolithic core that achieves high heat transfer in a small and lightweight package. This new recuperator technology fills a void between high performance, lightweight recuperators for space applications, and commercial recuperators for high capacity terrestrial cryocoolers. This paper describes the design and testing of a prototype recuperator.

Development of a Cryogenic Compressor for Airborne Cryocoolers [TO2-4]

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Superconducting electronics and spectral-spatial holographic systems are being developed for advanced digital communications. These devices must operate at cryogenic temperatures of near 4 K. Liquid helium is undesirable for military missions due to logistics and scarcity, and commercial low temperature cryocoolers are unable to meet size, weight, power, and environmental requirements for many missions. Creare is developing a reverse turbo-Brayton cryocooler that provides refrigeration at 4.2 K and rejects heat at 77 K to an upper-stage cryocooler or through boil-off of liquid nitrogen. The cooling system is predicted to reduce size, weight, and input power by at least an order of magnitude as compared to the current state-of-the-art 4.2 K cryocooler, and for systems utilizing nitrogen boil-off, the boil-off rate is reasonable. The design of the cryocooler has been previously reported. This paper reviews the development of the cryo-compressor, a key cryocooler component. The cryo-compressor has heritage in the cryogenic circulator used in the space-borne NICMOS cryocooler. To produce the pressure ratios and mass flow rates required by the cryocooler, the cryo-compressor must operate at much higher operating speeds than the cryogenic circulator while still at cryogenic temperatures. This operating condition presents a challenge for stable operation of gas bearings at low viscosities. The approach to overcome this challenge and the testing of the compressor at cryogenic temperatures will be the focus of this paper.

Comprehensive Performance Simulation of Low Capacity Open-Cycle Cryocooling System Driven by Miniature Thermoacoustic Expander [TO2-5]

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In low-capacity space applications, the gaseous cryogen is stored under the high pressure above supercritical states and expanded to produce instant cooling power in responding to occasional uses. The conventional cryocoolers for occasionally cooling applications are the J-T expander open-cycle coolers (JTE-OCC) which are broadly used in the end–stage guiding systems for ballistic missiles and space killing vehicles due to its low costs, simplicity, and high reliability. This paper reports the comprehensive simulation results on a new type of open-cycle cryocooler that is driven by a miniature thermo-acoustic expander (MTAE) associated with a small high-pressure cylinder and a recuperative heat exchanger. Since the MTAE produces cooling power effectively by heat extraction from expansion in proportion to the pressure drop ratio, the design and performance prediction of MTAE open-cycle cooler (MTAE-OCC) differ from JTE-OCC that produces cooling power in proportion to pressure drop difference. The simulations of MTAE-OCC demonstrate the advantages of the feasibility of operating gas types, quickly cooling time, and efficiently cooling performance in comparison to the JTE-OCC under the same gaseous cryogen storing conditions. The dynamic performance of MTAE-OCC due to the supply pressure declination is also simulated that is compared to JTV-OCC under the identical pressure cylinder discharging rate. The comprehensive optimization of MTAE-OCC design is discussed with the specified supply pressure cylinder temperature and capacity.

Improvement of Helium 3 Circulation Compressor of Closed Cycle Dilution Refrigerator for Space [TO2-6]

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In recent years, demands for high sensitivity observation in astronomical missions are increasing. In astronomical observation, in order to achieve superior sensitivity and energy resolution, it is necessary to cool down the detector for an extremely low temperature (100 mK or less) and to reduce thermal fluctuation noise emitted from the detector itself. The purpose of this research is to improve the performance of a closed cycle dilution refrigerator for space, which is developed with the aim of cooling below 50 mK. In order to achieve the cooling power of 1 uW at 50 mK, a low suction pressure (0.4 kPa or less) and a sufficient helium 3 flow rate (50 umol/s or more) are required for helium 3 circulation compressor. However, the circulation compressor that enables low suction pressure with high flow rate has a high technical difficulty, and it is challenging to develop. This paper describes the factors which limit performance of circulation compressor and evaluated those influences by analysis and compared it with experimental results. In particular, the flow path conductance performance of suction and exhaust valves, which are suggested to greatly affect the performance of the circulation compressor, were evaluated by analysis and experiment, and the design to improve performance of the valve was also shown.

Sorption-Based Compressor Operating with a Binary Gas Mixture [TO3-1]

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The University of Twente has a long history in developing Joule-Thomson coolers that operate with sorption-based compressors for ultra-low vibration applications such as cooling of optical detectors. It is well known that the efficiency of Joule-Thomson coolers can be improved by using a gas mixture as the working fluid. However, the application of gas mixtures in sorption compressors is expected to be seriously hampered by the selective ad- and desorption of the components in the compressor, resulting in demixing of the gas. At the previous ICC we already showed through modeling and experimental verification that this is not necessarily the case once the adsorption isotherms are known. We now report on an experimental setup in which a sorption compressor is operated with a mixture of nitrogen and ethane. A major innovation in this setup is that we can measure in situ the composition of the binary mixture as it flows from the high-pressure to the low-pressure side of the compressor. Experiments were performed with three different compositions (nitrogen/ethane mass percentages of about 50/50, 33/67 and 25/75). These experiments allow us to develop a dynamic model of sorption compressors operating with gas mixtures.

A 40 K Turbo-Brayton Cryocooler for Earth Observation Applications [TO3-2]

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Several types of active cryocoolers have been developed for space and military applications in the last ten years. Performance and reliability continuously increased to follow the requirements evolution of new generations of satellite: less power consumption, more cooling capacity, increase life duration. The microvibrations exported by the cryocooler is becoming the main source of microvibrations on-board the satellite. For some applications on-board earth observation instrument, the existing Stirling or Pulse Tube cryocoolers exceed the targeted microvibration level, even if active control is used on those cryocoolers. To offer an alternative solution, Absolut System develops a 40 K turbo-Brayton cryocooler using very high speed turbomachines in order to avoid any generated perturbations bellow 1000 Hz. This development is performed in the frame of ESA Technical Research Program -4000113495/15/NL/KML. The design and expected performances for this cryocooler have been already published and this paper will present the manufacturing outcomes and preliminary performances results.

Testing of a High-Capacity 20 K Cryocooler for Spaceborne Hydrogen Storage [TO3-3]

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For future long-duration space exploration missions, cryogenic propellants will need to be stored for extended durations with minimal cryogen boil-off and loss of propellant over time. To achieve this condition, an active thermal management system with a cryocooler is required to intercept the heat load on the storage tank and maintain the cryogen at a constant pressure and temperature. Space cryocoolers have been developed for cooling sensors that have modest cooling loads and are not suitable for high capacity applications. To address this need, Creare is developing for NASA a high-capacity 20 K cryocooler. The cryocooler operates on the reverse-Brayton thermodynamic cycle and utilizes three compressors with intercooling to compress and circulate the helium cycle gas, a turboalternator to expand the gas and provide refrigeration, and high-performance recuperators to transfer heat from the high pressure gas stream to the low pressure gas stream. Creare recently built a prototype cryocooler for a ground-based demonstration. This paper focuses on the cryocooler test results.

Investigation on Sorption Compressor Thermal Efficiency [TO3-4]

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Joule-Thomson (JT) cryocoolers operating with sorption compressors do not have moving parts, therefore, they have the potential for long life and vibration-free operation. The main challenge of JT sorption cryocoolers is their relatively low thermal efficiency, which is defined as the ratio between the input heat power to the compressor (at an elevated temperature) and the heat absorbed by the cold-end (at the required cryogenic temperature). The relatively low thermal efficiency is mainly determined by a significant temperature distribution in the sorption cell and heat losses to the surroundings. In the frame of our research on JT sorption cryocoolers, we investigate different configurations for the sorption cell. Several heating and cooling techniques are investigated, mostly numerically at this stage of the research. The presented work focuses on nitrogen-activated carbon systems operating at near ambient temperatures, aiming for cryogenic cooling at about 100 K.

CryoBlue – A Low-Vibration 50 K Stirling Cryocooler [TP1-1]

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The CryoBlue team, a UK consortium including TASitUK, Honeywell Hymatic and The Rutherford Appleton Laboratory, have started the development of a low mass, low vibration 50 K Stirling Cryocooler aimed at earth observation missions and funded by the European Space Agency. The CryoBlue team draws on specific strengths, experience and capabilities of its members; RAL have expertise in space cryocooler technology and have developed and supplied a wide range of active cooling systems. Honeywell Hymatic have extensive manufacturing capabilities and an existing range of reciprocating compressors for space applications. TASitUK designed and built the low vibration drive electronics for the 4 K cooler and supported integration on the successful Planck astronomy spacecraft. In this paper we present the development status and outline the plans for manufacturing and testing of the CryoBlue Stirling CryoCooler Engineering Model.

Improvement of a Pulse Tube Cryocooler Driven by a Superconducting Linear Motor [TP1-2]

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A Stirling-type pulse tube cryocooler (PTC) with a superconducting linear motor for a compressor unit was developed and demonstrated in our previous research. The pulse tube cryocooler achieved no-load temperature of 19.2 K and cooling power of 0.26 W at 20 K. The performance of the pulse tube cryocooler, however, was lower than what was expected from the numerical analysis. Only 4% of the available expansion work was converted to the cooling effect. Analysis on the loss in the pulse tube cryocooler revealed that the thermal loss from the regenerator was one of the main reason of the performance degradation. This research paper reports the improvement process of reducing the thermal loss of the regenerator, which contains the optimization of the regenerator and the determination of the phase controller dimensions for the optimized regenerator.

Experimental Investigation on the Active Magnetic Regenerative Refrigerator with the Pulse Tube [TP1-3]

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A hybrid refrigeration system with the active magnetic regenerator (AMR) and the pulse tube is introduced and experimentally investigated. The system consists of the AMR, the pulse tube, high temperature superconducting (HTS) magnet, and the helium gas flow system. The AMR is composed of four different magnetic materials with different Curie temperatures and designed to operate the temperature range between 80 K and 20 K. The HTS magnet can apply magnetic field to the AMR maximum 3 Tesla (150 A) within 3 seconds. The pulse tube is installed to the AMR system in order to actively utilize the pressure swing for refrigeration in the system. The oscillating helium flow (and also pressure oscillation) in the system is achieved by a helium compressor and solenoid valve set. The warm ends of the pulse tube and the AMR are cooled by a commercial cryocooler. The experimental apparatus and operating conditions are described in this paper. The temperature spans of the AMR with and without magnetocaloric effect are observed and the results are also discussed.

Development of a Two-stage Oil-less Linear Compressor for 4K J-T Cryocooler [TP1-4]

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In order to obtain compact and high efficiency cryocoolers operating at liquid helium temperature, this paper presents a Joule-Thomson cycle which precooled to around 10 K by a two stage high frequency pulse tube cryocooler. Thermodynamic cycle analysis of this hybrid cryocooler system is calculated by software of EES, which is used to optimize system operating parameters and some component dimensions for acquiring high thermal efficiency. The simulation results show that a high pressure ratio and high efficiency J-T compressor is essential and an oil-less two stage linear compressor is introduced in this paper, which consists of two dual opposed linear moving magnets drive motors. A comprehensive simulation model for this linear compressor consists of valve, gap leakage flows, piston dynamics, motor loss and compression process is built in this paper to investigate the compressor performances.

Development of an Efficient High Capacity Pulse Tube Cryocooler [TP1-5]

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To meet the demands of the high capacity cryocooler used in space application, Technical Institute of Physics and Chemistry (TIPC) has successfully developed a low-cost, high-capacity pulse tube cryocooler. The cryocooler was driven by a long-life liner compressor which works with two dual-opposed pistons and has a maximum swept volume of 10cc. In this paper, the operating frequency was optimized by adjusting the inertance tubes, and the performance of the pulse tube cryocooler has been carried out over a wide range of electrical power. With the operating frequency of 44 Hz and a mean working pressure of 4.0 MPa for helium gas, the high efficiency pulse tube cryocooler has a no load temperature of about 32 K. And it has a typical cooling performance of 7.2 W at 80 K, the high performance, 19.8% of Carnot was obtained under an input electrical power of 100 W at 300 K reject temperature. The highest cooling capacity of 15 W@80 K can also be achieved when the corresponding input electrical power of 230 W is provided.

A 10 K Gas-Coupled Two-Stage Stirling-Type Pule Tube Cryocooler [TP1-6]

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A gas-coupled two-stage Stirling-type coaxial pulse tube cryocooler driven by a dual-opposed-piston configuration linear compressor was designed and manufactured with numerical simulation and experiment test. The material and filling method of the regenerator was simulated by Sage software. The mixed stainless steel screen with different meshes were adopted as the first stage of regenerator, and the Er3Ni and stainless steel screen were added as the second stage of regenerator. The influence of phase shifter of the cryocooler was simulated. The double-inlet and inertance tube together with room-temperature reservoir were adopted as phase shifter of the first stage, and inertance tube and cold reservoir were adopted as phase shifter of the second stage. Under the condition of 2.5 MPa charging pressure and 27 Hz frequency, the second stage of the cryocooler can achieve the lowest temperature of 10 K, and the temperature of the first stage is 36 K.

A High Efficiency 5 W@60 K Pulse Tube Cryocooler for Infrared Sensors [TP1-7]

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A high-capacity single-stage coaxial pulse tube cryocooler operating at around 60 K has been developed for space infrared sensors. The design considerations were presented, and with the cryocooler model of the Sage, the optimizations on the length of regenerators were described. In an experiment, the influences of regenerator length on the optimal frequency were obtained. The investigation showed that using shorter length regenerator can increase the optimal frequency of cryocooler. Besides, the reject temperature dependence on the cryocooler was showed. Up to now, the engineering model of the cryocooler has been worked out, which typically provides the cooling power of 5 W at 60 K with the 150 W electrical power rejecting at 300 K, and achieving an efficiency of 13.3% of Carnot.

Design and Experimental Study of a Two Stage Gas-Coupled Pulse Tube Cryocooler Below 20 K [TP1-8]

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With the rapid development of space application technology, the need for cold source of liquid helium, especially the need for cold source of superfluid helium is very urgent. At present, the GM refrigerator has been used widely and maturely to precool JT refrigerator. However, the GM refrigerators limit their applications in space by their big size and heavy weight. In view of this situation, it is very pressing to develop a pulse tube cryocooler which is smaller and lighter can replace the GM refrigerator and meet the demand for precooling. However, most single-stage pulse tube cryocoolers are hard to reach 20 K at present. In order to provide the precooling for JT refrigerator, a two-stage gas-coupled pulse tube cryocooler which can provide cooling capacity and has relatively simple structure, small volume and light weight in 20 K temperature zone has been designed and developed independently. Sage software has been used to simulate and optimize the size of regenerator, phasing modulation and airflow distribution ratio at all levels. Meanwhile, the experimental verification of the cryocooler has been carried out. The results show that the cryocooler has achieved the initial experimental goal when the compressor scavenging volume is less than 8cc, the input electric power is 250 W, the operating frequency is 35 Hz, the no-load temperature can reach 15 K and the cooling capacity is 0.5 W@20 K.

Design and Development of Miniature Free Piston Free Displacer Dual Opposed Stirling Cryocooler [TP2-1]

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This paper presents the design of a miniature size Free Piston Free Displacer Dual Opposed Stirling Cryocooler with Helium as a working fluid, providing cooling effect at 80 K operating under ambient conditions. The Cryocooler is designed for the applications in Infrared Imaging as the sensitivity of the IR detectors is increased when its sensor temperature is reduced to cryogenic temperature. This class of Cryocoolers has advantages over the traditional coolers in energy efficiency, environmental friendliness, long life and less vibration. The Cryocooler is driven by moving magnet linear motor to have pure reciprocating motion in one direction. Compressor and Expander are two separate units connected via a small diameter tube for minimum vibration export. The Cryocooler was modeled in Sage Software. Variation of the design parameters on the performance of the Cryocooler was studied (Mapping in Sage). Frequency, displacer spring stiffness and displacer rod diameter were chosen as optimization variables. The optimization is done to maximize heat lift with work input as a constraint. Flexure spring was designed and analyzed using Ansys. The variable features were spiral angle, number of arms and gap width for required stiffness and safe stress, so as to operate the cooler near the resonance frequency. Behavior of the moving magnet linear motor was studied using Ansys Electromagnetics. Parts of the Cryocooler were modeled using Solidworks and then fabricated. Finally, the Cryocooler was tested for cooling effect and COP.

Research on 1 kg Miniature Pulse Tube Cryocooler [TP2-2]

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With the development of space and military fields, the cryocooler needs to be smaller. In this paper, a coaxial pulse tube cryocooler has been developed, which weighs less than 1 kg. And, it's linear compressor weighs only 692 g. Through coupling calculation, the optimized linear compressor is well matched with the high frequency cold finger whose external diameter is only 10 mm. The pulse tube cryocooler has achieved minimum temperature of 54.7 K and cooling capacity of 1.24 W at 80 K with the input power of 35 W. The optimal frequency of cold finger is 118 Hz.

Small Scale Cooler - Improvements [TP2-3]

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The Rutherford Appleton Laboratory (RAL) has previously developed a small scale cooler targeted at providing low cost active cooling at 77 K for small missions. The particular focus of that initial development was to simplify and miniaturize heritage technology whilst maintaining life and reliability and reducing manufacturing costs. The production and extension of that cooler into adjacent markets by Honeywell-Hymatic was presented at the ICC19. In the current paper we present recent developments focused on improving the thermal performance of the encapsulation and improving the accommodation and integration of the cooler into typical small mission instruments. In addition an efficient miniature modular drive electronics dedicated to the cooler is described.

Design Considerations for Using ADRs with Mechanical Cryocoolers [TO4-1]

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As cryogenic facilities and instruments increasingly rely on mechanical cryocoolers for basic cooling, the ability to reach temperatures below ~3 K requires auxiliary coolers that can operate using the cryocooler as a heat sink. A number of technologies are suitable for such use, with cooling powers that are appropriate for both general purpose and specialized facilities, and temperature capabilities that extend into the deep sub-kelvin regime. These include helium-3 and -4 refrigerators, dilution refrigerators, and adiabatic demagnetization refrigerators (ADR). Except for dilution refrigerators, these are inherently single-shot coolers which impose periodic heat loads on the cryocooler heat sink. When the cryocooler has relatively low cooling power – which is especially true for spaceflight units–the heat flow from the refrigerator may need to be regulated to stay within the available cryocooler capacity. Such throttling can significantly reduce overall performance and duty cycle. For ADRs, there are many design, configuration and operational strategies that have been developed to mitigate these limitations, and these will be discussed in the paper.

Sub-Kelvin Cooling for the BICEP Array Project [TO4-2]

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In the field of astrophysics, the faint signal from distant galaxies and other dim cosmological sources at millimeter and submillimeter wavelengths require the use of high-sensitivity experiments. Cryogenics and the use of low-temperature detectors are essential to the accomplishment of the scientific objectives, allowing lower detector noise levels and improved instrument stability. Bolometric detectors are usually cooled to temperatures below 1 K, and the constraints on the instrument are stringent, whether the experiment is a space-based platform or a ground-based telescope. The latter are usually deployed in remote and harsh environments such as the South Pole, where maintenance needs to be kept minimal. CEA-SBT has acquired a strong heritage in the development of vibration-free multistage helium-sorption coolers, which can provide cooling down to 200 mK when mounted on a cold stage at temperatures ≤5 K. In this paper, we focus on the development of a three-stage cooler dedicated to the BICEP Array project led by Caltech/JPL, which aims to study the birth of the Universe and specifically the unique “B-mode” pattern imprinted by primordial gravitational waves on the polarization of the Cosmic Microwave Background. Several cryogenic receivers are being developed, each featuring one such helium-sorption cooler operated from a 4 K stage cooled by a Cryomech pulse-tube with heat lifts of ≥1.35 W at 4.2 K and ≥36 W at 45 K. The major challenge of this project is the large masses to be cooled to sub-kelvin temperatures (26 kg at 250 mK) and the resulting long cool-down time, which in this novel cooler design is kept to a minimum with the implementation of passive and active thermal links between different temperature stages. A first unit has been sized to provide 230, 70 and 2µW of net heat lifts at the maximum temperatures of 2.8 K, 340 and 250 mK, respectively, for a minimum duration of 48 hours. The unit has been manufactured, assembled and tested. Its thermal performance will be presented.

A Closed Cycle 1 K Refrigerator Precooled by a 4 K Pulse Tube Cryocoolers [TO4-3]

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We have developed a closed cycle 1 K refrigerator with features of continuous operation, low vibration and high reliability. The 1 K refrigerator is precooled by a 4 K pulse tube cryocooler, which provides ~0.5 W at 4.2 K with a power input of 4.6 kW. A vacuum pump with peak pumping speed of 35m3/h was used to circulate helium from the 1 K pot to the liquefaction loop attached to the 4 K pulse tube cryocooler. The discharged helium gas is fed into the liquefaction loop to be precooled and condensed into liquid. An adjustable JT valve between the condenser and 1 K pot provides flexibility to obtain either the minimum temperature or the maximum cooling capacity on the 1 K cooling station. It can reach a minimum temperature of ~1.4 K and provide 200 mW of cooling at 1.65 K. The system design, optimization and performance is presented in this paper.

Compact 1.7 K Cryocooler for Superconducting Detectors [TO4-4]

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State of the art cryogenic detector systems operating at temperatures ranging from 10 K down to 50 mK are being implemented at numerous research facilities worldwide. Implementation has been greatly facilitated by the availability of closed-cycle refrigeration. However, in many cases, capacities of available refrigeration system greatly exceed cooling requirements by orders of magnitude. Thus, the availability of more compact and lower power consumption systems should facilitate further user acceptance. Toward this end, we are developing a compact 1.7 K closed-cycle pulse tube/Joule Thomson hybrid cryocooler targeting Superconducting Nanowire Single Photon detectors. A laboratory prototype consisting of the pulse tube cooler and the Joule-Thomson coldhead has demonstrated over 1mW of cooling at 1.7 K. The JT compressor is under development and remains the single largest risk item both in terms of reliability and contamination generation. The system, designed with manufacturing costs acceptable to commercialization as an objective, is projected to consume less than 300 W total wall power, be air cooled, and be mountable within a standard equipment rack.

Development of a Brassboard Active Magnetic Regenerative Refrigeration System For Low Temperature Remote Cooling [TO4-5]

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This paper reports on the development of an Active Magnetic Regenerative Refrigeration (AMRR) system for space applications. The AMRR can continuously provide remote/distributed cooling at temperatures in the range of 2 K with a heat sink above 11 K. The warm-end temperature is currently limited by the operating temperature of its superconducting magnets. The key enabling technologies for the AMRR include (1) a reversible circulator to circulate helium bi-directionally through magnetic regenerators; (2) two highly effective active magnetic regenerators with a structured matrix to enable the AMRR to achieve high thermal efficiency; and (3) advanced low-current, lightweight superconducting magnets that produce a gradient magnetic field with an optimum time-varying spatial distribution to enable the AMRR system to achieve high thermal efficiency. This paper first discusses the overall system design considerations and the optimization of key system design parameters. It then discusses the design and fabrication challenges for the key components. Next, it describes a brassboard test apparatus to assess the performance of a proof-of-concept AMRR and presents the preliminary test results. Finally, the paper discusses future research directions to further advance the AMRR technology.

Zero Boil-Off System Trades Applied to Nuclear Thermal Propulsion [WO5-1]

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A NASA team at GRC and MSFC are studying cryogenic thermal storage using zero boil-off technology applied to liquid hydrogen propellant tank of a Nuclear Thermal Propulsion vehicle. To achieve zero boil-off, efficient cryocoolers and high performing insulation is required. These designs have been studied previously; however, this iteration updates the modeling tool and includes more encompassing concept design, including a thermal/structural optimization of the vehicle itself and details on the configuration of the structural and fluid elements. A direct calculation of the heat removal of an upper stage, at 90 K, is presented, an improvement over the interpolation used in previous analyses. More detailed MLI analysis is used. A coupling of the broad area cooling pressure loss with the cryocooler cycle is accomplished. The trades presented optimizes the number of MLI layers, the number and size of the cooling loops on the tank and shield, a variation of the hot side temperature, and shows the system size with single and dual stage cryocooling.

Ball Low Vibration Cryocooler Assemblies (CCAs) [WO5-2]

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This paper describes the design, development, testing and performance at Ball Aerospace of a series of Low Vibe CCAs or Cryocooler Assemblies. These CCAs attenuate cooler vibration or EFT (Exported Force and Torque) by several orders of magnitude. They are also modular, stand alone and provide structural support as well as thermal heat rejection, They have been used to isolate both space cryocoolers (NGAS and Ball units) and tactical cryocoolers (Sunpower) for both space and airborne applications. To date, 7 CCAs have been built and tested and another 5 are in build. The CCAs provide passive isolation in all 6 degrees of freedom. The basic principal of operation is a low frequency isolation platform. However, many of the key and challenging aspects of the system are to minimize the transmission and impact of the parallel peripheral paths around the platform including cables, thermal links, insulation, and heat rejection. For these parallel paths, we have developed unique solutions that reduce the impact to the platform to negligible levels and reduce the parallel EFT transmission to levels below those transmitted by the base platform. The resulting CCA performance attenuates EFT peaks to less than 20 mN and 20 mN-m in any axis or harmonic and over a range of cooler operating frequencies. Additionally, we have developed several sizes of testbeds to verify and characterize the Low Vibe CCAs and the payloads that they are part of. These testbeds have resolution levels in the mN or less range and span the test article range from 5 lbs. coolers to 400 lbs. instruments. These CCAs have been developed in cooperation with the cooler teammates Ball, NGAS (Northrup Grumman Aerospace Systems), and Sunpower, the thermal link teammate SDL (Space Dynamics Lab), and the soft mount isolator teammate CSA/Moog.

Low Temperature Characterization of Mechanical Isolators for Cryocoolers [WO5-3]

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For spacecraft applications requiring active refrigeration, exported vibrations from a cryocooler can be a concern. One approach to minimizing the vibrations transmitted from cryocoolers to the spacecraft is to mount them on mechanical isolators. Many commercial off-the-shelf (COTS) mechanical isolators exist and have been characterized at room temperature for ground applications. However, the space environment presents challenges that complicate the selection process. Mechanical isolators in space must be made of materials that can withstand harsh radiation environments. Future instruments, such as the Mapping Imaging Spectrometer for Europa (MISE) on the planned Europa Clipper mission, are considering operating cryocoolers with low heat rejection temperatures and mounting them on mechanical isolators. However, the performance of many simple, traditional mechanical isolators at low temperatures is unknown. This paper describes the testing and results of various mechanical isolators able to withstand harsh radiation between 200 K and 300 K. The transmissibility of wire rope type isolators showed very little temperature dependence up to ~500 Hz. On the other hand, the transmissibility of silicone gel and fluorosilicone rubber isolators was strongly dependent on temperature as the materials had an abrupt change in stiffness near their glass transition temperatures.

The Importance of the Connection Between a Cryogenic Cooler and its Load [WO5-4]

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Coolers are used to cool and cool-down devices of all kinds. These can be anything from small electronic devices to large devices such as superconducting magnets. How the coolers are connected to the load is dependent on a number of factors that include the following; 1) the distance from the cooler cold head to the load, 2) the maximum allowable temperature drop between the load and the cooler cold head, 3) the required operating orientation of the cooler, 4) the need for a flexible connection, 5) vibration, 6) packaging issues, and 7) the required reliable operating time for the device. The two general types of connection between a cooler and the loads are; thermal conduction through a strap from the load to the cooler and a connection via fluid flow between the cooler and the load as in using a heat pipe or a thermal-siphon cooling loop. In general, small, devices are thermally connected directly to a cooler cold head. Large devices such as large superconducting magnets that generate stray magnetic field can be cooled and cooled-down using some form of cooling loop. This paper discusses both types of thermal connections in devices that are not intended for military or space applications.

Manufacturing and Testing of a Flight Like Cryostat for 30-50 K Two-Stage Pulse Tube Cooler Integration [WO5-5]

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The consortium constituted by Thales Cryogenics BV, CEA-SBTand Absolut System, developed in the frame of an ESA Technical Research Program (TRP - 4000109933/14/NL/RA), a Flight Like Cryostat integrating a 2-stages 30-50 K Pulse tube cryocooler. One of the objective of this project was to develop the key technologies like the 2-stages cryocooler or the Equipped cryostat components but also to demonstrate by test that such a configuration is a very good alternative to conventional Earth observation instrument using single stage cryocooler. Furthermore, the use of a 2-stage cryocooler in a dedicated 2-stage cryostat offers the possibility to operate the detectors at a lower temperature which is interesting for QWIP or MCT infrared detectors operation in the 40 K–45 K temperature range for an overall input power similar to the one required in current Earth Observation Infrared instruments. This paper will presents the final cryostat architecture, the manufacturing and elementary test performed on the different components (thermal links, supporting structure, cryocooler…) and the End-to-End tests performed on the Equipped cryostat. Finally the performances measured on our 2-stage cryostat will be confronted with conventional cryostat architecture to conclude on the interest of the proposed configuration.

Influence of Periodic Motions on the Performance of Stirling Pulse Tube Cryocooler [WO5-6]

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Cryocoolers can experience near-periodic heaving or side-to-side motion and acceleration in some applications, in particular on moving platforms. In this work, the effect of heaving and side-to-side movement on a Stirling pulse tube cryocooler was experimentally studied. Periodic heaving and swaying motions having various amplitudes and frequencies were imposed on the test section using a motion platform. The effects of the motions on the cooling performance of the Stirling pulse tube cryocooler was measured and analyzed. Reduction of cooling power were observed as a result of large acceleration and low frequency. The results also indicated that the cryocooler is more sensitive to swaying motions than heaving motions.

Influence of Reservoir Pressure Fluctuation on the Phase Shift of Pulse Tube Cryocooler [WP3-1]

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Pulse tube cryocoolers are used extensively in aerospace applications, environment studies, transportations and medical applications. It has the advantages of very low vibration and long life. This makes pulse tube cryocooler a better alternative to traditional small cryocoolers. Their disadvantages includes geometrical restrictions like orientation of cold tip and large reservoirs. The reduction of the size of reservoir was done by introducing additional phase shifting mechanisms like active phase shifting, work recovery displacer etc. This paper suggests the introduction of a reverse fluctuation in reservoir instead of a steady pressure to bring about the desired phase shift between the pressure and the mass flow rate in the cold heat exchanger. In order to introduce a reverse fluctuation in reservoir volume, compressor back volume of the hermetically sealed linear compressor is selected as the modified reservoir, which could replace the large reservoir of the coaxial Pulse tube cryocooler, and hence the cryocooler is simplified and compact in size. To ascertain the same, simulation and experimentation were done. The results suggests that the total reservoir volume can be reduced by at least 50% by making use of the compressor backspace volume and the pressure fluctuation within.

Analysis and Experimental Research on Tube-in-tube Heat Exchanger of a Space 4 K Hybrid JT Cryocooler [WP3-2]

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In view of its flexibility and relatively higher efficiency, hybrid JT cryocooler is widely used in space detectors working at 4 K. Tube-in-tube heat exchanger is commonly used in space 4 K hybrid JT coolers. The efficiency of the counter flow heat exchangers is one of the decisive factors which affect the performance of the hybrid JT cooler. Two different ways of the helium gas arrangement is analyzed when both of their efficiency is assumed to be 0.97. High pressure flowing in the inner tube and low pressure flowing in the outer side is compared with low pressure gas flowing in the inner tube and high pressure flowing in outer side. Besides, the influence of the size, such as length and diameter, of the heat exchanger is also discussed in detail. Then, experimental research is carried out.

Investigation of Inertance Phase Shifting Characteristics in Small Scale Pulse Tube Cryocooler [WP3-3]

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Phase shifting characteristics of inertance tube in small scale pulse tube cryocooler are investigated experimentally. It was found that the length of inertance tube whose diameter is 1mm has a more significant influence on the optimal frequency of the pulse tube cryocooler than the inertance tube with diameter 3mm. The performances of the pulse tube at the each optimal frequency are not great difference whatever the length of inertance tubes with 1mm diameter and 3 mm diameter are changed. Compressor behaviors dynamic behaviors influenced by inertance tube were investigated too. It was found that in the case of that the best performance of the cryocooler occurs dynamic behavior of compressor responds more intensely to the variety lengths of inertance tube.

Experimental Investigation of Mixture Optimization for Mixed Gas Joule-Thomson Cycle [WP4-1]

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This study expands on prior research by experimentally validating and refining a computational tool developed to optimize the gas mixture composition for a Joule-Thomson (JT) cycle with specific operating parameters. The mixture optimization model determines an optimal three-component mixture based on the analysis of the maximum value of the minimum isothermal enthalpy change, ΔhT, that occurs over a temperature range coupled with an evaluation of the percent of the heat exchanger that exists in a two-phase range. An initial prototype of the JT cryocooler was constructed and installed in a test facility capable of providing a range of gas composition, mass flow rate, and pressures. The prototype has been designed to enable easy access to the JT expansion orifice and to minimize the parasitic heat load due to conduction. The JT cryocooler has been operated while charged with several gas mixtures over a range of operating pressures. The mass flow rate, temperature at the outlet of the JT valve, and cooling load were compared to the expected values based on the mixture optimization model. Results were used to refine the model, particularly the heat exchanger performance, and gain confidence in its ability to steer future experimental iterations.

Closed Cycle Cryocoolers in Dry Cooling [WP4-2]

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Closed Cycle Cryocoolers are increasingly considered for application areas such as MRIs. Advantages arising due to drycooling cooling when compared with Liquid helium cooling have raised its possible use in cooling of MRI magnets. No quench is the other advantages that may be commonly encountered with Liquid helium based cooling. Possible downtime arising due to quench driven considerations has raised dry cooling as a better choice for MRI magnet cooling. And when the magnet is superconducting cryogenic temperature for operations is rarely disputed. Unlike liquid helium based cooling, closed cycle cryocooler based cooling requires some sort of conduction medium to transfer the heat to the cryocooler head(s). At the present state of art in the field of superconductivity, high temperature superconducting links have emerged as a possible choice to transfer the heat to the cryocooler head. Moreover instances of closed cycle cryocooler performance degradation can also be found and therefore possible remedial measures are warranted. Performance degradation sources could be magnetic fields that may affect motor of cryocooler and thus need to be suitable placed at distance and/or shielded with cost-benefit considerations. The paper examines the various aspects of closed cycle cryocooler based cooling for various applications, in particular MRI magnet systems where fields as high as 9Tesla, more or less are reported in applications.

A Gifford-McMahon Cryocooler Below 2 K with Helium 4 [WP4-3]

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Superconducting single photon detectors (SSPDs), which are under development at the National Institute of Information and Communications Technology in Japan, feature a high count rate, high detection efficiency, low noise (low dark count rate) and short jitter time compared with the existing avalanche photodiode (APD). Since 2012, a new, compact Gifford-McMahon (GM) cryocooler for cooling SSPD has been developed by Sumitomo Heavy Industries, Ltd. (SHI). The total height of the expander was reduced by 33% compared to a commercially-available RDK-101 GM expander and the total volume of the compressor was reduced by 50% compared with the existing CNA-11 compressor unit. In 2016, Hiratsuka et al. reported that an oil-free compressor was developed for a 2 K GM cryocooler. The cooling performance of a 2 K GM expander driven by an experimental unit of the linear compressor was measured. No-load temperature less than 2.1 K and the cooling capacity of 20 mW at 2.3 K were successfully achieved with an electric input power of only 1.1 kW. In principle, the performance of an SSPD improves as the cooling temperature decreases. Therefore, we studied the feasibility to achieve a temperature below 2 K with helium 4 by a numerical calculation and experimentally confirmed it using a commercially-available RDK-101 GM expander.

Progress on a Cryogen-Free Vuilleumier Type Pulse Tube Cryocooler Operating below 10 K [WP4-4]

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This paper mainly presents the latest experimental results on a cryogen-free Vuilleumier(VM) type pulse tube cryocooler (PTC), which is a new type of cryocooler driven by thermal compressor. Stirling type pre-coolers instead of liquid nitrogen are used to provide the required cooling power for the thermal compressor, which offers the flexibility of changing working temperature range of the thermal compressor. Compared with previous configuration, the thermal compressor was improved with a higher output pressure ratio. Utilizing the temperature difference between room temperature and cold end temperature of 72.6 K, pressure wave with a pressure ratio of 1.25 is generated. Lead and HoCu2 spheres having diameter around 0.2 mm are packed with the low temperature stage regenerator, and porosity are 0.4 and 0.36, respectively. With the optimal valve opening of orifice and double-inlet, a lowest no-load temperature of 6.31 K was achieved at an average pressure of 1.89 MPa, a frequency of 2.5 Hz and displacer displacement amplitude of 6 mm. In addition, the influences of different parameters such as average pressure, working frequency and displacer displacement amplitude on the lowest no-load temperature are were investigated.

A Looped Thermoacoustically-Driven Cooling System for Natural Gas Liquefaction [WP4-5]

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This research introduces a looped thermoacoustically-driven cryocooler which is used for natural gas liquefaction. Three heat thermoacoustic heat engines (THE) and one pulse tube cryocooler (PTC) are serially connected by resonance tubes in a loop. Parts of natural gas could be burnt to heat THE while PTC could be used to liquefy the rest of gas. In this configuration, acoustic power is cascade amplified for three times before consumed by PTC. By using different-diameter resonance tubes, better acoustic fields are achieved, thereby significantly improving the overall performance. With identical heating temperature of 873 K, the overall system achieved highest cooling power of 670 W and relative Carnot efficiency of 8.3 % at cooling temperature of 130 K. With identical heating temperature of 723 K, the overall system achieved cooling power of 620 W and relative Carnot efficiency of 9.9 %. This is the highest efficiency among the similar thermoacoustically-driven cooling system. With variable heating temperature of 673 K, 773 K and 873 K, the overall system achieved cooling power of 607 W and relative Carnot efficiency of 9.6 % at cooling temperature of 150 K.

Numerical Simulation and Experimental Study of Two-Stage Free Piston Stirling Cryocooler for a Large Cooling Power at 20 K [WP4-6]

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In order to expand the application range of Stirling cryocooler, this paper introduces the study of a two-stage Stirling cryocooler which has been modified over an existing system. Numerical simulation and experimental study have been performed. The two-stage Stirling cryocooler is driven by a moving magnet linear compressor and uses absorbing frame to reduce the vibrations transmitting to the ground. In order to achieve a better system efficiency and a larger cooling power than previous study, we used Sage software to optimize system operating parameters and some component dimensions. Furthermore, the second regenerator is filled with lead sphere instead of stainless steel meshes. Through optimization, we obtained better simulation results. It can provide a cooling power of 60.4 W at 20 K with an operating frequency of 37.5 Hz and 3364 W input acoustic power, and the relative Carnot efficiency of cryocooler is 25.06%. The cryocooler reaches a lowest no-load cold-head temperature of 12 K with an input acoustic power of 3480 W. Distributions of acoustic fields, including acoustic power, pressure wave, volume flow rate and their phase differences are presented. The dependence of system performance on frequency, average pressure and displacer damping coefficient are also investigated. Some experimental results will also be introduced with the comparison with simulation results.

Influence of Gas Contamination on a Stirling Cryocooler for HTS Applications [WP4-7]

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Today, the performance of high temperature superconducting (HTS) wire is improved and practical use of HTS devices is expected. To spread HTS technologies, it is essential to improve the performance of a cryocooler. More compact, efficient and reliable cryocoolers are required for the commercial use of HTS devices. Stirling cryocooler is one of the reasonable selections for an HTS cooling system owing to its high reliability and high efficiency in the liquid nitrogen temperature region. Recently, Sumitomo Heavy Industries, Ltd. (SHI) has been developing high-efficiency Stirling cryocoolers for HTS applications. A prototype unit was developed and a cooling capacity of 151 W at 70 K was achieved with an electric input power of 2150 W, corresponding COP of 0.07, and cooling water temperature of 30°C. Also, the vibration characteristics and the influence of external temperature on cooling performance was investigated, and the results were report in previous conferences. For some applications, cryocooler will be continuously operated for several years without maintenance. Therefore, the cryocooler is required to maintain its cooling capacity over thousands of hours. To confirm the cryocooler performance and reliability, a long-term operation test was conducted and the influence of gas contamination was investigated. The results will be reported.

Jet-Induced Phase Errors in Pulse-Tube-Refrigerator Compliance Pressure [WO6-1]

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In a high-frequency or large orifice pulse-tube refrigerator at full power, misleading pressure measurements can arise if the inertance points directly at the pressure sensor in the compliance, because of the time-dependent stagnation pressure of the pulsatile jet that is emitted from the end of the inertance during half of the oscillation. The effect appears most strongly in the pressure's phase, which could lead to an incorrect understanding of the phase of the volume flow rate into the compliance, and thence to an incorrect understanding of the phase of the volume flow rate throughout the refrigerator. The erroneous measured phase usually leads the true phase, although the opposite sign can occur when the transit time for vortex-ring propagation from the end of the inertance to the sensor is comparable to the oscillation period. Experiments confirm a simple, approximate estimate of the severity of this effect. The error in the phase of the pressure can be a few degrees for circumstances encountered in real refrigerators. Harmonic content in the pressure is a useful indicator of this problem. Avoiding the problem by locating the sensor away from the jet is recommended.

Effect of Reject Temperature on a 4 W/60 K Pulse Tube Cryocooler for Space Application [WO6-2]

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Spaceborne pulse tube cryocooler (PTC) is widely used for providing low-temperature for sensitive infrared, which orbits the Earth at a nominal altitude of thousands or even tens of thousands of kilometers. Thus, the ambient temperature of the PTC could drop down to less than - 60℃, which is a big difference from the reject temperature of 23℃ on the earth. The cooling performance of PTC is greatly affected by the reject temperature. In order to study the effect of reject temperature on the performance of a 4 W/60 K PTC for cooling a long-wave infrared detector, theoretical and experimental researches have been carried out. The reject temperature of the PTC is changed from -80℃ to 60℃, and its impedance characteristics, phase shifts, system losses and cooling performance are analyzed by changing the length of the inertance tube. Finally, the impacts of reject temperature are investigated in detail and the effective method is found out to optimize the cooling performance at low reject temperature on-orbit. The research results have a good effect on enhancing the applicability of the PTC in space application. Keywords: pulse tube cryocooler; 4 W@60 K; Reject temperature; Space application.

Integration of Multiple Cryocoolers for Efficient and Versatile Shipboard Superconducting Power Systems [WO6-3]

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Future all-electric ships and aircrafts is expected to have multiple large electric loads. Also, it is necessary to reduce the size of the ships to increase the fuel economy. High Temperature Superconducting (HTS) power systems are being considered for achieving the efficiency and versatility of shipboard power systems. Providing the required cryogenic environment for multiple HTS systems is a challenge. Integration of multiple superconducting systems with a large centralized cryogenic systems offer some advantages. Detailed models of potential configurations of integrated cryogenic systems are necessary to assess the system level implications and the relative pros and cons. Thermal network models with coupled electrical and cryogenic thermal behavior of the superconducting devices and the associated cryogenic systems have been developed to conduct parametric studies of integrated shipboard HTS systems. The models also study the benefits of cryogenic thermal storage to enhance the residency of the HTS systems. This paper presents the development of a fast tool based on thermal network model for superconducting devices. Several case studies have been conducted to find the optimal configurations. The response of the system for contingencies such as a cryocooler failure are also being considered. Using the developed models, design features that would enhance the stability of individual HTS power devices and the complete power system are being explored. The benefit of adding solid nitrogen as cryogenic thermal storage/buffer is being studied. This paper presents the modeling methodology, challenges encountered, solutions devised, and the case studies of several cryogenic system configurations are presented. The work is funded by the Office of Naval Research.

High Efficiency 35 K Single-Stage Inertance Pulse Tube Cryocooler for a Space Infrared Detector [WO6-4]

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The space infrared detectors have put forward the requirements for pulse tube cryocooler(PTC) to obtain the 35 K or lower temperature. Low cooling efficiency of the single-stage PTC makes it difficult for providing required cooling capacity at 35 K, especially for the PTC only with inertance tube and reservoir as the phase shifter. The impedance matching model is built to optimize the performance of the PTC from both cold finger and compressor. Based on the thermoacoustic theory, a 1-D simulation model of the 35 K PTC is built by using DeltaEC software for optimizing the coupling working parameters of the cold finger and compressor. The effects of the regenerator material, the inertance tube and the reservoir on the impedance of the cold finger are investigated theoretically. The test system is set up and the results show that the lowest temperature of 24.1 K, a 30 W increasing of the maximum input power of the compressor, the cooling power of 2 W at 35 K with electric power of 240 W can be obtained, which satisfy the applications of the space infrared detectors.

The Influence of Seal Clearance on the Performance of Stirling Cooler [WO6-5]

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It is an important factor of the resonance between the compressive piston and displacer that influence the performance of stirling cooler. Moreover, the seal clearance between the displacer and expansive shell influences the resonance characteristic of displacer. There may be contact and friction between the displacer and cylinder because of their slight seal clearance. It could influence the dynamic characteristic of displacer and the performance of the cooler. In the paper, the assembling state of displacer and cylinder was investigated. The impacts of parameters (for example, the friction coefficient and the seal clearance) on the performance of stirling cooler were analyzed. The results can help to improve the performance, lifetime and reliability of split stirling cooler.

Reduced Size Cryocooler Electronics for Space Applications [WO7-1]

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The explosion in SmallSat and CubeSat deployments has led to a need for miniaturized cooling solutions for sensors that require cooling. Since there are limited opportunities for miniaturization in the thermal mechanical unit (TMU) portion of the cryocooling system, much of the pressure to reduce size falls on the cryocooler control electronics (CCE). In the world of digital electronics, continuous size reduction is the expected norm, however, in the world of power electronics this is not the case. The number of components and their variety is greatly limited when selecting space grade electronics, typically resulting in designs that make space grade electronic solutions much larger than an equivalent circuit made of commercial grade electronics. One way to reduce the size of the power components is to switch at a higher speed.

The current generation CCE devices built by Iris Technology utilize MOSFET power transistors to perform power conversion. The characteristics of the power MOSFETs limit the switch rate to something on the order of 100 kHz, thus driving the energy storage requirements of the capacitors and inductors. If we could switch faster we reduce the required energy storage and thus the size of the inductors and capacitors. One solution to the switching frequency problem is the use of Gallium Nitride (GaN) FETs which can be switched on the order of 1 MHz. GaN FETs are inherently radiation tolerant, however recently GaN FETs have become available with space grade packaging. The space grade packaging is available with an integral radiation hardened high/low side driver. This integrated part provides further size reduction to the electronics design. Recently, high performance space grade microcontrollers have become available. These parts offer another integration opportunity, as the FPGA and ADC functions can be combined into a single smaller chip. Space grade GaN FETs when combined with the space grade microcontrollers provide an opportunity for significant reduction in the volume required for the CCE portion of a cryocooler system.

Recent Improvements in Cooler Drive Electronics [WO7-2]

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Stirling cycle Cryocoolers have been widely used in various IR electro-optical systems. In these systems, the performance of the IR dedector is highly proportional to the performance of the whole cryocooler performance. In the current generation IR EO systems, the miniature size, temperature based high precision stability, accuracy, low noise performance and high efficiency of the cryocooler drive electronics are all important criteria determining the overall system performance. This paper intends to describe the features and recent design technics used in cooler drive electronics. Electronic board and software development processes are to be given in detail. Crycooler Driver is tested on the off the shelf Stirling cycle linear and rotary products such as; Thales RM4, Thales RM2, Thales UP 7097, Ricor K563, IMTEK R500M, IMTEK R250M, IMTEK L600M, IMTEK L1500M.

The Influence of Flow Condition on Pulse Tube Off-Axis Losses [WO8-1]

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Pulse tube convection number has been used to estimate pulse tube off-axis losses. However, there is considerable inconsistency and scatter in the data when the pulse tube convection number alone is used as the correlating parameter. A review of the available data indicates that turbulence may occur in some experiments. In this work, experiments were conducted to investigate the effect of flow conditions, in particular the flow regime in the pulse tube, on pulse tube off-axis losses. A commercial Stirling-type pulse tube cryocooler prototype was tested at various cold-end temperatures, mass flow rates and off-axis angles to create desired flow conditions and pulse tube convection number. Cooling losses at different flow conditions but similar pulse tube convection numbers were compared. The result indicates that the flow regime in pulse tube should be considered when using pulse tube convection number to estimate off-axis cooling losses.

Performances Improvement of the 15 K Pulse Tube Cooler [WO8-2]

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A 15 K Pulse Tube cooler engineering model has been developed by Air Liquide, Thales Cryogenics BV and CEA through an ESA program. It has now reached TRL6 and provides more than 400 mW of cooling power at 15 K with 3 W at 90 K on the first stage. It has been integrated as part as a 300 K-50 mK cryochain demonstrator for ATHENA-XIFU and is also baseline on the Athena/X-IFU dewar where the cryogenic constraint are important. An improvement of the 15 K pulse tube performance would drastically improve the performances of the cryochain and possibly reduces its complexity. In the framework of a new ESA program, CEA-SBT jointly with Air Liquide and Thales Cryogenics is working on the maturity of the 15 K pulse tube cooler where one of the objectives is to increase the cooling power from the previous version. This paper will focus on the work done at CEA-SBT on the 15 K cold finger.

Investigation on the Radial Heat Transfer on a Gas-Coupled Two-Stage Pulse Tube Cooler with a Completely Co-axial Configuration [WO8-3]

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Co-axial pulse tube coolers are more and more popular for practical applications, however the radial heat transfer caused by the temperature mismatch can affect the system performance. For a gas-coupled two stage pulse tube cooler with a completely co-axial configuration, the radial heat transfer exists not only between the pulse tube and regenerator but also between the 1st stage pulse tube and the 2nd stage pule tube. In this paper, models with and without radial thermal contact have been constructed to analyze the mechanism theoretically and experimentally. Without radial thermal contact, temperature distributions of the pulse tubes are strongly non-linear, especially the 2nd stage pulse tube due to the large temperature span. The pulse tubes can be cooled down through the radial heat transfer, and thus the expansion efficiency of the pulse tubes are improved. Therefore, a well-matched geometrical arrangement of the co-axial configuration is essential for achieving the optimal performance. Experiments are then carried out. A completely co-axial two stage pulse tube cooler is set up. After eliminating the radial heat transfer between the 1st stage pulse tube and 2nd stage pulse tube warm section, the cooling power at 20 K decreases by 0.36 W (1.06W vs. 0.7 W) under the same conditions. These studies indicate that a proper radial heat transfer can be useful for improving the cooling performance through careful design in a co-axial structure.

Sunpower DS 30 Crycooler Development [WO8-4]

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High efficiency, small size, low mass, and long lifetime are the hallmarks of Sunpower free-piston Stirling technology. The existing line of Sunpower cryocoolers provide cooling capacity from 1.5 W to 15 W at 77 K. This paper will highlight the development and upcoming release of Sunpower's newest cryocooler, the DS 30. Building upon the solid foundation of Sunpower's gas bearing technology packaged in both integral and split-configuration cryocoolers, the DS 30 leverages the existing "back end" of the GT integral cryocooler, yet the DS 30 utilizes a dual-opposed piston configuration to create a balanced wave generator with a nominal input power of 480 W. A newly designed, split cold head offers 30 W of nominal cooling at 77 K with room temperature cooling fluid. The strategy of the product development was to maximize the use of existing components and subassemblies from the GT cryocooler in order to minimize new components design and development. This paper will review the development history and provide the current status of the product development along with information regarding product release. Data regarding mass, size, and actual cooling performance of a variety of spit configurations will be provided.

Study of a Free Piston Stirling Cryocooler with a Step Displacer [WO8-5]

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A free piston Stirling cryocooler with a step displacer is proposed and studied in this work. Compared with the general configuration, the step displacer has advantages of low mechanical stiffness, high reliability and stability due to the introduction of gas spring. However, the side effect of acoustic power dissipation associated with the clearance sealing intensifies, let alone the undesired interaction between the gas spring and the expansion space or that between the gas spring and the compression space. In order to systematically quantify the interaction and loss, a numerical model based on thermoacoustic theory is developed. The impact of the magnitude of the gas spring and the dimension of the clearance seals is carefully investigated. The results reveal that after optimization, a comparative performance of the cryocooler could be achieved with the step displacer and the pertinent loss could be minimized by applying rigorous sealing such as labyrinth configuration.

Performance Optimisation of a Stirling Pulse Tube Cryocooler with an Active Displacer [WO8-6]

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An in-line pulse tube cryocooler with an active displacer has been built and tested. An active displacer allows the mass flow and the pressure pulse at the cold end of the pulse tube to be easily adjusted for optimum performance. The effect of varying the active displacer phase and stroke on cryocooler performance was examined experimentally. It is demonstrated that both cooling power and relative Carnot efficiency have optimum displacer phase and stroke values. The pulse tube cryocooler can deliver up to 3.6 W of cooling at 80 K with an input power of 100 W (shaft power of 79 W) when operating at optimal displacer phase and stroke. Moreover, a numerical Sage model was used to assess how this variation in displacer phase and stroke affects the mass flow and pressure pulse at the cold end. It is shown that the variation in displacer phase affects the cryocooler performance by varying the amplitude of the mass flow at the cold end. This is because the back space of the displacer is connected to the warm end of the regenerator. On the other hand, changes to the displacer stroke lead to variations in both phase and amplitude of the mass flow at the cold end.

Design of a 30 K Single-Stage Free-Piston Stirling Cryocooler [WO8-7]

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Free-piston Stirling cryocooler (FPSC) is promising in cooling down electronic and high temperature superconducting (HTS) devices. Currently, most of the FPSCs work around 77 K due to high thermal efficiency and compact size. Most recently, a two-stage FPSC aiming at providing tens of watt cooling power at 30 K has been designed and tested by our group and the preliminary results showed positive prospect. In order to maintain the advantage of simplicity, in this work a single-stage FPSC working at 30 K is proposed on the basis of a single-stage FPSC which could efficiently supply a cooling power of 350 W at 80 K. This paper systematically studies the key parameters' sensitivity effect on the no-load temperature. The performance dependences on the regenerator and the phase shifter are analyzed in detail. The results reveal that a variable diameter regenerator and a hybrid phase shifter are conducive to achieving a competing efficiency compared with that of a two-stage FPSC.

A Large Single GM Cryocooler for Operating Temperatures of 10-30 K [THO9-1]

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Applications of cooling high temperature superconductors and liquefying hydrogen require large cooling capacities between 20 and 30 K. We are developing a large, single stage, low temperature GM cryocooler for these applications. The GM cryocooler has been designed and experimentally optimized in respect to structure and operating parameters. The performance of the regenerator with different spherical regenerative materials, such as Sn, Pb and Er3Ni, at the low temperature region have been investigated. So far, the single stage GM cryocooler (Model AL630) can reach a minimum temperature of ~10 K, and provide 100 W of cooling at 20 K and 200 W of cooling at 30 K while consuming ~13 kW of electrical power. A hydrogen liquefaction system based on the AL630 will be developed soon.

Investigation on a Precooled 4 K Stirling Type Pulse Tube Cryocooler [THO9-2]

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Stirling type pulse tube cryocoolers (SPTCs) working at liquid helium temperatures are appealing in space. However, it is still challenging for a SPTC to operate at 4.2 K with 4He as working fluid. In order to investigate the working mechanism of such SPTCs, we have designed and fabricated a SPTC precooled by a 2-stage GM cryocooler. The SPTC is of in-line configuration, so as to decrease losses. The SPTC is designed to operate at a mean pressure of 1.2 MPa and at a frequency of 25 Hz. The precooling temperature is about 20 K. Our model shows that it is able to achieve a no-load temperature of 3.8 K. The preliminary test reaches a no-load temperature of 4.0 K and a refrigeration power of 20 mK@4.5 K. The experiment on investigating the working parameters will be carried out recently, and the results will be reported in the conference.

Large Scale Cryocoolers for Industrial Applications [THO9-3]

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AFCryo is a joint venture company between Fabrum Solutions, of New Zealand, and Absolut System, of France specializing in the development and delivery of cryogenic equipments utilizing patented membrane cryocooler technology. A commercial product range has been developed these last 5 years using an innovative concept of metallic membrane Pressure Wave Generator patented by Callaghan Innovation coupled with high reliability Pulse Tube cold heads. This paper presents the latest performances of the commercial products developed by AFCryo with some examples of on-going applications used in industrial gases, liquid air, medical and HTS. In addition, the other products currently under development will be presented with their targeted performances.

Discussion on Interstage Heat Exchangers in a Cascading Pulse Tube Cooler [THO9-4]

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To extend the pulse tube technology to high cooling temperature for its no moving part at the cold head and potentially highly reliability, a cascading pulse tube cooler (CPTC), which drove by a linear compressor, and lots of pulse tube coolers connected through transmission lines one by one, has been proposed. Although there are lots of cold heads of pulse tubes, the cooling capacity of this new concept CPTC is only obtained at the same cold temperature under room temperature condition. This is quite different with the staged cold heads which could be cooled at different temperatures. That is, the cooling is not directly transferred from cold temperature to room temperature at same time but part by part. In principle, the Carnot efficiency of CPTC could be reached. It has been verified both in theoretically and experimentally. Recently, we found that the performance of CPTC could be increased by eliminating the heat exchanges at each hot end of pulse tubes. Based on the theory of classical linear thermoacoustic, the numerical simulation is applied to analyze the acoustic power losses of the interstage heat exchangers in the CPTC. It verified that the heat exchangers at each hot end of pulse tubes in the previous design causes acoustic power losses. The Sage model of the CPTC demonstrates that the acoustic power at the inlets of the transmission tubes could be increased without the heat exchanges at each hot end of pulse tubes. Three pulse tube coolers cascading in series have been built. The input electric power and cooling temperature were fixed at 500 W and 233 K respectively. After the two heat exchanges at each hot end of pulse tubes were removed, this cooler obtained a cooling capacity of 273.2 W, 9.46 % increasing compared to the original one.

A Linear Stirling Cooler for Extreme Ambient Temperatures [THO9-5]

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With the achievements made in the last decade with respect to reliability and cryogenic performance, the use of linear cryocoolers for new application areas has become viable. Thales Cryogenics has been challenged by its customers to deliver robust and compact solutions for a variety of applications. One of these challenges is the use of coolers in extreme environmental conditions. In this paper, a linear Stirling cooler is presented that is designed for use in such extreme conditions, one of which is an ambient temperature of 150°C. The application for which this cooler is intended - the cooling of electronics and imaging sensors – requires 25 W of cooling power between 423 K and 223 K. Because of the need for a high-efficient solution within a limited geometrical envelope, a Stirling cooler was selected as the most suitable cooler type. We will describe the impact of the high ambient temperatures on the fundamental thermodynamics of the Stirling cooler. Furthermore, we will present some of the practical challenges in the design of the cooler. Finally, we will present the results of the qualification and performance testing of the coolers that were built.

Development of 150 K–200 K Pulse Tube Cooler for Infrared Detector [THO9-6]

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As key part of infrared imaging system for space observation, the Infrared Focal Plane Array (IRFPA) detector needs quite low dark noise that can be achieved by cooling cryogenically. Due to the advantages of low vibration and high efficiency, the Stirling-type pulse tube crycooler (PTC) is well adapted to the need of IRFPA detector. The present work introduces a PTC prototype which is composed of a moving-magnet linear compressor and a coaxial pulse tube cold finger for compactness and easy integration. This cooler provides a cooling power between 40 W-100 W at 150 K–200 K. The oscillating linear compressor has a pair of opposite pistons to eliminate vibration and the electrical input is 500 W at maximum. Using Maxwell software the parametric optimization on the linear motor has been carried. A method of co-simulation is proposed based on combined electrical-mechanical-acoustic model. Some improvements on the mass-spring system of the compressor have been done to make the cooler resonant. Several matching experiments of the compressor and cold finger have been conducted. A typical cooling performance of 50 W at 170 K has been achieved with 230 W electrical power input at a rejection temperature of 293 K, provided by water cooling. The motor efficiency and specified Carnot efficiency are 92% and 16%. In addition, the cooling performance of the PTC at 200 K–230 K was shown in the paper. Not only could the PTC be used for space mission, but is also a promising alternative to domestic refrigerator.

3D-Printed Helium-Based Regenerator for 4K GM and Pulse Tube Cryocoolers [THO9-7]

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Rare earth materials such as ErNi or HoCu2 are used as the regenerator material in the low temperature region of 4K GM and pulse tube cryocoolers. For some applications, non-magnetic regenerators would be favorable. As the cost of the regenerator material is a substantial part of the production cost, materials with lower cost would be desirable. Additive manufacturing techniques have advanced to a level that cost-effective production of 3D-printed structures is within reach. The use of Helium gas as the regenerator material for the low temperature region in 4K GM and pulse tube cryocoolers has been discussed over decades as Helium also exhibits a high specific heat capacity in the temperature region of interest. Ideas to confine the Helium gas range from Helium-filled spheres to the use of adsorbents to trap the Helium gas. In this paper, we discuss an alternative approach for a Helium-based regenerator: a 3D-printed metal structure is used to confine the Helium gas as the regenerator. The size of the heat exchange surface as well as the flow resistance and dead volume can be tailored to the specific application.

Analysis of a Novel Micro Structured Regenerator Filler [THP5-1]

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Future progress with respect to improvement in the efficiency of PTRs depend on the development of new regenerator filler material that can provide low hydrodynamic resistance, low thermal conduction in the main flow direction, and most importantly high thermal capacity at very low temperatures. In this paper a CFD study is performed on a novel, non-rare earth micro-structured regenerator filler (Creare Microchannel Regenerator, CMR) that is under development. CMR is a microfabricated, multi-layer structure and provides a complex flow passage for the working fluid. Pore-level CFD analysis is performed by defining and finely nodalizing periodically repeating unit cells. The pore-level CFD-based study leads to the development of empirical correlations for friction factor, as well as heat transfer coefficient between the regenerator filler structure and the working fluid. The validity of the results of pore-level study is verified by CFD simulations where large segments of an entire regenerator consisting of a large number of unit cells are modeled.

Effect of Phase Angle on Thermodynamic Performance and Exergy Loss of Room-Temperature Stirling Cooler [THP5-2]

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The phase angle is a crucial operating parameter for efficient operation of Stirling coolers. With the SAGE software, a systematic investigation on the effect of phase angle on the thermodynamic performance and exergy loss of Stirling cooler is made in the paper. A room-temperature Stirling cooler operating with the cold-end and hot-end temperatures of 273 K and 330 K is analyzed as an example here. The simulated result shows that with the increasing of phase difference between the compression and expander piston, which varies from 10° to 170° the refrigeration efficiency of Stirling regenerative cooler arises firstly and then decrease, and it has a maximum value when the phase difference between these two pistons reaches at 60. In order to find how the phase angle affect the thermodynamic performance of the room-temperature Stirling cooler, the exergy losses in the regenerator and two heat exchangers are analyzed in details. The simulated result illustrates that exergy losses are mostly caused by gas viscosity, incomplete heat transfer between gas and solid, and axial heat conduction of the regenerator. In particular, when the phase difference between compression piston and expander piston varies from 10° to 170°, the fraction of total exergy losses in the three components in the Stirling cooler has a minimum value. These above-obtained results can give us meaningful guidance and understanding for constructing efficient room-temperature Stirling coolers.

Numerical Investigation of a Displacer Type Pulse Tube Refrigerator with 1 kW Cooling Power [THP5-3]

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A Stirling refrigerator with 1 kW cooling power at 77 K is an over half-century product. Till now, there is no Stirling type pulse tube refrigerator reaches the same cooling power with single cold head. There would be a technical difficult for it. In this paper, a 1 kW cooling pulse tube refrigerator with single cold head and displacer type phase shifter is discussed with numerical simulation. Theoretical efficiency of the displacer type pulse tube refrigerator is the same as that of the Stirling refrigerator, and there is no limitation of charge pressure, frequency and pressure ratio. It could be the solution to solve the technical problem that the efficiency of the Stirling type pulse tube refrigerator with inertance tube is hard to achieve over 20%. It would be the best phase shifter for 1 kW cooling power. The influence of the sizes of the heat exchanger, regenerator and pulse tube, and operation parameters such as pressure ratio, charge pressure and frequency are investigated, which is useful for the development of the 1 kW cooling power pulse tube refrigerator.

Evolution of Stratification and Self-Pressurization of Liquid Nitrogen for JT Cryocooler Under Micro and Elevated Gravity Condition [THP5-4]

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The prediction of thermal stratification in a cryogenic storage tank is necessary for the successful execution of the prolonged working of a J-T cryocooler in space related applications. The working fluid may be stored in the sub- cooled conditions and possibility of heat infiltration may lead to the increase of temperature as well as pressure of the cryogenic fluid. The rise in fluid pressure may also lead to cavitation in the turbo pump which has to be avoided. Commonly used stratification models are based on temperature and velocity correlation developed for flow over a flat plate. The evolution of stratification during lift off and accelerated conditions, coast phase will be different from that during normal ambient conditions. During lift off, the gravity value can reach up to 6g and microgravity (μg) conditions at the coast phase. So modeling of stratification in the cryogenic tank is essential as the tank pressure must satisfy pump inlet condition. A multiphase axi-symmetric computational model is developed which can simultaneously account for the heat exchanges within the storage tank and also heat transfer from ambient condition during lift off and coast phase condition. The results show that the self-pressurization during coast phase was due to phase change rather than thermal stratification. The temperature of bulk fluid temperature will be higher during lift off and accelerated condition and reduction in rate of pressure rise after lift-off was noted which was due to turbulence created by the liquid.

Performance of a 2 K Joule-Thomson Closed-Cycle Cryocooler [THP6-1]

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The Rutherford Appleton Laboratory (RAL) has developed a 2 K Joule-Thomson (JT) cooler for future space missions. The design of the cooler was described and cryogenic tests on the heat exchanger sub-assembly were presented at the ICC19. In this paper we report on characterisation of the compressor sub-assembly across a range of operating parameters. We also present the initial cryogenic performance of the complete cooler and make comparisons with modelling predictions.

Adiabatic Expansion of ^{3}He in ^{4}He [THP6-2]

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The adiabatic expansion of ^{3}He in ^{4}He, to obtain cooling in the mK range, is proposed by H. London already in 1951. In principle it is a single-cycle method, but it can produce continuous cooling by using two expanders working in opposite phase. It uses fixed amounts of ^{3}He and ^{4}He, has no moving parts, and is independent of gravity, so it may be a candidate for cooling in space. In this contribution we investigate the feasibility of the technique and show how a system, that provides a cooling power of 1 μW at 50 mK, could look like.

HiPTC: A Compact and Efficient Cooler for Space Science Missions [THO10-1]

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Since 2010, Air Liquide Advanced Technologies has developed a dual-stage pulse tube cooler for application to future space science missions. The target temperature for this cooler was 15 K. The cooler is dubbed HiPTC, standing for Heat intercepted Pulse Tube Cooler. This cooler includes a compressor designed and built by Thales Cryogenics b.v. and a dual stage cold finger developed with CEA.

Tests performed on one engineering model showed that 8.6 K zero load temperature could be reached using this cooler. This makes it suitable for terahertz detector transition.

Preparatory work has been undergone with Purple Mountain Observatory to adapt the cooler for use in an instrument on board the future Chinese space station. In the frame of this work, a test has been done with coupling of the cooler with a SIS mixer built by PMO. Cryogenic tests have been performed and show very promising results.

The result of this positive testing experience is the availability of a compact, efficient and low vibration cryocooler for terahertz applications. The power consumption of the cooler is less than 500 W. Vibration levels are expected to be low thanks to a well balanced compressor and to pulse tube technology. Total cooler mass is around 25 kg including drive electronics and the cooler fits in a reduced volume.

This cooler is particularly well suited for space applications or other mobile application where mass, energy, volume and vibration are key factors.

The presentation will display cooler characteristics as well as test results and will discuss potential applications for this cooler.

Synergies Between Designed-for-Space and Tactical Cryocooler Developments [THO10-2]

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In this paper, an overview is presented of the latest developments regarding the development of space cryocoolers at Thales Cryogenics B.V. Planned future developments for the LPT6510 cooler are presented, and the synergies between COTS and space are reviewed, such as design principles from space coolers being applied to an upgraded variant of the COTS LPT9310, as well as design principles from COTS coolers being applied to the LPT6510 for improved manufacturability.

Thales performed a simulation and experimental study into the coupling of an off-the-shelf pulse-tube to a designed-for-space, high-performance compressor, and a prediction is given regarding what performances could potentially be achieved with an optimized design.

Furthermore, an update is given regarding potential adaptation of the Thales COTS cooler drive electronics with active vibration reduction to a designed-for-space, radiation-hardened design.

Raytheon Inline Cryocooler Development Progress [THO10-3]

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Since the 1970s, Raytheon has developed, built, tested and integrated high performance cryocoolers. Our versatile designs for single and multi-stage cryocoolers provide reliable operation for temperatures from 10 to 200 Kelvin with power levels ranging from 50 W to nearly 600 W. These cryocoolers incorporate clearance seals, flexure suspensions, hermetic housings and dynamic balancing to provide long service life and reliable operation in all relevant environments.

Today, increasingly high performance sensors are placing ever more stringent demands on cryocooler performance characteristics. To optimally meet the needs of next generation passive IR sensors, the Compact Inline Raytheon Single Stage Pulse Tube (CI-RP1) and Compact Inline Raytheon Hybrid Stirling/Pulse Tube 2-Stage (CI-RSP2) cryocoolers are being developed. These cryocoolers combine proven 1-stage and 2-stage cold-head architectures with an inventive set of warm-end mechanisms, uniting previously separate cryocooler components into a single cooler module. This architecture allows all of the moving mechanisms and major gas motions in the cryocooler to be consolidated onto a common axis.

Placing all of the mechanisms in a single volume and on a common axis provides benefits in terms of package size, mass, thermodynamic efficiency and exported vibration performance. The main benefit of axial symmetry is that proven balancing techniques and hardware can be utilized to null all motion along the common axis. The capability for extremely low exported vibration translates to better sensor performance and allows direct cryocooler mechanical mounting, eliminating the need for expensive, heavy, and complicated mechanical damping hardware.

Maturation and Status of the Lockheed Martin Micro1-2 Cryocooler [THO10-4]

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This paper describes the maturation and status of the Lockheed Martin "High Power" Micro1-2 pulse tube cryocooler. This cryocooler, which was qualified to technology readiness level 6 in 2014, is the baseline cooler for the Jet Propulsion Laboratory Mapping Imaging Spectrometer for Europa (MISE) instrument aboard the Europa Clipper mission, and the Johns Hopkins University Applied Physics Laboratory Gamma Ray and Neutron Spectrometer (GRNS) aboard the planned Psyche asteroid mission. This paper will describe enhancements to the cryocooler made for the MISE program, specifically modifications to maximize the cooler efficiency at low heat rejection temperature (220 K) and to increase the operating frequency. The paper will also describe minor modifications for the GRNS program, specifically modification of the coldfinger for low thermal emissivity and the addition of a cold tip interface tab. Finally, the paper will describe modifications made for operation with 150 K heat rejection temperature and 35 K cold tip temperature for the Deep Space Cooling System (DSCS) project with Iris Technology.

Development of the European Stirling Radioisotope Generator (ESRG) [THO11-1]

G. Gilley, M. Crook, T. Bradshaw, T. Rawlings, J. Watson, C. Pulker, A. Dowell, J. Vrublevskis, D. Summers, A. Preece, P. Bailey, M. Dadd, P. Jamotton, K. Stevenson

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Thales Alenia Space, The Rutherford Appleton Laboratory, Oxford University, Centre Spatial de Liege and Qinetiq Space are developing the first European Stirling Radioisotope Generator (ESRG). The ESRG will be a key enabling technology for ESA's ambition to operate long-duration, deep space and planetary missions, that have a requirement to be independent of solar energy. This programme brings together expertise in: long-life space cryocooler engineering; Stirling cycle modelling; high temperature materials; systems & control engineering; and power conditioning. The goal is to provide 100 We DC at 28 V from 435 Wth harvested from the decay heat of Americium-241. Initial breadboard testing is about to take place with a resistive heater simulating the radioisotope fuel cells. This paper summarises the ESRG development and progress to date.

Mobile Cryogenic System for Industrial and Laboratory Applications [THO11-2]

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A previous paper by Sumitomo (SHI) Cryogenics of America Inc. described a mobile cryogenic system that has been fully commercialized to cool down or warmup a superconducting MRI magnet by circulating helium in a closed-loop system. Sumitomo (SHI) has been exploring other configurations of the system that will enable it to be used to warm up and/or cool down a device to about 25 K, or to cool a device and keep it cold, such devices might be proton therapy systems or HTS applications. In this paper we present the results of product development studies including expander performance at different speeds, the effect of circulator speed, and different configurations of the expanders that will facilitate adapting the system to other applications. The present system circulates helium which is cooled by single stage Displex®-type Gifford-McMahon (GM) expanders in a cryostat with heat exchangers integrated on the cold ends and warmed by heaters on the heat exchangers. The mobile & compact nature of the system enables users to cool superconducting magnets at an end user site or manufacturing hub. The benefits are: conservation of helium, the option of shipping a magnet warm, reduced cryogen expense, and reduced cryogenic handling during site commissioning. There are currently several systems in the field at production facilities, manufacturing hubs, and being used as maintenance tools, allowing customers to be more cost competitive and more responsive to their customer's needs.

Enabling Cooled Instrumentation and Electro Optics via Active Thermal Management for CubeSats [THO11-3]

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We explore the use of active thermal management and miniature cryocoolers on CubeSats to enable electro optical and subcooled instrumentation targeting advanced Aerospace missions. The Active CryoCubeSat project (ACCS) is a two stage Mechanically Pumped Fluid Loop (MPFL) heat exchanger system, targeting 6U CubeSat platforms, with the first stage consisting of a Ricor K508N cryocooler and the second an Ultrasonic Additive Manufacturing (UAM) heat exchanger to a deployed radiator fluid interchange. The use of cryocoolers and active thermal management are not new, SABER on TIMED and the Mars Rover being cases in point. However, the use of miniaturized cryocoolers and active thermal control for small satellites is relatively new and in great demand with the NOAA EON-IR missions as an example. This report focuses on the working theories of thermal management for satellites and their environments, the design of a ground based prototype in a relevant thermal vacuum environment, the fabrication and testing of the integrated MPFL heat exchanger and cryocooler system via UAM techniques, and the analysis of the results through analytical design tools and numerical modeling. The development of a design tool and methodology for future active control of CubeSats will also be explored. Ultimately, the ACCS project will further enable the capabilities of CubeSat based platforms for advanced earth observing, deep space, and helioscience missions through the use of miniature cryocoolers, cryogenic instrumentation, and thermal management for small satellites.

Miniaturization of Rotary Stirling Cryocoolers [THO11-4]

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The trend for miniaturized Integrated Dewar and Cooler Assemblies (IDCA) has been confirmed over the past few years with several publications of new generation IR detector's working at High Operating Temperature (HOT). This HOT-technology enables the use of cryocoolers with reduced cryogenic power. As a consequence, miniaturized IDCA are the combination of a HOT IR detector coupled with a low-Size, low-Weight and low-Power (SWaP) cryocooler. In the past 2 years Thales Cryogenics BV and Thales-LAS-Fr have jointly developed a new generation of SWaP coolers to be able to be used in the new generation detectors that could bring a competitive advantage to our customers. This new generation SWaP coolers of Thales consist of linear as well as rotary coolers. During the design development phases of the different concepts, several operational parameters were continuously reviewed in order to obtain best values solutions. In this paper special attention will be given to the design philosophy behind the defined SWaP rotary cooler RMs1. The design hypotheses used could lead to a new generation of rotary coolers which will be very versatile in the different utilization areas not limited to IR sensors.

The Influence of Cutting Conditions on Tool Life for Minimum Machining Cost in Turning of α-β Titanium; A Comparison of Near-to-Dry Cooling Techniques [THO11-5]

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Machining of titanium has got attention due to its reactive capability with most of the tool materials at high temperature resulting extensive tool wear. Titanium is difficult to cut material with higher machining time and cost associated with its material removal. This paper interrogates underlying the mechanism of critical challenges i.e., SR, temperature, tool life and cost under multifarious cooling environments, as considered critical performance measures in the literature. For this purpose, the effect of speed and feed rate on such performance measures were investigated as a function of cooling strategy to standardize the cooling technique as best alternative in machining. from results, Cryogenic cooling has found to be a preponderant for minimum SR, temperature, tool life, and cost under the machining of Ti6Al4V titanium. The feasibility of cryogenic cooling was investigated using iso-response technique in comparison with dry and Minimum Quantity Lubrication under cooling environments. Experimental results revealed minimum average machining cost and longer tool life in cryogenic cooling. cryogenic cooling found to be a predominant alternative reducing temperature, and cost while improving surface integrity. Whereas, dry machining evoked severe temperature and rapid tool wear. In a nutshell, it represents a sustainable cooling strategy, from environmental perspective.

Wideband Dynamic Absorber for Ruggedizing Infrared Integrated Detector-Dewar-Cooler Assembly [THO11-6]

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The concept of Integrated Dewar-Detector-Cooler Assembly is usually applied to a design of modern cryogenically cooled, low size, weight and power infrared electro-optical modules. In this approach, essential reduction of conductive heat load is achieved by using the thin-walled cantilevered cold finger of a cryogenic cooler as a mechanical support for the entire cold assembly. The resonant frequency of such a low damped mechanical structure often falls within the frequency range of typical operational and endurance random vibration profiles. The resulting structural resonant responses may affect the image quality and even cause mechanical failures due to material fatigue. Thickening the cold finger wall or use of front supports result in parasitic conductive heat load, increase in power consumption, vibration export, complicated heat sinking and mechanical complexity. The authors explore the concept of multiple wideband dynamic absorbers containing a plurality of lightweight and lightly damped mechanical resonators, the frequencies of which are tuned as to minimize the dynamic response of the cold assembly. The authors advise on the intuitive procedure of the device tuning and present a practical design.

Qualification Status of LPTC CryoCoolers for MTG Instruments [THO11-7]

R. Gary, G. Stocchi, D. Soffietti, D. Lopes, G. Darque

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As part of the MTG program, Air Liquide was selected to provide the Cryogenic cooler systems for FCI and IRS instruments. This represents a total of 6 cooling systems to be supplied, each composed of 2 complete independent cryocooler units (CCU). The retained technical solution is based on LPTC cooler. This cooler includes compressors designed, qualified and supplied by TCBV, electronics designed, qualified and supplied by AIRBUS Crisa and pulse tube qualified and manufactured by Air Liquide with design under license of CEA. For the purpose of qualification, a complete CryoCooler Unit (CCU) including all its sub-components and processes has been qualified successfully. Typical performances in terms of cryogenics and exported µVibration of the CCU will be presented. The presentation will also embed test bench description and capabilities, qualification concerns on sub-component and way-forward up to flight models.

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	Monday, June 18		Tuesday, June 19		Wednesday, June 20		Thursday, June 21		
7:00 AM			Session Chair Breakfast Meeting/Continental Breakfast		Continental Breakfast		Continental Breakfast		**7:00 AM**
8:00 AM	**Foundations of Cryocoolers Short Course**				**[WO5] Applications I**		**[THO9] Commercial and Laboratory Cryocoolers**		**8:00 AM**
8:15 AM									8:15 AM
8:30 AM			**Welcome Announcements** **[TO1] Aerospace Cryocoolers I**						8:30 AM
8:45 AM									8:45 AM
9:00 AM									**9:00 AM**
9:15 AM									9:15 AM
9:30 AM					**[WP3] Advanced Crycooler Components**	**[WP4] Commercial and Laboratory Cryocoolers**			9:30 AM
9:45 AM							**[THP5] Advanced Analysis and Modeling Techniques**	**[THP6] Very Low Termperature Cryocoolers**	9:45 AM
10:00 AM									**10:00 AM**
10:15 AM			**Break**						10:15 AM
10:30 AM			**[TO2] Advanced Cryocooler Components**						10:30 AM
10:45 AM					**[WO6] Advanced Analysis and Modeling Techniques**				10:45 AM
11:00 AM							**[THO10] Aerospace Cryocoolers II**		**11:00 AM**
11:15 AM									11:15 AM
11:30 AM									11:30 AM
11:45 AM									11:45 AM
12:00 PM			**Lunch**		**Lunch**		**Lunch**		**12:00 PM**
12:15 PM									12:15 PM
12:30 PM									12:30 PM
12:45 PM									12:45 PM
1:00 PM		**Registration**							**1:00 PM**
1:15 PM									1:15 PM
1:30 PM									1:30 PM
1:45 PM			**[TO3] Brayton and Sorption Cryocoolers**		**[WO7] Cryocooler Electronics**		**[THO11] Applications II**		1:45 PM
2:00 PM									**2:00 PM**
2:15 PM					**[WO8] Stirling/PT/Hybrid Cryocoolers**				2:15 PM
2:30 PM									2:30 PM
2:45 PM			**[TP1] Stirling/PT/ Hybrid Cryocoolers**	**[TP2] Miniaturization of Cryocoolers**					2:45 PM
3:00 PM									**3:00 PM**
3:15 PM									3:15 PM
3:30 PM									3:30 PM
3:45 PM									3:45 PM
4:00 PM			**[TO4] Very Low Temperature Cryocoolers**						**4:00 PM**
4:15 PM									4:15 PM
4:30 PM									4:30 PM
4:45 PM									4:45 PM
5:00 PM									**5:00 PM**
5:15 PM									5:15 PM
5:30 PM									5:30 PM
5:45 PM									5:45 PM
6:00 PM	**Welcome Reception (6:00 – 9:00 PM)**				**Conference Banquet (6:00 – 9:00 PM)**				**6:00 PM**
6:15 PM									6:15 PM
6:30 PM									6:30 PM
6:45 PM									6:45 PM
7:00 PM									**7:00 PM**