ICC 19

San Diego, CA · June 20-23, 2016

Program and Abstracts

CONFERENCE COMMITTEE

Conference Chairman
Dean Johnson
Jet Propulsion Laboratory, USA
Email: dljohnso@jpl.nasa.gov

Conference Co-Chairmen
Jose Rodriguez
Jet Propulsion Laboratory, USA
Email: Jose.I.Rodriguez@jpl.nasa.gov

Sidney Yuan
Aerospace Corporation, USA
Email : Sidney.Yuan@aero.com

Treasurer
Ray Radebaugh
National Institute of Standards and Technology (NIST), USA
Email: radebaugh@boulder.nist.gov

Proceedings Co-editors
Saul Miller
Retired
Email: icc_press@att.net

Ron Ross
Jet Propulsion Laboratory, USA
Email: rgrossjr@jpl.nasa.gov

Program Chair
Carl Kirkconnell
West Coast Solutions, USA
Email: carlk@wecoso.com

Deputy Program Chair
Mark V. Zagarola,
Creare, USA
Email: mvz@creare.com

Program Committee
Carl Kirkconnell, West Coast Solutions, USA - **Chair**
Mark Zagarola, Creare, USA, - **Deputy Chair**
Tonny Benchop, Thales Cryogenics BV, Netherlands
Peter Bradley, NIST, USA
Ted Conrad, Raytheon, USA
Gershon Grossman, Technion, Israel
Elaine Lim, Aerospace Corporation, USA
Jennifer Marquardt, Ball Aerospace, USA
Jeff Olson, Lockheed Martin, USA
John Pfotenhauer, University of Wisconsin – Madison, USA
Alex Veprik, SCD, Israel
Sonny Yi, Aerospace Corporation, USA

ICC Board
Dean Johnson, JPL, USA-**Chairman**
Ray Radebaugh, NIST, USA – **Treasurer**
Ron Ross, JPL, USA – **Co-Editor**
Jeff Raab, Retired, USA – **Past Chairman**
Rich Dausman, Cryomech, Inc., USA - **Past Chairman**
Paul Bailey, University of Oxford, UK
Peter Bradley, NIST, USA
Martin Crook, RAL, UK
Lionel Duband, CEA, France
Zhihua Gan, Zhejiang University, China
Ali Kashani, Atlas Scientific, USA
Takenori Numezawa, National Institute for Material Science, Japan
Jeff Olson, Lockheed Martin Space System Co., USA
Limin Qiu, Zhejiang University, China
Thierry Trollier, Absolut System SAS, France
Mark Zagarola, Creare, USA

WELCOME

On behalf of the ICC 19 Organizing and Program Committees, we welcome you to the 19th International Cryocooler Conference (ICC 19) being held June 20-23, 2016 in San Diego, California, 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 19***, approximately six months after the conference, which includes copies of the papers presented at ICC 19. These papers are peer reviewed by the session chairs to assure the quality of the proceedings.

Attendees at ICC 19 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 ICC19 in beautiful San Diego on the serene and picturesque grounds of the Town & Country Resort and Convention Center. Shopping, dining, entertainment and sightseeing options abound close by, throughout the city and the Greater San Diego area.

Please join us for our Welcome Reception on Monday, June 20th from 6:00 PM to 9:00 PM in the courtyard of the Town & Country Resort.

The ICC 19 Conference Dinner will be held on Wednesday evening, June 22nd from 6:00 PM to 10:00 PM at the San Diego Natural History Museum, in San Diego's beautiful Balboa Park.

We hope you will find the conference interesting, the venue enjoyable and your time well spent. Welcome to San Diego and ICC 19!

Dean Johnson
Conference Chairman
Jose Rodriguez & Sidney Yuan
Conference Co-Chairmen

Carl Kirkconnell
Program Chair
Mark Zagarola
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 19th International Cryocooler Conference (ICC 19) will take place on June 20-23, 2016 at the Town and Country Resort & Convention Center in San Diego, California. The oral and poster presentations will be held in the Windsor/Hampton and Sheffield Rooms, respectively, in the Resort's Regency Ballroom. There are 4 smaller meeting rooms (Ascot, Brittany, Clarendon, and Eaton) across the courtyard that will be available as preparation rooms (bring your own computer) or as private meeting rooms.

The Conference begins with an ice breaking Welcome Reception on Monday evening, June 20th at 6:00 PM in the courtyard near the Regency Ballroom. The Technical Program commences at 8:00 AM on Tuesday, June 21st. Approximately 110 papers will be presented in both oral and poster formats during the ensuing three days, concluding on Thursday afternoon, June 12th at 4:30 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.

POST-CONFERENCE FACILITY TOUR

Quantum Design International (member CSA), the world leader of cryogen-free measurement systems is proud to announce a private tour of its world headquarters to the ICC 19 conference attendees. Dr. Martin Kugler, the Chief Operating Officer of Quantum Design, has volunteered to lead the tour of the facility after the last Thursday afternoon session. Quantum Design will provide a private tour bus to transport interested people round trip from the Town & Country Resort to Quantum Design. The bus ride, tour and a social that includes refreshments at Quantum Design will last approximately 90 minutes. Look for a sign-up sheet on the message board in the Sheffield Room near the registration tables. (www.qdusa.com) This tour is not associated with the ICC conference.

REGISTRATION

Registration will be held in the Sheffield Room of the Regency Ballroom on Monday, Tuesday, Wednesday, and Thursday. All attendees must register. The onsite registration fee is $750, 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 Dinner are available for an additional fee of $100.

Payments to ICC 19 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 20:	1:00 PM – 6:00 PM	Sheffield Room
Tuesday, June 21:	7:00 AM – 4:00 PM	Sheffield Room
Wednesday, June 22:	7:00 AM – 3:30 PM	Sheffield Room
Thursday, June 23:	7:00 AM – 12:00 PM	Sheffield Room

WELCOME RECEPTION and CONFERENCE DINNER

The Welcome Reception will be held in the Courtyard behind Charlie's at the Town & Country Resort on Monday evening, June 20th from 6:00 PM to 9:00 PM. A variety of appetizers, finger foods, desserts and beverages will be served. The Resort has offered to serve complimentary margaritas the first hour of the reception so don't be late! 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 22nd from 6:00 PM to 10:00 PM a beautiful custom, catered dinner awaits you at the San Diego Natural History Museum. Cocktails and hors d'oeuvres will be enjoyed in the historic exhibit galleries starting at 6:30PM. Buffet dinner will be served in the grand, four story atrium. The lower two floors will be open for viewing, with Fossil Mysteries being the permanent exhibition in these galleries. This is an event that you won't want to miss!

In addition two drink tickets will be provided that can be used for soft drinks, mixed drinks, wine and beer. Additional beverages and mixed drinks will be available at a cash bar. Additional banquet guest tickets are available for $100 each. Guest tickets can be purchased prior to the event when registering online or at the onsite registration desk.

Transportation to and from the Natural History Museum will be provided by motor coach. The drive will take about ten minutes. Buses will depart from the conference hotel beginning at 5:45 PM and begin returning to the conference hotel at 9:30 PM.

CONFERENCE MEALS

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

All Session Chairs are invited to the Session Chair Breakfast Meeting at 7:00 AM on Tuesday, June 21st in The Garden Salon I on the second floor of the Regency Ballroom. This will be the only Session Chair Breakfast Meeting for the conference so please try and attend. The Program Chair 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 90 minute conference lunch break should provide adequate time for lunch. There are several eating locations at the resort (The Market, Charlie's and the Terrace). The Fashion Valley Mall, located directly behind the Resort a short 10 minute walk away, has a variety of restaurants, both self-order at the counter and sit-down, from which to select. The trolley (station located behind the resort) or the Town & Country Resort shuttle can quickly take you to Old Town to enjoy authentic Mexican cuisine.

SAN DIEGO, CALIFORNIA

San Diego is a large and pleasant coastal city right on the Pacific Ocean in Southern California. It is home to 1.4 million citizens and the second-largest city in the state, with many universities and good swimming beaches. It's also known for its ideal climate, biotechnologies and communications technologies, long history, nightlife, outdoor culture and ethnic diversity.

San Diego is the birthplace of California and is known for its mild year-round climate, extensive beaches, natural deep-water harbor, long association with the

United States Navy and recent emergence as a healthcare and biotechnology development center.

San Diego's main economic engines are military and defense-related activities, tourism, international trade, and manufacturing. The presence of the University of California, San Diego (UCSD), with the affiliated UCSD Medical Center, has helped make the San Diego area a center of research in biotechnology.

The conference hotel lies in the Mission Valley district of San Diego, Mission Valley is a wide river valley running east-west along the San Diego River, and was so named for the Mission San Diego de Alcalá which resides on the eastern end of the valley. Mission Valley was the site of the first Spanish settlement in California (1769) in what is now called Old Town.

With its large local craft brewing industry, San Diego has been called "America's Craft Beer Capital." (Time to explore people: www.drinkupsandiego.com)

If baseball is your thing, the Washington Nationals are in town to play the Padres at San Diego's Qualcomm Stadium June 17-19.

Area Websites of Interest:

San Diego Tourism Authority - (http://sandiego.org)

San Diego Natural History Museum – (http://sdnhm.org)

San Diego Trolley: (http://www.sdmts.com)

SAN DIEGO WEATHER

San Diego enjoys a very mild climate year round. During the month of June, the average high temperature is 71 °F (22 °C) and the average low temperature is 62 °F (17 °C). There should be little expectation of rain in June, but there may still be a lingering marine layer to provide overcast skies near the coast.

CONFERENCE HOTEL - THE TOWN AND COUNTRY RESORT & CONVENTION CENTER (www.destinationhotels.com/town-country)

The 35 acre Town and Country Resort & Convention Center is located on the north side of I8 on Hotel Circle North, in the heart of San Diego's Mission Valley district that encompasses the San Diego River valley. Amenities and features include guest room Wi-Fi, outdoor pools, sauna, fitness center, restaurants and lounge. For those who do arrive by car, the Resort offers reduced parking fees ($5 per day) for ICC19 attendees. The Town and Country is conveniently located to The River Walk Golf Course, the Fashion Valley Shopping Mall and the San Diego Trolley depot that can take quickly to Old Town, Downtown, the Wharf and the Gas Lamp District of San Diego.

The hotel shuttle service operates from 10am-7pm, based on availability, to the Riverwalk Golf Course, the Fashion Valley Mall, Old Town and the Mission Valley Center. Shuttle pick up and drop off is located at the Hotel Lobby. The Hotel does not provide shuttle service to or from the airport.

Have an extra day or two before or after the conference? Enjoy a round of golf at the nearby 27-hole Riverwalk Golf Course; take the San Diego Trolley to explore Old Town, Downtown San Diego and harbor or the Gas Lamp District, or just relax poolside at the Resort. Other sites just a short drive away include the San Diego Zoo, Safari Park, SeaWorld, The USS Midway Museum, Air and Space Museum, LEGOLAND, and of course the Mission Bay and San Diego beaches.

TRANSPORTATION

DRIVING DIRECTIONS from SAN DIEGO INTERNATIONAL AIRPORT (www.san.org) (~5 miles or 8 km)

By surface streets: From the car rental lot take Pacific Highway north (1.5 miles) to the Rosecrans/Taylor Street interchange. Turn right (East) onto Taylor St. and continue 1.5 miles. Taylor Street turns into Hotel Circle South after 1.3 miles. Take Hotel Circle North overpass across Interstate 8 and continue for 1 mile to the Town and Country Resort. Hotel Circle North and Hotel Circle South are the frontage roads that parallel Interstate 8.
By Freeway: Take Interstate 5 North to Interstate 8 East. Take first exit onto Taylor St (Hotel Circle South and turn left. Take Hotel Circle North over I8 and continue 1 mile to the Town and Country Resort.

TAXI or SHUTTLE

The Town and Country Resort does not offer free shuttle service to or from the airport. Nor is there public transportation that directly connects the Resort to the airport. However 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. You may also consider taking either Supershuttle or Primetime back and forth from the airport to the conference hotel. These shuttles can be booked on-line prior to your arrival. One way rates are as low as $12 each way (plus tip) between the airport and the Resort.

www.supershuttle.com
www.primetimeshuttle.com

AUTHOR / PRESENTER INFORMATION

INSTRUCTIONS for POSTER PRESENTERS

Poster sessions will be held on Tuesday at 3:15 PM, and on Wednesday and Thursday at 9:15 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 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, 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

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 19***.

INSTRUCTIONS for PAPER SUBMISSION

Authors must submit their manuscripts to conference registration/publications staff in the Sheffield Room, located in the Regency Ballroom by 5:00 PM on Tuesday, June 21st. 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 19***. 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 entire conference will be held in the Regency Ballroom. The Technical Program for the 19th ICC is organized into 12 oral sessions and 7 poster sessions containing approximately 110 papers. The conference will begin in the Windsor/Hampton Ballroom of the Regency Ballroom on Tuesday, June 21st at 8:00 AM with introductory remarks and instructions by the ICC 19 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 22nd and on Thursday June 23rd. The conference ends at 4:30 PM on Thursday, June 23rd. Please take the opportunity to tour the Quantum Design facility after the conference.

The seven 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 Regency Ballroom (Windsor, Hampton and Sheffield ballrooms) and in the meeting rooms across the courtyard. Details for the internet access will be available by the time of the conference.

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.cryocooler.org

TECHNICAL PROGRAM / SESSION CHAIRS

Tuesday, June 21, 2016					
Start	**End**		**Session #**	**Chair 1**	**Chair 2**
8:00	8:15	**Welcome to the Conference - Chair**			
8:15	10:15	**High Capacity and Commercial Cryocoolers**	TO1	Peter Bradley	Thierry Trollier
10:15	10:30	**Break**			
10:30	11:45	**Brayton and Joule-Thomson Cryocoolers**	TO2	Mark Zagarola	Sangkwon Jeong
11:45	1:15	**Lunch**			
1:15	3:00	**Stirling and Pulse Tube Cryocoolers**	TO3	Ted Nast	Gan Zhihua
3:00	4:15	**JT/Sorption Cryocoolers**	TP1	Nir Tzabar	Marcel ter Brake
3:00	4:15	**Regenerators**	TP2	Weibo Chen	Jim Butterworth
4:15	6:00	**Advanced Analysis & Modeling**	TO4	Gershon Grossman	Sonny Yi

Wednesday, June 22, 2016					
Start	**End**		**Session #**	**Chair 1**	**Chair 2**
8:00	9:00	**Aerospace Missions**	WO5	Ted Conrad	Elaine Lim
9:00	10:15	**Cryocooler Miniaturization**	WP3	Alex Veprik	Y.S. Kim
9:00	10:15	**Stirling/Pulse Tube Modeling and Simulation**	WP4	Alex Veprik	Y.S. Kim
9:00	10:15	**High Capacity Commercial/Laboratory Coolers**	WP5	Alan Caughley	Chao Wang
10:15	11:45	**Cryocooler Control Electronics**	WO6	Tonny Benschop	Dan Kuo
11:45	1:15	**Lunch**			
1:15	2:45	**Advanced Cryocooler Components**	WO7	Jennifer Marquardt	Ingo Ruelich
2:45	3:00	**Break**			
3:00	4:45	**Cryocooler Integration and Applications**	WO8	John Russo	Daniel Willems

Thursday, June 23, 2016					
Start	**End**		**Session #**	**Chair 1**	**Chair 2**
8:00	9:15	**Very Low Temperature Coolers**	THO9	Peter Shirron	Melora Larson
9:15	10:30	**Stirling/Pulse Tube Development**	THP6	Ryan Yates	Mostafa Ghiaasiaan
9:15	10:30	**Pulse Tube Phase Shifting**	THP7	Tom Mulcahey	Ray Radebaugh
10:30	11:45	**Cryocooler Miniaturization**	THO10	Lionel Duband	Marcus Mai
11:45	1:15	**Lunch**			
1:15	3:00	**Aerospace Cryocoolers**	THO11	Perry Ramsey	Paul Bailey
3:00	3:15	**Break**			
3:15	4:30	**JT/Sorption/Hybrid Cryocoolers**	THO12	John Pfotenhauer	Jeff Olson

Table of Contents

Results from a year of running a 12 L/hour pulse tube liquefier in an industrial application [TO1-1]

A. Caughley, N. Emery, M. Nation, A. Kimber, H. Reynolds[1], C. Boyle[1], J. Meier[1], J. Tanchon[2]

Callaghan Innovation, Christchurch, New Zealand
[1] Fabrum Solutions, Christchurch, New Zealand
[2] Absolut System SAS, Meylan, France

Callaghan Innovation and Fabrum Solutions, in collaboration with Absolut System, have produced a range of large pulse tube cryocoolers. The cryocoolers are based on Callaghan Innovation's metal diaphragm pressure wave generator technology (DPWG). The metal diaphragms in a DPWG separate the clean cryocooler working gas from the oil lubricated reciprocating mechanism. DPWG technology has matured over the last 10 years to become a viable option for providing acoustic power to large pulse tube cryocoolers. The largest cryocooler consists of three in-line pulse tubes working in parallel on a 1000 cc swept volume DPWG. It has demonstrated 1280 W of refrigeration at 77 K, from 24 kW of input power and was subsequently incorporated into a liquefaction plant to produce liquid nitrogen for an industrial customer. The liquefier has now had one year of operation, producing 12 litres of liquid per hour. Development of the pulse tube has continued with a single in-line pulse tube direct mounted to a 330 cc DPWG. The pulse tubes on the large cryocooler each produced 450 W of refrigeration at 77 K. Further optimization on the single unit has increased the cooling power to over 500 W at 77 K, with no change in input power. This paper presents the experiences from running the large liquefier for a year in an industrial setting and the results of the optimization exercise on the smaller cryocooler.

Smart Energy Compact Chiller for Helium Compressors [TO1-2]

J. Gardiner, T. Sayles, K. Knight, J. Sloan, S. Spagna

Quantum Design Inc, San Diego, CA 92121, USA

Recent advances in smart energy compressors for helium cryocoolers have shown to significantly reduce power consumption during operational lifetime, especially when the system is cold or in "standby" mode. However, these compressors typically require at least a 3 ton industrial chiller or larger for adequate chill water cooling.

This paper introduces an updated version of the Quantum Design (QD) smart energy chiller dedicated to operation with a variable speed, water cooled helium compressor (QD model HLC 4500). Running at fixed speeds (60 Hz capsule, 60 Hz head) with a Gifford-McMahon (G-M) cold head or pulse tube, cooling power is found to be similar to the cooling power of a standard compressor and industrial chiller with power savings of up to 2 kW. Additionally, the variable speed compressor can be adjusted to reduce power consumption when cooling power needs are less, resulting in potential power savings up to 5 KW.

The chiller features dedicated cooling of the helium and oil circuits leading to increased efficiency and a smaller footprint than other commercially available chillers. A weatherized housing allows for flexible installation options including operation outdoors in a variety of climates.

Dry compact 1kW compressor for GM-and pulse tube cryocoolers [TO1-3]

J. Hoehne

Pressure Wave Systems GmbH, Munich, Germany

Pressure Wave Systems GmbH has developed a dry and compact 1kW compressor system for the operation with GM- or pulse tube cold heads.

The compression unit consists of two metal below based “cylinders” of 500 cm^3 which are driven by electro-hydraulics. As compared to flexure bearing compressors the system runs at low frequency at about 1 Hz. The compressor is air-cooled, low vibration, orientation independent and runs from single phase power. Set-up, performance and application will be discussed.

Reliability Evaluation of Stirling Cryocooler for an Electric Vehicle High Temperature Superconducting Motor System [TO1-4]

K. Yumoto, K. Yagi, K. Nakano, Y. Hiratsuka

Sumitomo Heavy Industries, Ltd., Nishitokyo-city, Tokyo 188-8585, Japan

Owing to the performance improvement of high-temperature superconducting wires, the development of superconducting motors has been actively conducted. To demonstrate the efficiency improvement of an electric vehicle driven by a superconducting motor, development of superconducting motor and cooling system has been performed by the joint research of Sumitomo Heavy Industries, Ltd. (SHI) and Sumitomo Electric Industries, Ltd. (SEI). A result of the actual vehicle tests and simulations showed that it is possible to improve the efficiency by about 10% compared to a conventional electric motor. In this project, SHI developed a high-efficiency Stirling cryocooler. As a result, a cooling capacity of 151 W at 70 K with a compressor input power of 2.15 kW, corresponding COP of 0.07, has been achieved.

However, more compact, efficient and reliable cryocoolers are required for the commercial use of a superconducting bus. In this paper, investigation of the reliability of the cryocooler is introduced. The operation system, the safety measures, and the long-term operation and environmental performance test results will be explained.

A Low Maintenance and Vibration 4K G-M Cryo-Refrigerator with Independent Variable Speed and Valve Timing [TO1-5]

D. Snow, J. Lawton, J. Diederichs, R. Taff, M. B. Simmonds, S. Spagna

Quantum Design Inc., San Diego, CA 92121, USA

In the course of the development of a small scale cryogen-free physical property measurement system (VersaLab) we have learned a great deal about the strengths and weaknesses that commercially available G-M cryo-refrigerators present in regards to our specific application. This has motivated us to develop a novel low vibration G-M cryo-refrigerator with a nominal cooling power of 0.25 W at 4.2 K. The system features a valve assembly for dynamically controlling the intake and exhaust of the refrigeration gas between the cryo-refrigerator and compressor. Unique features of the valve assembly design are its significantly lower power consumption and frictional force which translates in improved durability and component longevity over existent designs. Combined with the ability to dynamically control the frequency and motion profile of the displacer, the precise control of the gas flow functions independently of the displacer mechanics allows for optimization of the cryo-refrigerator performance with regard to cooling power, efficiency, and vibration level. Additionally, all moving components and seals have been designed for near zero wear. Collaborations with other manufacturers and researchers have also given us insights into additional optimizations that may be quite desirable for other cryogenic instruments and platforms.

A 4 K Pulse Tube Cryocooler with Larger Cooling Capacity [TO1-6]

C. Wang

Cryomech, Inc., Syracuse, NY 13211, USA

Some applications, such as cryogen-free dry dilution refrigerator and large superconducting magnet, etc, require a large cooling capacity at 4 K. A two-stage pulse tube cryocooler with a cooling capacity of 2 W at 4.2K, model PT420, is developed at Cryomech, Inc. The PT420 can provide a cooling capacity of 60 W at 45 K and 2.0 W at 4.2 K simultaneously with a power input of ~11.5 kW. In another operation mode, it can provide 80 W at 45 K and 1.85 W at 4.2 K simultaneously. Optimization and operation of the PT420 will be presented in this paper.

Study on a Single-stage High Cooling Capacity Stirling Cryocooler Capable of Providing 1050 W Cooling Power at 77 K [TO1-7]

D. M. Sun, Y. Xu, Q. Shen, N. Zhang, X. Qiao

Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, China

Stirling cryocoolers are promising in cooling high temperature superconducting (HTS) devices and small scale gas liquefaction applications, due to their high cooling capacity, high efficiency, wide operating temperature range, and compact configuration. This paper presents a single-stage high cooling capacity Stirling cryocoolers driven by a crank-rod mechanism. Based on the previous research and application, a novel cold end structure of the cryocooler was proposed and optimized. The measurably maximum cooling power at 77 K is 1050 W, and the corresponding relative Carnot efficiency exceeds 33 %. The results indicate that the design of the cold end structure is very important for the performance of high cooling capacity cryocooler and its application.

Cooling power extraction from a high cooling capacity Stirling cooler aimed at LNG BOG liquefaction [TO1-8]

Q. Shen, D. M. Sun, Y. Xu, N. Zhang, T. Jin

Faculty of Engineering, Zhejiang University, Hangzhou 310027, PR China

High cooling capacity Stirling coolers is capable of providing kilo watts cooling power. For those high power Stirling coolers, the cooling performance test based on electric heating is suffering from burn-out problem for the high thermal conduction resistance. Vapor condensation provides kilo-watts of phase-change heat with very low thermal resistance, which is also the same process occurring in gas liquefaction application. A condensation performance test process is proposed while a condensing heat exchanger with 120 micro-channels is designed for a high power Stirling cooler. The cooling performance test is conducted and the performance contour is yielded based on nitrogen condensation under various pressures and flow rates. The results show that there is an optimal working condition achieving the maximum liquefaction rate and maximum liquid production. The Stirling cooler is then applied in an LNG filling station to liquefy the boil-off gas. The cooler has been continually working for months at a production rate of 30 L/h.

A 40 K Turbo-Brayton Cryocooler for Future Observation Satelite Generation [TO2-1]

J. Tanchon, J. Lacapere, J.C. Rey, A. Molyneaux[1], T. Tirolien[2]

Absolut System SAS, 38170 Seyssinet Pariset, FRANCE
[1] Ofttech Ltd, UK
[2] European Space Agency ESA-ESTEC, Noordwijk, NL

Several types of active cryocoolers have been developed for space and military applications in the last ten years. Performances and reliability continuously increase to follow the requirements evolution of new generations of satellite: less power consumption, more cooling capacity, increase life duration.

However, in addition to this increase of performances and reliability, the microvibrations requirement becomes critical. In fact, with the development of vibration-free technologies, classical Earth Observation cryocoolers (Stirling, Pulse Tube) will become the main source of microvibrations on-board the satellite.

A new generation cryocooler is thus developed at Absolut System 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.

This paper presents the status of this development project based on Reverse Brayton cycle with very high speed turbomachines.

Performance Testing of a High Effectiveness Recuperator for High Capacity Turbo-Brayton Cryocoolers [TO2-2]

D. Deserranno, M. Zagarola, D. Craig[1], R. Garehan[1], T. Giglio[1], J. Smith[1] J. Sanders[2], M. Day[2]

Creare, Hanover, NH 03755, USA
[1] Mezzo Technologies, Baton Rouge, LA 70814, USA
[2] Edare, Lebanon, NH 03766, USA

NASA is considering multiple missions involving long-term cryogen storage in space. Liquid hydrogen and liquid oxygen are the typical cryogens as they provide the highest specific impulse of practical chemical propellants. The net heat load to a hydrogen tank storing 38 metric tons of liquid hydrogen is estimated to be 20 W at 20 K. To enable long-duration zero boil-off storage, this heat load must be lifted using an active refrigerator. Creare has addressed this need by designing and performing proof-of-concept tests on a turbo-Brayton cryocooler that provides 20 W of refrigeration at 20 K. The key components in the 20 K, 20 W cryocooler are the electronics, compressors, turboalternator, and recuperators.

The recuperator for the 20 K, 20 W cryocooler is a five-module micro-shell-and-tube heat exchanger developed jointly by Creare, Mezzo Technologies and Edare. It has a predicted effectiveness exceeding 0.99, enabling the cryocooler to deliver 20 W of refrigeration for an input power below 1.4 kW, corresponding to a specific power of 70 W/W. This is significantly better performance than any 20 K cryocooler existing or (to our knowledge) under development.

In preparation of the cryocooler integration, the recuperator was tested between 300 K and 20K using helium at design flow rates. The topic of the conference paper is the design, fabrication, and testing of this high-effectiveness high-capacity recuperator for a 20 K 20 W cryocooler.

Performance Testing of a High Capacity Compressor for a 20K 20W Cryocooler [TO2-3]

K. Cragin, D. Deserranno, M. Zagarola

Creare LLC, Hanover, NH 03755, USA

Creare is currently developing for NASA a high capacity 20 K turbo-Brayton cryocooler for long-term cryogen storage in space. The cryocooler utilizes three compressors with intercooling to compress and circulate the helium cycle gas. The compressors operate on self-acting journal bearings, are driven by brushless permanent magnet motors at speeds exceeding 6000 rev/s, and have a nominal input power capacity of 500 W. As a result of the high speed and flow rates, the predicted aerodynamic efficiency is extremely high for all stages, resulting in net efficiencies of 63 to 67% for the three compressor stages. This is significantly higher than prior permanent magnet motor compressors developed by Creare which have shown a peak efficiency of around 50%. The high compressor efficiency results in a cryocooler input power below 1.4 kW, corresponding to a specific power of 70 W/W. This performance is significantly better than any 20 K cryocooler existing or (to our knowledge) under development. In preparation for cryocooler integration, the compressors will be tested at 300 K using helium at design flow rates. This conference paper describes the design, fabrication, and testing of these high-capacity compressors.

Experimental Study on a Precooled JT Cryocooler Working at Liquid Helium Temperature-Open Cycle [TO2-4]

D.L. Liu[1], X. Tao[1], Y.F.Yao[1], W.K. Pan, Z.H. Gan[1,2]

[1] Institute of Refrigeration and Cryogenics, Department of Energy Engineering, Zhejiang University, Zheda Road No. 38, Hangzhou 310027,China
[2] Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, China

JT cryocoolers working at 4 K have been used for various applications such as superconducting and space detection. For developing a long-life precooled JT cryocooler for space use, the cold head part of the JT cryocooler has been designed and tested.

The cold head part includes three counterflow heat exchangers (CFHXs), two precooling heat exchangers(PHXs), a cold head heat exchanger (CHHX) and an adjustable JT valve. The structures and parameters of the heat exchangers are listed.

In the test experiment system, a two-stage GM cryocooler was used as the precooler because of its sufficient and consistent cooling performance. The JT cryocooler successfully achieved 4.4 K in the open cycle experiment. Cooling power was tested with different values of high pressure.

It was found that, the JT cryocooler started to be unstable before the liquid helium was totally evaporated in the CHHX. Then the maximum cooling power could not be achieved. This phenomenon is further discussed and some improvements will be made to solve the problem.

Characterization of Emitted Vibration from Turbo-Brayton Cryocoolers [TO2-5]

K. Cragin, K. Rule, J. Wilbur, J. McCormick, S. Mellinger, M. Zagarola

Creare LLC, Hanover, NH 03755, USA

Turbo-Brayton cryocoolers are known for low emitted vibrations due to the lack of reciprocating parts. The only moving parts are the miniature turbomachine rotors which are precisely balanced and operate at extremely high rotational speeds (3000 to 10,000 rev/s are typical). The high operating speed, low rotor mass and low rotor imbalance results in physical displacements that are on the order of angstroms. The first space implementation of a turbo-Brayton cryocooler was for cooling the NICMOS instrument on the Hubble Space Telescope (HST). On-orbit operations indicated that the cryocooler could not be detected by the super-precise instruments on the HST. Future missions may have more restrictive vibration requirements or different integration approaches than HST and a quantitative assessment of emitted vibration from a turbo-Brayton cryocooler is needed. During the development of the NICMOS cryocooler, several tests were conducted to characterize the emitted vibrations from the cryocooler but these tests did not produce quantitative information due to either high background vibrations or non-prototypical operation of the cryocooler. Recent work at Creare has focused on quantifying the emitted vibration of turbo-Brayton cryocooler technology using two approaches. The first approach utilized computational fluid dynamics/structural simulations of representative turbo-Brayton components at prototypical operating conditions. The second approach involved testing with representative turbo-Brayton components at prototypical operating conditions at the Cryocooler Vibration Output Test Facility that was developed and is operated by the Aerospace Corporation. This paper describes the analysis work and test results.

Investigation of the Embedded Stirling Cryocooler [TO3-1]

K. Yang[1,2], K.Z, Zhu[1,2], B. Cai[1,2], P. Qi[1], H. J. Chen[1]

[1] Institute of Cryogenics and Electronics, Hefei, 230043, China
[2] The Provincial Laboratory of Cryogenics and Refrigeration, Hefei, 230043, China

A new type integral-type Stirling cryocooler is introduced in this paper. The compressor and expander are located along the same axis, and expander is embedded in the compressor. Key units of liner motor and regenerator are analyzed with relative theory , and the prototype is developed. The experimental results are analyzed to verify the feasibility of the new structure.

5W at 77K Without Breaking the Bank [TO3-2]

D. Wilcox, B. Rock, P. Spoor, J. Corey

Chart Inc. – Qdrive, 302 Tenth Street, Troy, NY 12180, USA

Chart Inc. has developed a small cryocooler for mass production at cost far less than prior art, using a novel external-stator motor-and-piston construction that eliminates electrical feedthroughs, springs, and flexures, combined with a coldfinger that eliminates all brazing and welding. This new acoustic-Stirling cooler operates directly on 60 Hz AC power, with direct forced air rejection to ambient (no other support services or equipment is required). Developed for local liquefaction of medical gases, this breakthrough in affordable, small cryocooling is now available in initial samples for any application. This paper presents the novel construction, performance maps, price estimates and ongoing development of this cooler.

Development of a Two-Stage Stirling Type Pulse Tube Cooler [TO3-3]

Xiaomin Pang[1,2], Xiaotao Wang[1], Wei Dai[1], Ercang Luo[1], Yuejing Zhao[1,2]

[1] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry of Chinese Academy of Sciences, Beijing 100190, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

This paper presents the performance of a high efficiency two-stage pulse tube cooler. In the system, an independent 50 Hz Stirling type pulse tube cooler is used to precool the middle of another Stirling type pulse tube cooler with a lower operating frequency, which forms a configuration called as thermal link two-stage configuration. The phase shifter of the first stage is inertance tube pulse reservoir and in order to enhance the performance, double-inlet valve is added in the second stage. Theoretical study based on Sage software is firstly carried out. Simulation results reveal that, with a middle heat exchanger inside the second stage pulse tube, the cooling performance can be improved. The pulse tube cooler can obtain 0.4 W cooling power at 10 K under the conditions of 2.5 MPa mean pressure and 30 Hz frequency. Then experiments are done to investigate the performance. The influence of the precooling temperature, mean pressure, frequency and heat conduction characteristics of the thermal link are also studied.

Theoretical Design and Optimization of a Next-Generation, Two-Stage, 20W at 20K Pulse Tube Cryocooler [TO3-4]

M.D. Perrella, S.M. Ghiaasiaan

Georgia Institute of Technology, Atlanta, GA 30332, USA

Cryocoolers are a special class of refrigerators that utilize the cyclical compression and expansion of high-purity helium through a series of tubes, orifices, and heat exchangers in order to provide cooling power at temperature below 100 K. Pulse Tube Cryocoolers consist of an inertance tube or office connected to a surge volume which together function as a hydrodynamic piston to produce the correct mass to pressure phase relationship in order to generate the desired cooling effect. The advantage of this approach is that PTCs possess no moving parts on their cold end which leads to greater robustness and reliability making them popular for aerospace and defense applications. Separate cryocoolers can also be combined into multi-stage systems in order to achieve lower operating temperatures. Modeling and analysis of cryocooler operation is significantly more difficult than traditional refrigeration systems due to the complex nature of thermal-fluid interactions between the solid cryocooler components and the gaseous working fluid as well as the conduction loses along the cryocooler components themselves. In this analysis, SAGE cryocooler modeling software will be used to design and optimize a two-stage, 20W at 20K pulse tube cryocooler. Parametric studies will be performed on key components including the 1st and 2nd stage regenerators and the trade-offs between cooling power and efficiency will be investigated. Additionally, the effect of internal friction factor on overall cooling power and efficiently will be analyzed.

A Design on a Two-Stage Stirling/Pulse Tube Hybrid Cryocooler [TO3-5]

C.H.Yin, B. Wang, Y.X. Guo, Z.H. Gan

Institute of Cryogenics and Refrigeration, Zhejiang University, Hangzhou, 310027, China
Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, China

The best charge pressure of the regenerator in regenerative low temperature cryocoolers which run at 30-40Hz is about 2.0-2.5MPa for 300-80K, 1.0-1.5MPa for 80-20K and 1.0MPa for 20-4K. Experimental studies show that it's very difficult for pulse tube cryocoolers to improve the pressure ratio at the cold end because of absence of moving parts. But Stirling/ pulse tube hybrid cryocoolers take advantage of the intrinsic strengths of both of these two cryocoolers, avoiding the wear and tear of multistage Stirling cryocoolers and the intrinsic inefficiency of pulse tube cryocoolers.

This paper designs a two-stage Stirling/pulse tube hybrid cryocooler at 20 K region, which adopts low temperature inertance tubes and a surge volume to adjust the phase difference. The simulation results show that when the input electrical power is about 200 W, the hybrid cryocooler can provide 0.5 W refrigerating capacity at 20 K. At the same time, the effects on the performance of the cryocooler from operation parameters and structure sizes are analyzed; the phase and pressure ratio in the displacer, the second stage regenerator, the pulse tube and inertance tubes are also discussed.

Gravitational Effects in Pulse Tube Cryocoolers [TO3-6]

T. Fang[1], T. I. Mulcahey[2], P.S. Spoor[3], T. J. Conrad[4], M.D. Perrella [1], S. M. Ghiaasiaan[1]

[1] Georgia Tech Cryo Lab, G.W. Woodruff School of Mech. Eng., Georgia Institute of Technology, Atlanta, GA 30332 USA
[2] CSA Medical Advanced Development, Lexington, MA 02421 USA
[3] Chart Industries, Biomedical Division, Troy, NY 12180 USA
[4] Raytheon Space and Airborne Systems, El Segundo, CA 90245 USA

Stirling-type pulse tube cryocoolers (PTC) are increasingly used in tactical applications as well as ground testing of space systems. Some PTCs exhibit sensitivity to gravitational orientation and often lose significant cooling performance unless situated with the cold end pointing downward. Previous investigations have indicated that some coolers exhibit sensitivity while others do not; however, a reliable method of predicting the level of sensitivity during the design process has not been developed. In this study, we attempt to derive a semi-analytical method that can be used to ensure that a PTC would remain functional at adverse static tilt conditions. The development of the method is based on experimentally-validated 3-D computational fluid dynamics (CFD) simulations that identify relationships between pulse tube geometry and operating conditions including frequency, mass flow rate, pressure ratio, mass-pressure phase, hot and cold end temperatures, and static tilt angle. The validation of the computational model is based on experimental data related to a number of pulse tube cryocoolers.

Gas Spring Effect In A Displacer Pulse Tube Refrigerator [TO3-7]

S. Zhu

Institute of Refrigeration and Cryogenics, School of Mechanical Engineering, Tongji University, 4800, Cao'an Road, Shanghai, 201804, China

After the development of the pulse tube refrigerator for spacing using, big effort is paid for increasing the efficiency of the pulse tube refrigerator. Till now, the efficiency of the pulse tube refrigerator is still lower than that of the Stirling refrigerator. A pulse tube refrigerator with a displacer as the phase shift is a potential type to overcome this problem because its theoretical efficiency is the same as Stirling refrigerator. There are a lot of things to know before it becomes a realistic refrigerator. How to let linear motor match cold head is one of the basic problems in this type of refrigerator. The relation among the operation frequency, piston diameter, and dead volume between compressor and after cooler is discussed by numerical simulation. The piston and dead volume have gas spring effect which influences the operation frequency. The rod of the displacer also has gas spring effect which is important at high operation frequency.

Development of cascade non-flammable mixed refrigerant Joule-Thomson refrigerator for 100K [TP1-1]

C. Lee, J. Yoo, L. Jin, J. Cha, S. Jeong

Cryogenic Engineering Laboratory, KAIST, Daejeon, 34141, South Korea

In this paper, a cascade type non-flammable mixed refrigerant (MR) Joule-Thomson (JT) refrigerator has been suggested to achieve 100 K cooling temperature. The working fluid utilized in the 1st stage (low temperature cycle) of the MR JT refrigerator is composed of nitrogen (N_2), argon (Ar), Tetrafluoromethane (R14) and Octafluoropropane (R218). Azeotropic mixture of R32 and R125 (R410A) is applied for the 2nd stage (high temperature cycle) where the cooling temperature is nearby 240 K. The design specifications of the refrigerator were modeled by using commercial software with Peng–Robinson equation of state (EOS). The optimal design was examined with the calculations under various conditions, such as the cooling temperature of the 2nd stage, the discharge pressure of the compressor, and the mass flow rate of the working fluid. The maximum COP and Carnot efficiency of the optimized MR JT refrigerator were obtained as 0.23 and 41.8%, respectively at 106.8 K. Also, this MR JT refrigerator was fabricated and tested to investigate the refrigeration performance in comparison with the simulated results. The compression system of the refrigeration cycle was installed by modifying commercial air-conditioning compressors. The composition of the MR was precisely identified with a gas chromatograph. The feasibility of the non-flammable MR in the MR JT refrigerator was validated at the lowest temperature of 96.7 K, which is even below the freezing point of pure R218 (125 K).

Investigation of the Flow Boiling Heat Transfer Coefficient Characteristic for Non-flammable Cryogenic Mixed Refrigerant [TP1-2]

J. Yoo, L. Jin, C. Lee, S. Jeong

Cryogenic Engineering Laboratory, KAIST, Daejeon, 34141, South Korea

In this paper, the flow boiling heat transfer coefficients are investigated for three kinds of the non-flammable cryogenic mixed refrigerant. The test section is composed of 1/8 inch copper tube for passing through the mixed refrigerant. Also, the manganin wire utilizes at the outside of the test section to generate heat transfer mechanism of the mixed refrigerant flow. The experimental apparatus is verified by the comparison of the experimental and the theoretical heat transfer coefficient of the gas phase nitrogen.

R218 (Octafluoropropane, C_3F_8), R14 (Tetrafluoromethane, CF_4), and argon are used to constitute to the three kinds of the mixed refrigerant. The molar compositions of each mixed refrigerant are R218 : R14 = 0.7 : 0.3, R218 : R14 = 0.3 : 0.7, and R218 : R14 : Ar = 0.24 : 0.56 : 0.2, respectively. The mass flux conditions are maintained to 22.0, 49.6, and 82.6 kg/m^{2}s. The heat flux conditions are 1.4, and 4.9 kW/m^2. The measurement for each mixture composition is conducted for the whole defined physical conditions. The effect of each component (R218, R14, and argon) to the boiling heat transfer of the mixed refrigerant is discussed by comparison of the experimental results.

Modified Brayton Refrigeration Cycles for Liquid Hydrogen in Spallation Neutron Source Moderator [TP1-3]

H.-M. Chang[1,2], S.G. Kim[2], J.G. Weisend II[1], H. Quack[3]

[1] European Spallation Source, SE-221 00 Lund, SWEDEN
[2] Hong Ik University, Seoul, 121-791, KOREA
[3] TU Dresden, D-01062 Dresden, GERMANY

A thermodynamic study on standard and modified Brayton refrigeration cycles is performed for application to sub-cooled liquid hydrogen in spallation neutron source moderator. The target moderators under operation or development require a refrigeration up to 30 kW at 20 K (depending on the beam power), which should be used for cooling the circulation flow of liquid hydrogen at 17~20 K and 1.5 MPa. A cryogenic refrigerator that can execute the refrigeration is designed with basis on reversed-Brayton cycle with helium as refrigerant, but a variety of modifications in thermodynamic structure are considered for improved efficiency and suitability under the specified thermo-hydraulic condition.

The reversed-Brayton cycles include different versions of two-stage expansion cycle, dual-turbine cycle, and dual cycles. Special attention is paid to the coldest heat exchanger, where liquid hydrogen is in thermal contact with cold helium gas at temperatures close to the freezing temperature of hydrogen (14 K). A few anti-freezing schemes such as warm-up flow, cross-flow, and cooling by high-pressure stream are also examined as part of the cycle analysis. Figure of merit (FOM) is defined as an index of thermodynamic performance, and quantitatively estimated with real fluid properties and a process simulator (Aspen HYSYS). The detailed features of various refrigeration cycles are presented and discussed in comparison with the existing or proposed systems.

Parametric Analysis of Turbo-Brayton Cycle for HTS Power Applications for Different Loads and Temperature Levels [TP1-4]

A. K. Dhillon, P. Ghosh

Indian Institute of Technology Kharagpur, Kharagpur, WB 721302, INDIA

High Temperature Superconductor based power appliances require a cooling system to operate them at a temperature range of 50-77 K. The advantages of reverse-Brayton cycle (RBC) cryocooler like long life, low maintenance, small size, high reliability and high efficiency make it a competitive system for cooling large scale power applications such as superconducting rotating devices, transformers and transmission lines. However, the cooling loads and temperature ranges vary among the applications and the HTS materials used. In this work, parametric analysis has been performed for RBC cryocooler for different load conditions varying from 300 W to 1.5 kW at temperature ranging to 65 to 80 K.

A simple reverse-Brayton cycle configuration is selected for the current study. The major components of the system are compressor, heat exchanger (recuperator) and turboexpander. The operating parameters like pressure ratio, mass flow rate, efficiency of compressor and expander are considered to get the specification of all the major component of the cryocooler. Helium and neon are selected as the working fluids for the system. The analysis of the system is carried out using Aspen HYSYS 8.6 software. The analytical model is verified with the experimental data available in the literature. The heat leak and losses associated with the components are also taken into account.

One of the major outcomes of the present work is selection and characterization of the components at different loads with different fluids. Recommendations have been provided for major components of RBC cryocooler operating for different applications in this paper.

Investigation of an Adsorption Refrigeration Model with Correlative Experiments [TP1-5]

X. Li[1, 2], T. Yan[1], Y.J. Liu[1], J.H. Cai[1]

[1] Key Laboratory of Space Energy Conversion Technology, Technical Institute of Physics and Chemistry, CAS, Beijing 100190, China
[2] University of Chinese Academy of Sciences, Beijing 100190, China

Adsorption refrigeration is an important support for space cryogenics. In this paper, we construct an adsorption refrigeration model and design correlative experiments. The desired model temperature range is from 50K to 0.8K.

In our research, there are two important parts: gas gap heat switch design and adsorption capacity performance. These two contribute chief achievements of this model. Theoretical model is verified by correlative experiments.

Improving designing adsorption refrigeration could be realized based on this model, which will benefit space cryogenics. Gas gap heat switch study has more promising application in other cryogenics fields.

Research on 100mW@6K Space Joule-Thomson Cryocooler [TP1-6]

Y.X. Ma[1], J. Wang, Y.J. Liu, J. Quan, J.T. Liang

Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry CAS, Beijing, 100190 China
[1] University of Chinese Academy of Sciences, Beijing, 100190 China

Due to its low vibration and relatively high efficiency, hybrid Joule-Thomson (J-T) cryocooler is widely used in space missions. In previous study, our laboratory has developed a hybrid liquid helium temperature J-T cryocooler by using a three-stage pulse tube cooler to precool J-T cycle.

In this study, a new J-T cryocooler is designed for the purpose of achieving 100mW cooling capacity. A direct way to improve cooling capacity is to increase mass flow rate of J-T cooler. Theoretical study is carried out to figure out the influence of charge pressure and diameter of orifice on mass flow rate. Besides, cooling capacity rises with decreasing temperature before throttling. However, precooling power will increase and high pressure ratio is hard to maintain when mass flow rate increases. Primary experimental data is also demonstrated verify the feasibility of the 100mW J-T cooler.

In-Space Cryogenic Propellant Storage Applications for a 20K 20W Cryocooler [TP1-7]

D. Plachta, J.R Feller[1]

NASA Glenn Research Center
[1] NASA Ames Research Center

NASA is currently developing cryogenic propellant storage and transfer technologies for future space exploration missions and scientific discovery missions by addressing the need to raise the technology readiness level of cryogenic fluid management storage technologies. Cryogenic propellants are part of the plans due to their inherent high specific impulse, yet their issue is inherently low boiling points, leading to substantial propellant boil-off losses in the long term. Recent developments on Reduced Boil-off Testing and an in-house Scaling Study provided important information on the benefit of an active cooling system applied to LH_2 propellant storage. Findings point to zero-boil off technology as reducing mass in LH2 storage systems when low Earth orbit loiter periods are greater than 2 months, which has spurred development of the 20K 20W cryocooler. The analysis presented explores the propellant tank sizes and heat loads that this cryocooler fits, to achieve zero-boil-off propellant storage. This is done with and without the integration of a 90K reduced boil-off cryocooler. Also, the 20K and 90K cooling requirement of larger tanks, such as those considered in the Mars Reference Mission, are considered.

Vortex Cooling of Cryogenic Hydrogen [TP1-8]

E. Shoemake, J. Leachman

Washington State University, Pullman, WA 99163, USA

Hydrogen offers a promising future as an alternative to current fuels. It has a wide variety of uses in chemical manufacture, space exploration, and is increasingly being discussed as part of the future of transportation. Significant research in recent years has gone into more environmentally friendly ways of obtaining hydrogen, improving the efficiency of hydrogen production, and improving performance of hydrogen fuel cells. Where research has been lacking, and what may be considered the biggest challenge to increasing hydrogen potential as an energy storage medium, is the capability and cost of current hydrogen liquefaction methods.

In this work, we present a novel liquefaction design based on the Ranque-Hilsch vortex tube and utilization of the catalyzed parahydrogen - orthohydrogen reaction to improve cooling efficiencies beyond the capabilities of current technologies. Initial results of a small scale hydrogen vortex cooler are shown at cryogenic temperatures, with discussion of optimal vortex tube parameters for cryogenic hydrogen cooling. The effectiveness of the parahydrogen - orthohydrogen reaction at improving vortex cooling efficiencies is also discussed.

A Double Pipe Regenerator for a 4K Gifford-McMahon Cryocooler [TP2-1]

S. Masuyama, T. Numazawa[1]

National Institute of Technology, Oshima College, Oshima Yamaguchi 742-2193, Japan
[1] National Institute for Materials Science, Tsukuba Ibaraki 305-0003, Japan

A new regenerator structure named a *double pipe regenerator* was experimentally investigated. This structure was adapted to the second stage regenerator of a 4K Gifford-McMahon cryocooler to improve the cooling efficiency at 4.2 K. The double pipe regenerator consists of a regenerator housing and a stainless steel pipe. This pipe with a thin wall is inserted in the co-axial direction into the regenerator housing. The second stage regenerator was divided into two parts by two kinds of regenerator materials of lead (Pb) and holmium copper 2 ($HoCu_2$) spheres. These filling volume rate were 50%, respectively. Only the Pb part has the double pipe regenerator in consideration of the temperature distribution and helium properties.

The experimental results show that the cooling power was affected by the pipe size and the first stage temperature. The maximum cooling power at 4.2 K of 1.33 W was achieved with an input electric power of 7.3 kW. This is an improvement in the cooling power by 7%, compared with a conventional two-layer structure. Detailed experimental results will be shown in this paper.

Finite Element Analysis of Magnetically Augmented Regenerators in Cryocoolers [TP2-2]

R. Kumar and S. Shoor

School of Mechanical Engineering, Lovely Professional University, Phagwara, Punjab, India-144411

Magnetic intermetallic compounds are employed in the regenerative type of cryocoolers to function well below 10K. Such materials exhibit large magnetocaloric effect (MCE) in these temperature ranges. Therefore, varying magnetic field is utilized for improving the thermal storage characteristic of the matrix material in these cryocoolers. Such configuration is termed as *magnetically augmented regenerator* (MAR).

This paper describes the performance of MAR in Stirling and Gifford-McMahon (GM) cryocoolers under various operating conditions. The Finite Element Method (FEM) is employed to evaluate MAR's performance. The regenerator matrix is modeled as porous media. The magnetic field distribution inside the regenerator is observed and matched with its effect on temperature distribution. Various parameters and conditions are modified. Gadolinium gallium garnet (GGG), erbium nickel (ErNi) and Er_3Ni are used as regenerator materials one by one. The pressure ratio of the compressor is varied from 2:1 to 10:1. The working fluids specified in the simulation model are liquid helium and mixture of helium-nitrogen in different proportions. The magnetic field imposed is from 0T to 10T.

The aim of the current work is to assess the advantages of improved configuration for regenerative cryocoolers using magnetism. The cooling capacity and temperature of cold heat exchanger are observed from 4.2K to 300K. The results of the simulations are also compared with that present in literatures and the causes of deviation are discussed due to non-ideal effects.

Analysis of Phase Distribution in Regenerator Based on Lagrange Method [TP2-3]

Menglin Liang[1,2], Yanjie Liu[1], Tao Yan[1], Jingtao Liang[1]

[1] Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, 100190, China
[2] University of Chinese Academy of Sciences; Beijing, 100190, China

In this study, the phase distribution in the regenerator of pulse tube cryocooler is calculated by a one-dimensional model. The model follows the thermodynamic processes of gas parcels under the conditions of different phase distributions in regenerator and gives the thermodynamic parameters of gas parcels throughout the processes. According to the thermodynamic parameters, the performance of the pulse tube cryocooler is calculated and the influence of the phase distribution is analyzed in Lagrangian's view. The model also calculates the phase distribution under the conditions of different regenerative materials in regenerator. By using appropriate regenerative material combination，the phase distribution can be optimized and better performance of pulse tube cryocooler can be obtained. This simulation result can be useful in regenerator designing and performance optimization of pulse tube cryocooler.

Periodic Flow Hydrodynamic Resistance Parameters for Multiple Regenerator Filler Materials at Cryogenic Temperatures [TP2-4]

M.D. Perrella, S.M. Ghiaasiaan

Georgia Institute of Technology, Atlanta, GA 30332, USA

The regenerator is a critical component of all Stirling and Pulse Tube cryocoolers. It generally consists of a microporous metallic or rare-earth filler material contained within a cylindrical shell. The accurate modeling of the hydrodynamic and thermal behavior of different regenerator materials is crucial to the successful design of cryogenic systems. Previous investigations have used experimental measurements at steady and periodic flow conditions in conjunction with pore-level CFD analysis to determine the pertinent hydrodynamic parameters, namely the Darcy permeability and Forchheimer coefficients. Due to the difficulty associated with experimental measurement at cryogenic temperatures, past investigations where performed at ambient conditions. These results are assumed to be accurate for cryogenic temperatures since, for fully-developed flow, the Darcy and Forchheimer coefficients should depend only on the geometry of the porous medium. There is, however, a pressing need in the literature to determine the hydrodynamic parameters for several regenerator materials under prototypical conditions and verify the validity of the foregoing assumption. In this analysis, regenerators filled with several common materials including spherical Er50Pr50 powder were assembled and tested under periodic helium flow at cryogenic temperatures. The mass flow and pressure drop data was correlated with a porous media CFD model to determine the Darcy Permeability and Forchheimer coefficients. These results are compared to the previous investigations at ambient temperature conditions, and the relevance of room-temperature models and correlations to cryogenic temperatures is critically assessed.

Influence of Regenerative Material on Performance of 6K Level High Frequency Pulse Tube Cryocooler [TP2-5]

Quan J[1], **Liu YJ**[1], **Li XY**[1,2], **Liang JT**[1]

[1] Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, 100190, China;
[2] University of Chinese Academy of Sciences; Beijing, 100190, China

As very low temperature high frequency pulse tube cryocooler has been a hot topic in the field of pulse tube cryocooler, improving the cryocooler's performance is a common goal of researchers. By integrating the former results, we found that regenerative material is a key factor for the improvement of pulse tube cryocooler's efficiency. In this paper, some experiments were conducted to find the regenerative material which is suitable for 7K, besides this, methods of simulation and experiment were used to investigate the influence of stacking style for performance of 7K high frequency pulse tube cryocooler. Finally, the lowest temperature has dropped from 8.8K to 6.7K and more than 10mW cooling power is able to be provided at 8K with a two-stage thermal-coupled high frequency pulse tube cryocooler used. The results of the cryocooler create a possibility of space application for terahertz detectors.

Real gas effects on the COP of regenerators working at low temperatures [TO4-1]

Q. Cao

Institute of Refrigeration and Cryogenics, School of Mechanical Engineering, Tongji University, Shanghai 201804, PR China

Real gas properties impose profound effects on regenerators at temperatures close to and below the critical point of the working fluid. The enthalpy flow associated with the pressure dependence, abbreviated as the pressure-induced enthalpy flow, generally affects the energy balance of regenerators. Thus the COP of regenerators working with helium gas is usually seriously decreased at temperatures near 4 K. However, the pressure-induced enthalpy flow is actually negative at some temperature above the critical point. Will the negative pressure-induced enthalpy flow increase the COP? The influence mechanism has not been clearly determined yet. In this paper, the thermodynamic analysis will be carried out. The expressions of the COP of regenerators at low temperatures will be derived.

Numerical Simulation and Experimental Analysis of Stirling type Pulse Tube Refrigerator with an Active Phase Control [TO4-2]

S. Yang, Z. P. Zhou, Y. N. Wu, Z. H. Jiang, A. K. Zhang

Shanghai Institute of Technical Physics, Chinese Academy of Sciences
No.500 Yu Tian road, Shanghai, 200083, P. R. China

The free warm expander pulse tube is a novel type of cryocooler for long life applications, in which the inertance tube and the reservoir are replaced by a secondary piston. In this study, a Stirling type pulse tube refrigerator with an active phase control has been experimentally investigated. An electrically driven and mechanically damped linear compressor, which is directly connected at the warm end of the pulse tube, is used as the active phase controller (APC). The influences of the temperature, the phase angle between two pistons and the swept volume of two pistons on the performance of the pulse tube refrigerator were discussed. A numerical model of Stirling type pulse tube refrigerator with an active phase control was performed using a two-dimensional axisymmetric CFD. The predicted performances of the pulse tube refrigerator are in reasonable agreement with the experimental data.

An Overview of the Theoretical Research on Vibration Suppression for Space Cryocoolers [TO4-3]

Z. Z. Zhang[1,2], Y. Gao[1,2], J. Y. Zhang[1,2], Y. D. Lu[1,2], K. Z. Zhu[1,2]

[1] Institutes of Cryogenics and Electronics, Hefei, 230043, China
[2] The Provincial Laboratory of Cryogenics and Refrigeration, Hefei, 230043, China

Space cryocoolers are miniature refrigerators operated to cool inherently sensitive space-borne infrared instruments to cryogenic temperature. Initial cryocooler characterization includes power, temperature, vibrations, mounting techniques, and heat rejection. Of particular important is vibration suppression, since the cooler-generated vibration excites spacecraft structural resonances and prevents on-board sensors from achieving their operational goals with respect to resolution and pointing accuracy. Most space coolers are Stirling and pulse tube coolers that have compressors with a series of discrete harmonics at their operating frequency and multiples thereof; nearly all have adaptive active vibration suppression systems built into their drive electronics that reduce the peak unbalance forces to acceptable levels. The best practice relies on a concept of actively assisted momentum cancellation; meanwhile the controls must be adaptive because vibration dynamics are expected to change over time. The vibration suppression originated from the expanders is implemented in terms of a mass-spring passive balancer, a "counter-balancer" motorized linear counterbalance driven by a separate controller, and the expander rigid mounting technology.

This paper establishes the mathematical description of both the vibration export and vibration suppression, reviews the vibration suppression technologies of typical linear-drive space cryocoolers over the past 25 years, outlines the history of development about typical performance of the various active and passive vibration suppression systems, and presents a universal derivation of the cooler mass-spring dynamics.

Electric-Mechanical-Acoustic Coupling Characteristics for Pulse Tube Cryocoolers [TO4-4]

L. Y. Wang, Y.X.Guo, Z. H. Gan

Institute of Cryogenics and Refrigeration, Zhejiang University, Hangzhou, 310027, China
Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, China

A pulse tube cooler driven by a linear compressor can be equivalent to a network consisting of electric, mechanical and acoustic parts, among which the coupling is a critical issue for improving cooling performance. However, it is still a research area that remains poorly understood. In this work, we obtain a coupled phasor diagram containing electric, mechanical and acoustic parts using vector analysis method, which reveals the coupling characteristics inside a pulse tube cryocooler, especially the electric-to-acoustic conversion efficiency, the power factor and so on. This is expected to help with the design and performance improvement of a pulse tube cryocooler.

Performance assessment of a pulse tube cryocooler using different regenerator configurations [TO4-5]

M. S. Kamran, Z. Haider, H. O. Ahmad N. Hayat, S.M. Ghiaasiaan[1]

Department of Mechanical Engineering, University of Engineering and Technology, Lahore, Pakistan. 54890.
[1] G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology; Atlanta, GA 30332-0405

Regenerator being the key component of a pulse tube cryocooler (PTC) serves as a temporary heat storage as well as a heat exchange medium to and from the working fluid oscillating in the system. Regenerator performance is strongly dependent upon its filler type, (e.g. wire mesh, thing wires, particles etc.), size and material. Regenerators are often either cylindrical or annular in geometry. However, some recent CFD simulations have shown that with these monotonic configurations the periodically flowing working fluid essentially bypasses some parts of the regenerator.

An investigation was carried out to examine the feasibility of reducing the size and enhancing the efficiency of a PTC regenerator by streamlining its geometry in order to reduce or eliminate the unused parts of the regenerator. Starting with selected fully designed and optimized PTC systems, their regenerator components were simulated in detail using periodic boundary conditions borrowed from system-level models. The geometric configuration of the regenerators was then modified, in order to reduce the regenerator volume while maintaining its performance. The results confirm that such volume reduction is feasible.

Design of Miniature Bellow in a Conceptual Joule-Thomson Cooler [TO4-6]

F. Can[1], A. Erdogmus[1], M. Baki[1], M. Aktas[2], M. Güler[2]

[1] Dept. of Mechanical Design, ASELSAN INC, Ankara, Turkey
[2] Dept. of Mechanical Engineering, TOBB University of Economics and Technology, Ankara, Turkey

Fluid flow control is required in many engineering problems. Different mechanisms can be applied for fulfillment of this objective. Since there is a depleted gas source in open cycle Joule-Thomson (JT) coolers, resource should be used cautiously for maintaining sustainability for limited operation times. Without any controller, the temperature drop time will be longer or the operation time will be shorter. In the literature, most of the JT coolers employ bellows as a controller. Bellows filled with high pressure gas can be applied to decrease consumption of coolant. It regulates the gas flow area. However in the design and production phases, different concerns should be taken into considerations. Generally, one side of bellows has connected with a probe. The probe contacts with the coolant which is liquefied by Joule-Thomson effect. When the cryogenic temperature is detected, bellows experience contraction because of pressure and temperature gradient. As a result, the bellow shrinks and the needle contacted with the cold of the bellow moves towards the bellow. Flow area will be decreased. On the other hand, the decline in temperature from the room temperature to cryogenic temperature makes a pressure decrease inside the bellow. It is the other reason for structural contraction. In the design phase of JT devices, those two mechanisms should be modeled sensitively. In this study, three dimensional conceptual model of bellow is simulated by using numerical methods. Steady-state behavior is determined based on the temperature dependent material properties, e.g., thermal expansion coefficient, thermal conductivity and elasticity modules. The displacement is calculated depending on the inside pressure and temperature distribution on the surface of bellows. A comparison is accomplished among different inside pressures and outside temperature distributions. By this way, the sources of contraction will be evaluated and the most important component is determined.

Measurement of RRR for aluminum alloy based on a cryocooler [TO4-7]

C.H. Yin, B. Wang, X. Tao, H. R. Deng, Z.H. Gan

Institute of Cryogenics and Refrigeration, Zhejiang University, Hangzhou, 310027, China
Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, China

Three main methods of measuring alloy RRR (residual resistivity ratio) at present were introduced, the respective advantages and disadvantages were compared. Then the new test method based on the cryocooler was proposed. Through theoretical analysis and experimental verification, it is known that not only the RRR value of the material, but also material resistance values at various temperatures could get by this method which has the unique advantages compared from the current three main methods. Finally, the measured results of cryocooler and those from PPMS were compared, which demonstrated the accuracy of the measurement results and the rationality of the test method based on cryocooler.

Status of AIM Space Cryocoolers [WO5-1]

M. Mai, C. Rosenhagen, Th. Wiedmann, S. Zehner, I. Ruehlich

AIM INFRAROT-MODULE GmbH, Theresienstr. 2, 74072 Heilbronn, Germany

The growing market of commercial space applications and satellite programs has significantly increased the demand for infrared detectors. High performance Infrared (IR) detector systems are mostly equipped with Stirling or Pulse Tube Coolers to provide sufficient cryogenic cooling for maximum electro-optical performance. The focus for these cryocoolers is on specific performance, reliability and life time but also on cost. To fulfill these demands AIM has focused on Integrated Detector Cooler Assemblies (IDCA) with long life cryocoolers also being used for tactical applications.

Design of this cooler family is based on all-welded compressors featuring flexure bearing and moving magnet technology with customer specific thermo-mechanical and electrical interfaces. In distinction to most of the tactical applications a Pulse Tube is used instead of a Stirling coldfinger.

Some years ago, AIM delivered a MW-IR-IDCA with a SF400 Pulse-Tube cooler for a Korean Space program. This unit was launched in March 2015 and is the first European Pulse-Tube cooler in space.

An overview of ongoing AIM space cryocooler development activities will be presented. This includes latest cooling performance maps, environmental tests, and life test results of the SF-cooler family. Status of life time testing with > 65,000 real-time hours at elevated temperature and high power operation will be presented.

The reliability of the system can be increased by a redundant cooler system. For a standard compact IDCA a fully redundant cooling system cannot be achieved. Therefore a switching valve has been developed to allow operation of a Pulse Tube with a redundant compressor. This activity was supported by German DLR Space Agency in a study "Reliability and redundancy concepts for space cryocoolers used in IDCA solutions". The improvement of this valve is the topic of phase II. The valve was optimized in regard to reliability and lifetime. An overview about these activities will be presented.

Design of Superconducting Gravity Gradiometer Cryogenic System for Mars Mission [WO5-2]

X. Li, F. Lemoine, H. Paik[1], M. Zagarola[2], P. Shirron, C. Griggs[1], M. Moody[1], S. Han[3]

NASA Goddard Space Flight Center, Greenbelt 20771, MD, USA
[1] University of Maryland, College Park, MD 20742, USA
[2] Creare LLC., Hanover, NH 03755, USA
[3] University of Newcastle, Australia

Measurement of a planet's gravity field provides fundamental information about a planet's mass properties. The "static" gravity field reveals information about the internal structure of a planet, including crustal density variations that provide information on the planet's geological history and evolution. The time variations of gravity result from the movement of mass inside of a planet, on the surface, and in the atmosphere. NASA is interested in a Superconducting Gravity Gradiometer (SGG) as an instrument with which to measure the gravity field of a planet from orbit. An SGG instrument is under development with the NASA PICASSO program which will be able to resolve the Mars static gravity field to degree 200 in spherical harmonics, and the time-varying field on a monthly basis to degree 20 from a 255 x 320 km orbit. The SGG instrument has a precision two orders of magnitude better than the electrostatic gravity gradiometer that was used on the ESA Gravity Field and Steady-State Ocean Circulation Explorer.

The SGG instrument operates at the superconducting temperature of 6 K. This study developed a cryogenic thermal system to maintain the SGG at the design temperature in Mars orbit. The system includes fixed radiation shields, a low thermal conductivity support structure and a cryocooler. The fixed radiation shields use double aluminized polyimide to emit heat from the warm spacecraft into the deep space. The support structure uses carbon fiber reinforced plastic, which has low thermal conductivity at cryogenic temperature and very high stress. The low vibration cryocooler has two stages, which the high temperature stage operates at 65K and the low temperature stage works at 6K, and the heat rejection radiator works at 300K. The total power budget is 160 W for the cryocooler.

Testing of a GM Compressor for Deployment Onboard SOFIA Aircraft [WO5-3]

B. Helvensteijn, A. Kashani, L. Hofland, J. Wang, F. Pichay, R. Rowan, A. Gee, P. Fusco[1], G. Sasaki[1], J. Brown[1], S. Rosner[2], C. Rkasacher[3]

MEI Company, Moffett Field, CA 94035, USA
[1] NASA-ARC, Moffett Field, CA 94035, USA
[2] Wyle Labs, Moffett Field, CA 94035, USA
[3] Max Planck Institute, Bonn, Germany ryocooler Institute, Redondo Beach, CA 90278, USA

This paper presents results from vibration, temperature and pressure environmental acceptance tests performed on a Sumitomo Heavy Industries (SHI) model CSA-71A cryocooler compressor intended for installation in the Stratospheric Observatory for Infrared Astronomy (SOFIA) main cabin to support the upGREAT science instrument.

The first series of tests were performed on a large moving platform at the NASA-Ames Research Center's Vertical Motion Simulator with slow (1 Hz) bouncing of the compressor to various g-force levels: 0.1 g to 0.5 g, at 0.1 g intervals. The next series involved tilting the running compressor over a range of angles to be expected in flight on board SOFIA. After this sequence the compressor was mounted on a shake table where it was subjected to vertical and horizontal random vibration from 10 to 2000 Hz over a range of g-forces.

For the last sequence of tests the compressor was placed inside an environmental chamber, which was to simulate variations on board SOFIA: Altitude variation by changing the chamber's air pressure, and by changing the chamber temperature settings.

Lifetime Test and Heritage on Orbit of SHI Coolers for Space Use [WO5-4]

K. Narasaki, S. Tsunematsu, K. Otsuka, H. Sugita[1], Y. Sato[1], K. Mitsuda[1], T. Nakagawa[1], T. Nishibori[1]

Sumitomo Heavy Industries, Ltd.
[1] Japan Aerospace Exploration Agency (JAXA)

Sumitomo Heavy Industries, Ltd. (SHI) has developed two types of small stirling coolers and two types Joule-Thomson (JT) coolers with temperature range from 80K to 1K level for space use since 1991. Ground lifetime tests of four types coolers were conducted to demonstrate their long life and reliability. Three single-stage Stirling coolers were tested for 113640, 105027 and 101429 hours from 1998 and a two-stage Stirling cooler was tested for 72906 hours. Two 4-K class coolers with He^4 was tested for over 2.5 years and 3.8 years and a 1-K class coolers with He^3 was tested for over 1 year from last year. These coolers have shown good results on orbit. Three single-stage Stirling coolers were carried on the X-ray astronomical satellite “SUZAKU” (launched in 2005), Japanese lunar polar orbiter” KAGUYA” (launched in 2007), and the Japanese Venus Climate Orbiter “AKATSUKI” (launched in 2010 and after 5 years passed, successfully has gone into Venus orbit in November 2015). Two units of a two-stage Stirling cooler were carried on the infrared astronomical satellite “AKARI” launched in 2006. A 4-Kclass cooler was carried on the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) aboard the Japanese Experiment Module (JEM) of the International Space Station (ISS). SMILES was launched in 2009. Next Japanese X-ray astronomy satellite “ASTRO-H” included a 4K-class cooler, two two-stage Stirling coolers and two single-stage coolers will be launched in February 2016. This report describes the updated results and operating status of ground lifetime testing and achievements on orbit of SHI coolers for space use.

Efficient miniature pulse tube cooler [WP3-1]

H. Chen[1], E. Xing[1,2], Q. Tang[1], Y. Xun[1], J. Cai[1], J. Liang[1]

[1] Technical Institute of Physics and Chemistry, CAS, Beijing 100190, China
[2] University of Chinese Academy of Sciences, Beijing 100190, China

This paper describes a new miniature pulse tube cooler developed by the Technical Institute of Physics and Chemistry, CAS. The mass of the small cooler is 1.6kg and the frequency is higher than 100Hz. It is scaled from TIPC's former cooler heavier than 5kg for the frequency of 50Hz. At higher frequency, the swept volume of the linear compressor could be reduced, so both the compressor and the cold finger could be scaled down. The small cooler substantially retains the cooling efficiency and can provide 2W@80K with the input power of 45Wac at a reject temperature of 298K. This paper describes the performance of the small cooler over a range of input powers and reject temperatures.

Fabrication of MEMS Linear Actuator [WP3-2]

T. E. Hemanth Kumar, R. Karunanithi, S. Jacob

Centre for Cryogenic Technology, Indian Institute of Science,
Bangalore – 560012, India

This paper describes the Fabrication of MEMS Linear Actuator. The authors present a linear actuator fabricated using photo lithography and surface micromachining. The Oxide etching is done by sacrificial layer etching method and actuator structure release by Critical point Drying (CPD) to prevent stiction. The performance of the actuator is measured using Laser Doppler Vibrometer (LDV). The displacement is plotted against the frequency, which can be interpreted to give the resonant frequency for having maximum displacement. The structure is excited using a constant DC offset voltage of 2V and variable frequency AC of 5 volts. The LDV is used to measure the displacement of the suspension, by sweeping the frequency from 0 kHz to 100 KHz. The present design shows an actuator having beam length of 650μm with observed resonance at 20 KHz.

Development of a Miniature Coaxial Pulse Tube Cryocooler for a High Pure Germanium γ-Detector [WP3-3]

Q. Tang[1], Y. Xun[1], J. Cai[1], Y. Xun[1]

Technical Institute of Physics and Chemistry, CAS, China

High pure germanium γ-detectors usually work in cryogenic temperature and are very sensitive to the mechanical vibration. Because of the low vibration of the cold head, pulse tube cryocoolers are ideal cooling sources for high pure germanium γ-detectors in portable detection device.

A miniature coaxial pulse tube cryocooler, weighting less than 2.5Kg, is developed to cool high pure germanium γ-detector. The cold finger of the cryocooler can support about 800 gram. The structure of the cold finger is designed to avoid that the natural frequency of vibration being close to the working frequency.

Overview of Micro-Miniature Stirling Cryocoolers for High Temperature Applications [WP3-4]

X.P. Chen, H. Sun, X.L. Nie

Kunming Institute of Physics, Kunming, 650223, P.R. China

Micro-miniature Stirling cryocoolers for high temperature applications are rapidly developed in the last years to meet market trends. The paper compares micro-miniature Stirling cooler for HOT applications with miniature cooler for 2^{nd} FPA base on the four sub-systems of cooler. Thermal dynamics is inherent impetus to SWaP, so the regenerator is the key component of coolers. The paper also presents the novel micro-miniature cooler and CDE for HOT.

Experimental Study for Optimizing the Cold Finger of a Miniature Stirling Cryocooler [WP3-5]

Z Z Zheng, Y Gao, W G Shan, B Wang, C L Yin

Institute of Cryogenics and Electronics, Hefei, 230043, China
The Provincial Lab of Cryogenics and Refrigeration, Hefei, 230043, China

The cold finger of a linear split miniature Stirling cryocooler was optimized in order to improve the performance. The optimization of the key parameters of cold finger, spring stiffness Ks, displacer length L and the stroke S by theoretical study and experimental results increases the assembly qualified rate of from 70% to 90%. In addition, the optimization of the assembling structure of the spring, matrix and displacer in experiments increases the performance of the cryocooler to 1.8W@80K at room temperature and 1.2W@80K at high temperature. The investigation provides some reference to the design of cold finger of a linear split Stirling cryocooler.

Study of a 300 Hz Three-Stage Traveling-Wave Thermoacoustic Heat Engine by Computational Fluid Dynamics [WP4-1]

GY. Yu[1], JY. Xu[1,2], W. Dai[1], ZH. Wu[1], EC. Luo[1]

[1] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China

A 300 Hz three-stage traveling-wave thermoacoustic heat engine (TSTHE) might be a desired pressure wave actuator for pulse tube cryocooler due to its attractive virtues of no moving components, potentially high thermal efficiency and large specific power (output power divided by mass). In this work, a 2D computational fluid dynamics (CFD) simulation has been conducted on a 300 Hz TSTHE which was designed and optimized with the thermoacoustic software. Fundamental characteristics such as the distributions of dynamic pressure and volume flow rate have been studied. Moreover, interesting features such as the acoustic streaming and multi-dimensional effect have been presented and discussed. The study brings to light the complicated flow and heat transfer process and sets the basis for further improvement.

Numerical Investigation of Environmental Temperature on Performance of Integral Crank-Driven Stirling Cryocooler [WP4-2]

Y.J Hong, J. Ko, H.B. Kim. S.J. Park

Korea Institute of Machinery & Materials, Daejeon, 31403, Korea

Typical performance factors of the Stirling cryocooler are cool-down time, cooling capacity, power consumption and efficiency. These factors depend on operating conditions of the cryocooler such as charging pressure of the helium gas, rotational speed of driving mechanism, thermal environment and etc..

The cooling capacity and power consumption are directly related to its thermal environment. The efficiency of the Stirling cryocooler increases with increasing cooling temperature, while the efficiency decreases with increasing environmental temperature.

In this study, effects of the environmental temperature on performances of the integral crank driven Stirling cryocooler were investigated by numerical analyses using the SAGE software. Thermodynamic losses due to regenerator inefficiency, pressure drop, shuttle heat transfer and solid conduction are taken into account. Contributions of each loss to the cooling capacity as change of the environmental temperature are showed as a result.

Investigation of a 40K Single Stage Pulse Tube Cryocooler [WP4-3]

X.T. Liu, J. Quan, Y.J. Liu, M.G. Zhao, J.T. Liang

Technical Institute of Physics and Chemistry, CAS, Beijing, China

A single-stage high capacity coaxial pulse tube cryocooler is designed to cool down the infrared photon detector .The parameters such as regenerator diameter, frequency, input power, phase shifter are experimented and optimized. The pulse tube cryocooler achieve no-load temperature of 25K and cooling capacity of 2.4W at 40K with input electrical power of 250W rejecting at 310K.

Progress in Development of High Capacity Stirling Cryocooler Using a Linear Compressor [WP5-1]

J. Ko, H. Yeom, Y. Hong, H. Kim, S. In, S. Park

Korea Institute of Machinery & Materials, Daejeon, 34103, Korea(S)

A reliable and efficient high-capacity cryocooler is essential for the industrialization of HTS electric power devices. Previously, we developed a Stirling cryocooler with a dual-opposed linear compressor as a pressure wave generator. The piston and displacer are supported with a flexure spring and arranged with gamma-type configuration. A slit-type heat exchanger is adopted for the cold and warm-end, and the generated heat is rejected by cooling water. In previous test, it showed 47.8 K of the lowest temperature, cooling capacity of 440 W at 78.1 K with 6.45 kW of electric input power and 19.4 % of Carnot COP.

In this study, we improve the cryocooler by increasing thrust force of linear compressor and changing regenerating material. In cooling performance test with the improved cryocooler, the dynamic behavior is analyzed from the measured waveforms of voltage, current, displacement and pressure. The developed cryocooler in this study reaches to 43.2 K with no-load and shows cooling capacity of 650 W at 76.8 K with 8.81 kW of electric input power and 21.5 % of Carnot COP.

Development of a Mechanical-Magnetic Hybrid Refrigeration System for Hydrogen Liquefaction and Recondensation [WP5-2]

J. Baik[1], S. Karng[2], I. Oh[2]

[1] Florida Solar Energy Center, Cocoa, FL 32922, USA
[2] Korea Institute of Science and Technology, Seoul 02792, South Korea

A design study of a mechanical-magnetic hybrid refrigeration system has been performed to demonstrate feasibility of small scale hydrogen liquefaction and recondensation by cryocoolers in a single cryostat. The Florida Solar Energy Center and the Korea Institute of Science and Technology have developed a 1 L/hr scale hydrogen liquefaction system using a commercially available G-M cryocooler in 2013. As an extension of the collaboration efforts, we have been developing a hydrogen recondensation system that is performed by a custom made magnetic refrigerator inside of the former hydrogen liquefaction unit.

Various thermal loads on cryocoolers including heat loads in current leads, AC losses in magnet, heat leaks into the cryostat and inner components, and recondensation cooling load are thoroughly identified and analyzed to minimize overall system losses and maximize recondensation rate. In this paper, a design scheme and analysis results for a mechanical-magnetic hybrid refrigeration system will be discussed more in detail.

Development Status of a High Cooling Capacity Single Stage GM Cryocooler [WP5-3]

Q. Bao, M. Xu, K. Yamada[1]

Technology Research Center, Sumitomo Heavy Industries, Ltd., Nishitokyo-city, Tokyo 188-8585, Japan
[1] Cryogenics Division, Precision Equipment Group, Sumitomo Heavy Industries, Ltd., Nishitokyo-city, Tokyo 188-8585, Japan

Continuous improvement of high temperature superconducting (HTS) materials leads to a thriving development of various applications including superconducting motor, superconducting power transmission cable and superconducting power generator, etc. Those applications, in common, require a high-capacity and highly reliable cooling solution to keep the superconducting material being under proper temperature.

To meet such requirement, a high capacity GM cryocooler which can provide about 650 W cooling power at 80 K was developed. Since the physical size of this prototype unit is considerably larger compared with current available GM cryocoolers, parameters including regenerator size and valve timing should be redesigned carefully in order to get an optimized performance.

An unsteady-flow, 1-D simulation method was used to predict the behavior of the prototype cryocooler, and the result was used to form the guideline of the basic design. After the first prototype unit became available, the design was improved by feedbacking the experiment results of prototype units. In this paper, both the simulation method and experimental results will be reported.

Performance Analysis of the Active Magnetic Regenerative Refrigerator with the Conduction Cooled HTS Magnet [WP5-4]

I. Park, S. Jeong

KAIST, Daejeon, Republic of Korea

An active magnetic regenerative refrigerator (AMRR) with the conduction cooled high temperature superconducting (HTS) magnet is designed and experimentally investigated. Key components of the AMRR are two-stage layered active magnetic regenerator (AMR), conduction cooled HTS magnet, and the helium gas flow system. Since magnetic refrigerants are only effective in the limited temperature range near the Curie temperatures, the layered structure with four magnetic materials (GdNi2, Gd0.1Dy0.9Ni2, Dy0.85Er0.15Al2, Dy0.5Er0.5Al2) is employed on the AMR to increase the temperature span of the AMR. The AMR is designed to operate with the temperature range between 80 K and 20 K. The HTS magnet is cooled down by the two-stage GM cryocooler and generates maximum magnetic field of 3 T to the AMR. 9 kW DC power supply, a solenoid current switch and an external dump resistor are used for a continuous ramping operation of the HTS magnet. Oscillating helium flow in the AMR is generated and controlled by the helium compressor, rotary valve and two solenoid valves. This paper describes the experimental results of the AMR system and the technical issues on the results are discussed.

Toward a Quantified Understanding of Cryocooler Contamination [WP5-5]

P. Spoor

Chart Inc. – Qdrive, 302 Tenth Street, Troy, NY 12180, USA

It is well-known that small amounts of condensable contaminants can hurt the performance of a cryocooler. The solutions to this problem are also well-known: use low-outgassing materials, vacuum bake and/or purge until clean, and only use fill gas known to be pure. Verification is a challenge, however, because many months of runtime are required to verify stability. At the same time, as lower-cost mass-produced cryocoolers are being developed, there is considerable incentive to enable quick turnaround of changes in design and manufacturing methods, and to specify the processes that will provide acceptable cleanliness with the least cost and processing time. To that end, we have found it useful to quantify acceptable levels of contamination based on results in the literature, derive a simple model of contaminant outgassing, and develop associated experiments to measure the level of contamination (i.e. the number of grams of contaminant that will outgas and eventually freeze in the cold end of a cryocooler). This presentation will review acceptable contamination levels, the simple model of outgassing, and long-term test data on both clean and contaminated coolers, comparing their performance with the predictions of the model.

20K Cryogenic Helium Forced Flow Circulation Loop [WP5-6]

T. Trollier, A. Ravex, J. Tanchon, J. Lacapere

Absolut System SAS, 38170 Seyssinet Pariset, France

MgB2 based superconducting electro-technical equipment under development require distributed high cooling power in the 20K temperature range.

For such applications, Absolut System designed a supercritical (20 bar) helium forced flow circulation loop with a net cooling capacity requirement in the range of 70-100W at 20K.

The circulation loop makes use of two Cryomech AL325 mono stage Gifford-MacMahon type coolers as the cold source. In order to enhance the efficiency and to reduce the foot print, a cryogenic circulator Noordenwind type from Cryozone is used for the forced flow instead of a traditional room temperature compressor and counterflow heat exchangers. Thermal shielding is provided with pressurized LN2.

The design optimizations will be reported in this paper, as well as outcomes of manufacturing and preliminary performance testing.

Design of Long Life Linear Compressor Without Oil [WP5-7]

K. Z. Zhu[1,2], K. Yang[1,2], Y. Yang[1,2]

[1] Institute of Cryogenics and Electronics, Hefei, 230043, China
[2] The Provincial Laboratory of Cryogenics and Refrigeration, Hefei, 230043, China

A new type of long life compressor without oil is design. Key parts of linear motor, gap seal structure, and suction and discharge valve are designed, and the prototype is developed. The last work in this paper is to leave the experimental results and analysis.

Challenges in Electronics Design and Qualification for Earth Observation Pulse Tube Space Cryocoolers [WO6-1]

A. Gardelein, R. Gary

Air Liquide Advanced Technologies, Sassenage, France

Since more than 10 years, Air Liquide Advanced Technologies has engineered a wide range of cryocooler systems addressing diverse applications, thus translating into different performance ranges on cooling power, thermal stability, or mechanical vibration.

For Earth Observation applications, the critical performances of a cryocooler system are the cooling efficiency, the temperature stability, and the ability to keep the exported vibrations levels low. Such performance requirements induce many challenges for electronics driving and controlling the cryocooler. Those challenges cover domains such as power electronics, small signal acquisitions or digital logic design.

The aim of the paper is to show how important it is to associate electronics design at the highest level of system design. For instance one major contributor to system wall-plug efficiency is the electrical power factor of the cryocooler, which drives directly the maximum output of power supply and hence power components performance. On digital side the choice of communication bus, or the control loops drive which technology to use to implement the control logic, and again impacts directly the overall system efficiency.

Eventually selection of electrical parts is mainly driven by two factors. Some of the critical components are either under ITAR restriction or are not qualified according to appropriate standards. The former concerns mainly FPGAs, 16-bits ADCs, PWM controllers. For the latter several components generally need a qualification program to be used on satellites, such as thermal sensors, hermetic connectors and force sensors.

James Webb Space Telescope Mid Infra-Red Instrument Instrument Cryocooler Electronics [WO6-2]

D. Harvey, T. Flowers, N. Liu, K. Moore, D. Tran, P. Valenzuela, B. Franklin[1], D. Michaels[1]

Space Systems Division, Northrop Grumman Aerospace Systems, Redondo Beach, CA 90278
[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

The latest generation of long life, space pulse-tube cryocoolers require electronics capable of controlling self-induced vibration down to a fraction of a newton and coldhead temperature with high accuracy down to a few kelvin. Other functions include engineering diagnostics, heater and valve control, telemetry and safety protection of the cryocooler subsystem against extreme environments and operational anomalies. The electronics are designed to survive the thermal, vibration, shock and radiation environment of launch and orbit, while providing a design life in excess of 10 years on-orbit. A number of our current generation high reliability radiation-hardened electronics units are deployed on-orbit on space flight payloads. This paper describes the features and performance of our latest flight electronics designed for the Pulse-Tube and Joule-Thomson cryocoolers that providing 6K cooling for the James Webb Space Telescope (JWST) Mid Infra-Red Instrument (MIRI). The electronics is capable of highly accurate temperature control over the temperature range from 4K to 15K. Self-induced vibration is controlled to low levels on all harmonics up to the 16^{th}. A unique active power filter controls peak-to-peak reflected ripple current on the primary power bus to a very low level. This paper provides a design overview and ground-test data for the MIRI Joule-Thomson and Pulse-Tube flight Cryocooler Control Electronics units.

Low Temperature RSP2 Production Cryocooler and Electronics Performance [WO6-3]

T. Conrad, B. Schaefer, R. Yates, D. Bruckman, M. Barr

Raytheon Space and Airborne Systems, El Segundo, CA 90245, USA

The Low-Temperature Raytheon Stirling / Pulse Tube 2-stage (LT-RSP2) hybrid cryocooler is a long-life, robust machine designed to operate efficiently at a first stage temperature of 55K and a capacity of 5W and a second stage temperature of 10 K and a capacity of 300mW. The LT-RSP2 design was finalized in mid-2009, with fabrication of the prototype unit taking place in late 2009 and early 2010 and execution of the production program in 2011 – 2016. It has recently been mated to a set of production electronics and subsequently undergone characterization and dynamometer testing. The results of this testing are presented along with aspects of the production cryocooler and electronics designs.

Ball Aerospace Scalable Configurable Cryocooler Electronics (SCCE) [WO6-4]

E.D. Marquardt, S. Horacek, J. Simons, and J.S. Marquardt

Ball Aerospace & Technologies Corp., Boulder, CO 80301, USA

Perceiving a need for space-qualified tactical cryocoolers suitable for shorter, higher risk-tolerant missions, Ball established a new approach to cryocooler electronics. An entirely new architecture, rooted in past experience and optimized with today's technology, was developed that could be scaled to different power needs and could be configured for different missions or coolers as appropriate. To reflect this flexibility, the new architecture is called the Scalable Configurable Cryocooler Electronics (SCCE). The first SCCE iteration drove a Sunpower MT cryocooler to a measured efficiency over 95% with 3 W tare power. Control of an active balancer for vibration reduction was also demonstrated. The second SCCE iteration drove a Ball SB235E Stirling cryocooler. This iteration demonstrated the same electronics hardware could be used to drive different cryocoolers with only minor software changes. The design has 2 high power drive channels and two low power channels. This allows the same design to be used for two independent tactical coolers or a single larger aerospace Stirling class cooler. It is also possible to replace one channel with a small power supply for a single board solution to drive a small tactical cooler under 25 W. Thus, a single hardware solution can drive coolers ranging from 15 W to 350 W or higher with minor changes to parts selection and software. Various operational modes are possible including constant power, constant temperature, constant stoke or open loop. These can be combined so that the power mode becomes a limit so that a user can select a temperature set point, and the cooler will be controlled from ambient down to cryogenic temperatures without violating the power limit.

Characterization Testing of Iris Cryocooler Electronics [WO6-5]

K. Frohling, T. Luong, R. Purcell

Iris Technology, Irvine, CA 92614, USA

Two versions (100W and 200W) of the Low Cost Cryocooler Electronics (LCCE) have been developed by Iris Technology in collaboration with the Jet Propulsion Laboratory (JPL) to provide radiation hardened, high performance, modular, affordable cryocooler electronics. To date, the LCCEs have been used to drive and control a wide range of linear coolers, including the AIM SF100 (pulse tube and Stirling versions), Thales LPT 9510, Thales LPT9310, Lockheed Martin Microcryocooler, Northrop Grumman Micro Pulse Tube Cooler, and the Ricor K527. Both of these new LCCEs include input ripple filters to mitigate the current ripple impressed on the input DC power and vibration mitigation to reduce the vibration exported by the cryocooler. This paper describes the performance testing of these LCCE devices, including test results and performance demonstrations of the LCCEs.

Integrated Cryocooler Assemblies for Miniature Satellite Applications [WO6-6]

M. Jambusaria, A. Burkic, J.Olson[1]

Iris Technology Corporation, Irvine, CA 92616, USA
[1] Lockheed, Martin Space Systems, Palo Alto, CA 94304, USA

The dramatic increase in small satellite use for commercial and government applications can be linked to their growing technological capabilities. But as requirements for remote sensing and science gathering missions grow more demanding, the need to mature small cryocooler systems enabling high performance mid-wave infrared (MWIR) and short-wave infrared (SWIR) sensors becomes more evident. To this end, the Microsat Cryocooler System (MCS) and Cubesat Cryocooler System (CCS) are radiation-hard, space-qualified integrated cryocooler assemblies (ICA) for miniature satellite platforms. The MCS and CCS have been developed on AFRL and NASA SBIRs, respectively, and are designed with a high-reliability miniature cryocooler, a set of miniature Low Cost Cryocooler Electronics (mLCCE), supporting thermal management components, and isolation structures.

The mLCCE supports any of a wide range of linear cryocoolers in its design output power range (nominally 25W) and with minor adaptation, can accommodate rotary coolers as well. This paper highlights the evolution of the mLCCE supported by test results from the brassboard phase of the more recent CCS program and the flight module phase of the more mature MCS program. For the MCS, a space-grade mLCCE has been built, integration tested with multiple cryocoolers, and qualified to TRL-6. These test results are discussed herein, and the overall CubeSat-compatible mechanical subsystem design is also presented, including a description of the thermal management approach.

In addition to discussing advances in miniature cryocooler electronics, this paper also presents innovation in miniature cryocoolers, thus improving the overall ICA design. The CCS focuses on further refining the mLCCE design, and in-partnership with Lockheed Martin, has targeted mLCCE integration with a first in size-class, two-stage miniature cryocooler utilizing Lockheed Martin’s existing TRL-6 microcompressor. Electronics test data and cryocooler performance estimates are also presented, documenting more recent ICA development efforts.

Cooling Power of a 4K-GM Cryocooler Using $Er_xHo_{1-x}N$ as Regenerator Materials [WO7-1]

T. Nakagawa, T. Miyauchi, T. Shiraishi, K. Shoda, T. A. Yamamoto, Y. Fujimoto, S. Masuyama[1]

Osaka University, Suita, Osaka 565-0871, Japan

[1] National Institute of Technology, Oshima College, Oshima, Yamaguchi 742-2193, Japan

$Er_xHo_{1-x}N$ is promising as a new magnetic regenerator material for 4K-GM cryocoolers because, depending on the composition *x*, $Er_xHo_{1-x}N$ has a large peak of specific heat at a temperature range from 4 to 12K[1, 2]. When these nitrides are actually used as a regenerator material for 4K-GM cryocoolers, it is possible to cool below 4.2 K (liquefaction temperature of He)[3, 4]. Since particle sizes and filling amount of $Er_xHo_{1-x}N$ were not unified in the previous works, the optimum composition *x* of $Er_xHo_{1-x}N$ obtaining maximum cooling power was not known.

In present work, we packed 41 g of $Er_xHo_{1-x}N$ (x = 1, 0.75 and 0.5) spheres with a size of 180-212 at the low temperature side of -stage regenerator of a GM cryocooler (SRDK 101D, 0.1 W at 4.2 K) instead of $HoCu_2$. $Er_xHo_{1-x}N$ was obtained by nitriding Er_xHo_{1-x} alloy spheres in hot isostatic pressing process (200 MPa of N_2 gas at 1823 K for 2 h).

The cooling power (CP) of the cryocooler was measured with different nitride composition. When the ErN (*x* = 1) spheres were packed, the CP at 4.2 K was 0.153 W. 0.206 and 0.187 W of CP were observed at 4.2 K when the $Er_xHo_{1-x}N$ with *x* = 0.75 and 0.5 were used, respectively. The lowest achieving temperature of the cryocooler was 2.3 K when $Er_{0.75}Ho_{0.25}N$ was used. From these results, $Er_{0.75}Ho_{0.25}N$ is the optimum composition for regenerator material for 4K-GM cryocoolers among $Er_xHo_{1-x}N$.

[1]S. Nishio et al., J. Appl. Phys. 99 (2006) 08K901.

[2]T. Nakano et al., Mater. Res. Soc. Symp. Proc. Vol. 1492 (2013) 53.

[3]T. Nakano et al., Appl. Phys. Lett. 101 (2012) 251908.

[4]K. Shoda et al., J. Cryo. Super. Soc. Jpn. 50 (2015) 132.

Flexible Thermal Link Assemblies Solutions for Space Applications [WO7-2]

T. Trollier, J. Tanchon, J. Lacapere, P. Renaud, J.C. Rey, A. Ravex

Absolut System SAS, 38170 Seyssinet Pariset, France

ABSOLUT SYSTEM is designing and producing Thermal Link Assemblies (TLA) to be used on board space observation programs (CNES observation programs including IASI-NG, MTG ESA program, etc.)

The TLA have the main following functions:

- to ensure a high conductive coupling between both cryocoolers cold tips (nominal and redundant) and detectors or Cold Optical Bench,
- to have a reduced stiffness allowing misalignment and relative dynamical displacement between cold tips and detectors,
- to filter micro-vibration coming from cryocooler cold tips toward detectors, and should also be compliant with stringent constraints which are common for space products
- to have a reduced mass
- to stay inside the static and dynamic IRD reduced volume
- to be compliant with the cleanliness requirements imposed by the detector proximity,
- to survive without performance degradation to the launch loads and to the thermal cycling.

This paper will present different technical trade-offs performed on the material candidates and production constraints. Current thermal, mechanical, and cleanliness performances on TLA FMs made of 5N high purity aluminum foils and OFHC copper foils. Several on-going TLA designs and performances will be also presented, including TLA made of Pyrolytic Oriented Graphite (POG) foils developed for a 2-stage cryostat (presented in a companion paper).

Design of a Flight Like Cryostat for 30-50K Two-Stage Pulse Tube Cooler Integration [WO7-3]

J. Tanchon, T. Trollier, P. Renaud, J. Mullié[1], H. Leenders[1], T. Prouvé[2], I. Charles[2], T. Tirolien[3]

Absolut System SAS, 38170 Seyssinet Pariset, France
[1] Thales Cryogenics BV, Hooge Zijde 14, 5626 DC, Eindhoven, NL
[2] University Grenoble Alpes, CEA INAC-SBT, 38000 Grenoble, F
[3] European Space Agency ESA-ESTEC, Noordwijk, NL

An ESA Technical Research Program (TRP - 4000109933/14/NL/RA) is run by TCBV/CEA/AS consortium for the development, optimization and testing of a cryostat actively cooled by a 2-Stage High Reliability Pulse Tube cryocooler (presented in a companion paper). The interest of this concept is to allow the operation of detectors – for example QWIP or MCT infrared detectors - at lower temperatures, in the range of 40K-45K, for an overall input power similar to the one required by current Earth Observation programs.

Several cryostat concepts have been traded-off to provide optimized mechanical, thermal and electrical interfaces between the 2-stage cryocooler, the detector assembly and the external structure while minimizing the impact of 2 stage cooling on the Detector's Assembly Integration and Test phases.

For this project, an innovative supporting structure concept has been developed by Absolut System in order to offer a good compromise between thermal and mechanical performances. High performance flexible Thermal Links Assemblies (TLA) have been also optimized using our background developed for European on-going space projects (MTG, IASI-NG and others, presented in a companion paper).

This paper will present the outputs of the conceptual study, the detailed design phase including thermal and mechanical justification and the final design description of the cryostat. The outcomes of current manufacturing will be also presented.

Performance of Sunpower Cryocooler with High Heat Capacity Regenerator [WO7-4]

Y. Kim, J. Wade, K. Wilson[1]

Sunpower® Inc., a unit of AMETEK®, Inc., 2005 E. State St., Suite 104, Athens, OH, 45701, USA

The CryoTel® MT is a Sunpower cryocooler that achieves 5 watts of lift at 77 K temperature, resulting in 17.8% of Carnot efficiency, which like all CryoTel cryocoolers is the highest in the industry for that heat lift. The performance of the MT and all Sunpower cryocoolers drops off at about 40 K due to the regenerator material. Sunpower and Creare have been working in cooperation to develop a new regenerator material that will improve cryocooler performance at lower temperatures.

Prediction shows that this new regenerator has about 2 to 4 times greater heat capacities than that of the current regenerator. Sage simulation shows that the high heat capacity regenerator would put the no load temperatures at about 30 K for CryoTel cryocoolers which would open up new several markets. Sunpower is planning to build and test a prototype cryocooler with this new regenerator.

Thermal Test Results of an Advanced 4K Regenerator with Non-Rare Earth Material [WO7-5]

W. Chen, M. Jaeger, K. Rule

Creare LLC, Hanover, NH 03755, USA

This paper presents separate effects test results of an advanced regenerator for a 4K regenerative cryocooler. The regenerator is made of a non-rare earth material. It utilizes a unique approach to significantly enhance the regenerator’s thermal capacity, which is the key to the efficient operation of a regenerative cryocooler. The regenerator employs a unique microchannel configuration that enables it to achieve high thermal performance at a low pressure drop. These performance features together will enable a regenerative cryocooler to achieve high thermal efficiency at low temperatures. To determine its effective heat capacity and heat transfer performance under prototypical conditions, the thermal response of the regenerator to a step temperature change in the inlet flow is characterized. This paper first describes the testing approach and the test setup. It then presents the measured heat capacity and the predicted values. Finally, the volumetric specific heat of the regenerator is compared with those of typical rare earth materials used in a 4K regenerator.

Mid InfraRed Instrument (MIRI) Cooler Compressor Assembly Characterization [WO7-6]

M. Petach, M. Michaelian, T. Nguyen, R. Colbert, J. Mullin

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

The Cooler Subsystem for the Mid InfraRed Instrument (MIRI) of the James Webb Space Telescope (JWST) utilizes a remotely mounted subassembly containing a compressor and gas precooler to provide pressurized and precooled gas to the Cold Head Assembly as the final cooling stage of the precooled Joule-Thomson cooler. The flight model sub-assembly, called the Cooler Compressor Assembly, has been built and has completed its in-process performance testing prior to delivery to acceptance testing. This paper describes the Cooler Compressor Assembly and summarizes its cryogenic refrigeration performance results.

Improved Power Efficiency for Cryogenics at the VLA [WO8-1]

D. Urbain, W. Grammer, S. Durand

National Radio Astronomy Observatory, NM 87801, USA

The National Radio Astronomy Observatory (NRAO) recently completed a major upgrade to the electronics in the Karl Jansky Very Large Array (VLA) telescope, including all eight cryogenic Front End receivers. With the new systems now fully deployed and operational on the 27-antenna array, the focus of development has shifted toward improving efficiency and reliability to reduce maintenance, downtime and power consumption. One of the antennas was selected as a test bed for developing new instrumentation technologies and techniques in pursuit of these goals.

A particular focus is on the cryogenic system, as it requires frequent maintenance by a crew of trained, skilled workers, and the Helium compressors consume a considerable fraction of electrical power supplied to the array. Careful evaluation of the current system and preliminary tests of new techniques have demonstrated a significant power savings is possible, along with an overall reduction in maintenance.

This paper will describe the application of a Variable Frequency Drive (VFD) for powering the cryogenic refrigerators, to tailor the flow requirement to an individual receiver and possibly extend refrigerator life. Additionally, the benefits of Multi-Layer Insulation (MLI) for the receivers are described and quantified. Combined, these should allow up to a one-third reduction in electrical power consumption, by elimination of one helium compressor per antenna. Predictions on improvements in reliability and required maintenance are also given.

Design of a Versitle Cryogenic Helium Gas Circulation System Consisting of Multiple Cryocoolers for Superconducting Power Devices [WO8-2]

N. Suttell[1], C. H. Kim, J. Ordonez[1], S. Pamidi[1]

Center for Advanced Power Systems, Florida State University, Tallahassee, Florida, 32310
[1] FAMU-FSU College of Engineering, Tallahassee, Florida, 32310

The cryogenic cooling capacity required for many superconducting applications is rather large and multiple cryocoolers, heat exchangers, and circulation pumps need to be integrated into a single efficient system. Cryocoolers have been used for High Temperature Superconducting (HTS) power applications. Most HTS power devices are cooled with liquid nitrogen and the cryocoolers have been used to sub-cool liquid nitrogen that is circulated through the application. Many applications are designed to operate at temperatures below the liquid nitrogen range and require gaseous helium or neon circulation systems. One of the challenges with cryogenic gaseous circulation systems is that the pressure drop across the heat exchanges attached to the cryocoolers and the superconducting applications is high and the circulation pumps cannot handle the pressure drops at the required flow rates. This paper describes the modelling efforts in designing a versatile cryogenic helium circulation system and the experimental validation of the design parameters. The paper also describes the potential applications of the circulation system and a case study and its performance in a superconducting power device.

Advanced Liquid Hydrogen Operations Using Integrated Refrigeration and Storage [WO8-3]

A. Swanger, W. Notardonato[1], W. Johnson[2], T. Tomsik[2]

NASA Kennedy Space Center, Cryogenics Test Laboratory, NE-M5, KSC, FL 32899 USA
[1] NASA Kennedy Space Center, Cryogenics Test Laboratory, UB-R1, KSC, FL 32899 USA
[2] NASA Glenn Research Center, Cryogenic and Fluids Branch, LTF0, Cleveland, OH 44135 USA

NASA has used liquefied hydrogen on a large scale since the beginning of the space program as fuel for the Apollo upper stages, and more recently to feed the three space shuttle main engines. The LH_2 systems currently in place at the Kennedy Space Center (KSC) launch pads are aging and inefficient compared to the state-of-the-art. Therefore, the need exists to explore advanced technologies and operations that can drive commodity costs down, and provide increased capabilities.

The Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH_2) was developed at KSC to pursue these goals by demonstrating active thermal control of the propellant state by direct addition and removal of heat using a cryocooler. The project has multiple objectives including zero loss storage and transfer, liquefaction of gaseous hydrogen, and densification of liquid hydrogen. The key technology challenge was efficiently integrating the cryogenic refrigerator into the LH_2 storage tank. A Linde LR1620 Brayton cycle refrigerator is used to produce up to 900W cooling at 20K, circulating 23 g/s gaseous helium through the liquid via approximately 1000 feet of tubing.

The GODU-LH_2 system is fully operational, and is currently under test. This paper will discuss the design features of the refrigerator and storage system, as well as the current test results.

Connecting Coolers to S/C Magnets with a Thermal-Siphon Cooling Loop [WO8-4]

M. A. Green

FRIB, Michigan State University, East Lansing, MI 48824, USA
Lawrence Berkeley Laboratory (retiree), Berkeley, CA 94720, USA

Coolers are used to cool and cool-down cryogen-free superconducting (S/C) magnets and other types of loads at cryogenic temperatures. Coolers are also used to re-condense helium boil-off gas in S/C magnet cryostats such as for MRI and NMR magnets. There is an in between case where a natural-convection thermal-siphon cooling loop is used to connect the cooler cold head to the load being cooled and cooled down. This works well when the magnet is indirectly cooled by the coolant flowing through tubes attached to the magnet cold mass. This works for a helium cryostat that has a small liquid volume. A thermal-siphon loop fluid can work with hydrogen, neon, or nitrogen, which permits the magnet to be liquid-cooled (over the proper temperature range for the fluid) to ensure that the temperature variation within the magnet is minimized. For a flammable gas like hydrogen or a rare gas like neon, the loop can be prefilled and sealed. A thermal-siphon loop will work with the coolers some distance from the magnet provided the cold head heat exchanger is far enough above the highest point in the magnet cryostat. This type of cooling system is used to cool and cool-down the cyclotron gas-stopper magnet at Michigan State University. Calculated cool-down times will be compared for a thermal-siphon cooling loop between a cold mass of 500 kg and a single Cryomech PT415 pulse tube cooler with the cooling loop filled with helium, hydrogen, and neon at initial pressures of 0.2 MPa, and 0.5 MPa.

Design a Cryocooler Platform for Effective Thermal Conductivity Measurement of MLI [WO8-5]

F. J. Li[1,2], J. Y. Yang[3], Z. H. Gan[1,2], X. Xu[3], J. M. Ying[4]

[1] Institute of Cryogenics and Refrigeration, Zhejiang University, Hangzhou, 310027, China
[2] Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, China
[3] College of Metrology and Measurement Engineering, China Jiliang University, Hangzhou, 310018, China
[4] Hangzhou Forstar Special Material Co., LTD, Hangzhou, 311112, China

Most calorimeters for effective thermal conductivity measurement of multilayer insulation use liquid cryogen to control the cold boundary temperature, the performance of multilayer insulation is determined by measuring the rate of evaporation of the boiling temperature of the liquid cryogen. But considering the safety of liquid hydrogen and cost of liquid helium, it is a challenge to do this measurement with liquid cryogen methods. With the development of cryocoolers, a vertical cylindrical calorimeter is designed by utilizing the GM cryocooler to control the cold boundary and a cooper rod to determine the performance of the multilayer insulation. Two concentric oxygen-free high-conductivity copper drums are wrapped with multilayer insulation, which are connected by copper rod. The inner drum is cooled by the 2nd stage of the cryocooler, the outer drum is cooled by connecting it to the first stage of the cryocooler. The performance of multilayer insulation is determined by measuring the temperature difference across the copper rod. The unique feature is that the cold boundary temperature can be set by the cryocooler and permits a wide range of temperature, which is great significance to match the requirements of the application.

Cryocooler-based Helium Recovery Plant for Applications Requiring Gas or Liquid with Extreme Purity [WO8-6]

M. Gabal, C. Rillo, J. Sesé[1], J. Diederichs[2], G. Rayner[2], S. Spagna[2]

ICMA (CSIC – Universidad de Zaragoza), Zaragoza, Spain.
[1] INA, Universidad de Zaragoza, Zaragoza, Spain.
[2] Quantum Design Inc., San Diego, CA, USA

A cryocooler based helium recovery plant adapted to store, compress and purify helium gas collected from one or more helium-using instruments, as well as to liquefy and redistribute the purified gas within a closed system, is presented. The recovery plant is adapted to match the purification and liquefaction rate of the system with the consumption rate of the coupled instruments in an attempt to achieve zero loss. In addition, extreme purity helium (gas and liquid) is obtained by the combination of cryocondensation of impurities and further chemical adsorption by a getter. Problems like clogging of low temperature impedances by impurities normally present in helium have been definitely solved using this plant concept.

Cryocooler for 10 MW HTS Wind Power Generator [WO8-7]

Q. Li, M. Mueller

Superconductivity Group, University of Edinburgh, EH9 3JL UK

This presentation will introduce the most lately progress of our project on large HTS power generators for offshore wind turbines, particularly its cryocooler design. Our target is to address a cost-effective approach to develop a 10 MW power generator with high power density. This generator will be comparable to conventional five MW machines in terms of machine mass, in order to reduce the cost of supporting tower foundation and make it feasible for offshore delivery. Unlike many approaches trying to use massive superconducting materials to develop fully superconducting machines, which does trigger thermal stability concerns and create almost unmanageable cooling difficulties, our scenario is to balance superconductors and conventional materials to optimize the generator design in order to achieve an acceptable ratio between mass and power. The new design, names clawpole generator, is based on homopolar topology. This new topology has a superconducting field winding on stator and modular cores on rotor, and only 15 km MgB2 or 3.4 km YBCO is applied after optimization for this 10 MW generator, which is less than 10% of other projects [1-3]. This design has a flux density of as high as 2 T. The cooling system is on stator, simple to install and easy for maintenance. A linear prototype has been construed, for experimental measurement. Modeling and experimental results match very well.

[1] A. B. Abrahamsen, N. Mijatovic, et al, Supercond. Sci. Technol. 23(3):034019 (2010).

[2] G. Snitchleer, B. Gamble, et al, IEEE Trans. Appl. Supercond. 21(3):1089-92 (2011).

[3] Y. Teral, M. Sekino, et al, IEEE Trans. Appl. Supercond. 22(3):5201904 (2012).

Development of a 3 Stage ADR for Space [THO9-1]

D.A. Paixao Brasiliano, J-M Duval, N. Luchier, S. D'Escrivan[1]

CEA/Inac/SBT, Grenoble, France
[1] CNES, Toulouse, France

The next generation of astronomy missions requires cooling down to 50 mK for high sensible bolometers such as SPICA/SAFARI for far-IR observations and ATENA/X-IFU for X-ray spectroscopy. ADR (Adiabatic Demagnetization Refrigerator) systems are a suited solution for space applications in this range of temperature. We present in this paper a design of a 3 stage ADR for the range 4 K – 0.05 K. Results of preliminary study and design of the main components such as the heat switches and paramagnetic materials are discussed.

Qualification Program of the Engineering Model of the 50 mK Hybrid Sorption-ADR Cooler [THO9-2]

L. Duband, JM. Duval

Univ. Grenoble Alpes, INAC-SBT, F-38000 Grenoble, France

For several years, we have been working on a sub-kelvin hybrid cooler concept based on the combination of a 300 mK sorption stage and a small adiabatic demagnetization stage. A first prototype of this hybrid 50 mK cooler has been developed with ESA support to demonstrate its feasibility for the IXO (International X-Ray Observatory) mission, which is now the European-led mission called ATHENA. Based on this successful development, on the knowledge gained during this work and thanks to a funding support from CNES, an advanced hybrid cooler has been designed and built to fulfill the requirements of the SAFARI instrument on board the SPICA mission as of 2014. This compact 5 kg hybrid cooler provides net heat lifts of 0.4 and 14 µW respectively at 50 mK and 300 mK, for an overall cycle duration of 48 hours and a measured duty cycle of over 78%. This result has been obtained with limited resources, 5 and 10 mW at respectively 1.8 K and 4.9 K. The cooler successfully went through its qualification program, which comprises thermal and vibration tests, and has now reached TRL 6. These results along with a description of the unit built will be presented.

Development of a Two Stage Adiabatic Demagnetization Refrigerator [THO9-3]

H. Fukuda[1,2], R. Arai[1,2], Y. Kobayashi[1,2], J. Li[2], H. Nakagome[2], T. Numazawa[1]

[1] Environment and Energy Materials Division, National Institute for Materials Science Tsukuba, Ibaraki 305-0003, Japan
[2] Department of Urban Environment System, Chiba University Chiba 263-8522, Japan

Currently, many space missions using cryogenic temperatures are being planned. In particular, high resolution sensors such as Transition Edge Sensors need very low temperatures, below 100 mK. It is well known that the adiabatic demagnetization refrigerator (ADR) is one of most useful tools for producing ultra-low temperatures in space because it is gravity independent. We studied a continuous ADR system consisting of 4 stages and demonstrated it could provide continuous temperatures around 100 mK. However, we have found to need to increase the amount of heat transferred between stage 4 and 3 in order to improve cooling power. Therefore, we have tried increasing the sectional area of the thermal strap and improving the performance of the heat switch between stage 4 and 3 when the heat switch is turned on. We show the effect of using the new thermal strap and discuss a cascaded Carnot cycle consisting of 2 ADR units.

Initial On-Orbit Performance of the Astro-H/SXS Liquid Helium and Adiabatic Demagnetization Refrigerator System [THO9-4]

M. DiPirro, P. Shirron, M. Kimball, and the SXS Team

NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

ASTRO-H is the 6th X-ray observatory launched by Japan. The Soft X-ray Spectrometer instrument on board ASTRO-H contains a complex cryogenic system extending from room temperature to 50 mK. The cooling chain consists of four 2-stage Stirling cycle cryocoolers, one JT expansion cryocooler, and a liquid helium tank; all produced by Sumitomo Heavy Industries of Japan, and a 3-stage adiabatic demagnetization refrigerator (ADR) produced by NASA. This talk will present the initial results of the SXS liquid helium and ADR subsystems. As of this writing ASTRO-H will launch from Tanegashima Space Center on February 12, 2016. The cryocoolers are designed for 5-year life and the liquid helium system for a minimum of 3 years. The 36-pixel microcalorimeter detector array operates at 50 mK. This ultra-low temperature can be produced by the ADR with either a <1.3 K liquid helium heat sink, or a 4.5 K JT heat sink when the liquid is depleted. We will report on the initial results with the helium tank at about 1.12 K and two of the three ADR stages producing 50 mK using the liquid helium as a heat sink. From ground testing we expect the ADR to hold 50 mK for 48 hours per cycle with a 45 minute recycle. Measured ground heat loads extrapolate to 4 years liquid helium life. Projections from the first few months of operation will be used to update these numbers.

Development of a 2K Joule-Thomson Closed-Cycle Cryocooler [THO9-5]

M. Crook, T. Bradshaw, G. Gilley, M. Hills, S. Watson, B. Green, C. Pulker, T. Rawlings

STFC Rutherford Appleton Laboratory, Harwell, Oxford OX11 0QX

The Rutherford Appleton Laboratory (RAL) is currently developing a 2K Joule-Thomson cooler targeted at future space science missions requiring low temperatures, for example as part of the cryogenic chain for the ESA Athena X-ray telescope. The cooler builds on previous closed cycle cooler developments at RAL; in particular the very successful 4K JT cooler that was flown on the ESA Planck mission, however the working fluid for the 2K JT cooler will be ^3He and two extra stages of compression have been added to provide a much lower return line pressure and a greater overall compression ratio. In addition the cooler will take advantage of recent improvements to the RAL linear motor design that reduces the motor size and gives a corresponding benefit to the overall mass of the compressor mechanisms. The design of the cooler is described, encompassing the compressor mechanisms, the heat exchanger system and the ancillary gas handling system, with reference to lessons learnt from Planck, and results of the test program to date are presented.

Progress on 30K-50K Two Stage EM PT Cold Finger for Space Applications [THP6-1]

T. Prouvé, I. Charles, H. Leenders[1], J. Mullié[1], J. Thanchon[2], T. Trollier[2], T. Tirolien[3]

Univ. Grenoble, Alpes, CEA INAC-SBT, Grenoble, France
[1] Thales Cryogenics BV, Eindhoven, The Netherlands
[2] Absolut System SAS, Seyssinet Pariset, France
[3] ESA-ESTEC, Noordwijk, The Netherlands

In the framework of an ESA Technology and Research Program (TRP-4000109933/14/NL/RA) lead by TCBV, and in collaboration with Absolut System, CEA/SBT has improved the performance and the EM qualification level of the two stage coaxial pulse tube developed at CEA/SBT in 2012 under a R&T program co-funded by CNES. This work will be presented in this paper.

The developments have been focused on the second stage thermal performances with breadboarding on regenerator material and phase shifting with inertance design and double inlet implementation. The EM mechanical developments have been focuses on the pulse tube warm flange with electrical feedthrough, optional V2 implementation and flanges sealed assembly. The TCBV compressor (180W electrical power), integrating design improvements, has heritage from LPTC cryocooler, for which TCBV is currently manufacturing MTG compressor flight models.

Without V2, the ultimate T will be 86 K and 22K respectively at first and second stage. With a load of 3W-1W, temperatures will raise to 111 K and 36.5 K. With V2, the ultimate T will be 82 K and 20K at first and second stage. With a load of 3W-1W, expected temperatures will raise to 108K and 35.5K.

After environmental qualification the cryocooler will be mounted in a breadboard cryostat developed by Absolut System in the framework of this TRP program (see dedicated paper). The cryocooler and the cryostat design are made in closed collaboration in order to demonstrate interest of such 2 stage configuration for demanding earth observation mission.

Raytheon High Frequency Pulse Tube Cryocooler Testing [THP6-2]

T. Conrad, R. Yates, B. Schaefer, D. Kuo, M. Barr

Raytheon Space and Airborne Systems, El Segundo, CA 90245, USA

Over the past several years Raytheon has designed and tested several pulse tube cryocoolers utilizing advanced regenerator technology, which is capable of operating efficiently at high frequencies and outperforming traditional screen regenerators. These include the Raytheon Dual-Use Cryocooler (DUC), the Raytheon Advanced Miniature (RAM) cryocooler, and a next-generation compact inline pulse tube cryocooler. In this paper, test results and performance predictions for several of these cryocoolers are presented covering an operating frequency range of approximately 60 to 100 Hz.

Small Scales Cooler: Extending Space Developed Technology into Adjacent Markets [THP6-3]

C. Chun, N. Hardy, P. Iredale, S. Barclay, N. Hill, M. Crook[1], T. Bradshaw[1], S. Brown[1], G. Gilley[1], S. Watson[1]

Honeywell Hymatic, Redditch, UK
[1] STFC, Rutherford Appleton Laboratory, Didcot, UK

Honeywell Hymatic in collaboration with STFC / RAL have further developed the prototype design of the Small Scale Cooler (SSC), presented at Space Cryogenics workshop at ESTEC 2013, to a production ready system capable of serving the original market i.e. space, but in addition serving applications such as EO/IR & radioisotope detection. The aim is to provide a SSC with low mass, cooling power of 0.75W at 77K and with high reliability built upon heritage design language.

This work builds upon the achievements of the initial prototype build by RAL with particular attention being paid to optimizing the overall cooler system efficiency, adapting the design for manufacturing at production volume and accommodating differing system integration requirements, whilst maintaining a level of commonality suitable for multiple applications.

Productization activities include full system drawing release, definition of manufacturing and process methodology to assure product quality, development of tooling and assembly equipment and procedures to build and test coolers.

The presented work describes the approach to address the requirements of both space missions and adjacent markets on a sustainable manufacturing basis.

A Pulse Tube Cryocooler Employing A Cold Compressor [THP6-4]

B.P.M. Helvensteijn, A. Kashani, J.R. Maddocks, T.C. Nast[1], E. Roth[1], J.R. Olson[1], P. Champagne[1]

MCG LLC, Middleton, WI 53562, USA
[1] Lockheed Martin, Palo Alto, CA 94304, USA

Future NASA missions will require cryocoolers providing cooling capacities in excess of 0.3 W at 35 K with heat rejection capability to temperature sinks as low as 150 K at input powers up to 10 W. Under a contract from NASA-Goddard Space Flight Center a single-stage u-shaped pulse tube cooler (PTC) that employs a cold compressor has been developed to demonstrate this capability. The compressor is a Lockheed Martin “Mini” compressor. The cold head was designed using the Sage™ cryocooler modeling program. Predictions of the designed PTC indicate that the goal of 0.3 W at 35 K with 10 W of power input can be achieved at the rejection temperature of 150 K. To simulate the 150 K rejection temperature the PTC system is heat sunk to a cold plate cooled by a GM cryocooler.

This paper presents the design, fabrication and results from the preliminary tests performed on the PTC.

The Study on the Effect of Gas Contamination in Stirling Cryocooler [THP6-5]

C. L. Yin[1,2], Y. Gao[1,2], K. Yang[1,2], X. H. Fan[1,2], K. Z. Zhu[1,2]

[1] Institute of Cryogenics and Electronics, Hefei, 230043, China
[2] The Provincial Laboratory of Cryogenics and Refrigeration, Hefei, 230043, China

One of the most important characteristics of a spaceborne Stirling cryocooler is its reliability over a lifetime. The wear abrasion and gas contamination existing in Stirling cryocoolers are the main failure modes that influence the reliability of the spaceborne Stirling cryocoolers. While design improvements have reduced the probability of the wear abrasion, the excessive gas contamination is still a major risk, typically in excess of 10 years.

Aimed at the gas contamination failure mode in the Stirling cryocooler, experiments were realized in order to study the effect of contamination on the working gas in the Stirling cryocooler operating at 80 K in the paper. The accelerated contamination experiments were performed to quantify the effect of impurity gas. The curve of the outgassing rate in the Stirling cryocooler as a function of the time was obtained and discussed. The results supported the reliability design and test of Stirling cryocooler.

Experimental Investigation of Piston-Free Expander Accompanied by Cold Linear Compressor [THP7-1]

J. Park, S. Jeong

Cryogenic Engineering Laboratory, School of Mechanical and Aerospace Engineering, Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon, Rep. of Korea

This research focuses on the study of Stirling-type pulse tube refrigerator (PTR) in conjunction with a linear compressor that produces a mechanical power (PV power) at a ‘cold environment’ (‘cold’ means colder than ambient condition including cryogenic state.). The generated PV power is directly generated at cryogenic temperature and transmitted to the cold expansion volume without experiencing precooling process. Implementing a cold reservoir as a heat rejecter and regulating the entire operating temperature range of the PTR under sub-atmospheric temperature will enable a PTR to operate efficiently under cold environment like space.

The experimental investigation is conducted with the cold linear compressor operating at 78 K as a proof of concept; cooling power of 1 W at the cold expansion temperature of 20 K (no-load temperature of 18.7 K) is achieved. This PTR including the cold linear compressor is expected to be further optimized for the whole system operating between 78 K and 20 K at the resonant state. This paper covers both the preliminary test results and further discussions for an ‘optimized’ PTR system.

The Performance of Parallel Threaded Adjustable Inertance Tubes [THP7-2]

W. Zhou, J.M. Pfotenhauer, G.F. Nellis

Department of Mechanical Engineering, University of Wisconsin Madison, 1500 Engineering Dr. Madison, WI, USA 53706

The cylindrical threaded adjustable inertance tube creates an acoustic element using the engagement of two threads. It is therefore possible to change the characteristics of the element easily and during operation by adjusting the rotational position of the outer screw thread. The threaded adjustable inertance tube has the capability to shift the phase angle between pressure and flow between 0^0 and -30^0, as demonstrated by previously reported experimental test results and supported by predictions made using the distributed component model. However, the performance of the current iteration of the device is limited by the leakage paths that are inherent between the engaged threads of the two screws. Since the working fluid flows through the leak to the average pressure in the channel formed by the root of the two screws, it is reasonable to connect these two flow channels in parallel to eliminate the leakage effect. Therefore, this paper reports the performance of the parallel threaded adjustable inertance tube using the appropriately modified distributed component model by eliminating the leaks terms and introducing another inertance tube in parallel with the original one. The preliminary modeling results suggest that the phase angle shift ability of the modified device will increase from 0^0 to -30^0 to 60^0 to -60^0 by using two inertance tubes in parallel.

Diaphragm-Type Mechanism for Passive Phase Shifting in Miniature PT Cryocooler [THP7-3]

S. Sobol, G. Grossman

Technion – Israel Institute of Technology, Haifa, Israel

Properly operating Pulse Tube (PT) cryocooler requires flow-to-pressure phase shifting at the hot end for providing close to zero phase within the regenerator and the cold heat exchanger. Typical optimum flow-to-pressure phase at the hot end is around -60 degrees; thus, the phase shifting mechanism should provide a distinct inertial behavior with a certain capability to dissipate acoustic power.

The most common method of creating the proper phase shift involves the use of Inertance Tube (IT), a long and thin tube with a reservoir attached to its far end. However, as a PT cryocooler is scaled down, the IT efficiency degrades due to the rapid increase of the resistive fluid impedance. Additionally, miniaturization of the cryocooler is generally accompanied by an increase of the operating frequency, which, in turn, magnifies the ineffectiveness of the IT further. Combination of the IT with a bypass flow tubing is also not sufficient for adequate shifting of the flow-to-pressure phase in ultra-miniature PT cryocoolers.

In fact, the only available method of creating the proper phase in a miniature high-frequency PT cryocooler entails the use of a warm mechanical expander. We propose to construct an expander consisting of a passively oscillating mass suspended on soft silicone diaphragms, which are frictionless, provide perfect dynamic seal, easy to miniaturize, and perform the necessary function of a viscous damper. The research includes an analytical model, numerical simulations and actual prototype of the proposed phase shifting mechanism tested on our MTSa ultra-miniature PT cryocooler.

Investigation on the Phase Shifting Characteristics of the Inertance Tubes in Small Scale Pulse Tube Cryocoolers [THP7-4]

Q. Tang, Y. Xun, H. Chen, J. Cai

Technical Institute of Physics and Chemistry, CAS, China

Phase shifting characteristics of the inertance tube in small scale pulse tube cryocoolers are investigated experimentally. It was found that the length of inertance tube with a smaller diameter has more significant influence on the optimal frequency of the pulse tube cryocooler than the inertance tube with a bigger diameter.

The influence of inertance tube on the compressor dynamic behaviors is also investigated. It was found that in the cases of that the compressor working under resonance frequency, the dynamic behavior of compressor responds more intensely to the variety lengths of inertance tube.

Passive Mechanical Device for Phase Shifting in a Pulse Tube Cryocooler [THP7-5]

D. Radchenko, G. Grossman[1]

Ricor Cryogenic and Vacuum Systems, Ein Harod Ihud, Israel
[1] Technion – Israel Institute of Technology, Haifa 32000, Israel

Pulse tube cryocoolers have been proposed as a variation of the Stirling cycle, where the displacer is eliminated and replaced by a pressure wave generated by some passive mechanism. While the efficiency of the cryocooler is thereby reduced relative to the reference Stirling, elimination of the problematic piston at the cold end contributes greatly to the reliability and ease of operation of the device.

The flow at the warm heat exchanger of this device must be at an optimal phase angle relative to the pressure. Various passive mechanisms have been proposed to generate the proper phase shift, including a combined inertance tube and reservoir. Neither works well for miniature cryocoolers, because of the limited phase shift abilities. The objective of this study is development of a passive mechanical mechanism for phase shifting, to serve in an existing miniature Pulse Tube cryocooler, and replace the combined inertance tube and reservoir.

Passive piston supported on flexure bearings was proposed as a mechanical mechanism for phase shifting. The passive piston development included modeling of the pulse tube cryocooler with the proposed mechanism by a simplified theoretical model based on phasor theory, and numerical simulation and optimization of design parameters of the pulse tube cryocooler with the proposed mechanism for phase shifting by commercial software (Sage®). For the comparison of the theoretical model with experiments it was necessary to measure the passive piston displacement at high frequencies; a contactless displacement measurement system was designed for this purpose. The concept of using a mechanical mechanism for flow phase shifting in pulse tube cryocooler was thus validated.

The paper describes the theoretical and experimental results and their comparison. Conclusions and recommendations for further work are presented.

Miniature Stirling Cryocoolers at Thales Cryogenics: Qualificaiton Results and Integration Solutions [THO10-1]

D. Willems, R. Arts, G. de Jonge, J. Mullié, T. Benschop

Thales Cryogenics BV, Eindhoven, The Netherlands

In 2015, Thales Cryogenics has presented new miniature cryocoolers and cooler drive electronics for high operating temperatures (HOT). In this paper, an update is given regarding the qualification program performed on these new products. Integration aspects are discussed, including an in-depth examination of the influence of the dewar cold finger on sizing and performance of the cryocooler.

The UP8197 and UP8497 and the corresponding cooler drive electronics will be placed in the reference frame of the Thales product range of high-reliability linear cryocoolers. Compatibility of the cryocoolers design with new and existing ¼” dewar designs is examined, and potential future developments are presented.

Characterization Testing of Lockheed Martin Standard Micro Pulse Tube Cryocooler [THO10-2]

I. McKinley, D. Johnson, J. Rodriguez

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

This paper describes the thermal performance, exported vibration, and magnetics testing and results of a Lockheed Martin standard micro pulse tube cryocooler. The thermal performance of the microcryocooler was measured in vacuum for heat reject temperatures between 150 and 300 K. The cooler was driven with Thales XPCDE4865 drive electronics for input powers ranging from 4 to 20 W and drive frequency between 84 and 98 Hz. The optimal drive frequency was dependent on both input power and heat reject temperature. In addition, the exported forces and torques of the cooler were measured with the cooler driven by Thales CDE7232 drive electronics for input powers ranging from 4 to 20 W and drive frequency between 88 and 96 Hz. The exported forces were dependent on both input power and drive frequency. Moreover, the automatic vibration reduction function of the drive electronics was able to decrease the force in the compressor axis to below 10 mN 0-peak. Finally, the DC and AC magnetic fields around the cooler were measured at various locations.

Development of Microcryocoolers for Space and Avionics Applications [THO10-3]

T. Nast, J. Olson, P. Champagne, E. Roth, E. Saito[1], B. McCay[1], A. Kenton[2], C. Dobbins[3]

Advanced Technology Center, Lockheed Martin Space Systems Company, Palo Alto, CA 94304, USA
[1]Santa Barbara Focalplane, Lockheed Martin Missiles and Fire Control, Goleta, CA 93117, USA
[2]DCS Corporation, Shalimar, FL 32579, USA
[3]U.S. Army and Aviation and Missile Research Development and Engineering Center (AMRDEC), Redstone Arsenal, AL 35898 USA

Lockheed Martin's Advanced Technology Center has developed a series of microcryocoolers for a range of applications including avionics and space sensors and instruments. These pulse tube coolers are very low mass, approximately 350 grams, and use long-life clearance seal and flexure bearing technology which is extensively employed for space missions of 10 years or more.

We will discuss the capability and configuration of these units, which includes a new compact design specifically developed for fast cool down avionics applications as well as other high and low power versions with a range of cooling capabilities. While these units were initially developed for high operating temperature focal planes (150 K), they can provide cooling at temperatures as low as 65 K, and are capable of power input as high as 70 W. The low mass and compact envelope makes the Lockheed Martin microcryocooler an excellent candidate for cube sat applications requiring long mission lifetime.

Ongoing programs and life testing activities will be discussed.

Multimodal Tuned Dynamic Absorber for Split Stirling Linear Cryocooler [THO10-4]

A. Veprik, A. Tuito[1]

SemiConductor Devices POB 2250, Haifa 31021, Israel
[1]Israel Ministry of Defense, Kirya, Tel Aviv, 64734, Israel

Forthcoming low size, weight, power and price split Stirling linear cryocoolers may rely on single-piston, contact seals compressors. Because of the high driving frequency, the weight of moving assemblies and their strokes are small. This results in low levels of cooler induced vibration adequate for most of applications.

In vibration sensitive payloads, the inline mounting of compressor and expander units results in consolidation of vibration export along single axis, thus allowing for effective use of single inline mounted translational Tuned Dynamic Absorber (TDA). Unfortunately, this configuration is not always feasible due to the packaging constrains.

The authors are presenting novel type of tunable multimodal TDA, having one translational and two tilting modes tuned to the same frequency. In one of the possible embodiments, a round planar spring supports the proof mass comprising two coaxial rings. The primary ring is connected to the peripheral portion of the planar spring and the secondary (correction) ring is movable along the primary ring, thus allowing for the fine adjustment of the aggregate moment of inertia without changing aggregate mass. Because of the planar spring design and tuning feature, frequencies of the tilting modes may be finely matched to the fixed frequency of translational mode. The dynamic reactions (force and moment) produced by such a TDA are simultaneously counterbalancing vibration export produced by compressor and expander units of the U-shaped cryocooler and, therefore, reducing both linear and angular dynamic responses of the payload.

High-efficiency Joule-Thomson Cryocoolers with an Ejector [THO10-5]

H.S. Cao, S. Vanapalli, H.J. Holland, C.H. Vermeer1, T. Tirolien2, H.J.M. ter Brake

University of Twente, P.O.B. 217, 7500 AE, Enschede, NL
[1]SuperACT, Marterstraat 66, 7559 AJ Hengelo, The Netherlands
[2]European Space Agency, P.O.B. 229, 2200 AG, Noordwijk, NL

Joule-Thomson (JT) cryocoolers have no moving parts and therefore are vibration-free. These cryocoolers are attractive for cooling small optical detectors in space for earth observation and science missions. JT cryocoolers produce cooling by expanding high-pressure gas through a JT restriction. This, however, is a highly irreversible entropy-generating process. If work could be extracted during the expansion process, the efficiency of the cooling cycle would be significantly improved. In this paper, a JT cooling cycle with an additional ejector is proposed. The high-pressure gas, as the primary fluid of the ejector, is used to compress the low-pressure gas leaving the evaporator, thus reducing the cold-end temperature or/and the input power of the compressor. Compared to a basic JT cycle, the improvement in the COP of the cycle with an ideal ejector is analyzed. The effects of frictional and mixing losses on the real performance of an ejector are estimated through numerical simulations, which aid the understanding of ejector theory and provides information for optimizing the ejector under certain operating conditions. Moreover, the real improvement in the performance of the cycle though the addition of an ejector and its dependence on the position of the ejector in the cycle will be discussed.

LPT6510 Pulse Tube Cooler for 60-150 K Applications [THO11-1]

R. Arts, J. Mullié, J. Tanchon[1], T. Trollier[1]

Thales Cryogenics B.V., Eindhoven, The Netherlands
[1] Absolut System SAS, Seyssinet-Pariset, France

The LPT6510 cryocooler, based on the Thales Cryogenics MPTC compressor originally developed under ESA TRP and the Absolut System SSC80 Pulse-tube cold finger, was designed to fill this niche in an elegant manner. In this paper, an update is given regarding the ongoing development on this cryocooler.

Key performance data as well as an overview of the MAIT processes as compared to the LPTC compressor heritage is shown. A novel new design for the buffer-inertance assembly will be presented. The presentation will conclude with a discussion on various integration aspects. This will include the heat sink and mounting design as well as the induced vibration characteristics of this cooler when operated with and without active vibration control.

LPT9310 COTS Cooler for ECOSTRESS [THO11-2]

R. Arts, J. Mullié, D. Johnson[1], J. Rodriguez[1], I. McKinley[1], T. Benschop

Thales Cryogenics B.V., Eindhoven, The Netherlands
[1] Jet Propulsion Laboratory, Pasadena, CA 91109 USA

For the past four years, a significant effort has been performed at the Jet Propulsion Laboratory to characterize commercial-off-the-shelf (COTS) Pulse-tube cryocoolers for use in cost-effective spaceflight applications. This has resulted in the selection of the Thales LPT9310 cryocooler for the ECOSTRESS instrument that will fly on the Japanese Experiment Module (JEM) of the International Space Station.

The Thales LPT9310 cryocooler nominally provides over 4 W of cooling capacity at 80 K, and has been produced in large quantities with a proven capability of multi-year continuous operation without any instances of cooler failure. However, this capability has only been proven in terrestrial (commercial) applications. In order to provide sufficient justification for using an off-the-shelf cooler for a flight application, additional tests have been performed on the delivered flight coolers, to attain a sufficiently controlled level of quality while leveraging the heritage of the COTS cooler. The test program philosophy will be explained, and results will be discussed.

Restrictions in both the available electrical power and the heat exchanger fluid to the instruments onboard the JEM erased the performance margin bookkept for the cryocoolers, prompting the need to find more efficient operating cryocoolers. Thales Cryogenics responded with an upgrade to the LPT9310, replacing the stainless steel pulse tube with titanium alloy, and a re-optimization of the regenerator matrix for 60K while leaving the baseline design intact. The resulting performance enhancement from the additional cryocooler efficiency at lower temperatures will be presented.

European 15K Pulse Tube Cooler for Space [THO11-3]

J. Butterworth, Yan Pennec, Sylvain Martin, M. Linder[1], J.M. Duval[2], I. Charles[2], G. de Jonge[3], J.Mullié[3]

Air Liquide Advanced Technologies, Sassenage, France
[1] European Space Agency (ESA-ESTEC), Noordwijk, The Netherlands
[2] SBT, UMR-E CEA / UJF-Grenoble 1, Grenoble, France
[3] Thales Cryogenics, Eindhoven, The Netherlands

Air Liquide, in collaboration with ESA, CEA and Thales Cryogenics, has developed and tested a 15K Pulse Tube Cooler for satellite borne applications.

This cooler is particularly adapted to the pre-cooling needs of cryogenic chains designed to reach 0.1-0.05K for focal plane cooling on scientific space missions such as ATHENA.

The design includes two cold fingers mounted on a common warm flange driven by a single high power compressor (240W PV power) specially developed for this application. The first cold finger is used to pre-cool the second, low temperature stage.

The cooler provides cooling power >0.4W at 15K with a no load temperature of 9.3K, an electrical power budget of 300W (excluding electronics) and a 287K rejection temperature. Significant cooling power at an intermediate temperature (typically 3.5W @ 90K) is also available.

Comparable results have been achieved using both active and passive phase shifting techniques. A trade-off between these two options will be presented.

Qualification of a European Large Pulse Tube Cooler System for Space Applications [THO11-4]

T. Wiertz, J. Urbano

Air Liquide Advanced Technologies, Sassenage, France

Since 2010, Air Liquide Advanced Technologies has been going through the process of preparing and conducting the qualification of Large Pulse Tube Coolers (LPTC) for earth observation and meteorological Infra Red instruments. It is the first European space cooler based on pulse tube technology. The LPTC consists in a compressor, a pulse tube and a driving electronics. It ensures cooling of infra red detectors at temperatures between 50K and 80K with cooling power between 2W and 7W.

On a total of 24 flight coolers ordered on 3 different European programs, the first flight models have been delivered.

The addressed tasks during qualification include product industrialization; verification engineering; clean room facilities set up; test bench design, manufacturing and acceptance; test engineering; qualification test conducting and test data processing. Qualification scope not only covers the integrated system, but also process and components.

Space coolers are particularly exposed to qualification risks because of their complexity. In fact, they are among the pieces of space hardware addressing the largest spectrum of technical disciplines: mechanics, heat transfer, fluid, thermodynamics, fracture mechanics, mechanisms, micro-vibrations, power electrics, analog and digital electronics, EMC, radiation…

Thanks to the involvement of the highly skilled space coolers team, we are now achieving successful qualification of the LPTC for its first application program. Main events and achievements of this qualification, together with lessons learnt will be presented.

Evolution of a 4-Stage Pulse Tube Cryocooler for 4 K Cooling in Space [THO11-5]

T. Nast, J.R. Olson, P. Champagne, E. Roth, K. Stone[1], J. Kawamura[1]

Advanced Technology Center, Lockheed Martin Space Systems Company, Palo Alto, CA 94304, USA
[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

A major concern during the early stages of 4 K cooler development was whether high operating frequency (20-40 Hz), required for size and weight reduction would work at 4 K. Commercial Gifford McMahon coolers achieved these temperatures at frequencies of a few Hz. Another more complex approach is a hybrid cooler with a pulse tube or Stirling combined with a low temperature Joule Thomson stage driven by a separate compressor.

The Lockheed Martin cryocooler is designed to meet NASA's cryocooler needs for low temperature, with application to missions akin to Terrestrial Planet Finder, Constellation-X, and other future space-science missions. Utilization as a precooler for Adiabatic Demagnetization Refrigerators is also a primary need.

Lockheed Martin has built and tested many high frequency multiple-stage pulse tube cryocoolers, achieving temperatures as low as 3 K with a unique 4-stage cold head. The simplicity of a cooler with just a single compressor, coldhead, and electronic controller makes it very appealing because of high reliability, reduced weight, and low cost. The system can easily be modified for different cooling requirements by modifying the inertance tubes.

Demonstration of Two Stage Temperature Control for Raytheon Hybrid Cryocoolers [THO11-6]

T. Conrad, B. Schaefer, D. Bruckman, D. Kuo, M. Kieffer

Raytheon Space and Airborne Systems, El Segundo, CA 90245, USA

A two stage temperature control algorithm has been demonstrated for the Raytheon Stirling/pulse tube hybrid (RSP2) cryocoolers. This algorithm adjusts the input power and Stirling displacer phase command in order to independently control the temperatures of both cryocooler stages without the addition of any trim heat. The ability to independently control the temperatures of the two stages is thus related to the unique capability of Stirling/pulse tube hybrid cryocoolers to shift cooling capacity between stages through the adjustment of the Stirling displacer phase. The Raytheon Low Temperature RSP2 (LT-RSP2) cryocooler was used to exercise the algorithm and demonstrate its performance in several scenarios, including during cooldown and under changing load conditions at constant 1st and 2nd stage temperatures.

Development of a Turn Key Cryogenic Cooling Module for Space Flight Based on a Commercial Cryocooler [THO11-7]

P. Ramsey

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

Commercial cryocoolers have significant price and lead time advantages over coolers built exclusively for the space market, but there are many challenges that must be overcome before using a COTS cooler for flight. The initial cost advantage is significantly narrowed by the cost of adapting the COTS cooler for flight.

JPL is developing a “turn key” cryogenic cooling solution based on a commercial cryocooler with the intention that it can become a standard product. The goal is to develop a complete, fully redundant cryogenic cooling solution based on the Thales 9310. The system includes the cooler, brackets to provide mounting and cooling, supporting structures, vibration isolation, thermal straps, thermal switches, and drive electronics.

The 9310 is a split pulse tube cooler in the five watt class. It is designed for ground operation. Use in space will require addition of structures suitable for securely mounting and for waste heat removal. Bond-on aluminum brackets will provide rigid structural support and include interfaces for heat pipes for cooling the compressor and expander. Low cost drive electronics provide power, as well as temperature and exported vibration control.

The two cryocoolers mount on a single central plate. Visco-elastic isolators provide vibration isolation, both to reduce launch loads into the cooler and exported forces and torques from the operating cooler. Flexible connection to the payload is provided by graphite foil thermal straps. Differential CTE thermal switches thermally isolate the non-operating cryocooler.

Experimental Verification of a Numerical Model for Predicting the Adsorption of Mixed Gases [THO12-1]

N. Tzabar, H.J. Holland, C.H. Vermeer, H.J.M. ter Brake

Energy Materials and Systems, Faculty of Science and Technology, University of Twente, Enschede 7500AE, the Netherlands

An ongoing effort is invested in developing a sorption compressor for driving Joule-Thomson cryocoolers with mixed refrigerants. In previous work we presented a numerical model that determines the adsorption of mixed gases based on the pure-component adsorption characteristics. In the present paper an experimental verification of the numerical results is presented. The experimental setup is suitable for simulating the sorption cycle in a compressor. The current research is focused on binary mixtures containing nitrogen and alkanes.

Cooling Temperature of Binary Mixed Refrigerants: Vapor-Liquid-Liquid Equilibrium Versus Vapor-Liquid Equilibrium [THO12-2]

N. Tzabar, H.J.M. ter Brake

Energy Materials and Systems, Faculty of Science and Technology, University of Twente, Enschede 7500AE, the Netherlands

Joule-Thomson cryocoolers which operate with pure gases provide stable cooling temperatures at the respective boiling points. Mixed refrigerants have enhanced specific cooling power, therefore, they enable operating at much lower pressures, relative to pure refrigerants. An attractive method for allowing a stable cooling temperature with binary mixed refrigerants is to choose mixtures which form vapor-liquid-liquid equilibria. In a previous research the cooling temperature of binary mixtures were estimated by calculating their vapor-liquid equilibrium state. Recently, the vapor-liquid-liquid equilibrium of those mixtures was calculated and the current paper presents a comparison between the results of the two methods.

Hybrid Cryogenic Refrigerator: Coupling of Pulse Tube Refrigeration and Active Magnetic Regenerative Refrigeration System [THO12-3]

Rajendra Kumar and Sumit Shoor

School of Mechanical Engineering, Lovely Professional University, Phagwara, Punjab, India-144411

The regenerative types of cryocoolers employ magnetic intermetallic compounds as matrix material to function well at low temperatures. The use of such materials and similarity in oscillating flow patterns makes it possible to couple two such systems.

This paper proposes an ideal configuration of a cryogenic refrigerator which is a hybrid of pulse tube refrigeration (PTR) system and active magnetic regenerative refrigeration (AMRR) system. The gas cooling cycle is followed by magnetic cooling cycle. Along with the components of valved PTR such hybrid system supposedly has additional heat exchanger, magnetically augmented regenerator and cold reservoir compressor which contribute to the magnetic cooling cycle. The regenerator matrix is supposed to be made up of compounds that exhibit large magnetocaloric effect (MCE) at low temperature ranges. The magnetic field swing is assumed to be from 0T to 7T. The cooling process in such system is explained and reasons for its feasibility are discussed with suitable assumptions. First and second law analyses of the hybrid cryocooler are worked upon. The cooling capacity as well as performance of the cryocooler is evaluated from 4.2K to 300K. Also the possible causes of irreversibility that can occur in such system are discussed.

The objective of this paper is to present an ideal model of a new type of hybrid cooling system working at cryogenic temperatures and to discuss the factors that facilitate the coupling of two different regenerative cooling processes.

JT Micro Compressor Test Results [THO12-4]

J.R. Olson, P. Champagne, E. Roth, T. Nast

Advanced Technology Center, Lockheed Martin Space Systems, Palo Alto, CA 94304, USA

We report the results of operational testing of a 200 gram closed-cycle Joule-Thomson Micro Compressor. This unique compressor is a modified version of our TRL 6 Pulse Tube Micro Compressor, using the same Oxford-style flexure bearing, clearance seal architecture common in highly reliable long life cryocoolers. The compressor is capable of delivering closed-loop gas flow with a high pressure ratio, suitable for driving a Joule-Thomson cryocooler.

The JT compressor was operated while charged with nitrogen gas at pressures ranging from 50 PSI to 150 PSI. Output pressure ratios were varied from 2:1 to as high as 6:1 at different gas flow values. In all cases, the compressor operated smoothly, without any indication of unusual mechanical or gas dynamics such as instabilities or excessive gas backflow through the check valves. Power conversion efficiency was calculated based on the theoretical power required to deliver specific pressures and gas flows vs. the measured compressor power. Conversion efficiency ranged from 15% for the highest pressure ratios, to greater than 30% for lower pressure ratios. These values are in close agreement with the expected efficiency of approximately 25%, based on predicted check valve, clearance seal, and surface pressurization losses.

TRL5 Vibration-Free Sorption-Based Cooler for 15-30 K [THO12-5]

H.J.M. ter Brake, H.J. Holland, C.H. Vermeer[1], J.F. Burger[2], A. Maas[3], M.Linder[4]

University of Twente, P.O.B. 217, 7500 AE, Enschede, NL
[1] SuperACT, Marterstraat 66, 7559 AJ Hengelo, NL
[2] Cooll SES, Blekerstraat 47, 7513 DR Enschede, NL
[3] Airbus DS Netherlands, POB 32070, 2303 DB Leiden, NL
[4] European Space Agency, P.O.B. 229, 2200 AG, Noordwijk, NL

At the University of Twente, a vibration-free hydrogen-based sorption cooler is under development for cooling optical detectors in future scientific space missions. Depending on the operating pressures in the system, the cooler can be used as a stand-alone cooler in the temperature range 15-30 K, or as a precooling stage for a helium cooler establishing 4 K. The sorption compressor cells of the hydrogen cooler are at a radiator temperature of 87K. A second small radiator is used to precool the high pressure gas to 51K. The gas is compressed in two stages: from 0.1 bar to 3 bar and from 3 to 50 bar by heating the sorber cells to 175K and 220K, respectively. In this compression phase the cells are isolated from the heat sink by gas-gap heat switches. The cold tip of the JT cold stage reaches 14.5K and has a net cooling power of 19 mW. We will report on an ESA project in which the TRL level of this cooler is to be increased from TRL 4 to TRL 5. In this project, carried out in cooperation with Airbus Defence and Space, the compressor cell is redesigned to withstand launch loads and to increase reliability.

Notes:

Notes:

Notes:

Notes:

	Monday, June 20		Tuesday, June 21	Wednesday, June 22	Thursday, June23	
7:00 AM			Session Chair Breakfast Meeting/Continental Breakfast	Continental Breakfast	Continental Breakfast	**7:00 AM**
8:00 AM	Foundations of Cryocoolers Short Course		Welcome Announcements [TO1] High Capacity and Commercial Cryocoolers	[WO5]	[THO9] Very Low Temperature Coolers	**8:00 AM**
8:15 AM						8:15 AM
8:30 AM						8:30 AM
8:45 AM						8:45 AM
9:00 AM				[WP3] Cryocooler Miniaturization [WP4] Stirling/PT Modeling & Simulation [WP5] High Cap Commercial/Lab Coolers		**9:00 AM**
9:15 AM					[THP6] Stirling/PT Development [THP7] PT Phase Shifting	9:15 AM
9:30 AM						9:30 AM
9:45 AM						9:45 AM
10:00 AM						**10:00 AM**
10:15 AM			Break	[WO6] Cryocooler Control Electronics		10:15 AM
10:30 AM			[TO2] Brayton and JT Cryocoolers		[THO10] Cryocooler Miniaturization	10:30 AM
10:45 AM						10:45 AM
11:00 AM						**11:00 AM**
11:15 AM						11:15 AM
11:30 AM						11:30 AM
11:45 AM			Lunch	Lunch	Lunch	11:45 AM
12:00 PM						**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			[TO3] Stirling and Pulse Tube Cryocoolers	[WO7] Advanced Cryocooler Components	[THO11} Aerospace Cryocoolers	1:15 PM
1:30 PM						1:30 PM
1:45 PM						1:45 PM
2:00 PM						**2:00 PM**
2:15 PM						2:15 PM
2:30 PM						2:30 PM
2:45 PM				Break		2:45 PM
3:00 PM			[TP1] JT/Sorption Cryocoolers [TP2] Regenerators	[WO8] Cryocooler Integration and Applications	Break	**3:00 PM**
3:15 PM					[THO12] JT/Sorption/Hybrid Cryocoolers	3:15 PM
3:30 PM						3:30 PM
3:45 PM						3:45 PM
4:00 PM			[TO4] Advanced Analysis & Modeling			**4:00 PM**
4:15 PM						4:15 PM
4:30 PM					Quantum Design Facility Tour	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 – 10:00 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**