International Cryocooler Conference 17

July 9-12, 2012

Program and Abstracts

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WELCOME

Welcome to the 17th International Cryocooler Conference (ICC 17) being held July 9-12, 2012 in Los Angeles, 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. 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 17, approximately six months after the conference. The Proceedings will include copies of the papers presented at ICC 17 that are peer reviewed to assure the quality of the proceedings.

Attendees at ICC 17 include commercial and military cryocooler users; mechanical, electrical, and software engineers engaged in cryocooler design; system engineers responsible for selecting and/or integrating cryocoolers; educators, particularly those interested in cryogenics and/or thermal management; cryogenic component manufacturers and suppliers.

We are very pleased to host the event in this exciting location! Shopping, dining, and entertainment options abound within walking distance of the beautiful Universal Sheraton hotel. With ready access to the vast array of Los Angeles County museums, entertainment and restaurants, you may find it difficult to find time for the exciting Technical Program listed in this Abstract Book.

Please join us for our Welcome Reception on Monday July 9 from 6:30 to 9:00 PM in the Starview room on the 21st floor of the Sheraton Universal hotel.

The ICC 17 conference banquet begins with a Private Studio tour of Universal Studios Hollywood followed by a reception and dinner at their Globe Theatre. You will be picked up at the Sheraton Universal hotel at 6:00 pm on Wednesday July 11. This will be a great event that you won't want to miss!

Welcome to Los Angeles and ICC 17.

Jeff Raab
Conference Chairman

Dale Durand
Program Chairman

Manny Tward
Conference Co-Chairman

Mark Michaelian
Program Co-Chairman

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 cryocooling. 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 17th International Cryocooler Conference (ICC 17) will be held July 9-12, 2012 at the Sheraton Universal Hotel in Universal City, California. The venue is located centrally in Los Angeles, California, a major metropolitan area with multiple tourist destinations including many world class museums, theatres, music venues, beaches, theme parks, etc. The hotel is adjacent to Universal Studios Hollywood and Universal CityWalk.

The Conference begins with a Welcome Reception in the Starview Room on the 21st floor of the Sheraton Universal hotel on Monday evening, July 9 at 6:30 PM. The Technical Program commences at 8:00AM on Tuesday, July 10. Approximately 100 papers will be presented in both oral and poster formats during the ensuing three days, concluding on Thursday afternoon, July 12 at 3:45 PM. A very full Social Program includes the Welcome Reception on July 9 and a Private Studio Tour of Universal Studios Hollywood on Wednesday July 11 that is followed by a reception and conference dinner at their Globe Theatre. The papers are being presented in consecutive Oral and Poster Sessions. For your convenience, a complete overview of the Conference Schedule is provided both on the back cover and on the website.

REGISTRATION

All attendees must register. The onsite registration fee is $655, which includes attendance at 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 tickets to the Private Studio tour of Universal Studios Hollywood and the Reception and Conference Dinner are available for an additional fee ($85).

Payments to ICC17 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. Onsite registration hours are as follows:

Monday, July 9:	12:00PM – 5:00PM
Tuesday, July 10:	7:00AM – 5:00PM
Wednesday, July 11:	7:00AM – 3:30PM
Thursday, July 12:	7:00AM – 12:00PM

WELCOME RECEPTION and CONFERENCE BANQUET

The welcome reception will be held in the Starview Room on the 21st floor of the Sheraton Universal hotel on Monday evening, July 9 from 6:30 PM to 9:00 PM. The reception includes a bar and light refreshments and hors d'oeuvres. You will be supplied with a ticket for one drink. Additional beverages are available at a cash bar.

The conference banquet will be at the Globe Theatre in Universal Studios Hollywood. Entertainment at dinner will be provided by a DJ. Shuttles will leave promptly at 6:00 PM from the Sheraton Universal Ballroom Entrance for a Private Studio tour of Universal Studios Hollywood and will then bring you to the Globe Theatre at 7:00PM for a reception on Baker Street. Following the reception, you will be served dinner catered by Wolfgang Puck from 7:45 PM until 10 PM. Trams will then return you down the mountain to the Sheraton (or you can walk, if desired). Since the venue is inside Universal Studios Hollywood that is closed to the public during evening hours, access to enter the park for the dinner will only be via the shuttles.

Your ICC registration package includes one "ticket" to the Tour, Reception and Dinner. The reception and dinner includes a soft bar with soft drinks, wine and beer. Each "ticket" includes the reception, a full dinner and drinks. Mixed drinks are available at a cash bar. Additional guest tickets are available for $85 each. These must be purchased prior to the event at registration, either online or at the onsite registration desk.

WHAT TO DO IF YOU MISS THE TRAM at 6:00 PM

- Walk out the front doors of the Sheraton Lobby
- Walk to the elevator NEXT to the parking garage. (Please do NOT go in the elevator located inside the parking garage)
- Take the elevator up one floor.
- When you exit the elevator, you will be in the drive area.
- Make a left exiting the elevator, and proceed down the sidewalk.
- This sidewalk will dead-end into the sidewalk alongside Universal Hollywood Drive.
- Make a RIGHT onto the sidewalk alongside Universal Hollywood Drive.
- You will soon approach Hotel Drive.
- Please take the crosswalk to the other side of Hotel Drive, and the base of the bridge.
- Take a LEFT over the bridge, and the bridge will let you out behind Saddle Ranch.
- Walk towards the Main Entrance to the Theme Park, then veer LEFT towards the Frankenstein Parking Structure.
- You will find the Black Iron Gates, and the entrance to the Globe Theatre on your right-hand side.

MEALS

Your registration includes a light breakfast every morning before the Technical Program (Tuesday through Thursday) at 7:00AM and refreshments during the day at breaks and coincident with Poster sessions.

All oral presenters, poster presenters and session chairs are invited to the Speaker's Breakfast at 7:00 AM in Terrace A on the day of your presentation. At that breakfast you will be able to meet and get to know the participants in your session. The Welcome Reception on July 9 will serve only hors d'oeuvres and drinks. The conference dinner will be held on July 11.

For lunch we recommend the hotel restaurants and encourage you to enjoy the many local restaurants within walking distance of the hotel, especially at Universal CityWalk.

LOS ANGELES, CA

Los Angeles County, as of the 2010 census, had a population of 9,818,605, making it the most populous county in the United States. Los Angeles County alone is more populous than 42 of the 50 individual U.S. states. The county seat is the city of Los Angeles, the largest city in California and the second-largest city in the United States after New York City. The county is home to over a quarter of all California residents and is one of the most diverse counties in the country. It includes two offshore islands, San Clemente Island and Santa Catalina Island, two mountain ranges, magnificent sand beaches and wonderful and varied climates characteristic of a semi-desert moderated by the heat capacity of the cold Pacific Ocean. The county is home to 88 incorporated cities and many unincorporated areas. At 4,083 square miles (10,570 km2), it is larger than the combined areas of the states of Rhode Island and Delaware.

There is an average of only 35 days with measureable rainfall in a year. The conference venue of Universal City is located in the San Fernando Valley at the foot of the Santa Monica Mountains. The climate in July in this interior valley has an average high temperature of 86F (30C) and an average low temperature of 62F (17C). It is quite likely that it will be sunny during the day with a low probability of any clouds.

There are many tourist, cultural, music, theatre and sport attractions in the area. As one example, there are 841 museums and art galleries in Los Angeles County, more museums per capita than any other city in the world. Another example is the almost daily summer concerts at the Hollywood Bowl, a very large amphitheatre within a few miles of the Sheraton. A short list of major museums can be found on the conference website, cryocooler.org.

For more information about Los Angeles and the many activities available to you, please visit

http://en.wikipedia.org/wiki/Los_Angeles and http://discoverlosangeles.com/

CONFERENCE HOTEL - THE SHERATON UNIVERSAL HOTEL

The beautiful Sheraton Universal Hotel is the focal point of the conference-related activities. In addition to providing preferred lodging arrangements for all ICC 17 attendees, the Sheraton is the site of the Welcome Reception, the Technical Program, and the Cryogenic Society of America (CSA) Cryocooler Course. The Sheraton is within walking distance of many restaurants, shops and entertainment at Universal CityWalk and Universal Studios Hollywood, the site of the conference banquet.

TRANSPORTATION

Driving Directions

From Los Angeles International Airport (27.8 miles or 44.5 km)Take Century Boulevard East for approximately 1 mile to the 405 Freeway North. Merge onto the 101 Freeway South heading towards Los Angeles. Exit at Lankershim Boulevard/Universal City. Turn right onto Cahuenga Boulevard and continue for approximately 2 blocks. Turn right onto Lankershim (go under the freeway) and turn right onto Universal Hollywood Drive.

From Burbank (Bob Hope) Airport (5.7 miles or 9.1 km) Exit Airport. Turn right (south) on North Hollywood Way and proceed for 1.9 miles to W. Magnolia Blvd. Turn right and proceed for 0.9 miles to Cahuenga Blvd. Turn left and proceed for 1.5 miles to Lankershim Blvd. Turn left and proceed for 0.3 miles to Universal Hollywood drive. Turn left. The hotel is on the right.

From North Travel south on Interstate 5 to Hollywood State Route 170. Travel south on State Route 170 to Highway 101 South. Exit at Lankershim Boulevard and turn right. Proceed 2 blocks on Lankershim Boulevard to Universal Hollywood Drive.

From West Travel east on Highway 101 and use the Lankershim Boulevard Exit. Turn right onto Lankershim Boulevard and proceed 2 blocks to Universal Hollywood Drive. Turn right onto Universal Hollywood Drive and proceed up the hill to the hotel.

From South Travel north on Highway 101 and exit onto Lankershim Boulevard. Turn right and travel 1 block to Universal Hollywood Drive. Turn right and proceed up the hill to the hotel.

From East Travel west on Interstate 10 to Highway 101 North. Proceed north on Highway 101 and exit onto Lankershim Boulevard. Turn right and proceed 1 block to Universal Hollywood Drive. Turn right onto Universal Hollywood Drive and proceed up the hill to the hotel.

Hired Transportation

Taxi cabs are available to and from the airports. They do not require reservations and can be obtained on short order either at the airport or at the hotel.

Shuttles to and from the airports are typically more economical than taxicabs and require reservations. Two large companies are Super Shuttle (supershuttle.com) and Prime Time (primetime shuttle.com). Fees from LAX are $20. Fees from Burbank airport are $16.

Public Transportation

Public transportation is available throughout the Los Angeles area with the Universal City Subway station and bus lines near to the hotel. Routes can be accessed at http://socaltransport.org/tm_pub_start.php. We do not recommend the use of public transportation to and from LAX unless you want a 60 to 90 minute tour of Los Angeles.

AUTHOR / PRESENTER INFORMATION

SPEAKER'S BREAKFAST

All oral presenters, poster presenters and session chairs are invited to the Speaker's Breakfast at 7:00 AM in Terrace A on the day of your presentation. At that breakfast you will be able to meet and get to know the participants in your session.

INSTRUCTIONS FOR POSTER PRESENTERS

Three poster sessions will be held Tuesday and Wednesday in the morning at approximately 10 AM and on Wednesday afternoon. The exact times are listed in the program. Presenters are expected to only attend to their poster during their respective session. We encourage all poster session papers to be posted by 9:00 AM of the day of the session and request that they be removed by 5:00 PM. Papers not removed in a timely manner will be discarded.

Each poster presenter will be provided with a poster mounting area 48" (1.22 m) 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.

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 12-13 minutes, with 2-3 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 5:00 pm of the day prior to their presentation. Presentations must be submitted in Microsoft Power Point format (but may be saved as a PDF) and should be turned in to the Publication Room (located in the Performers Room) at the conference It is strongly recommended that presenters save their Power Point presentations with True Type fonts attached. Acceptable media include CD 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 5:00 pm of the day prior to their presentation, they may be required to present their paper without accompanying vugraphs.

MANUSCRIPT SUBMISSION

Authors should submit their manuscripts to conference staff in the Publications Room, located in the Performers Room in the conference area by 5:00 PM on Tuesday July 10. Technical papers will be distributed by the publications staff for peer review prior to publication in the conference proceedings (Cryocoolers 17).

TECHNICAL PROGRAM

The Technical Program for the 17th ICC is organized into 11 oral sessions and 3 poster sessions containing 95 papers. The conference will begin on Tuesday July 10 at 8:00AM in the West Ballroom with a fifteen-minute introduction by the ICC 17 Organizing Committee. The technical sessions will begin at 8:15 AM on Tuesday, July 10th immediately following the Introduction. Technical sessions on Wednesday July 11 and Thursday July 12 will begin promptly at 8:00 AM. The conference ends at 3:45 PM on Thursday July 12.

The entire conference will be held at the Sheraton Universal Hotel, Universal City, CA. All oral technical sessions will be held in the West Ballroom. The three poster sessions will be held in the adjacent Producers room and will provide an excellent opportunity for close personal interaction with authors of these specialized topical subjects. The poster sessions will be held on the first two days of the conference and are scheduled to coincide with breaks. Light refreshments will be served during the poster sessions.

THIS ABSTRACT BOOK

This Abstract book is arranged in order of presentation of the papers. This is illustrated on the facing page with the Dates, Time, Session #, Session Name and Session Chairmen. The following Table of Contents and the Abstracts are also arranged in the same chronological order.

The abstracts and the Table of Contents are also posted on line at cryocooler.org as a searchable pdf document.

TECHNICAL PROGRAM/SESSION CHAIRS

Time	#	Session	Session Co-chairs		
		Tuesday, July 10, 2012			
8:00 AM - 8:15 AM		**Introduction**			
8:15 AM - 10:00 AM	[TO1}	**Aerospace cryocoolers 1**	S. Breon	J. Marquardt	
10:00 AM- 11:00 AM	[TP2]	**Advanced cryocooler component technology**	M. Barr	W. Chen	T. Nguyen
11:00 AM- 12:15 PM	[TO3]	**Compressors and Expanders**	A. Kashani	P. Bailey	
12:15 PM - 1:45 PM		**Lunch**			
1:45 PM - 3:45 PM	[TO4]	**JT Cryocoolers**	D. Johnson	J. Tanchon	
3:45 PM - 4:15 PM		**Break**			
4:15 PM - 5:45 PM	[TO6]	**Commercial and laboratory cryocoolers**	R. Radebaugh	Sk. Jeong	
6:30 PM - 9:00 PM		**Board dinner meeting**			
		Wednesday, July 11, 2012			
8:00 AM - 9:45 AM	[WO1]	**Advanced cryocooler component technology**	T. Fraser	J. Cha	
9:45 AM- 10:45 AM	[WP2]	**Commercial & laboratory cryocoolers / Pulse tube cryocoolers**	T. Conrad	J-M. Duval	R. Boyle
10:45 AM- 12:00 PM	[WO3]	**4K Cryocoolers**	L.Duband	S. Yuan	
12:00 PM - 1:30 PM		**Lunch**			
1:30 PM - 3:15 PM	[WO4]	**Pulsetube modeling/experiments**	C. Wang	J. Olson	
3:15 PM - 4:15 PM	[WP5]	**Advanced analysis and modeling techniques / Miniaturization and MEMS**	E. Luo	M. Ghiaasiaan	A. Veprik
6:00 PM - 10:30 PM		**Conference Event at Universal Studios**			
		Thursday, July 12, 2012			
8:00 AM - 9:30 AM	[THO1]	**Tactical Cryocoolers and applications**	I. Ruhlich	D. Kuo	
9:30 AM- 9:45 AM		**Break**			
9:45 AM- 11:45 AM	[THO2]	**Aerospace cryocoolers 2**	E. Pettyjohn	T. Trollier	
11:45 AM - 1:00 PM		**Lunch**			
1:00 PM - 1:45 PM	[THO3]	**4K Regenerators**	F. Miller	C. Kirkconnell	
1:45 PM-2:15 PM		**Break**			
2:15PM - 3:30 PM	[THO4]	**High Capacity Coolers**	M. ter Brake	P. Bradley	

Table of Contents

Raytheon Low Temperature RSP2 Cryocooler [TO1-1]

Brian R. Schaefer, Mike Ellis, Ted Conrad, Lowell Bellis

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

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 250mW. While some aspects of the expander warm-end mechanical design are carryovers from the existing High Capacity RSP2, the compressor module and expander cold head have been substantially optimized for increased efficiency and capacity at low cryogenic temperatures. The LT-RSP2 design was finalized in mid-2009, with piece-part fabrication taking place in late 2009 and early 2010. Assembly and initial testing in an ambient benchtop configuration occurred in 2010/2011. Major aspects of the mechanical and thermodynamic design will be presented in this paper, including information regarding the final operating point, performance, and packaging details. Results from the fabrication, assembly, and testing will be discussed, as will observations regarding the achieved system performance. Future testing and design enhancement plans will be discussed as well.

7 K - 15 K pulse tube cooler for space [TO1-2]

J-M Duval, I. Charles, J. Butterworth[1], J. Mullié[2], M. Linder[3]

CEA Grenoble/Inac/SBT, Grenoble, France

[1]Air Liquide Advanced Technologies,(AL-AT) Grenoble, France

[2]Thales Cryogenics, Eindhoven, The Netherlands

[3]ESA Noordwijck, The Netherlands

High sensitive bolometers as used for X-ray (e.g. XMS on Athena) or Far-IR (e..g SAFARI on SPICA) observations require cooling down to 50mK. To achieve this in a closed cycle cooling chain, offering long-life missions, a 15K pre-cooler for the JT cooler is required. One solution currently under development and funded by ESA is the 15K Pulse Tube cooler. This cooler is a 3-stage cooler providing cooling power at 15 K, 50 and 120 K. This project includes a breadboarding phase to demonstrate the feasibility of our concept, followed by the design and manufacture of an engineering. We present here the experimental results for a breadboard pulse tube cold finger providing cooling capacity from 7 K to 15 K. In a laboratory configuration, the specification of 400 mW of cooling power at 15 K has been exceeded. The configuration selected for the engineering model cooler is presented.
This configuration is based on a coaxial two-stage pulse tube cooler providing precooling to a low temperature pulse tube cooler. Details on the trade-off and experimental results are presented.

Demonstration of a 10 K Turbo-Brayton Cryocooler for Space Applications [TO1-3]

J. Breedlove, K. Cragin, M. Zagarola

Creare Incorporated, Hanover, NH, USA 03755

Creare is extending its turbo-Brayton cryocooler technology for space sensor cooling applications that require refrigeration in the 10 to 20 K temperature range. Prior Creare efforts have focused on refrigeration load temperatures primarily in the 30 to 120 K range. These systems provide a strong technology base that we are now applying to lower temperatures with support from the Department of Defense and NASA. Brayton cryocoolers have the potential to achieve unprecedented thermodynamic efficiency at these temperatures. Creare recently demonstrated operation and functional performance of a low-temperature turboalternator that is optimized to provide 300 mW of refrigeration at 10 K. In early 2012, this turboalternator will be installed in a two-stage turbo-Brayton cryocooler, and the cryocooler will be tested at temperatures from 10 to 20 K at the colder stage and 70 to 90 K at the warmer stage. This paper will review the development history and heritage, and provide results from the cryocooler performance test.

14.5 K Hydrogen-based Sorption Cooler: Design, Construction and Test Experiments [TO1-4]

H.J.M. ter Brake, J.F. Burger[1], H.J. Holland, D.R. Zalewski, C.H. Vermeer, T. Tirolien[2], M. Linder[2]

University of Twente, P.O.B. 217, 7500 AE, Enschede, NL

[1]Cooll SES, Blekerstr 47, 7513 DR Enschede, NL

[2]European Space Agency, P.O.B. 229, 2200 AG, Noordwijk, NL

At the University of Twente, a 14.5 K hydrogen-based sorption cooler is under development. It can be used as a stand-alone cooler, or as a precooler e.g. in combination with a 4 K helium-based sorption cooler. The advantage of sorption coolers is the absence of moving parts and, as a result, their vibration-free operation and potentially very long life. We developed and built a 4.5 K helium stage under ESA-TRP contract and in 2008, we started a new ESA-sponsored project on a hydrogen cooler stage. A demonstrator cooler has been designed with a gross cooling power of 35 mW at 14.5 K requiring an input of only 4.2 W as electric power fed into a sorption compressor that is heat sunk at a 87 K radiator. The required radiator area is 1.6 m^2. The compressor contains two stages consisting of cells filled with activated carbon. The cells are thermally cycled between the heat-sink level of 87 K and 200 K for the first stage and 240 K for the second, causing hydrogen to be periodically adsorbed and desorbed. As a result, hydrogen is pumped from a low-pressure buffer at 0.1 bar to a medium-pressure buffer at 3 bar, and subsequently to the high-pressure side of the cold stage at 50 bar. The flow direction in this process is controlled by passive valves. In the cold stage the working fluid is precooled by a 50 K radiator (0.1 m^2). In the paper, the design, construction and tests of this hydrogen-based sorption cooler will be presented and discussed.

150K pulse tube cooler for micro-satellites [TO1-5]

J. Tanchon, T. Trollier, Y. Icart, A. Ravex, C. Chassaing[1], J. Butterworth[1], C. Daniel[2], R. Briet[2]

Absolut System SAS, Meylan, FRANCE, 38240

[1]Air Liquide Advanced Technologies, Sassenage, FRANCE, 38360

[2]Centre National d'Etudes Spatiales, Toulouse, FRANCE, 31420

A recent need for "high temperature" cryogenic's applications [150K-200K] has emerged in Europe with observation missions on-board micro satellite platforms. Passive cooling can be used for some of these applications but sometimes, the operational constraints together with the mass and the size are too critical and require the use of mechanical cryocoolers.
To answer this need for mechanical cryocoolers, the CNES has awarded a contract to Air Liquide for the development of the overall system (cooler and electronics) with Absolut System SAS responsible for development of the cold finger and cryocooler optimization. The aim is to develop an evolution of the existing 80K MPTC (Miniature Pulse Tube Cooler) towards higher operating temperatures. This cooler has been re-designed and optimized to meet micro satellite budgets (input power, mass, size) and lifetime.
The paper presents the optimization of the cooler design with discussions on the cooler configuration trade-offs. The expected performances of the cooler are finally described.

Development Status of 50 mK Hybrid Coolers for space applications at CEA-SBT [TO1-6]

L. Duband, JM. Duval, N. Luchier

CEA / INAC / Service des Basses Températures, Grenoble 38054 FR

For several years, CEA-SBT has been developing an original concept to produce temperature down to 30 mK. This concept is based on the combination of a 300 mK sorption stage and a small adiabatic demagnetization stage. This hybrid architecture allows designing low weight and compact coolers. Because the sorption cooler is probably the lightest solution to produce sub-Kelvin temperatures, it allows the stringent mass budget of space missions to be met.
Several systems have been built from prototypes to engineering model. Different combinations are possible and the cooler can be designed as a one shot unit providing cooling power at 50 and 300 mK, or a mix of continuous stages, either at 50 mK or 300 mK or both. Most future space missions are designed as cryogen free satellite and use mechanical coolers to provide temperature down to 1.5 K. Solutions to couple our sub-Kelvin unit to these intermediate stages with limited resources have been demonstrated. Advanced solutions are being developed to maximize the duty cycle efficiency. A fully integrated engineering model intended for the ATHENA mission has been produced. Mechanical analysis and measurements validate high TRL.
A second engineering model dedicated to the SAFARI instrument on board the SPICA satellite is currently being produced. In parallel, work has also been carried out on a slightly different configuration which includes a continuous 300 mK stage. This cooler could be used in the BLISS instrument, a US candidate to SPICA.

Demonstration of a High-Capacity Cryocooler for Zero Boil-Off Cryogen Storage in Space [TO1-7]

M. Zagarola, J. Breedlove, K. Cragin

Creare Incorporated, Hanover, NH, USA 03755

NASA is planning a ground demonstration of the thermal control system for zero boil-off liquid oxygen storage. The purpose of this demonstration is to advance the technology readiness level of the overall system to 6. A key sub-system is the cryogenic refrigerator that intercepts parasitics and provides pressure control for the cryogen. Turbo-Brayton cryocoolers are ideal for these systems because they scale well to the high capacities associated with cryogen storage and can interface directly with a distributed cooling network located on a cryogen tank, obviating the need for a separate circulator. In support of NASA's program, Creare developed and demonstrated a single-stage cryocooler that provides up to nominally 20 W of refrigeration at 100 K. The cryocooler comprises components built for a prior flight program that were configured to meet the specific requirements of a cryogen storage system. The subjects of this paper are the cryocooler design, the interfaces with the cryogen storage tank, and the results from the cryocooler performance test conducted at Creare prior to delivery of the cryocooler.

Experimental Investigation of Regenerator Material on Performance of Multi-stage High Frequency Pulse Tube Cryocooler [TP2-1]

Quan Jia, Liu Yanjie, Liang Jingtao

Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry CAS, Beijing, China 100190

Multi-stage high frequency pulse tube cryocooler is a way to meet the requirements of infrared detectors, superconducting devices and equipments for deep space exploration. As thermal-coupled cryocooler's mass flows are easier to control and energy flows are more readily monitored than gas-coupling type, a 10K level thermal-coupled two-stage pulse tube cryocooler was newly designed. We used it and different kinds of regenerator material to experimentize. In this paper, besides the introduction of newly-designed two-stage pulse tube cryocooler that uses He-4 as working fluid, we mainly deal with the experiment results, find a kind of regenerator material which is fit for multi-stage high frequency pulse tube cryocooler, analyze the influence of different regenerator material filled styles on performance of the cryocooler. The experiment results shows that Er_3Ni is a better regenerator material for 10K level high frequency pulse tube cryocooler and multilayer filled style is useful for the improvement in the performance of multi-stage cryocooler. The results will provide scientific basis for the design of multi-stage high frequency pulse tube cryocooler.

Development of a Linear Compressor for Stirling-Type Cryocoolers Activated by Piezoelectric Elements in Resonance [TP2-2]

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A new drive mechanism for a linear compressor employing a piezo actuator operating in resonance was developed theoretically and was built practically during this research. The compressor is designed to drive a miniature Pulse Tube cryocooler, particularly our MTSa model, which operates at 100 Hz and requires a filling pressure of 40 bar and a pressure ratio of 1.3. Since piezo-electric stack actuators generally possess a natural frequency on the order of 10 kHz, a resonance operation of the piezo compressor at 100 Hz was achieved by incorporating the piezo ceramics into the moving piston, and, additionally, by reduction of the effective piezo stiffness using hydraulic amplification. An analytical spring-mass-damper model of the drive mechanism was developed and validated by a preliminary test setup, which showed a fine agreement between the simulations and the test results. According to the preliminary results and the simulations, the resonance operation of the piezo compressor improves the electromechanical efficiency by hundreds of percents relative to the quasistatic operation, in which the efficiency is on the order of merely ten percents. The high efficiency together with a no moving parts design can make the piezo compressor a good alternative to the electromechanical, for applications requiring long life and reliability.

Separation of Pulse tube losses based on measurement of energy flow and computational fluid dynamics analysis [TP2-3]

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Pulse tube losses are consisted of shuttle heat transfer loss, second-order flow loss, and natural convection loss. It is difficult to quantify and separate the pulse tube losses in actual operating condition. In this paper, the pulse tube losses are precisely measured and separated by measurement of energy flow and CFD (Computational Fluid Dynamics) analysis. First, two Stirling-type pulse tube refrigerators consisted of different compressors and pulse tube configurations are fabricated. The detailed physical conditions of working fluid are measured at each critical component of Stirling-type pulse tube refrigerators by varying operating frequency and charging pressure. The summation of pulse tube losses is calculated by the energy flow concept and the measured results. Second, the physical conditions of the measured results are used in the CFD analysis to separate the pulse tube losses. In this process, possibility about the separation of pulse tube losses is confirmed and the portion of each pulse tube loss is evaluated. The results of this paper can be used for better understanding the tendency of pulse tube losses and estimating each pulse tube loss in Stirling-type pulse tube refrigerators.

Real Time Phase shifting with an Adjustable Inertance Tube [TP2-4]

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As a follow up to previous exploratory measurements, we report on the phase shifting characteristics of an adjustable inertance tube coupled to a pulse tube refrigerator. The phase difference between mass flow and pressure oscillations at the inlet of the adjustable inertance tube is measured using calibrated pressure and mass flow transducers and a Labview-based lock-in amplifier. The mass flow signal is obtained from the pressure drop across a screen pack, suitably designed by balancing the competing requirements of a sufficiently large signal size and minimal acoustic power loss. The acoustic power generated by the linear compressor is approximately 1700 W while that at the inertance tube inlet is on the order of 100 W. Alternate designs for adjustable inertance tubes are explored.

Effect of Warm-End Temperature on Performance of the Pulse Tube for Stages Near 30 K [TP2-5]

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Losses within the pulse tube component of pulse tube cryocoolers can be significant, but few measurements have been made on such losses. For multi-stage pulse tube cryocoolers there is often some flexibility on the warm-end temperature of the lower-temperature stages. Little is known about how the warm-end temperature influences the effectiveness of the pulse tube component. We report measurements of pulse tube performance for a second-stage pulse tube operating nominally at ~ 30 K for varying warm-end temperatures from ~ 80 K to above 120 K. The pulse tube effectiveness at various warm-end temperatures is determined by measurements of the time-averaged enthalpy flow and the acoustic power flow in the pulse tube. Enthalpy flow is determined from measurements of the heat flow through a weak thermal link connecting the pulse tube warm end to the first-stage of the cryocooler. Low temperature, cooling power, flow-to-pressure phase measurements at the pulse tube and reservoir are presented and discussed.

Electrical Analogue Model of an Integrated Circulator [TP2-7]

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The problem of cooling gimbaled optics and LWIR focal planes can be solved by placing the entire cryocooler on gimbal. However, a large mass penalty is paid for such configurations, because the gimbal itself must grow in size and mass in order to support the cryocooler. To address the requirements of cooling across a two-axis gimbal, flexible joint, or to multiple locations on a spacecraft, we are developing an Integrated Circulator - a lightweight, continuous-flow cooling loop directly integrated into the coldhead of a Pulse Tube Cryocooler (PTC). The basis of the Integrated Circulator is a cold rectifier that converts the oscillating flow of the PTC into a steady flow of cold gas that can readily be distributed over distances of several meters to multiple loads. Because the cooling loop can be made of capillary tubing, it is easily made mechanically compliant by means of coiling, thus allowing the cryocooler to be located off gimbal. In this paper, we describe an electrical analogue model of the cooling loop and use it to investigate the dependence of average mass flow rate on buffer volume size. The calculations agree well with recent measurements.

Integrated Testing of the Iris LCCE and NGAS Micro Pulse Tube Cooler [TP2-8]

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The Northrop Grumman micro pulse tube (micro) is a long-life (>10 years), extremely compact and lightweight (<800 g) cryocooler with the capability of supporting a wide range of applications. Previously published experimental results demonstrate cooling between 50K and 150K with over 1.2 W capacity at 80K with a rejection temperature of 300K. The strong legacy of the micro to the Technology Readiness Level (TRL) 9 High Efficiency Cryocooler (HEC) makes this cooler attractive for critical, risk-averse missions. The Iris Low Cost Cryocooler Electronics (LCCE) has been designed to provide basic cryocooler electronics functionality in a radiation hard, space-compatible physical package. Much of the complexity of traditional space cryocooler electronics, such as fine multi-harmonic active vibration cancellation, has been eliminated in the interest of reducing cost, size, and mass. The targeted mass and volume design requirements for the spaceflight version of LCCE are 250 g and less than 15 cubic inches. This compact size and low mass makes the LCCE well suited for the NGAS micro pulse tube cooler. Integrated testing of the micro and a radiation hard brassboard version of the LCCE has been performed. Automated cool down, temperature stability, and high DC-AC power conversion efficiency have all been demonstrated. Test results are presented, and the Integrated testing of the micro and a radiation hard brassboard version of the LCCE has been performed. Automated cool down, temperature stability, and high DC-AC power conversion efficiency have all been demonstrated. Test results are presented, and the path forward to a space-qualified is discussed.

Testing of New Non-Rare-Earth Composite Regenerator Plates [TP2-9]

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This paper discusses a new kind of microchannel regenerator for 4 Kelvin pulse tube cryocoolers. These cryocoolers are used in applications such as military defense radio frequency transmission. The proposed regenerator design is referred to as MIRAH. The design utilizes circular silicon disks with a perforated outer edge and a center puck consisting of a non-rare-earth composite material.

Typically, a solid material is used at cryogenic temperatures to provide capacitance in regenerators at low temperatures. However, most materials have very low specific heats at 4 Kelvin. Creare is developing a non-rare-earth composite material that promises to achieve a very high specific heat. The composite material will be thermally coupled with the silicon outer ring of an exchanger disk, creating what could be a significant improvement in regenerator plates used in cryogenic applications.

This paper discusses the development of a test facility that will compare the MIRAH disks against other rare earth metal disks. The testing facility is a cryostat composed of a Dewar that bathes a stainless steel test chamber in liquid helium. The tests are carried out within the chamber at temperatures below 10 Kelvin and pressures in excess of 1 MPa which are consistent with the conditions experienced inside of a cryocooler. Thermal waves will be propagated through the regenerators and CernoxTM temperature sensors will measure the transient time. A longer time response observed in the MIRAH compared to a typical rare earth metal regenerator will suggest a greater heat capacity and therefore, an improvement in regenerator plates.

Low Vibration Split Stirling Cryogenic Cooler for Infrared Aerospace Applications [TP2-10]

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The space-borne infrared instrumentation is known to be inherently susceptible to cryocooler induced vibration, the attenuation of which usually relies on active multi-tonal momentum cancellation under supervision of a dedicated controller.
In this approach, the typical single-piston expander is actively counterbalanced by a motorized counterbalancer and the typical dual-piston compressor is counterbalanced by actively synchronizing the motion of the opposing moving piston assembly. The feedback signals are usually provided by external vibration sensors (force transducers or accelerometers).
Although compliant with the most stringent space requirements, such a conservative vibration control approach can result in using outdated, oversized, overweight and overpriced cryogenic coolers for some applications. Such a "space heritage" practice becomes increasingly unacceptable for space agencies now operating within tough monetary and time constraints.
The authors are advocating the purely passive approach to a vibration control relying on the combined principle of tuned dynamic absorber and low frequency vibration isolator having a potential to outperform the systems of active vibration cancellation with respect to overall system effectiveness. This approach warrants particularly strong consideration for cost-sensitive missions.

Verification of the Back-EMF Method for Piston Velocity Measurements [TO3-1]

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Linear compressors are used to drive pulse tube or Stirling cryocoolers, and they can be used as expanders in place of inertance tubes when inertance tubes cannot provide sufficient phase shifts between flow and pressure. Commercial linear compressors rarely incorporate position sensors, so PV power, flow rates, and flow-pressure phase at the piston are usually unknown. Use of the back EMF to measure piston velocity was previously proposed. A comparison of this derived velocity with that determined from an accelerometer attached to the piston showed good qualitative agreement. However, no measurements have been reported on its accuracy or on comparisons with position sensors. We report here on a comparison of velocity measurements determined from the back-EMF method with that from a linear variable displacement transducer (LVDT) attached to a piston of a commercial linear compressor. The back EMF is the complex voltage difference between normal operation and when the pistons are locked to prevent movement for the same current. The velocity is simply the back EMF divided by the force constant of the motor. Methods for measuring the force constant are discussed. Measurements made with the locked pistons provide the resistance and inductance of the coil. Our results show that the velocity amplitudes determined from the back-EMF method and the position sensors agree within 5 % for both a heavily loaded compressor and for one open to the atmosphere. The phase determined from the back EMF leads the phase determined from the position sensor by about 10^{o} for both 16 Hz and 30 Hz measurements. Other simultaneous measurements performed to verify self consistency are discussed. Comparisons using a second compressor with a laser position sensor are also discussed.

Partial funding by the Office of Naval Research is acknowledged.

Loss-Related Design Tradeoffs in Floating Piston Expanders [TO3-2]

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Piston expanders are widely used in cryogenic machinery, but are plagued by a multitude of thermodynamic losses which reduce their performance. Many of these losses favor different geometries or operating parameters; however, the tradeoffs between such losses are only clear if their effects are considered in aggregate. The matter is further complicated in high-pressure-ratio expanders, where widely-used analyses of fluid flow behavior in the clearance space between the piston and cylinder prove inadequate for modeling purposes.

This work examines the loss-related design tradeoffs in a particular type of piston expander known as a floating piston expander (FPE). Such expanders use differences in gas pressure instead of mechanical linkages to control piston motion, and are being incorporated into a Collins-type cryocooler capable of providing 20 and 100 Watts of cooling at 25 and 100 Kelvin, respectively. The tradeoffs are examined using a cyclic-steady-state time-domain model which considers heat transfers in the cold working volume, irreversible “blow-in” and “blow-out” through cold-end valves resulting from imperfect expansion and recompression, irreversible mixing, and the effects of the clearance space (or “appendix gap”) between the piston and cylinder. For the latter, a newly-developed model is used to solve for the gap mass flows and heat transfers; this model is well suited to the high pressure ratios and low operating frequencies of the expanders in question.

The model predicts several interesting (and often unexpected) results which should be of interest to expander designers; intentionally increasing blow-in and blow-out, for example, can improve expander performance by decreasing the required stroke and diameter and thereby reducing appendix gap losses. The results also demonstrate the cross-coupling between design variables and suggest strategies for mitigating the impact of various manufacturing constraints.

Appendix Gap Losses with Pressure-Driven Mass Flows [TO3-3]

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The clearance space or "appendix gap" between the long pistons and cylinders used in cryogenic expanders plays a key role in the performance of those machines. Losses arising from this gap are well known in the cryogenic and Stirling literature, and result from a combination of fluid flow, pressure fluctuations, and piston motion in the presence of axial temperature gradients. However, existing analyses of these losses do not include the effects of large, pressure-driven mass flows into and out of the appendix gap and are therefore not applicable to high-pressure-ratio cryogenic expanders.
To overcome the limitations of existing models, a new analysis was carried out which considers the effects of large, pressure-driven mass flows concurrently with the effects of large pressure fluctuations in the gap, cyclic piston motion, and transient conduction in both the piston and cylinder in addition to all first-order cross terms. The resulting analytical expression agrees with existing literature for heat transfer due to piston motion alone ("shuttle heat transfer") and supplements it with four additional terms describing the effects of fluid motion and pressure fluctuations as well as their interaction with piston motion.
The new appendix gap analysis was further extended to yield a complete model of the appendix gap. Since fluid density and material properties of the piston and cylinder are strong functions of temperature, one-dimensional numerical integration was used in conjunction with a shooting method to solve for the approximate temperature, heat transfers, mass flows, and pressure variations as a function of axial position along the piston, along with an estimate of the temperature of fluid exiting the gap for use in cryocooler models. The appendix gap model predicts a minimum gap loss for intermediate gap sizes as well as highly non-linear temperature profiles at large gap widths, and was successfully applied to examine design tradeoffs in a model of a high-pressure-ratio cryocooler.

CFD modelling of a Diaphragm Stirling Cryocooler [TO3-4]

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Industrial Research Ltd has developed a unique diaphragm-based pressure wave generator technology for employment in pulse tube and Stirling cryocoolers. The system uses a pair of metal diaphragms to separate the clean cryocooler gas circuit from a conventionally lubricated mechanical driver, thus producing a clean pressure wave with a long-life drive. The same diaphragm concept has been extended to support and seal the displacer in a free piston Stirling expander. Diaphragms allow displacer movement without rubbing or clearance gap seals, hence allowing for the development of cost-effective, long-life and efficient Stirling cryocoolers. A proof-of-concept prototype has achieved cryogenic temperatures.
The diaphragm's round, flat geometry produces a significant radial component to the oscillating flow fields inside the cryocooler which are not modelled in one dimensional analysis tools such as Sage. Compared with standard pistons, the gas-to-wall heat transfer is increased due to the higher velocities and smaller hydraulic diameters. This paper presents the results of Computational Fluid Dynamics (CFD) techniques used to model the flow and gas-to-wall heat transfer inside the cryocooler including experimental validation of the CFD to produce a robust analysis.

Theoretical analysis and experimental validation of a pulse tube cryocooler with cold reservoir [TO3-5]

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In order to further improve the cooling performance of pulse tube cryocoolers, the present paper proposes a novel pulse tube cryocooler characterized by a reservoir connected to the cold end of the pulse tube. The cold reservoir helps to generate the in-phase volumetric flow vector with pressure, which can produce the cooling power according to the enthalpy flow theories. The linear model is used to analyze the performance of both the single orifice and the double-inlet type of the pulse tube cryocoolers with a cold reservoir. The caculation results reveal that the cold reservoir can significantly enhance the cooling power. And, coefficient of performance can also be improved with the increase of the volume ratio of cold reservior to pulse tube. The experiments with cold reservoir were further implemented on a single-stage double-inlet G-M type pulse tube cryocooler.

Sorption-based vibration-free cooler for the METIS instrument on E-ELT [TO4-1]

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METIS is the 'Mid-infrared ELT Imager and Spectrograph' for the European Extremely Large Telescope. This E-ELT instrument will cover the thermal/mid-infrared wavelength range from 3 - 14 μm and requires cryogenic cooling of detectors and optics. We present a vibration-free cooling technology for this instrument based on sorption coolers developed at the University of Twente in collaboration with Dutch Space. In the baseline design, the instrument has four temperature levels: N-band: detector at 8 K and optics at 25 K; L/M-band: detector at 40 K and optics at 77 K. The latter temperature is established by a liquid nitrogen supply with adequate cooling power. The cooling powers required at the lower three levels are 0.4 W, 1.1 W, and 1.4 W, respectively. The cryogenic cooling technology that we propose is based on the cyclic adsorption and desorption of a working gas on a sorber material such as activated carbon. Under desorption, a high pressure can be established. When expanding the high-pressure fluid over a flow restriction, cooling is obtained. The big advantage of this cooling technology is that it contains no moving parts and, therefore, generates no vibrations. This, obviously, is highly attractive in optical systems. In a Dutch national research program we aim to develop a demonstrator version for METIS. In the paper we will describe our cooler technology and discuss the developments towards the METIS cooler demonstrator.

Fabrication of a high frequency micro cooler using MEMS technology [TO4-2]

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The performance of electronic devices can be improved by lowering the operating temperature which improves the signal to noise ratio and bandwidth of the system. In several cases the device which is to be cooled is very small and they require effective cooling due to heat generated that is to be dissipated from a relatively low surface area. The miniaturization of cryocooler is often accompanied by involved with possible frequencies up to several hundred hertz. MEMS technology is highly suitable for the fabrication of microcooler because of high accuracy, possibility of integration of system with electronics, and low cost per unit due to batch processing. The micro cooler is based on a JT cycle with a mixture of gases operating at a pressure of 110 bar and a mass flow rate of 1 mg/s. The temperature of the cold tip is 85 K. The most crucial element in the JT based cryocooler is the design of Counter Flow Heat Exchanger. The effectiveness of Counter Flow Heat Exchanger lies in the geometry design of heat exchange between the high and low pressure lines.

Binary Mixed Refrigerants for Joule-Thomson Cryocooling to 80, 100 K [TO4-3]

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Cooling to 80 - 100 K with Joule-Thomson cryocoolers is often implemented with two pure gases: nitrogen or argon. Alternatively, mixed gases are suggested as refrigerants. Usually, a mixture with 2 - 3 components is applied for open cycle cryocoolers operating at elevated pressures. The mixed refrigerant objectives are to reduce the cool-down time and to increase the total cooling duration relative to operation with pure refrigerants. Mixtures containing 4 - 7 components are usually used for reducing the operating pressures and thus suit for closed cycle cryocoolers driven by compressors.
In the present research we investigate binary mixtures, which are analytically calculated in a more convenient manner, as refrigerants for Joule-Thomson cryocoolers. Nitrogen, argon, methane, ethane, ethylene, and propane are considered as components. The phase diagrams at low pressures are calculated and cooling temperature aspects are discussed. The isothermal Joule-Thomson effects (Δh_T) are also calculated and analyzed to study the cooling power of the different mixtures. Finally, experimental results are presented to verify some of the analytical results.

The performance analysis of Joule-Thomson cryocooler supplied with gas mixture [TO4-4]

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Joule-Thomson (J-T) cryocoolers working in closed cycle and supplied with gas mixture have been studied theoretically and experimentally for the variety applications. This paper presents the thermodynamic analysis of the cooler filled with gas mixture based on nitrogen and hydrocarbons, designed to provide 100 W of cooling power at temperature of 100K, working with commercially available refrigeration compressor. Special attention was paid to the optimization analysis of the mixture composition. The results of the analysis based on the Second Low of Thermodynamics are presented and described. The paper gives also the results of the tests.
The application of the cooler depends on the temperature level of cooling power. The cooler can be coupled with "warm" gas separation technology like membrane or PSA to produce chosen mixture component in the liquid phase. The paper gives also the concept of the small, independent generators of liquid nitrogen and oxygen.

Multi-Stage and Mixed-Gas Single-Stage Microcooler Developments [TO4-5]

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The development of micromachined Joule-Thomson (JT) coolers is an ongoing and successful research project at the University of Twente. In this research, we develop MEMS-based cryocooling systems for cooling small electronic devices, such as amplifiers and infrared sensors. By cooling these devices their performance is highly improved. Fully micromachined cold stages were developed consisting of stacks of three glass wafers. The high and low-pressure channels with supporting pillars, evaporator volume and flow restriction were structured in these wafers. After successfully fabricating and testing single-stage JT microcoolers with cooling capacities of around 10 mW at 100 K, we now present the development of two-stage microcoolers and of single-stage microcoolers that operate with gas mixtures. A two-stage microcooler was designed with dimensions of 90 x 20 x 0.7 mm. The first stage operates with nitrogen between 80 bar and 1.2 bar and the second with hydrogen between 55 bar and 3.1 bar. The mass flows of 20.6 mg/s and 1.1 mg/s, respectively, result in a cooling power of 17 mW at 35 K. Also, single-stage microcoolers with dimensions of 60 x 10 x 0.7 mm were designed and realized for operating with hydrocarbon gas mixtures. This facilitates the operation at lower pressure ratios, thus relaxing the compressor requirements. A microcooler was combined with a linear compressor to obtain a closed-cycle cooler. Operating with a ternary mixture of methane, ethane and isobutane between 9.4 bar and 1.3 bar, a net cooling power of 66 mW at 150 K was obtained at a mass flow of 1.3 mg/s.

A Vibration-Free 35 K Cryocooler Driven by Electrochemical Compressors [TO4-6]

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This paper reports on the development of a vibration-free cryocooler for infrared detectors for surveillance and missile tracking. The cryocooler employs a solid-state Electro-Chemical Hydrogen Compressor (ECHC) for vibration-free operation. A unique single-pressure dilution cycle was developed that enables
an upper stage driven by an ECHC to provide precooling at about 85 K for the lower hydrogen Joule-Thomson stage. The ECHC uses an advanced anhydrous proton conducting membrane to compress hydrogen through an electro-chemical process. This compressor produces high pressure ratios with no moving parts. Proof of concept anhydrous proton conductive membranes were fabricated, and their performances were characterized in a test cell. Based on the membrane performance data, the thermodynamic cycle design of the cryocooler was optimized and then the cryocooler performance was estimated. Preliminary mechanical designs for the ECHCs and their solid models were also developed.

Improvement of a Numerical Analysis for Joule-Thomson Cryocoolers [TO4-7]

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The cool-down time of a Dewar-Detector-Cooler Assembly (DDCA) is governed both by the cryocooler performances and the Dewar structure. In order to calculate the exact temperature at every location of the Dewar as a function of time, a finite-element model of the complete DDCA has been developed and published elsewhere. The original analysis calculates the heat transfer in the Dewar and the Joule-Thomson (JT) cryocooler, the coolant flow rate, and the pressure drop in the vessel that supplies the coolant to the JT cryocooler. The current improvement of the analysis incorporates the back-pressure effect in the JT cryocooler which is enhanced with flow rate increase.
A verification of the analysis is conducted against experimental results with pressure vessels of 60 cc and 150 cc filled with argon at 69 MPa and 23^{o}C and operate at -25^{o}C, 23^{o}C, and 60^{o}C. A good agreement is obtained between the analysis and the experimental results.

A 1K 4He close cycle loop precooled using a PT415 Pulse Tube for the BLISS test bed cryostat [TO4-8]

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The Background Limited Infrared Submillimeter Spectrometer (BLISS) is an instrument proposed for the Japanese space borne telescope mission SPICA. The BLISS cryogenic chain is a hybrid solution, coupling a continuous 300mK 3He sorption cooler with a single-shot 50mK adiabatic demagnetization refrigerator (ADR). On SPICA, the instrument and cooler operate from thermal stages at 4.5 K and 1.7 K. The peak power dissipation to these stages must meet the SPICA allocations of <10mW and <5mW respectively. To test the BLISS cryogenic chain prototype, a large pulse tube cryostat has been built that replicates the SPICA cryogenic interface. The 4.5K and 1.7K interfaces are regulated at constant temperature and cooled by the cold head from a Cryomech PT415 pulse tube and a 1K 4He close cycle loop respectively. The 4He gas for the 1K cooling loop is circulated by a room temperature dry pump, precooled by a heat exchanger soldered onto the pulse tube, passed through a Joule-Thompson expander before it flows back to the dry pump. Passive graphite heat switches are used to expedite the initial cool down of the BLISS cooler from room temperature as an alternative solution to exchange gas. In this paper, we describe in detail the design and performance of the 4He close cycle 1K loop and graphite heat switches.

The Development of CryoTel DT Cryocooler [TO6-1]

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Sunpower has developed a small split Stirling type cryocooler driven by a dual-opposed wave generator for low vibration applications, and achieved a record-high COP. The normal cooling capacity measured in lab tests demonstrated 1.85W @77K, with a power input of 25W and a 35^{o}C reject temperature. With the COP reaching 0.074 it is 15% higher than that of the current CryoTel production coolers. The CryoTel family of cryocoolers such as MT, CT, and GT, are being widely used in many field applications, and are all integral type Stirling utilizing a single piston inline configuration with a balancer on the back plate.
The newly developed CryoTel DT is intended for smaller and more portable systems where size, mass, efficiency along with a low vibration signature is important. The two opposing pistons of the wave generator share a single compression space and thus canceling the vibrations of each other. The cold head utilizes a small balancer on its back side to attenuate the remaining vibration induced by the light-mass displacer. The Wave generator unit measures 127 mm in length, 55 mm in diameter and weighs 1000 gm. The cold head is 128 mm in length, 39 mm in diameter and weighs 200 gm. Thus total mass of the cooler is 1.2kg. This paper presents the details of the design and the test results for the CryoTel DT cryocooler.

A Miniature Coaxial Pulse Tube Cooler Operating above 100 Hz [TO6-2]

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The increase of frequency can bring a more compact pulse tube cooler. This article focus on the pulse tube cooler operating above the frequency of 100 Hz. Firstly, the numerical simulation was carried out to investigate the effect of frequency on the performance. The results indicate that the optimized size of regenerator can keep unchanged as the frequency changes from 100 to 300 Hz. This means that the same pulse tube cooler can operate at different frequency after using different inertance tube. In this article, a miniature coaxial pulse tube cooler was designed and fabricated. Influences of various parameters such as frequency and inertance tube have been investigated experimentally. Typically, this cooler can produce 2 W cooling at 77 K with an acoustic power of 40 W and reached a no-load temperature of 50 K when operating at 100 Hz. After the frequency was increased to 300 Hz, the no-load temperature raised to 60 K.

Cryogen-free dilution refrigerator with 1K-stage [TO6-3]

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In most research applications in the sub-Kelvin temperature regime, dilution refrigerators (DR) are used, mainly because the dilution of 3He in 4He is the only method to produce these temperatures continuously with sizeable refrigeration power. In recent years, DRs precooled by pulse tube cryocoolers (PTC) have become quite popular among scientists because they are easy to use and economical. In the cryogen-free DR which we introduced some years ago and also in practically all commercial cryogen-free DRs, there is only one flow circuit, namely the 3He/4He dilution circuit; a separate condensation stage (formerly referred to as "pot") is not necessary because the condensation of the 3He flow is taken over by the PTC. In recent work, however, we have added a 4He cooling stage to the DR, in order to increase the cooling capacity of the cryostat at temperatures just above 1 K. High cooling capacities are often needed in experiments where cold amplifiers and coax lines have to be cooled, e.g. in superconducting quantum circuit technology. Refrigeration capacities of up to 100 mW have been reached. DR (base temperature 10 mK) and 1K-stage are precooled by the same PTC. They were previously operated independently of each other. In the work presented here, we show how these two cooling circuits can be combined by implementing a heat exchanger in the 1K-stage where the 3He stream of the DR is cooled to ~ 1 K. As a result, in addition to the high cooling power of the 1K-stage, a high liquefaction rate in the initial condensation of the 3He/4He mash is attained (120 std.l./h). In our presentation, the cryostat assembly is described and cooling capacities and low temperature performance of the modified DR are given.

Matching of AC superconducting magnet - cryocooler systems [TO6-4]

A.T.A.M. de Waele, T. Reis, B. Oswald

This paper deals with the matching of AC superconducting magnets and cryocoolers. In the steady state the cooling power of the cooler is equal to the sum of the losses. The latter include the AC losses of the magnet, losses via the current leads, the power needed to distribute the cooling (e.g. by a cryofan), and cryostat losses. The AC losses go down if the temperature is reduced, but also the COP of the cryocooler goes down. In order to solve these conflicting requirements a complete set of expressions is derived which governs the system. A number of practical cases is discussed which shows the interdependence of the various system parameters such as type of cryocooler, type of flow distribution, working fluid (helium and/or neon), working pressure, etc.

A Powerful 10 K Pulse Tube Cryocooler with Cold Helium Circulation [TO6-5]

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We have developed a high capacity two-stage 10 K pulse tube cryocooler for remote cooling MgB2 superconducting magnet, cryoprobe, etc. The pulse tube cryocooler is equipped with a cold helium circulation circuit which includes two count flow heat exchangers and two heat exchangers on the 1st and 2nd stage. It circulates sub 10K helium gas to a remote cooling station. The cryocooler compressor supplies a small portion of flow rate of ~12% for the cold helium circulation.
The pulse tube cryocooler provides 12W at 10K and 30W at 20 K on the 2nd stage when there is no heat load on the first stage. It has 9W at 10K and 21 W at 20K on the 2nd stage when the 1st stage is at ~72K with a heat load of 80W. The power input of the pulse tube cryocooler is ~10 kW. For the remote circulation cooling, this system will provide >4W at 10K. The system design and experimental results will be presented in this paper.

A modular architecture for helium compressors larger than 2.5 KW [TO6-6]

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In oil cooled helium scroll compressors only about 10% of the heat generated ends up going into the helium, but that helium should be cooled to <20 ^{o}C for best performance (especially with pulse tubes). The big heat load is from cooling the oil, but the oil does not need to be cooled below around 50 ^{o}C if the flow rate stays high. Thus, there are rather different cooling requirements for the helium and for the oil. This distinction has not been appreciated in traditional water-cooled or air-cooled helium compressors. We describe two compressor configurations, with and without a chilled water loop available. For the more familiar configuration in which chilled water is available the only changes to our compressor are to the water side of the cooling loop which employs two brazed-plate heat exchangers (BPHX) in series. This modification would not be possible with traditional water-cooled compressors that use a single 3-fluid heat exchanger. When the water is not available, we break the link between the two BPHX's previously in series and provide for independent cooling of the helium and oil circuits. The oil is cooled via a commercial copper tube-in-plate heat exchanger, fan, and small water pump. The helium is cooled with an automatic expansion valve plus refrigeration connectors on the helium BPHX. The inside unit comprises the Copeland condenser and a small finned-tube heat exchanger to cool the suction-side R134a refrigerant to an appropriate temperature before it goes back into the Copeland compressor capsule.

High Speed Compressors [WO1-1]

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There is a requirement for small cryocooler compressors with a high power density, and one method of achieving this is to increase the operating frequency of the compressor. The 'Oxford' type clearance seal/flexure bearing compressors are typically operated close to their resonant frequency, which can theoretically be increased by either reducing the moving mass, increasing the spring stiffness or both.
There are potential improvements to be made in the design of the flexures - traditional designs have a poor method of clamping the springs, and use of high strength alloys and improvements in surface finish can give a significant improvement in spring stiffness. However, in a typical compressor the mechanical spring stiffness is typically about a third or a quarter of the total stiffness, with the remainder coming from the gas spring effect of the compression process. If the mechanical spring rate is doubled, the frequency will increase by about 12%.
A large increase in spring stiffness can be obtained by use of an auxiliary gas spring, which could be located at the opposite end of the compressor to the main piston. Use of such a gas spring has some disadvantages: there is a second piston/cylinder assembly to manufacture, assemble and align, together with extra thermodynamic losses.
This paper describes how the losses from a gas spring can be evaluated in order to optimize the size and stiffness of such a spring. An example is given, based on an existing Stirling cycle compressor, of how the power output of a compressor can be doubled with a 40% increase in size.
Though this describes the theoretical increase in power of an existing machine, it is hoped that these techniques can used in the design of small compact cryocooler compressors.

Demonstration of an Ultra-Miniature Turboalternator for Space-Borne Turbo-Brayton Cryocooler [WO1-2]

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A key component of turbo-Brayton cryocoolers is the cryogenic expansion turbine. This component removes work from the cycle gas at cryogenic temperatures, producing refrigeration. The design objectives for these components are high aerodynamic efficiency and low overhead losses. The latter objective is achieved in dual-temperature turbines by minimizing heat leak from the warm to cold end of the unit, and in isothermal turbines by minimizing electromagnetic and viscous losses. Turbines for space systems have adopted the use of electrical alternators (i.e., turboalternators) for turbine speed control and reduced cryocooler input power by recovering the turboalternator generated power. Creare recently built and demonstrated its smallest isothermal turboalternator. This turboalternator was optimized for operation in a cryocooler providing 1 to 2 W of refrigeration at 35 K. It is a 2/3-scale version of the flight-qualified NICMOS turboalternator and is our first turboalternator utilizing new fabrication techniques that enable higher aerodynamic efficiency. This turboalternator was tested at temperatures from 19 to 60 K and demonstrated high efficiency at all temperatures. In this paper, we review our turboalternator technology and heritage, and present results from the cryogenic testing of our ultra-miniature turboalternator.

Testing results for low exported force and torque cryocooler mounts [WO1-3]

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Increasingly, exported forces and torques (EFT) from cryocoolers are a system level concern with lower levels becoming the norm for instruments with cryocoolers. Capabilities in the 0-500 Hz range are < 50 mN force and < 25 mN-m torque. In anticipation of these lower levels, Ball Aerospace & Technologies Corp. developed a low EFT cryocooler mount design with passive isolators for both a single-stage Northrop Grumman Aerospace Systems (NGAS) High Efficiency Cryocooler (HEC) and a two-stage Ball SB235E (TIRS) cryocooler. Together with the design and testing program, a modeling program was undertaken to allow model correlation from testing for future design maturity. Test results show the mount design successfully reduces EFT within the desired limits.

Very compact integration of an ultra-low vibration platform for space cryocoolers using miniature high frequency actuators [WO1-4]

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Air Liquide advanced Technologies in collaboration with Cedrat Technologies and SMAC has performed a study of a compact vibration control platform for mechanical cryocoolers. This solution has been proposed as an alternative approach to cryocooler integration with respect to suspended systems which must be mechanically locked during the launch phase. This system allows significant reduction of the platform's physical size and mass.
The platform filters vibrations generated by the cryocoolers above 150Hz using passive dissipation in metallic or elastomeric mounting blocks. Vibrations generated by the cryocoolers below 150Hz are suppressed through a vibration cancellation algorithm which balances the opposed piston compressor (piston axis) and by miniature high frequency actuators for the other axes.
An overview of the system is presented together with results of initial tests.

Development of a Passive Check Valve in a Cold Cycle Dilution Refrigerator [WO1-5]

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Future astrophysics missions will rely on a new generation of cooling technologies to improve the resolution of infrared and x-ray sensors. We are developing a novel, continuous, cold cycle dilution refrigerator (CCDR) to provide cooling for these sensors at temperatures below 100 milliKelvin. A passive check valve for liquid 4He-3He mixtures is a key technological innovation required to implement the CCDR. Design of a reed style passive check valve and initial results from tests with helium gas at room temperature and 80 Kelvin are presented. A scaling argument is made that indicates the valve should provide adequate functionality in liquid 3He-4He mixtures, as well.

Recuperative Cooling Capability of Miniature Thermoacoustic Expanders (MTAEs) below 77K [WO1-6]

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The experimental investigations on recuperative cooling performances of Miniature Thermo-Acoustic Expander (MTAE) run below the cryogenic temperature of 77K are reported in this paper. This study is to demonstrate the feasibility of a fundamental configuration of the MTAE cooling system which enables run blow 77K as the second-cold-stage after they are pre-cooled by the first-stage regenerative type of cryocoolers in order to provide the distributable cooling power for LWIR or VLIR applications. The MTEA is a novel cold-head driving the miniature recuperative type of cryocoolers, which uses high-intensive acoustic wave systems to produce cooling power from dc pressure drops. In this experimental approach, the pressurized helium is cooled down to 77K by liquid nitrogen before the MTAE recuperative cooling system. The final temperature on MTAE cold-stage is descended from 77K by the recupertor, and determined by the MTAE cooling power in addition to the thermodynamic efficiency of the recuperator. The cooling power production and heat rejection temperature of MTAE between 77K and 40K are examined as to explore the limit of this technology's feasibility in both the miniaturized scale and the selected operating conditions. The characteristics of acoustic wave systems driven in the miniature channel under different pressure along with the recuperating cooling temperature declination will be reported. The challenges of the thermo-acoustic streaming phenomenon occurred in miniature channels will be discussed.

A Comparison of LVDT and RC Methods to Characterize the Performance of a Linear Compressor [WO1-7]

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A recently employed approach for characterizing the PV power of a linear compressor using a resistive-capacitive (RC) type acoustic circuit is compared to the more conventional approach that utilizes linear variable displacement transducers (LVDT) mounted on the compressor pistons. Experiments using the two methods have been carried out and results show that the trends of both approaches agree well with calculations of the PV power at the piston face. In terms of absolute numbers, the PV power at the compressor outlet (that is the inlet of a regenerator) obtained by RC approach is 5%~25% lower than the PV power on piston face obtained by the LVDT method. The RC load approach provides advantages such as simple assembly, non-contact, and the ability to simulate the impedance conditions of cold heads. In addition it may provide new methods for investigating losses in linear compressors.

Development and Investigations of a GM Type Single Stage PTR Reaching 30K [WP2-1]

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Development of Pulse Tube Refrigerator due to their chief advantages of absence of moving components in cold region, vibration free working and no maintenance requirement has progressed immensely in the last couple of decades. Although two and three stage Pulse Tube Refrigerators for reaching below 4 K temperatures are already developed, the single stage Pulse Tube Refrigerator are still important for relatively higher temperatures applications that demand more refrigeration power.
In the present work a GM type single stage Pulse Tube Refrigerator is designed and developed for reaching no-load temperature of 30 K. Experiments are conducted for measuring refrigeration power at different temperatures. Effects of frequency, charging pressure and opening of orifice and double inlet valve on its performance in terms of refrigeration power and no-load temperature are investigated and reported.

Cryo-Cooled Helium Purifier [WP2-2]

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He gas recovered in laboratories from cryogenic instruments via hoses, He bags, compressors, and pressure storage, typically has up to ½% of impurity gases such as Nitrogen. Purification of such recovery gas is typically achieved using liquid Nitrogen cooled molecular sieve purifiers.
Here we present a molecular-sieve-free, cryo-cooled purifier for flow rates up to 20 liter/min normal He gas and pressures up to 2 atm. The purifier is designed for large impurity capacity, quick regeneration, and removes impurities to better than 5 ppm.

Design and performance of oxygen liquefaction system based on G-M cryocooler [WP2-3]

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Gifford-McMahon cryocoolers have been studied theoretically and experimentally for a wide range of applications. Pressure Swing Adsorption (PSA) is well known and commercially available technology for gaseous oxygen production. The purity of produced oxygen is limited to 95%, with the rest being essentially argon. This paper gives the concept of the system for liquid oxygen production in small quantities based on the combination of this two technologies.
The experimental installation has been designed and started up at Wroclaw University Technology. The oxygen stream is separated from dry and oil-free compressed air by PSA method. The cooling power needed to liquefaction process is provided by G-M cryocooler. The assumed capacity of the system is equal of 0.5 kg/h of LO2.
The paper describes the liquefier design, the parameter selection of the temperature PID control loop and the results of the system preliminary tests. The special attention is paid to the heat exchanger calculation procedure.

Experimental Investigation of High-efficiency 4 K GM Cryocoolers [WP2-4]

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4 K GM cryocooler has been widely used for cooling superconducting magnets, such as, magnets in MRI systems. A large amount of power consumption in a MRI system is consumed by the cryocooler. Especially at night, more than a half of power consumption is used by the cryocooler since no diagnosis is performed.
The power consumption for a conventional 1 W 4 K GM cryocooler at SHI is about 7 kW when the compressor is operated at 60 Hz. Recently, SHI started to develop a high-efficiency 4 K GM cryocooler. The goal is to achieve the same performance as a conventional SHI 1 W 4 K cryocooler with less than 5 kW input power when the compressor is operated at 60 Hz.
A typical cooling capacity of more than 40 W at 43 K at the first stage and more than 1.0 W at 4.2 K at the second stage has been achieved with about 5 kW input power when the compressor is operated at 60 Hz. The cooling performance vs. orientation, static charging pressure, etc. has been investigated. The experimental results will be reported in this paper.

Performance of a 4 Kelvin Pulse-Tube Cooled Cryostat with DC SQUID Amplifiers for Bolometric Detector Testing [WP2-5]

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The latest generation of cosmic microwave background (CMB) telescopes is searching for the undetected faint signature of gravitational waves from inflation in the polarized signal of the CMB. To achieve the unprecedented levels of sensitivity required, these experiments use arrays of superconducting Transition Edge Sensor (TES) bolometers that are cooled to sub-Kelvin temperatures for photon-noise limited performance. These TES detectors are read-out using low-noise SQUID amplifiers. To rapidly test these detectors and similar devices in a laboratory setting, we constructed a cryogenic refrigeration chain consisting of a commercial two-stage pulse-tube cooler, with a base temperature of 3 K, and a closed-cycle 3He/4He/3He sorption cooler, with a base temperature of 230 mK. A commercial DC SQUID system, with sensors cooled to 4 K, was used as a highly-sensitive cryogenic ammeter. Due to the extreme sensitivity of SQUIDs to changing magnetic fields, there are several challenges involving cooling them with pulse-tube coolers. Here we describe the successful design and implementation of measures to reduce the vibration, electromagnetic interference, and other potential sources of noise associated with pulse-tube coolers.

Investigation of Multi-bypass Pulse Tube Cryocooler with Precooling [WP2-6]

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A multi-bypass pulse tube cryocooler was designed and tested, and the no load temperature reached to 23.1K with 200 W input power, while the hot end was placed in room temperature. It is difficult to reach temperature below 20K for single-stage Multi-bypass Pulse Tube Cryocooler. In order to gain lower temperature, multi-bypass pulse tube cryocooler with precooling is considered.
Basing on previous single-stage multi-bypass pulse tube cryocooler which we have designed and tested, we design a multi-bypass pulse tube crocooler with precooling, thus the hot end is placed at lower temperature. The system can reach no-load temperature of 10.54K with 200W input power, while the hot end around 60K. In this paper, the effect of cold inertance tube, double inlet and multi-bypass in lower temperature are discussed. In the experiment, we also investigate the effect of frequency, and average pressure and precooling stage temperature.

Experiment investigation of a 40K miniature pulse tube cryocooler [WP2-7]

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A 40K miniature pulse tube cryocooler has been designed, fabricated and tested. The pulse tube cryocooler is designed to provide 2W of cooling power at 40K with input electrical power less than 200W. The cryocooler system incorporates a compressor with a single-stage co-axial pulse tube configuration. The performance of 1.6W at 40K with input electrical power of 175W is achieved.

Cooling characteristics of GM-type pulse tube refrigerator with neon as working gas [WP2-8]

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This paper describes experimental study of single stage GM-type pulse tube refrigerator (PTR) with neon as a working gas. An orifice valve and gas reservoir are adopted as phase control device in the fabricated PTR. In experiments, both gases of neon and helium are used as working gas with same compressor and pulse tube refrigerator. No-load temperature, cooling capacity and compressor input power are measured as operating frequency and opening of orifice valve for each working gas. Characteristics of cooling and operating for two different working gases are compared and discussed with experimental results. The fabricated PTR in this study show improved cooling performance with neon gas.

HEC Pulse Tube Cooler Performance Enhancement [WP2-9]

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The High Efficiency Cooler (HEC) space flight cooler performance has been extended both at lower temperatures (<35K) and at higher temperatures (>140K) with higher cooling powers. The 21 flight coolers delivered to date were configured for each of their payloads with customized linear and coaxial one and two temperature cold heads. The one temperature cold head requirements ranged down to 40K and in the case of the 2 stage coolers, upper temperature requirements ranged as high as 140K. Recently the need for higher cooling power coolers below 40K and above 140K has motivated us to develop pulse tube cold heads to address these requirements. In both cases only the cold heads are changed and are variants of existing designs that can be integrated with the existing flight proven compressor and flight drive electronics. As a consequence these higher capacity coolers have similar low masses (<5.5kg) to the existing flight coolers.
The low temperature cooler performance has been extended to <30K The high temperature 4.1 kg cooler performance at 140K can be substantially increased from its current 25W capability. The performance of both these coolers will be reported.

Raytheon Airborne Low Temperature RSP2 Cryocooler Testing [WP2-10]

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The Low-Temperature Raytheon Stirling / Pulse Tube 2-stage ("LT-RSP2") hybrid cryocooler is a long-life, robust machine designed to operate efficiently at a first stage temperature of 55K and a capacity of 5W and a second stage temperature of 10 K and a capacity of 250mW. The LT-RSP2 design was finalized in mid-2009, with piece-part fabrication taking place in late 2009 and early 2010. Initial testing in an ambient benchtop configuration occurred in early 2011. During the later part of 2011 a significant amount of testing was performed to determine if the cryocooler was ready for integration into an airborne sensor. Major aspects of the testing and results will be presented in this paper.

Development of Orientation Free High Power Stirling type Pulse-tube Cryocooler [WP2-11]

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For the purpose of cooling high-temperature superconductor devices, superconductor motor, SMES, current fault limiter, the large cooling capacity Stirling type pulse-tube cryocooler was design, as the demand specification from the devices to the cryocooler, smaller light weight, the high efficiency, high reliability are examined. Especially, the efficiency is demanded a crocooler with COP >0.1.
As the experimental result, the In-line type expander of cooling performance was cooling capacity 210W at 77K, a minimum temperature 37K with compressor input power 3.8kW, operating frequency 48Hz~50Hz. Moreover, the U-type expander for the miniaturization was examined and it could get performance about 10% decrease of In-line type expnander. And the decline of the cooling capacity caused of the inclination to the expander was within 3%.
This report is that the experimental results are described.

Numerical Simulations of a 4 K GM Cryocooler [WO3-1]

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A numerical simulation program has been developed to predict the theoretical cooling capacity and losses in regenerators, heat exchangers, etc. The clearance between the cylinder and the displacer functions as a pulse tube in a pulse tube cryocooler. Usually, a slip seal is installed at the warm-end of the first stage. Therefore, the clearance can be considered as a pulse tube in a basic pulse tube cryocooler. On the other hand, there is no seal on the warm end of the second stage. Therefore, the clearance can be considered as a pulse tube in a basic double inlet pulse tube cryocooler. The spiral on the second stage displacer can be also considered as a pulse tube in a basic double inlet pulse tube cryocooler. The simulation results are compared with the experimental results obtained from a SHI 4 K GM cryocooler. The simulation results are consistent with the experimental results in a great degree.

Development of Novel 4K Cryocoolers with Improved Performance and Reliability [WO3-2]

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In order to meet requirements in cryogenic cooling application, Nanjing Cooltech Cryogenic Technology Co., Ltd (NCCT) has developed new types of 4K GM cryocoolers and pulse tube cryocoolers with long-life compressors. The gap in a GM cryocooler between cylinder and displacer works as a pulse tube and performs cooling effect by using an internal phase shift mechanism. It results in cold seal elimination and performance improvement. The comparative experiments between the conventional cold head structures and the novel (NCCT's) structure have been carried out. The NCCT's structure presented a better performance. At the second stage, the temperature decreased from 2.37 K to 2.20 K with no-load and from 3.98 K to 3.66 K with a constant heat load of 1.0 W. More efforts have been made for a purpose of reliability, stability and life. As next-generation product, a new type of pulse tube cryocooler with Automatic Phase Controller (APC) has been also developed. A controlling box has been deployed in the pulse tube cryocooler system. Phase shift between the gas pressure and mass flow is optimized by the controller based on the temperature feedback from the cold ends of the pulse tube cryocooler. The pulse tube cryocooler with APC presents high performance, good long-term stability and long life.

A typical cooling capacity of 1.5 W @ 4.0 K at the 2nd stage and 45 W @ 42.8 K at the 1st stage has been achieved with a 6 HP compressor. The cryocoolers system reliability has been improved by developing a new long-life compressor with nano filtration channel oil separation technology.

3He/4He Pulse Tube Cryocooler Performance Optimization [WO3-3]

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A single-stage pulse tube cryocooler capable of using either 3He or 4He as the working fluid was designed to achieve 35 mW of refrigeration power at 4.2 K when energized by a 30 Hz pressure wave generator. This system by design is unique as an active expander is utilized to achieve the desired cold end phase angle for maximizing refrigeration power. Initial results from this system showed poor performance related to non-ideal thermal stratification in the pulse-tube component. Due in part to this larger than expected pulse-tube loss, performance goals were not achieved. This paper addresses work performed relative to optimization of the pulse tube component and associated transitions in a 4 K pulse tube cryocooler using 3He and 4He as working fluids to achieve the desired operational characteristics. This optimization was performed using a commercial CFD solver coupled with design models for the regenerator, expander, and heat exchanger performance. Based upon the fluid dynamic modeling results, the geometry of the pulse tube and associated transition components were modulated. Performance impacts of these changes on the system are reported utilizing the component changes for both working fluids.

Optimal design of a cold end heat exchanger for a 4 K pulse tube cryocooler [WO3-4]

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The cold end heat exchanger is an essential component for efficiently producing cooling in cryocoolers. Considering heat transfer under oscillating flow at liquid helium temperatures, cold end heat exchangers for 4 K pulse tube crycoolers must be more compact and optimally designed than conventional heat exchangers in order to enhance the heat transfer. In this paper, the optimal geometric configuration of a slot heat exchanger, which is widely employed in 4 K pulse tube cryocoolers, is discussed. Based on the optimal geometric design, a CFD modelwas carried out for heat transfer at liquid helium temperatures in the slot heat exchanger under oscillating flow. The CFD calculation helps to examine the performance improvement of the designed 4 K slot heat exchanger, and should be instructive in the design of 4 K pulse tube cryocoolers.

Coaxial Pulse Tube Refrigerator for 4 K [WO3-5]

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We report on a pulse tube refrigerator in coaxial design capable to provide cooling power at 4.2 K. The refrigerator combines the two stage arrangement with a full coaxial design. Two needle valves at the hot end of each pulse tube create a valve controlled active phase shifting. The basic design of our four valve pulse tube concept was presented in previous papers /1/. Now the second stage regenerator has been replaced by a three layer combination of lead-coated wire mesh screens and two rare-earth compounds: ErNiCo and ErNi spheres.
In this setup no-load cold tip temperatures below 4 K are reachable. The cold tip temperature has been measured for different heat loads to both stages with special attention to 4.2 K.
Further the theory of thermodynamics and magnetism predicts a strong proportionality between magnetic heat capacity and the surrounding magnetic field at a given temperature. Therefore the influence on the cooling power of higher external magnetic fields than the earth's was investigated.

1. T. Koettig, R. Nawrodt, M. Thürk, and P. Seidel, “Performance Characteristic of a Two-Stage Pulse Tube Refrigerator in Coaxial Configuration" Cryocoolers 14 (2006), pp 171-176

A simulation of single and multimaterial AMR regenerator [WO4-1]

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The efficient and compact cooling over a broad range of temperatures is of great important for the commercial application of magnetic refrigeration in room temperature. Until now, gadolinium (Gd) metal and its alloys are wildly used in magnetic cooling prototypes for its good magnetocaloric performances at room temperature, good mechanical properties, low hysteresis. However, the small operation temperature span limits the use of Gd as refrigerant on a large scale application.
Multimaterial AMR regenerator is expected to instead of a single regenerator with Gd or its alloy to improve the performance of AMR for the high magnetocaloric effect in wide operation temperature span. Although this idea is felt to be a way of improving magnetic refrigeration, it still requires much more simulation study and experimental verification.
In this paper, we simulated multimaterial AMR regenerator and compared its performance with the single AMR regenerator. In order to deeply understand multimaterial AMR regenerator, we also studied the influence of the inner temperature field in AMR beds during the magnetization and demagnetization.
Typical results are presented, including the temperature distribution inside AMR regenerator. It is hoped that the results will provide useful information for optimum design of multimaterial AMR regenerator.

Investigation of the performance sensitivity of a 300 Hz pulse tube cooler [WO4-2]

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High frequency Stirling type pulse tube cryocooler promises higher specific power which is attractive for many applications. For the past several years, we have been working on a 300 Hz pulse tube cryocooler. At such a high frequency, acoustics plays an important role in determining the cryocooler performance. This paper studies the dependence of cryocooler performance on the dimensions of inertance tube, connecting tube and void volume inside the system from the acoustic viewpoint. While similar influence exists in case of lower frequency systems, the cryocooler are more sensitive to these parameters when the frequency increases up to 300 Hz. Such a study is helpful in guiding the design of the system.

CFD simulation and experimental study on the optimum expansion volume of a pulse tube operating in the hundred Hz Range [WO4-3]

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The expansion efficiency of a pulse tube is significantly influenced by its dimensions, and the associated losses can be minimized by choosing an appropriate volume. In such a case the expansion efficiency increases, as well as the overall efficiency. This paper calculates the expansion efficiency of various pulse tubes with different volumes using the method of CFD simulation. In addition, relevant experiments have been carried out on a single stage in-line pulse tube cryocooler operating at 120 Hz. The results of the simulation play an important role in guiding the design of pulse tubes operating at very high frequencies.

CFD Simulation and Some Novel Observations of Heat Transfer of Oscillating Flow with Compressible Gas [WO4-4]

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Understanding the internal mechanism of oscillating-flow heat transfer with compressible gas is a still fundamental issue for designing an efficient regenerative cryocooler. Though many previous researches have been conducted in the past decades, it is found that there are still a lot of unclear questions about the heat transfer of oscillating flow. This paper studied the heat transfer characteristics of a simple circular tube with CFD simulation. The simulated circular tube has a constant wall temperature, and its open end is oscillated by a reciprocating piston. Helium is the working gas. Many operating conditions have been simulated, including different pressure ratios, different tube lengths, etc. Based on the CFD simulation, much useful information including the skin heat transfer coefficient and the heat transfer temperature difference between the wall and helium gas can be obtained. Some unique features were observed, including negative and infinite heat transfer coefficient. The simulated results and observation imply that the classical treatment of characterizing convective heat transfer for steady flow is not suitable for oscillating flow. Thus, a new characterizing heat transfer performance of the heat exchanger subjecting to oscillating flow with compressible gas is really necessary. The simulated details will be reported in the paper, and a new characterizing methodology will be reported in the companion paper during the ICC17 conference.

Study on phase shifting mechanism of inertance tube at low temperatures [WO4-5]

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Inertance tube is widely used as phase shifter at ambient temperature in high frequency pulse tube cryocoolers, but it is difficult to obtain a rather large phase shift when there is a smaller acoustic power at the inlet of the inertance tube. However, inertance tube at cryogenic temperature, so called cold intertance tube, can provide a solution to this difficulty. Based on the transmission line theory by introducing real-gas properties of helium, the operating pressure, pressure ratio and reservoir volume on the performance of inertance tube at different temperatures are studied. The results indicate that the cold inertance tube can provide a better phase angle even with a smaller acoustic power. That phase angle increases with the decrease of temperature and pressure ratio. For the design convenient, the charts of inertance tube working at different temperatures and dimensions are also provided in this paper.

Drag coefficient and Nusselt number for laminar pulsating flow in porous media [WO4-6]

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Periodic flow occurs in the heat exchangers of Stirling and pulse tube cryocoolers. In this paper transient (pulsating) flow in micro heat exchangers is numerically simulated. Laminar 2-D pulsating flow through homogeneous arrays of ten rows of heated square rods is simulated for frequencies of 0-80 Hz. Cycle-average and maximum drag coefficients, and cycle-average Nusselt numbers are reported for each of the ten rods in the simulated array. Correlations are presented which relate maximum and cycle-average drag as well as Nusselt number to the following: Reynolds number, frequency, porosity (ratio of flow area to total area), and row number. A wake galloping effect has been observed which significantly amplifies the drag on the leading rods and reduces and instantaneously reverses the sign of the drag force on the rods located in the wake region. Cycle average drag was found to decrease with increasing Reynolds number and porosity, and is only a weak function of pulsation frequency. Peak drag was found to decrease with increasing Reynolds number and porosity, but linearly increase with increasing frequency. The cycle-average Nusselt number decreased with increasing porosity, but monotonically increased with both Reynolds number and frequency.

2-Dimensional Cryogenic Temperature Visualization under Steady State Using Rayleigh Scattering Thermometry with 266 nm Nd:YAG Laser [WO4-7]

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Planar laser Rayleigh scattering thermometry is an attractive technique to diagnose 2-dimensional temperature distribution at cryogenic temperature due to no requirement of additional tracers or fluorescent particles in visualization objects. Preliminary to the visualization of temperature distribution in pulse tube refrigerator, the validation experiment of planer laser Rayleigh scattering thermometry for 2-dimensional cryogenic temperature visualization is conducted in steady state and results are discussed in this paper. Cylindrical quartz tube with anti-reflection coating is attached to the commercial Stirling cryocooler and electric heater to make 2-dimensional temperature distribution from 220 to 310 K. Scattering cross section area of gas in the experiment is increased to get high intensity of scattering signal. The noble gases such as krypton and xenon with higher Rayleigh scattering cross section area than helium and nitrogen are used in the experiment. The 266 nm Nd:YAG UV laser is applied since the Rayleigh cross section area is inversely proportional to the forth power of the wavelength of laser beam. Enhanced visualization with increasing scattering cross section area, accumulated photography, and low pass filtering process is progressed to achieve high accuracy and precision of temperature measurement.

Experimental Investigation and CFD Simulation of the Gas Flow in a Pulse Tube Cooler with two Pulse Tubes [WP5-1]

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In order to realize larger and heavier mass supporting without additional supporting components, a new structural pulse tube cooler based on traditional U-shape pulse tube cooler and with one regenerator and two parallel pulse tubes has been proposed. In previous works, two prototypes of U-shape two-pulse-tube paralleled cooler have been designed and tested. In this paper, to help characterize the gas flow in the new structural pulse tube cooler, experiment is designed to measure the oscillating pressure wave and velocity for Helium gas at the inlet of the regenerator and the outlet of the two pulse tubes with different inertance tubes. A two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model is also developed to simulate oscillating fluid flow and heat transfer in the cooler. Results obtained from experiments and CFD simulations are presented and discussed in this paper.

Modified Reverse-Brayton Cycles for Efficient Liquefaction of Natural Gas [WP5-2]

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A thermodynamic study on modified reverse-Brayton cycles is carried out, aiming at efficient liquefaction of natural gas. Since natural gas is a mixture of hydrocarbons, the specific heat varies considerably with temperature along the liquefaction process. In order to achieve a high efficiency, it is important to reduce the entropy generation due to temperature difference in heat exchangers. Mixed-refrigerant is generally effective in reducing the temperature difference with a small number of component items in Joule-Thomson cycles. On the other hand, reverse-Brayton cycles with expansion turbines have been used for peak shaving on a small scale. The objective of this paper is to seek an improved efficiency by modifying and combining reverse-Brayton cycles for application to lately emerging market of off-shore or floating systems (FPSO) on a larger scale.

Various modified cycles with two turbines are considered, including parallel and series cycles, branching cycles, and their combinations. Refrigerant is nitrogen, and a cubic equation of state (Peng-Robinson) is incorporated for calculating the thermodynamic properties of refrigerant and natural gas. The FOM (figure of merit) of liquefaction is calculated with commercial process simulator (Aspen HYSYS) based upon selected design specifications, such as minimum temperature approach in heat exchangers, adiabatic efficiency of turbine, and composition of natural gas feed. The results are compared and discussed in terms of itemized thermodynamic irreversibility and required heat exchanger size.

This research is supported by a grant from the LNG Plant R&D Center funded by the Ministry of Land, Transportation and Maritime Affairs (MLTM) of the Korean Government.

Influence of Ambient Temperature on Performance of a Joule-Thomson Refrigerator [WP5-3]

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The Joule-Thomson refrigerator consists of the counter flow heat exchanger with a double helical tube and fin, a nozzle, a mandrel and Dewar. Typical performance factors of the Joule-Thomson refrigerator are cool-down time, temperature of a cold end, running time and gas consumption. The above performance factor depend on operating conditions such as the pressure of the gas, thermal environment and etc..

In this study, effects of the ambient temperature on the thermal performance of the Joule-Thomson refrigerator were investigated by numerical analyses. Effectiveness-NTU approach was adopted to predict the thermodynamic behaviors of the heat exchanger of the Joule-Thomson refrigerator. One dimensional isentropic model was used to calculate the mass flow rate through nozzle.

In results, the Joule-Thomson refrigerator in the low ambient temperature has the large cooling capacity and mass flow rate. But, the low ambient temperature results in the decrease of the initial pressure of the gas in the vessel. So the J-T refrigerator, which is installed in the low ambient temperature condition, has a negative aspect in the pressure of the gas, but a positive aspect in the mass flow rate of the gas and the cooling capacity for achieving fast cool-down.

CFD modeling of tilt induced cooling losses in inertance tube pulse tube cryocoolers [WP5-4]

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Modern pulse tube cryocoolers are often sensitive to gravitational orientation, leading to a significant loss of cooling power as tilt angle increases from the traditional cold tip down configuration. A number of theories exist as to the cause of this phenomenon, but most agree that natural convection can develop in the pulse tube, leading to a short-circuit between the warm and cold heat exchangers at either end. In order to further elucidate this phenomenon we have developed 3-dimensional Computational Fluid Dynamic (CFD) models of the pulse tube section of a low temperature inertance tube pulse tube cryocooler, and compared key results with experimental data collected during static tilt testing. Results are presented for static tilt configurations of 0-90 degrees between the pulse tube axis and the gravitational vector. Modeling indicated the presence of natural convection as well as significant loss of cooling capacity at angles above 45 degrees consistent with physical observations.

Performance of thermoelectric coolers with boundary resistance for different optimization criteria [WP5-5]

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The cooling capacity, efficiency and cooling flux for a single stage thermoelectric cooler, as part of a multistage cooler, is analyzed in this study. The Lagrange Multiplier method is used to develop nonlinear algebraic equations for the optimum condition for different objective functions. The analysis includes the effect of heat leak, thermal boundary resistances with thermal reservoirs and electric contact resistance at the boundary of the thermoelectric element. The effect of thermal contact resistance and thermal spreading resistance are included in the thermal boundary resistance. In addition to important thermoelectric properties, the effect of the electric and the thermal contact resistances, the thickness of the thermoelectric material and the area aspect ratio of thermoelectric elements on the performance of the thermoelectric cooler at the optimum condition is presented and discussed. The results are presented in terms of nondimensional variables convenient for system design analysis and performance evaluation.

Exergy-based performance estimation of multistage cryocoolers with variable mid-stage cooling loads [WP5-6]

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Based on a new Figure of Merit (FOM) for regenerative and recuperative heat exchangers developed and analyzed previously, this study considers a method to estimate the performance of multistage cryocoolers under a variable condition at each stage. Using exergy analysis, the FOM for the heat exchangers used in multistage cryocoolers is extended to include variable load conditions using separation of exergy destruction due to heat transfer and fluid flow. Therefore, the effect of intermediate cooling load and load temperature at the midstages under off-design conditions can be estimated. The effect of the irreversibility of the expansion process is taken into account using an exergetic efficiency for expansion convenient for estimating overall performance of multistage cryocoolers with only a few free parameters. The result of the model developed in this study based on exergy analysis is compared to the performance of multistage cryocoolers reported in the literature.

Experimental Research and Optimization Design on a Miniature Cryogenic J-T Cryocooler [WP5-7]

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Mechanical cryocoolers are a key enabling technology for utilizing low temperature instruments for the next generation of space missions, the J-T cryocooler is adopted as it has no moving parts and its cooling power can be transmitted to several meters away. The miniature J-T cryocooler lower than 20K has broad application prospects, we designed a throttling cooling system using liquid nitrogen and liquid helium as the precooling source. A copper plate is bolted to the bottom of the liquid helium stage, a 4He tube is spiraled in the plate to transfer heat from the high-pressure gas to the plate. 4He is precooled by the liquid nitrogen stage to about 80K, and then cooled by the liquid helium stage to above 20K at the copper plate. The trottling component is a capillary with a diameter of 1mm. The precooling system and the throttling system are improved and we have obtained some impressive results, the temperature of 4He gas drops from 25K to 22K after throttling in the capillary, which lays solid foundation for the future design of cryogenic J-T cryocooler.

Compact Integration of Cryogenic LNA on Miniature Cryocooler [WP5-9]

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Cryogenic low-noise amplifiers (LNAs) have been used in radio astronomy for some time. They have been used as the first stage of receivers at microwave frequencies and more recently in IF sections following mixers at millimeter-wave and sub-millimeter-wave frequencies.

For some of these applications, the cryogenic LNA is mounted onto a cryocooler. However, compactness and energy efficiency of the whole system are seldom a major requirement. Two-stage coolers are thus widely used as they provide both low temperature and significant cooling power, necessary to cool down a low-loss input line in order to minimize the receiver noise temperature.

HYPRES is currently developing an approach for an all cryogenic receiver, comprising a split architecture. This configuration detaches the analog radio frequency (RF) components in front of the analog-to-digital converter and houses it in a much smaller module, cooled by a single-stage cryocooler, that allows placement close to the antenna; the rest of the components are left in a larger module including a two-stage 4K cooler.

In this paper we focus on the remote module, and describe the integration of a 20 GHz cryogenic LNA onto a miniature single stage Stirling cooler. The objective of this cryogenic packaging is to optimize the technical performance of the LNA (gain, linearity and noise temperature) and the size, weight and power of the system. We discuss different solutions studied for the input and output RF lines, both in terms of electrical performance and heat load, and describe the different technological choices adopted to comply with strict size requirements. Finally we present preliminary RF measurements of the final system.

Fabrication of MEMS Linear Actuator [WP5-10]

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Cryogenic microcoolers are under development in our laboratory. They can be used to cool small electronic devices to improve their performance. The actuator forms the key component in the fabrication of the microcoolers. The performance of the actuator strongly influences the overall performance of the micro cooler. 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.

Design of a 4K Hybrid Stirling/Pulse Tube Cooler for Tactical Applications [THO1-1]

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Iris Technology is leading a three-partner consortium in the development of a low temperature cryocooler for superconducting electronics (SCE) applications. The intended applications are tactical, so cost is a primary concern, as are package size and mass. Because of the lack of a correlated thermodynamic model for this new type of cryocooler, the modeling efforts are premised upon using three proven cryocooler software modeling tools. Each tool is used for the aspect of the modeling for which it is particularly well suited. Computational domains are deliberately overlapped so that the results from different software tools can be compared to enhance modeling confidence. Using this technique, a thermodynamic design was developed that predicts net refrigeration of 4.0 W at 60K, 0.30 W at 11.5K, and 0.2W at 4K for 800 W of input pressure-volume (PV) power. The next step in the development is the build and test of a sufficiently representative cryocooler to correlate the model. Detailed design of a prototype cryocooler for this purpose is underway. To reduce development cost, the prototype will make heavy reuse of existing assets. These constraints, how the team is working around these constraints, the resulting projected performance of this demonstration prototype cooler, and the analysis methods used are presented. The initially targeted performance is 50 mW @ 5K, which the authors assert is sufficient to both correlate the model and demonstrate the three-stage hybrid Stirling/pulse tube cryocooler concept.

Thermal and mechanical integration of a linear coaxial pulse-tube cooler [THO1-2]

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Thales Cryogenics (TCBV) has an extensive background in delivering long life cryogenic pulse-tube coolers. These coolers are based on flexure bearing compressors in combination with coaxial pulse-tube cold fingers.

Pulse-tube coolers are often used in applications that require a high cooler reliability and are vibration sensitive. The latter requires correct integration of the cooler in the system with a minimum of transfer of induced vibrations to the cooled detector. Often active vibration control is implemented in addition, to further reduce the vibration signature of the cooler. In order to utilize the potential of the pulse-tube cooler to its maximum the thermal integration of the pulse-tube cooler in the system is essential. This not only requires in depth knowledge concerning thermal design parameters, but also detailed knowledge concerning the optimal thermal management of the pulse-tube cooler itself.

The mechanical and thermal integration of the LPT9310 pulse-tube cooler into a higher level system will be discussed. Design trade-offs for both mechanical and thermal aspects will be described and discussed. Thermal performance tests and the determination of transfer functions will be outlined.

Finally the performance and impact of the use of fully digital cooler drive electronics using active vibration control will be discussed.

Small Scale 80K Pulse Tube Cooler for RAPID e-APD infrared Camera [THO1-3]

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The RAPID project (Revolutionary Avalanche Photodiode Infrared Detector) aims to develop highly-sensitive HgCdTe avalanche diode matrices (e-APD), typically 320x256 pixels in size, operating at cryogenic temperatures. This next generation of detectors will target applications such as medical imaging, scientific instrumentation, spectroscopy for gas analysis, and military applications like hyperspectral detection and active imaging. The first demonstrations of the RAPID project will concern the astronomical applications of such detector with a high performances infrared wavefront sensor and an infrared fringes sensor for interferometric light combination of several ground based telescopes.
A high efficiency 1.5W@77K coaxial pulse tube cooler has been developed, manufactured and tested for this project. An LSF91xx type commercial compressor from Thales Cryogenics BV has been modified to enhance the overall efficiency of the cooler. The paper presents the optimization and the successful test results of the small scale cooler. The integration constraints of the cooler inside the RAPID cryostat and RAPID camera are also presented.

Transient Behavior of an Integral Rotary Cryocooler [THO1-4]

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This paper describes an investigation of the transient behavior of an integral rotary cryocooler, capable of relatively fast cool-down from ambient to about 50 K. A series of experiments was conducted, in which different amounts of excess thermal mass were added at the cold end. For each of them, the cold-end temperature was measured as a function of time in a complete cool-down and subsequent warm-up cycle, with no heat load. A transient heat transfer model developed under a separate study was applied to consider the effects of the cooling power produced by the cryocooler and that of the heat inlet (gain) from the ambient on the cool-down time. The heat gain factor was calculated from warm-up data. Using the same model with cool-down data enables a determination of both the gross and net cooling power as functions of time, but more importantly - as functions of the cold end temperature. An expression was derived for the cold-end temperature as a function of time for any amount of excess thermal mass.

Cryogenic Helium Circulation System Using Cryocoolers [THO1-5]

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Superconducting power applications require cryogenic environments. Most of high temperature superconducting applications use liquid nitrogen as the cryogen. Liquid nitrogen limits the operating temperatures to 67-77 K. Most defense applications require lower weight and size which can be achieved by lower operating temperatures to take advantage of higher critical current densities. Circulating helium gas has been successfully implemented for US Navy Degaussing System. The main challenge in using gaseous helium as cooling medium is its lower thermal capacity compared to that of liquid nitrogen. Hence high pressure and large flow rates are necessary to provide sufficient cooling to any superconducting power application.

The Center for Advanced Power Systems (CAPS) has been working on a superconducting DC Cable based on cryogenic gaseous helium circulation. One the challenges in the project is achieving sufficiently low temperature and large enough flow rate of helium gas circulation. Efficient transfer of heat from the gas stream to the cryocooler cold head is a challenge because large heat exchangers produce significant pressure drop that is too difficult for the helium circulation fans that drive the flow. This paper will present details of the design and test results of the helium circulation system developed at CAPS. New approaches that are under investigation to achieve large flow of cryogenic helim gas circulation systems will also be discussed.

Linear Cryogenic Coolers for Hot Infrared Detectors [THO1-6]

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In spite of a wide spreading the uncooled night vision technologies, the cooled systems are still known to be superior in terms of working ranges, resolution and ability to recognize/track objects in dynamic infrared scenes.
Recent technological advances allowed development and fielding of high temperature infrared detectors working up to 200K while showing performances typical for their 77K predecessors.
The direct benefits of using such detectors are the lowering of the optical, cooling and packaging constraints resulting in a smaller and cost effective optics, electronics and mechanical cryocooler.
The authors are formulating requirements and general vision of prospective cooled ultra-compact, long life, lightweight, power efficient, acoustically and dynamically quiet linear cryogenic cooler towards forthcoming infrared imagers.
In particular, the authors are revealing the outcomes of the feasibility study and discuss downscaling options.

An overview of Ball Aerospace cryocoolers [THO2-1]

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Over the last 20 years, Ball Aerospace & Technologies Corp. has developed very high efficiency Stirling and hybrid cryocoolers for aerospace and tactical applications. The single-stage HIRDLS cryocooler has been operating successfully on orbit for the last eight years (> 69,000 hours) without any performance outages. The two-stage SB235E TIRS cooler provides two stages of cooling with measured performance of 2.25 W at 42 K, 13.3 W at 100 K for 159 W motor power at 0^{o}C rejection temperature. Hybrid coolers have been demonstrated for low temperatures, low exported disturbances, and load leveling.

Aerospace Micro Cryocooler [THO2-2]

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Lockheed Martin's Advanced Technology Center has developed a very lightweight aerospace cryocooler for space and tactical cooling applications. A prototype pulse tube cryocooler was built and tested, utilizing a new micro compressor with a mass of less than 200 grams. The "Oxford type" compressor uses the same long-life features of Lockheed Martin's larger compressors: long-life flexure-bearing clearance-seal technology, with a simple moving magnet design designed both for long life space applications, and low-cost tactical applications.

The compressor operated flawlessly with electrical input power as high as 25W. Test data will be presented for the prototype single-stage pulse tube cooler. Predictions for the cooling capability of optimized coldheads under a variety of cold tip temperatures and heat loads will also be presented.

Extended Performance Testing of the ABI Proto-Flight Cryocoolers [THO2-3]

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The GOES-R Advanced Baseline Imager (ABI) first flight module is undergoing assembly and test at Exelis Geospatial Systems, Fort Wayne, IN During recent testing of the combined Active Cooler and Aft Optics subsystem, the compressor power needed to drive the cold components to required temperatures exceeded predictions. This resulted in additional testing of the cryocoolers to determine the cause of the high compressor power.

A methodical test program was developed, designed to build up the systems one piece at a time, so components could be individually exonerated. The first phase was a detailed characterization of the individual cryocoolers, operating each at known conditions of compressor power, compressor temperature, and temperature and heat load of both cold heads. These results were used to fit cryocooler models developed for the prototype coolers.

The second phase involved testing with thermal straps attached, including a controllable heat load at the end. This test demonstrated that the thermal strap blanket heat leak was approximately 2.5 times the expected value. Blanket design and installation revisions were made; retesting verified this was the principal source of the excess power consumption.

The third test demonstrated the performance of the integrated active cooler subsystem, with both coolers and straps connected through controllable heater blocks. This test showed that the integrated system performed as expected. It also demonstrated the heat leak of the non-operating cooler using a static measurement technique. Results compared favorably with previous test results that used dynamic methods that derive the heat leak from warm up tests.

TIRS Cryocooler Integration and Test at Instrument Level [THO2-4]

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The Thermal Infrared Sensor (TIRS) is an instrument on the Landsat Data Continuity Mission (LDCM) currently scheduled for launch in December 2012. The TIRS data in the thermal infrared band will provide land-use information, volcanic and fire monitoring, and water resource management. The focal plane consists of three Quantum Well Infrared Photodetectors (QWIP) arrays requiring cryogenic cooling to 43 K. That cryogenic cooling is provided by a two-stage Ball Aerospace cryocooler. That cooler was delivered to GSFC in April 2011 and immediately integrated into the TIRS instrument. Since that integration, the TIRS instrument has undergone complete environmental testing including random vibration, launch loads and thermal vacuum. This paper discusses this integration as well as the cooler performance during functional and environmental testing.

AIM Space Cryocooling System Qualification [THO2-5]

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IR-Space applications require very long life together with highest cooling performance at minimum energy consumption, compact and low weight design and extended environmental resistance. Depending on satellite design, mission life time and orbital conditions each on-board sub-system is subject to specific qualification procedures at different levels.

Since 2007, AIM has been developing and delivering Integrated Detector Cooler Assemblies (IDCA) including corresponding electronics for different space programs. The cooling systems of such IDCA's typically consist of a long-life cryocooler with AIM Flexure Bearing Moving Magnet compressor, a ½" Pulse Tube coldfinger with buffer volume, and a fully redundant Cooler Drive Electronics (CDE). All components and manufacturing processes of AIM cryocoolers are based on volume production to meet highest quality and reliability requirements. In a former AIM article of ICC 16, two space programs with its cryocooler hardware were introduced and qualification procedures presented.

This paper gives an overview on the latest qualification activities of cryocoolers as well as the cooler drive electronics. Major requirements of the mechanical and electrical environmental qualification and respective performance results will be presented and discussed in detail. Focus will be put on current life time tests of different long-life cryocoolers used within AIM space programs.

Integrated Detector Cooler Assembly for Space Applications [THO2-6]

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Integrated detector cooler assemblies are widely used in tactical military applications to integrate coolers with an infrared focal planes into an evacuated dewar. Because the space environment is already evacuated they have rarely been used in space payloads despite their test advantage prior to launch. In this paper we report the design, fabrication and test of an Integrated Detector Cooler Assembly (IDCA) that was designed for space around our micro cryocooler and that could be easily modified to accommodate a wide variety of MWIR and SWIR focal planes. The IDCA is a hermetically sealed evacuated dewar containing an optical window, a cold shield, provision for a cold filter, a 640x480 pixel InSb focal plane, wiring to a 41 pin hermetic connector and cooled by the integrated pulse tube cold finger. The IDCA is a variant of previous devices that have been built in quantity for tactical applications whose environmental requirements exceed those typically found for space optical hardware. Since the typical focal plane dissipation (including this InSb focal plane) is much less than 100mW, and the parasitic loads are much less than the cooler's rated capacity at 80K, this IDCA subsystem could also be used for some LWIR systems if the reject temperature is lowered

Low temperature thermal trades between a multistage TEC's and a tactical Cryocooler for space and Mars [THO2-7]

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Multi-spectral optical science missions frequently seek temperatures near 200K on the optical focal plane because it reduces dark current and increases the signal-to-noise ratio (SNR). This requirement has significant radiator size, system mass, and power implications, however. Furthermore, while choosing a tactical cryocooler can drop the power requirement it also has important mechanical implications regarding survival temperatures, reliability, and vibration. This paper presents a code written to analyze the performance and trades between these technologies when applied to a mission in low earth orbit (LEO) and surface mission to Mars on a robotic arm.

Low Cost Split Stirling Cryogenic Cooler For Aerospace Applications [THO2-8]

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Cryogenic coolers are usually conjugated with sensitive electronics and sensors of military, commercial or scientific space payloads. The general requirements are high reliability and power efficiency, low vibration export; ability to survive launch vibration extremes and long-term exposure to space radiation.
A long standing paradigm of using exclusively space heritage derivatives of legendary "Oxford" cryocoolers featuring linear actuators, flexural bearings, contactless seals and active vibration cancellation is so far the best known practice aiming at delivering high reliability components for the critical and usually expensive space missions.
The recent tendency of developing mini and micro satellites for the budget constrained missions has spurred attempts to adapt leading-edge tactical cryogenic coolers to meet the above space requirements. The authors are disclosing theoretical and practical aspects of developing a space qualified cryogenic refrigerator based on the Ricor model K527 tactical cooler and Iris Technology radiation hardened, low cost cryocooler electronics.
The initially targeted applications are cost-sensitive flight experiments, but should the results show promise, some long-life “traditional” cryocooler missions may well be satisfied by this approach.
Keywords: tactical cryocooler, space cryocooler, split Stirling linear cooler, vibration, reliability.

Intrinsically-porous materials and their use as regenerators in 4K cryocoolers [THO3-2]

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We target new solutions for replacing the Rare-Earth (RE) alloys which act as low-temperature magnetic regenerative heat exchangers (regenerators) in 4 K cryocoolers, such as Gifford-McMahon and pulse-tube refrigerators. Despite more than 20 years of research, RE alloys are the only materials that have been successfully employed thus far. The volumetric heat capacity of helium gas at pressures encountered in a typical cryocooler under working condition reaches large values [1], which compare favorably with that of RE-based regenerators at cryogenic temperatures. This suggests that the helium gas itself could be considered as an excellent 4 K regenerator, if a method is provided for confining the gas into a well-defined volume in thermal contact with the main flowing gas. Here we present our results that demonstrate that intrinsically-porous materials can provide such a trapping medium. Therefore, the regenerator to be considered is not just the porous material itself; rather it is the combination of this material and the trapped 4He. Our solutions are expected to drastically reduce the actual cost associated with RE-based regenerators, without any deterioration in the performance.

[1] R. D. McCarty, J. Phys. Chem. Ref. Data 2(4), 923 (1973).

Effect of Flow-Pressure Phase on Performance of Regenerators in the Range of 4 K to 20 K [THO3-4]

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Modeling with REGEN3.3 has shown that the phase between flow and pressure at the cold end of 4 K regenerators has a large effect on their second-law efficiency. The use of inertance tubes in small 4 K pulse tube cryocoolers have limited phase shifting ability, and their phase shift cannot be varied unless their dimensions are varied. We report here on the use of a miniature linear compressor, operating at the pulse tube warm end of about 30 K, as a controllable expander that can be used to vary the phase over 360^{o}. We also use the back EMF of the linear motor to measure the acoustic power, flow rate amplitude, and phase between flow and pressure at the piston face. We discuss the measurements of the linear motor parameters that are required to determine the piston velocity from the back EMF as well as the measurement procedures to determine the back EMF when the expander is operating at a temperature around 30 K. Our experimental results on the performance of a regenerator/pulse tube stage operating below 30 K show an optimum performance when the flow at the phase shifter lags the pressure by about 40^{o} to 50^{o}, which is close to the model results of about 60^{o}. Temperatures below 10 K were achieved at the cold end in these measurements. The efficiency of the compressor operating as an expander is also discussed.

Development of a 4 Kelvin Regenerator Test Facility [THO3-5]

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Recent advances in superconducting electronic systems are requiring larger envelopes for cooling power, efficiency, and operational environments from commercial based cryogenic cooling systems. One such system targeted at meeting these requirements is the pulse tube cryocooler. While the pulse tube cryocooler system is a well-documented technology at moderate cryogenic temperatures (40-80 Kelvin), its behavior at 4 Kelvin is not well understood. Recent modeling results using REGEN3.3 and CFD models have shown that 4 Kelvin pulse tube cryocoolers can be successfully applied to superconducting electronic systems. To gain confidence in the modeling predictions, experimental validation is required. This paper discusses a test facility designed and constructed to allow for precise measurement of all relevant regenerator and pulse tube energy flows when operating over the temperature range of 4-30 Kelvin, frequency range of 10-30 Hz, and cold end phase angle range of -15^{o} to -45^{o}. The novel features of this test facility include independent regenerator and pulse tube characterization, modulation of the system phasing using a commercial expander operating at 4 Kelvin, precise off-axis rotation, and rapid experimental turnaround time. A comparison of REGEN3.3 modeling predictions and initial experimental measurements for a regenerator matrix of Er50Pr50 are presented with discussion.

Staging Two Coolers through a Quarter-Wave Tube [THO4-1]

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Stirling coolers have high efficiency, in part because the displacer recovers acoustic power (pV work) from the gas near the cold heat exchanger, delivering it to the ambient end of the cooler. However, pulse-tube coolers have lower cost because they have no cold moving parts. In a new scheme with both high efficiency and no cold moving parts, acoustic power from the gas near the cold heat exchanger of a first cooler is recovered via a tube almost a quarter-wavelength long. The long tube's acoustic characteristics boost the pressure amplitude, lower the volume-flow-rate amplitude, and alter the time phasing between them, while transmitting acoustic power from the first cooler's cold temperature to a higher temperature, typically ambient temperature. The transformed oscillation is optimal to drive a second cooler, such as a pulse-tube cooler. The efficiency of this combination is higher than that of two separate pulse-tube coolers, because the second cooler is driven entirely by acoustic power that would otherwise be dissipated in the termination impedance (e.g., orifice) of the first pulse-tube cooler.
Experiments with two coupled coolers operating from room temperature to 200 K confirm the basic concept, demonstrating good performance despite a turbulent boundary layer in the long tube and even when the long tube is coiled for compactness. The technique is attractive for powers around 1 kW or higher, where only a small fraction of the recovered acoustic power is dissipated on the walls of the long tube. The technique seems most useful for first-stage cold temperatures above 80 K, for which the acoustic power available at the first cold heat exchanger is worth recovering. Production of liquefied natural gas at 111 Kelvin is one candidate.

Remote Helium cooling loops for laboratory applications [THO4-2]

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In order to provide high cooling capacity to vibration sensitive experiments, remote Helium cooling loops have been developed, manufactured and tested by Absolut System SAS. The customer's application is thermally anchored to a heat exchanger through which circulates a secondary, cryo-cooled, closed loop Helium mass flow to absorb the heat load. The secondary Helium loop makes use of a dedicated circulator, typically a compressor package from CRYOMECH Inc. It is cryo-cooled by a Gifford-McMahon (GM) closed cycle cryocooler from CRYOMECH Inc, and a counterflow heat exchanger. The GM cooling station is separated with several meters (typically 5 meters) from the customer cold application by a dedicated high performance Helium transfer line eliminating the vibrations and offering the possibility to operate the sensitive system and the GM station in separated environments (clean room, mechanical or optical benches for example).
Two remote Helium cooling loops will be presented and discussed. One is aiming to provide 17W@50K remote cooling for IR detector electro-optical characterization. The second is aiming to provide 30W@30K remote cooling to HTS equipment, making use of an intermediate LN2 cooling stage in the counterflow heat exchangers.

Results on a large acoustic-Stirling ("pulse tube") cooler designed for 800W at 70K [THO4-3]

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The emergence of high-power superconducting devices such as fault-current limiters, and demand for on-site liquefaction and storage of cryogens and fuels such as hydrogen and natural gas, have in turn spurred demand for larger point-ofuse cryogenic cooling. This paper describes the development and testing of a very large acoustic-Stirling ("pulse-tube") cooler driven by a 20 kWe pressure-wave
generator (PWG), and featuring a coaxial coldfinger and long transfer line separating the coldfinger and PWG. The coldfinger design and the 'split' configuration readily enable integration into most relevant applications, though they do present unique challenges at this scale. This system was developed in response to the Department of Energy's "HTS4" specification and the related "Cryogenic Roadmap". In this paper we will discuss the challenges inherent in building an acoustic cooler at this large scale, some strategies for lowering cost in production, and preliminary test results on the prototype cooler.
This work was sponsored by the U.S. Department of Energy.

Co-axial pulse tube development [THO4-4]

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[2]Absolut System SAS, Grenoble, France

Industrial Research Ltd (IRL) previously developed a single-stage, co-axial, pulse tube for use with their 60 ml swept volume metallic-diaphragm pressure wave generator (PWG); 85 W of cooling power @ 80 K was achieved. This paper describes the development and testing of a larger cryocooler designed and built for small scale liquefaction. The pulse tube was based on a similar co-axial design, and was close coupled to a 90 ml swept volume metallic-diaphragm PWG. Sage pulse tube simulation software was used to model the pulse tube and predicted 100 W of cooling power @ 80 K. A prototype was designed and constructed. Experimental optimization resulted in 120 W of cooling power @ 80 K, with electrical input power of 3.1 kW. The pulse tube operated at 50 Hz, with a mean helium working pressure of 2.5 MPa. Details of the development, experimental results and correlations to the Sage model are discussed.

A Stirling-type Coaxial Pulse Tube Cryocooler with 400 W cooling power at 77 K [THO4-5]

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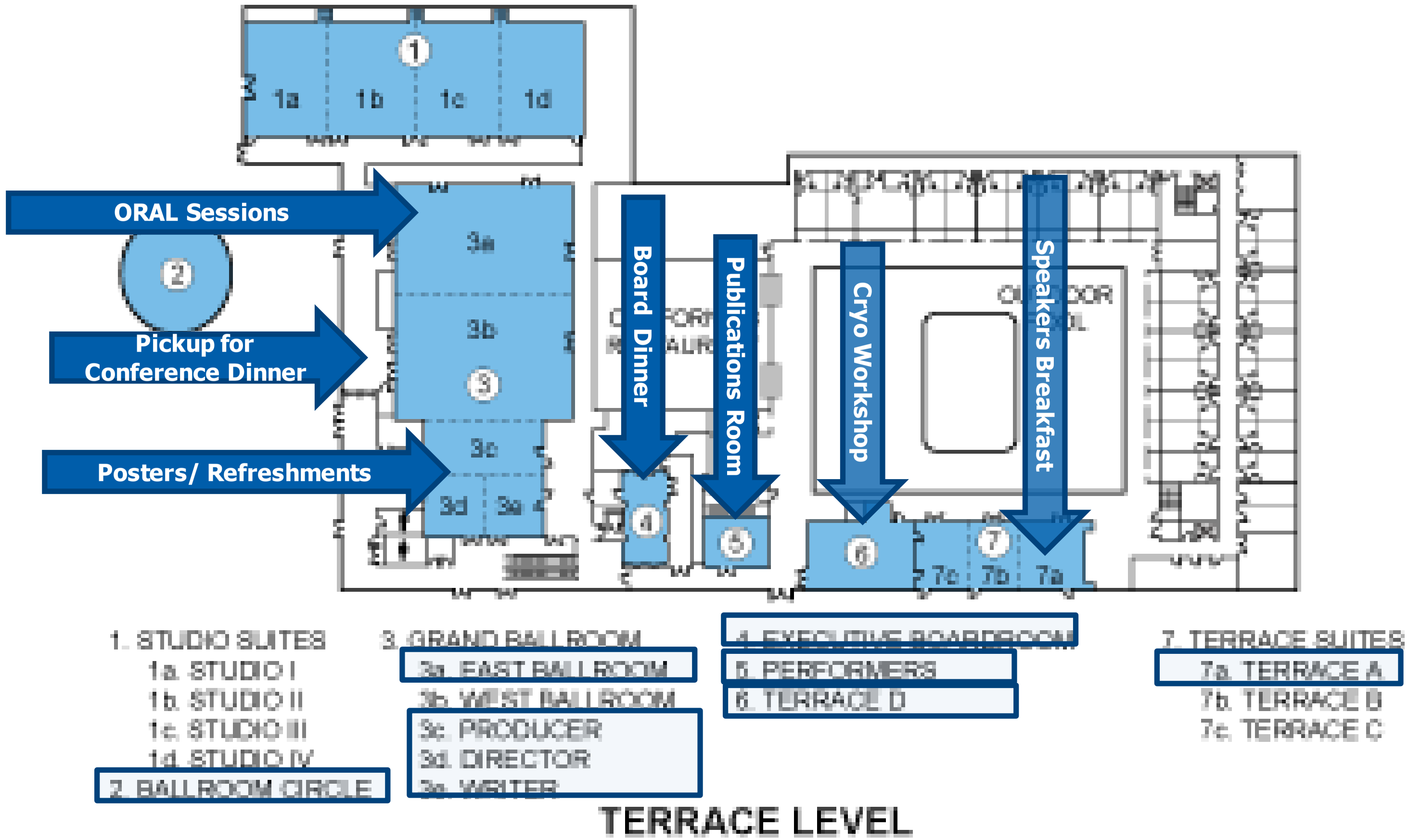
100 years of superconductor discoveries have long fostered the vision of a revolutionary lossless electric power grid. The discovery of high temperature superconductors (HTS) has brought this vision a major step closer to reality. The HTS devices are generally working at liquid nitrogen temperature, and high reliability, high efficiency, low cost cryocoolers are needed to cool them. Stirling-type pulse tube cryocooler is considered as one of the best candidates to cool the HTS power grid. In this paper, a linear compressor driven pulse tube cryocooler with 400 W cooling power at 77 K is developed to meet the need. It is single-stage and co-axial designed. Building such a high power pulse tube cryocooler generally involves some unique challenges, including Rayleigh streaming, increased risk of nonuniform flows, and heat exchanger design. The details of these problems will be presented in this paper. The charging pressure of the system is 3 MPa and the working frequency is 50Hz. With 6 kW electric power input, the cold finger can offer about 400 W cooling power at 77 K. The relative Carnot efficiency is higher than 19%.


ORAL Sessions
Pickup for Conference Dinner
Posters/ Refreshments
Board Dinner
Publications Room
Cryo Workshop
Speakers Breakfast
1a
1b
1c
1d
3a
3b
3c
3d
3e
7a
7b
7c
1. STUDIO SUITES
1a. STUDIO I
1b. STUDIO II
1c. STUDIO III
1d. STUDIO IV
2. BALLROOM CIRCLE
3. GRAND BALLROOM
3a. EAST BALLROOM
3b. WEST BALLROOM
3c. PRODUCER
3d. DIRECTOR
3e. WRITER
4. EXECUTIVE BOARDROOM
5. PERFORMERS
6. TERRACE D
7. TERRACE SUITES
7a. TERRACE A
7b. TERRACE B
7c. TERRACE C
TERRACE LEVEL

	Monday, July 9		Tuesday, July 10	Wednesday, July 11	Thursday, July 12	
7:00 AM			Speaker Breakfast/ Continental Breakfast	Speaker Breakfast/ Continental Breakfast	Speaker Breakfast/ Continental Breakfast	7:00 AM
8:00 AM			WELCOME	[WO1]	[THO1]	8:00 AM
8:15 AM					Tactical	8:15 AM
8:30 AM			[TO1]	Advanced	Cryocoolers	8:30 AM
8:45 AM			Aerospace	cryocooler	and	8:45 AM
9:00 AM	Foundation		Cryocoolers	component	applications	9:00 AM
9:15 AM			1	technology		9:15 AM
9:30 AM	of				Break	9:30 AM
9:45 AM				[WP2]		9:45 AM
10:00 AM	Cryocoolers		[TP2]	Commercial & laboratory		10:00 AM
10:15 AM			Advanced cryocooler	Pulse tube	[THO2]	10:15 AM
10:30 AM	12		component technology	cryocoolers	Aerospace	10:30 AM
10:45 AM					cryocoolers	10:45 AM
11:00 AM	Short			[WO3]	2	11:00 AM
11:15 AM			[TO3]			11:15 AM
11:30 AM	Course		Compressors	4K Cryocoolers		11:30 AM
11:45 AM			and			11:45 AM
12:00 PM			Expanders			12:00 PM
12:15 PM					Lunch	12:15 PM
12:30 PM				Lunch		12:30 PM
12:45 PM			Lunch			12:45 PM
1:00 PM					[THO3]	1:00 PM
1:15 PM		On-Site				1:15 PM
1:30 PM				[WO4]	4K	1:30 PM
1:45 PM			[TO4]		Regenerators	1:45 PM
2:00 PM		Registration		Pulse tube		2:00 PM
2:15 PM			JT	modeling	Break	2:15 PM
2:30 PM			Cryocoolers	and		2:30 PM
2:45 PM				experiments	[THO4]	2:45 PM
3:00 PM						3:00 PM
3:15 PM				[WP5]	High Capacity	3:15 PM
3:30 PM				Advanced analysis	Coolers	3:30 PM
3:45 PM			Break	& modeling techniques		3:45 PM
4:00 PM				Miniaturization and MEMS		4:00 PM
4:15 PM			[TO6]			4:15 PM
4:30 PM			Commercial			4:30 PM
4:45 PM			and			4:45 PM
5:00 PM			laboratory			5:00 PM
5:15 PM			cryocoolers			5:15 PM
5:30 PM						5:30 PM
5:45 PM						5:45 PM
6:00 PM				Conference		6:00 PM
6:15 PM				Event		6:15 PM
6:30 PM	Welcome Reception			at Universal Studios		6:30 PM
	6:30 to 9:00 PM			6 to 10 PM		
	Starview Room			(Pickup at Sheraton)		

MEETING ROOM MAP IS ON INSIDE COVER