



ICC 18

SYRACUSE, NY • JUNE 9-12, 2014



2014 INTERNATIONAL
CRYOCOOLER
CONFERENCE



PROGRAM AND ABSTRACTS

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WELCOME

On behalf of the ICC 18 Organizing and Program Committees, we welcome you to the 18th International Cryocooler Conference (ICC 18) being held June 9-12, 2014 in Syracuse, New York, 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 18*, approximately six months after the conference. This includes copies of the papers presented at ICC 18 which are peer reviewed to assure the quality of the proceedings.

Attendees at ICC 18 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 ICC18 in Syracuse on the picturesque, hilltop campus of Syracuse University. Shopping, dining, entertainment and sightseeing options abound throughout the city and the Greater Syracuse area.

Please join us for our Welcome Reception on Monday, June 9th from 6:00 PM to 9:00 PM at Club 4-4 inside Syracuse University's Carrier Dome.

The ICC 18 Conference Dinner will be held on Wednesday evening, June 11th from 6:00 PM to 10:00 PM at the Milton J. Rubenstein Museum of Science and Technology, the M.O.S.T., in historic Armory Square. Dinner, catered by Syracuse's own, nationally acclaimed Dinosaur Bar-B-Que, will be held inside the museum and accompanied by live entertainment. Transportation to and from the dinner will be provided. This is an event that you won't want to miss!

Welcome to Syracuse and ICC 18!

Rich Dausman
Conference Chairman

Carl Kirkconnell
Program Chair

Chao Wang
Conference Co-Chairman

Michael J. Ellis
Deputy Program Chair

CONFERENCE OVERVIEW

The biennial International Cryocooler Conference is the premier international forum for the presentation, discussion, and dissemination of the latest research and development activities related to all aspects of 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 18th International Cryocooler Conference (ICC 18) will take place on June 9-12, 2014 on the campus of Syracuse University in Syracuse, New York. The proceedings will be held in Goldstein Auditorium, located inside the Schine Student Center. Schine Student Center is across the street from the conference hotel and is one block from Marshall Street where you'll find a wide variety of restaurants and shops.

The Conference begins with a Welcome Reception at Club 4-4 inside the Carrier Dome on Monday evening, June 9th at 6:00 PM. The Technical Program commences at 8:30 AM on Tuesday, June 10th. Approximately 115 papers will be presented in both oral and poster formats during the ensuing three days, concluding on Thursday afternoon, June 12th at 3:45 PM. A very full Social Program includes the Welcome Reception on June 9th and the Conference Dinner at the Milton J. Rubenstein Museum of Science and Technology, the M.O.S.T., on Wednesday, June 11th. The papers are being presented in consecutive Oral and Poster Sessions. For your convenience, a complete overview of the Conference Schedule is provided both on the back cover and on the website.

REGISTRATION

Registration will be held in the Sheraton Hotel lobby on Monday. Registration on Tuesday, Wednesday, and Thursday will be in Goldstein Auditorium. All attendees must register. The onsite registration fee is \$655, which includes the Technical Program, all of the Social Program events and provided meals, conference materials, and the Conference Proceedings, which will be mailed to each participant approximately 6 months after the event. Companion guest tickets to the Conference Dinner are available for an additional fee of \$75.

Payments to ICC 18 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 and locations are as follows:

Monday, June 9:	1:00 PM – 7:00 PM	Sheraton Lobby
Tuesday, June 10:	7:00 AM – 4:00 PM	Goldstein Auditorium
Wednesday, June 11:	7:00 AM – 3:30 PM	Goldstein Auditorium
Thursday, June 12:	7:00 AM – 12:00 PM	Goldstein Auditorium

WELCOME RECEPTION and CONFERENCE DINNER

The Welcome Reception will be held at Club 4-4 inside the Carrier Dome on Monday evening, June 9th from 6:00 PM to 9:00 PM. The Carrier Dome, home to Syracuse University’s sports teams, is on the campus of Syracuse University and is a short walk across campus from the conference hotel.

A wide variety of appetizers, finger foods, desserts and beverages will be served inside this exclusive club. You will be supplied with tickets for two drinks that can be used for soft drinks, wine and beer. Additional beverages and mixed drinks will be available at a cash bar. For those interested, a tour of the Carrier Dome and its inner workings will begin at 7 PM.

The Conference Dinner will be held on Wednesday evening, June 11th from 6:00 PM to 10:00 PM at the Milton J. Rubenstein Museum of Science and Technology, the M.O.S.T. Situated in the heart of Armory Square, the M.O.S.T is just minutes from Syracuse University and the conference hotel. Attendees and their guests will have exclusive, full access to the entire museum and a private screening in its domed IMAX Omnitheatre. Armory Square, located in downtown Syracuse’s historic 19th Century warehouse district, is home to specialty restaurants, nightclubs, boutique shops and entertainment venues.

Dinner, catered by Syracuse’s own, nationally acclaimed Dinosaur Bar-B-Que, will be held inside the museum and accompanied by live entertainment. Your conference registration package includes one ticket to the Museum, IMAX Movie and Dinner. In addition two drink tickets will be provided and can be used for soft drinks, wine and beer. Additional beverages and mixed drinks will be available at a cash bar. Additional guest tickets are available for \$75 each. Guest tickets can be purchased prior to the event when registering online or at the onsite registration desk.

Transportation to and from the dinner will be provided by coach bus. Buses will depart from the conference hotel beginning at 5:45 PM and begin returning to the conference hotel at 9:45 PM.

MEALS

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

All Session Chairs are invited to the Session Chair Breakfast Meeting at 7:00 AM on Tuesday, June 10th in Schine Student Center. This will be the only Session Chair Breakfast Meeting for the conference. The Program Chair will address a number of topics including how the sessions will run, the collection of papers, the review process of the papers and other pertinent information.

The Welcome Reception on Monday, June 9th will serve finger foods, hors d'oeuvres, desserts and beverages.

The Conference Dinner will be held on Wednesday, June 11th and will serve appetizers, dinner, desserts and beverages.

For lunch, in addition to the food court in Schine Student Center and the Sheraton's restaurant, we encourage you to enjoy the wide variety of restaurants in the Marshall Street area which is two blocks from Goldstein Auditorium.

SYRACUSE, NEW YORK

Located in the heart of New York State, Syracuse is both a cosmopolitan city and a college town with attractions and events that draw visitors from all over the world. It is a city of hills, valleys, lakes and streams. The Greater Syracuse Area has a population of 700,000 and is home to three major universities, a symphony orchestra, an opera company, professional sports teams, and more than 30 art and cultural venues all within close distance to one another. In addition, numerous tourist destinations such as Niagara Falls, Baseball Hall of Fame, Turning Stone Resort and Casino, and the beautiful Finger Lakes Wine Region are all within easy reach.

There are a number of shopping centers in and around Syracuse including Destiny USA, a six-story super-regional shopping and entertainment complex on the shore of Onondaga Lake. It is the sixth largest shopping center in the nation and the largest in the state of New York. Armory Square, an urban neighborhood in downtown Syracuse, boasts a variety of boutique shops, dining, and entertainment venues. This National Historic District retains a significant and well-preserved concentration of historic buildings exhibiting a variety of architectural styles.

The Conference will take place on the campus of Syracuse University which is situated atop a hill overlooking the City of Syracuse. Shops, restaurants, parks and residential neighborhoods are all found within the University Hill area. Downtown Syracuse is just minutes from the university neighborhood.

During the month of June, the average high temperature is 76F (24C) and the average low temperature is 55F (13C). Average rainfall for the month is 3.3 inches (8.4 cm).

Area Websites of Interest:

Syracuse Visitors and Convention Bureau - www.visitsyracuse.org

Downtown Syracuse - <http://www.downtownsyracuse.com>

Destiny USA - www.destinyusa.com

Armory Square - www.armorysquareofsyracuse.com

Everson Museum of Art - www.everson.org

I Love NY - www.iloveny.com

Finger Lakes Tourism - <http://fingerlakes.org>

CONFERENCE HOTEL - THE SHERATON SYRACUSE UNIVERSITY HOTEL & CONFERENCE CENTER

The Sheraton Syracuse University Hotel & Conference Center is located on the campus of Syracuse University. The recently renovated hotel is providing preferred lodging arrangements for all ICC 18 attendees. Amenities and features include indoor pool, sauna, fitness center, restaurant and lounge. The hotel also offers free internet, free parking in an attached garage and free shuttle service to the airport and local destinations. The Sheraton is conveniently located across the street from the Schine Student Center, site of the conference proceedings, as well as within short walking distance of many local shops and eateries in the University Hill neighborhood.

TRANSPORTATION

DRIVING DIRECTIONS from HANCOCK INTERNATIONAL AIRPORT (9.1 miles or 14.6 km)

Take Col. Eileen Collins Boulevard Southeast for approximately 1.7 miles to the ramp for Interstate 81 South (I-81S). Continue on the ramp for 0.8 miles and

merge onto I-81 South heading towards Syracuse. In approximately 6 miles, take Exit 18 toward Harrison St/Adams St and keep left at the fork, following signs for Adams St. At the bottom of the ramp proceed onto Almond Street and merge into the left hand lane. Proceed for approximately 0.3 miles and turn left onto Adams Street. Take Adams Street for approximately 0.4 miles and turn right onto University Avenue. The Sheraton is on the left hand side of the street.

HOTEL SHUTTLE

The Sheraton Hotel and Conference Center offers free shuttle service. Contact the hotel on your arrival to arrange for shuttle service to the hotel. The hotel phone number is (315) 475-3000.

HIRED TRANSPORTATION

Taxi cabs are available to and from the airport. Syracuse Regional Airport Taxi provides taxi and van service on an exclusive basis at Syracuse Hancock International Airport. Passengers requiring ground transportation service can register with Syracuse Regional Airport Taxi at one of the dispatch areas located near each baggage claim location. These areas are staffed between the hours of 5:00 AM and 2:00 AM. Syracuse Regional Airport Taxi also offers a shuttle van service, which is an economical alternative for individuals traveling to the same location. If you have any questions regarding ground transportation provided by Syracuse Regional Airport Taxi please contact their office at (315) 437-5555. You may also visit their website at www.syracusetaxi.com

PUBLIC TRANSPORTATION

Public transportation is available on Centro, Syracuse's bus system. **Please note** that Centro does not operate to the Syracuse Hancock International Airport. From the airport, take a taxi to the William F. Walsh Regional Transportation Center, located only a few miles from the airport, to connect to a bus. Travelers heading to the airport may take Centro to the Regional Transportation Center and pick up one of the many taxis stationed there to complete their journey. Centro bus schedules are available on their website www.centro.org

AUTHOR / PRESENTER INFORMATION

INSTRUCTIONS for POSTER PRESENTERS

Poster sessions will be held on Tuesday at 3:15 PM, and on Wednesday and Thursday at 9:15 AM. Presenters are expected to only attend to their poster during their respective session. We encourage all poster session papers to be

posted before the start of the day's session or during lunch and request that they be removed by 5:00 PM. Papers not removed in a timely manner will be discarded.

Each poster presenter will be provided with a poster mounting area 36" (0.91m) wide by 48" (1.22 m) high. The poster boards have a foam core or corkboard surface and papers must be affixed with pushpins, which will be provided. Only pushpins may be used to attach materials to the poster boards.

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 to 13 minutes, with 2 to 3 minutes available for questions. You are expected to notify the session chair of your presence 10 minutes before the start of the session so that he/she knows that you are present. There will be no rearrangement of papers within an oral session to accommodate absences or cancellations. The time that you have been assigned within the oral session is fixed. Please inform your session chair if you must withdraw your paper from the program on site at the conference.

All oral presenters are required to submit an electronic version of their presentation by the close of the Publication Room 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 Goldstein Auditorium) 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 the close of the Publication Room of the day prior to their presentation, they may be required to present their paper without accompanying vugraphs.

PUBLICATION ROOM HOURS and LOCATION

Monday, June 9:	1:00 PM – 5:00 PM	Sheraton Hotel Lobby
Tuesday, June 10:	7:00 AM – 5:00 PM	Goldstein Auditorium
Wednesday, June 11:	12:00 PM – 4:00 PM	Goldstein Auditorium
Thursday, June 12:	7:00 AM – 12:00 PM	Goldstein Auditorium

INSTRUCTIONS for PAPER SUBMISSION

Authors must submit their manuscripts to conference staff in the Publications Room, located in Goldstein Auditorium by 5:00 PM on Tuesday, June 10th. Please bring the following:

- An electronic version on a CD or flash drive
- One print-ready hard copy
- Three additional hard copies for use by the technical reviewers

Technical papers will be distributed by the publications staff for peer review prior to publication in the conference proceedings, *Cryocoolers 18*.

TECHNICAL PROGRAM

The Technical Program for the 18th ICC is organized into 13 oral sessions and 5 poster sessions containing approximately 115 papers. The conference will begin on Tuesday, June 10th at 8:15 AM in Goldstein Auditorium with a fifteen-minute introduction by the ICC 18 Organizing Committee. The technical sessions will begin at 8:30 AM on Tuesday, June 10th immediately following the Introduction. Technical sessions on Wednesday, June 11th and Thursday, June 12th will begin promptly at 8:00 AM. The conference ends at 3:45 PM on Thursday, June 12th.

The entire conference will be held in Goldstein Auditorium, located inside the Schine Student Center on the campus of Syracuse University. All oral and poster sessions will be in Goldstein Auditorium. The five poster sessions will provide an excellent opportunity for close personal interaction with authors of these specialized topical subjects. The poster sessions will coincide with breaks. Light refreshments will be served during the poster sessions.

INTERNET ACCESS

Wi-Fi is available in Schine Student Center and Goldstein Auditorium. Access is available for guests with computers, tablets and smartphones for one week at no charge. You may connect more than one device at a time.

The AirOrangeGuest wireless network provides unsecured access and is available to any campus guest on a temporary basis. The network is not secured by any sort of encryption – *proceed at your own risk!*

A text-capable mobile phone is required to complete the process.

- Connect to the AirOrangeGuest wireless network and wait for the Network Guest Service Portal to open on your device. If it doesn't open on its own, open your browser to <http://airorangeguest.syr.edu>.
- Click on the self-sponsored guest account creation on the left side of the screen.
- Enter your cell phone number.
- A password will be texted to your phone.
- Click on "Enter Password" in the left column.
- Enter the password from your phone.

ABOUT THIS ABSTRACT BOOK

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

This Abstract Book is also posted online at www.cryocooler.org

TECHNICAL PROGRAM / SESSION CHAIRS

Tuesday						
Start	End		Session #	Chair 1	Chair 2	Chair 3
8:15	8:30	Welcome to the Conference - Chair				
8:30	9:30	Space Missions	TO1	Mark Zagarola	Rob Boyle	
9:30	9:45	Break				
9:45	11:00	Regenerators	TO2	Dale Durand	Alan Caughley	
11:00	1:00	Lunch				
1:00	2:00	Cryocooler Applications I	TO3	Peter Bradley	Gan Zhihua	
2:00	3:15	Commercial Cryocoolers I	TO4	Weibo Chen	Ryan Taylor	
3:15	4:15	Cryocooler Applications II	TP1	Jose Rodriguez	Tonny Benchop	
3:15	4:15	Stirling and Pulse Tube Cryocoolers	TP2	Tanh Nguyen	Markus Mai	Sidney Yuan
4:15	6:00	Miniature Cryocoolers	TO5	Dan Kuo	Julien Tanchon	

Wednesday						
Start	End		Session #	Chair 1	Chair 2	Chair 3
8:00	9:15	Aerospace Cryocoolers I	WO6	Jeff Olson	Mike Ellis	
9:15	10:15	Advanced Cryocooler Component Technology	WP3	Jennifer Marquardt	Eric Marquardt	Dai Wei
10:15	11:30	Advanced Analysis and Modeling I	WO7	Ted Conrad	Chris Dodson	
11:30	1:15	Lunch				
1:15	2:15	Advanced Cryosystem Components	WO8	Ingo Ruelich	Mostafa Ghiaasiaan	
2:15	2:30	Break				
2:30	4:00	Very Low Temperature Cryocoolers I	WO9	Ray Radebaugh	Lionel Duband	

Thursday						
Start	End		Session #	Chair 1	Chair 2	Chair 3
8:00	9:15	Commercial Cryocoolers II	THO10	Alex Veprik	Steve Nieczkoski	
9:15	10:15	Advanced Analysis and Modeling II	THP4	Tom Mulcahey	Thierry Trollier	David Gedeon
9:15	10:15	Very Low Temperature Cryocoolers II	THP5	Kurt Uhlig	Ted Nast	
10:15	11:30	Brayton, JT, and Sorption Cryocoolers	THO11	L. Barry Penswick	Nir Tzabar	
11:30	1:15	Lunch				
1:15	2:15	Aerospace Cryocoolers II	THO12	Jeff Raab	Daniel Willems	
2:15	2:30	Break				
2:30	3:45	Emerging Cryocooler Technology	THO13	Dean Johnson	Tom Fraser	

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AIRS Pulse Tube Cooler Performance Update – Twelve Years in Space [TO1–1]

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The Atmospheric Infrared Sounder (AIRS) instrument pulse tube cryocoolers began operation 39 days after launch of the NASA EOS/AQUA on May 4, 2002. They have now been operating continuously in space for 12 years with little or no degradation. Designed with redundant cryocoolers (a primary and a backup), the instrument began operation using a single cooler to bear the load of both the detector and the non-operating, backup cooler. During the early months of the mission, contamination of the cryogenic surfaces led to increased cryocooler loads and the need for periodic decontamination cycles. A change in operating strategy was made in November 2002 to run both coolers simultaneously to both overcome the increased cryogenic contamination load and to allow operation at a much reduced compressor stroke level. This change led to the successful continuous operation of the coolers and the non-interruption of science data collection from the AIRS instrument.

After a brief review of the AIRS instrument cryogenic design, this paper presents detailed data on the highly successful continuous operation of the AIRS pulse tube cryocoolers and instrument thermal design over the past twelve years. The data show that the cryogenic contamination reached an equilibrium level after a year of space operation and the cooler stroke required for constant-temperature operation has only increased a few percent since that time. At this time AIRS maintains continuous operation in space providing important scientific data on Earth's atmospheric parameters.

Mid InfraRed Instrument (MIRI) Cooler Cold Head Assembly Acceptance Testing and Characterization [TO1-2]

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The Cooler Subsystem for the Mid InfraRed Instrument (MIRI) of the James Webb Space Telescope (JWST) utilizes a remotely mounted Cold Head Assembly as the final cooling stage of the precooled Joule-Thomson cooler. The cooler's Cold Head Assembly recently completed its acceptance testing. This paper describes the Cold Head Assembly and summarizes the cryogenic refrigeration performance results. These results are compared with theory and program requirements. These results are also compared to the test results from the flight-like model which preceded it, which was used in the JWST ISIM Cryo-Vac1 testing.

OCO-2 Cryocooler Development, Integration and Test [TO1-3]

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The Orbiting Carbon Observatory (OCO-2) is currently in its final stages of assembly and checkout at this time in preparation for a July 2014 launch aboard a Delta II from Vandenberg Air Force Base in California. OCO-2 will collect space-based global measurements of atmospheric carbon dioxide (CO_2) with the precision, resolution and coverage needed to characterize regional-scale sources and sinks of this important greenhouse gas. The observatory consists of a dedicated Orbital Sciences Corporation (OSC) LEOStar-2 spacecraft bus that carries a single instrument. The instrument uses three HgCdTe focal plane arrays that are cooled by a Northrop Grumman Aerospace Systems (NGAS) High Efficiency Cryocooler (HEC) pulse tube cryocooler operating at 110 K. The cryocooler is powered and controlled by the NGAS Advanced Cryocooler Electronics (ACE).

The development of this cryocooler system was a collaborative effort that involved qualification and characterization testing at NGAS and JPL, instrument integration at JPL, and observatory integration at Orbital Sciences Corporation (OSC) in Gilbert, Arizona.

This paper presents the development, characterization, flight qualification and flight integration test results, including detailed thermal and temperature control performance within the flight instrument boundary conditions, for the OCO-2 cryocooler system.

Development of Low Cost Cryocoolers for Space [TO1-4]

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In the past two decades, flexure-bearing technology has gained a firm footing in the tactical cryocooler market. This has dramatically increased the reliability of COTS (commercial off-the-shelf) systems, making them a viable choice for low-cost space missions.

Thales Cryogenics is currently involved in several projects to develop cryocoolers suitable for space applications based on its tactical heritage. An overview is presented of COTS activities for space applications now running such as the use of flexure bearing Stirling and pulse tube coolers. In the presentation design concepts and choices will be discussed. Furthermore performance graphs of the optimized cryogenic cooler performance as well as an assessment of the product robustness will be presented.

The presentation is concluded with an outlook on COTS technologies that may be suitable for space deployment in the future.

4 Kelvin Regenerator Loss Measurements [TO2-1]

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Past work has described the development of a three-stage regenerator test facility for validation of predicative regenerator models over a temperature range of 80-4 K. This specific test facility is unique as the regenerator loss for a given configuration can be measured over a wide operational space that includes the ability to modulate the cold end test temperature from 3-5 K, warm end test temperature from 18-30 K, charge pressure from 1-2 MPa, and cold end phase angle from -15° to -45° .

This work presents initial experimental results from this new regenerator test facility over a temperature range of 4-30 K. A discussion of the calibration procedures and results is presented along with discussion of the experimental errors in the fundamental measurements and the computed quantities of interest. Initial regenerator loss data is presented for regenerator matrix configurations that include: Pb, Pb + Er50Pr50, Er50Pr50, and Er50Pr50 + GOS (gadolinium oxysulfide). For each regenerator matrix configuration, the regenerator loss is presented for a charge pressure of 1 MPa, operating frequency of 30 Hz, warm end temperatures of 20 K and 30 K, and a range of cold phase angles. The experimentally measured losses for each test permutation are compared to REGEN3.3 predictions using identical conditions. A discussion of the agreement between model and experiment is provided.

Optimization Design and Experimental Study on a 2.8W@80K Stirling Cryocooler Regenerator [TO2-2]

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The regenerator is the key of high efficiency operation of a Stirling cryocooler. In this paper, the regenerator of a 2.8W@80K Stirling cryocooler was optimally designed. The regenerator length, the pressure ratio at the cold end, and the mesh number of the matrix were optimized by using REGEN 3.3. Experimental study was carried out and it's found that the efficiency of the regenerator can be improved by changing the mesh parameter and the packing form of the matrix, what's more, while with the same mesh number, a finer mesh of stainless steel could further improve the efficiency of the regenerator.

Parametric Optimization Study Using REGEN3.3 [TO2-3]

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A parametric study using REGEN3.3 has been conducted to develop a set of design charts for a variety of common operating conditions of single-stage Stirling-type regenerative cryocoolers. By optimizing the COP over the set of variables including the cold end phase angle, average pressure, pressure ratio, regenerator length, and mass flux for fixed values of cold end temperature and operating frequency, a set of optimized parameters are obtained at temperatures of 80 K, 60 K, and 35 K and with frequencies from 30 Hz to 300 Hz. The results allow approximate optimized designs for temperatures and frequencies intermediate to those studied here via interpolation. In addition, changes in design as a function of cooling power at any of the fixed temperature, frequency points are enabled by a simple scaling relationship. Results of the model are compared with published cryocooler performance values.

Numerical Analysis of Hydraulic Characteristics in Cryogenic Regenerator [TO2-4]

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A regenerator is a key component for a regenerative cryocooler. Hydraulic behavior of the regenerator has a strong influence on the cryocooler performance. Different from previous studies, a 3-dimensional model with real mesh configuration has been established. The flow characteristics are observed with both steady flow and oscillation flow conditions. Effects of frequency, average pressure, pressure ratio and local phase relationship between pressure and volume flow have been studied. Specially, the anisotropic behavior based on real mesh configuration is one of the focuses. Finally, the numerical results are compared with the experimental ones to validate the model.

A Novel Design Concept for Cold End Heat Exchangers in High Power Pulse Tube Cryocoolers [TO2-5]

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The cold end heat exchanger (CHX), which is the only component for harvesting cooling power from the cryocooler, becomes one of the limitations for higher efficient cryocoolers with development of high power pulse tube cryocoolers (HPPTCs). New design concepts, like energy gate and energy dimension switch, are used for analyzing the thermodynamics process in the heat exchangers. The new method reveals that the traditional design for CHX in small capacity PTC are not applicable for CHX in HPPTC. Compared with the traditional design, the COP of HPPTC can be improved over 10% with the new designed CHX in simulation.

Pulse Tube Cooler Apply to Vacuum Cryogenic Optics System [TO3-1]

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The objectives of this paper are to design and analysis a vacuum cryogenic optics system. The temperature of this system is about 80K, so we apply the pulse tube cooler to the system. But, the system is very complex and in order to get the right temperature, so must choose an appropriate pulse tube cooler. This paper use the ANSYS to analysis every parts' temperature of the vacuum cryogenic optics system with different pulse tube cooler.

Lessons Learned Concerning the use of 4K Coolers to Cool LTS Magnets [TO3-2]

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Coolers have been used to keep MRI magnets cold for many years. The key to keeping these magnets cold was having a low heat leak cryostat. For the most part, MRI magnets have not had to deal with powered leads. Since the late 1990's coolers have been used to keep LTS magnets cold that run continuously through powered leads. While there have been many successes in the use of coolers to cool LTS magnets, there have been many magnets where the coolers were unable to cool-down the magnet or they were unable to keep the magnet at the proper operating temperature (say <4.7 K for Nb-Ti magnets) using the coolers alone. This report deals with mistakes that have been made and the steps that needed to be taken in order to make it possible to cool-down and keep cool an LTS magnet.

Mistakes made usually fall into a number of categories, which are as follows: 1) Estimates of the heat leaks onto the magnet cold mass and shield are usually optimistic. As a result, a decision is made to use too few coolers. 2) Bad workmanship during the assembly of the magnet cryostat is often the root of most cooling problems. 3) The magnet radiation shield and cold mass support intercept temperatures are often too high, which leads to higher heat flow to the 4 K cold mass. 4) The connections between the 4 K cold heads and the cold mass are not properly designed. The result is a higher cold mass temperature and longer cool-down times. 5) The leads that connect the tops of the HTS leads to room temperature are often not properly designed. This results in larger heat loads to the HTS leads, which can result in their failure. 6) It is difficult to determine what went wrong with the magnet when you don't have performance curves for the coolers. 7) Finally, there aren't enough calibrated temperature sensors installed in the system to know what went wrong when the coolers don't keep the magnet cold.

Application of Cryocoolers for Prototype Testing and Operation of Helium Gas Cooled Superconducting Power Devices [TO3-3]

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Many types of Cryocoolers have been used for High Temperature Superconducting (HTS) power applications. Most HTS power devices are cooled with liquid nitrogen and the cryocoolers have been used to sub-cool liquid nitrogen that is circulated through the application. The operating temperature of such liquid nitrogen cooled HTS power devices is limited to 65-77 K. Lower operating temperatures offer higher critical current densities in superconducting materials and provides enhanced operating margin. Gaseous helium cooled superconducting power devices can be operated over a wide range of temperature without any phase change. There have been a few applications, mostly Navy related, that have been demonstrated the use of gaseous helium for superconducting devices. This paper will present details of successful demonstration of gaseous helium cooled superconducting DC cable and technical challenges encountered and the solutions developed. The paper will also describe other novel applications of cryogenic helium gas circulation systems for characterizations of superconducting power device components.

This work is supported by the ONR, Office of Naval Research.

Ruggedizing Infrared Integrated Dewar-Detector-Cooler Assemblies for Harsh Environmental Conditions [TO3-4]

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Cryogenically cooled infrared electro-optical payloads have to operate and survive frequent exposure to harsh vibrational and shock conditions typical of the modern battlefield. This necessitates the development of special approaches to ruggedizing their sensitive components.

The ruggedizing requirement holds true specifically for Integrated Dewar-Detector-Cooler Assemblies (IDDCA) where the infrared Focal Plane Array (FPA) is usually supported by a thin-walled cold finger placed inside an evacuated Dewar envelope. Without sufficient ruggedizing of the FPA support, the harsh environmental conditions may lead to its resonant dynamic response spoiling the imagery quality and even to mechanical fractures resulting from material overstressing.

The authors present their approach to the ruggedizing of IDDCA by semi-rigidly supporting the FPA from the dynamically damped Dewar envelope. The mathematical model relies on the experimentally evaluated set of frequency response functions of the reference system and lumped model of wideband dynamic absorber. By adding only 2% to the weight of the IDDCA, the authors attenuated 3-fold the relative deflection and absolute acceleration of the FPA. The analytical predictions are in full agreement with the experimental findings.

A Compact Cold Helium Circulation System with GM Cryocooler [TO4-1]

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A new type of cold helium circulation system with a GM cryocooler was developed for remote cooling. A set of check valves connects to the cold head expansion chamber to convert a small portion of AC flow in the cold head to DC gas flow for circulating cold helium in the remote loop. The GM cryocooler, Cryomech model AL200 (nominal 200W at 77K), is used to build the cold helium circulation. The cold helium circulates through a 4.9 m long flexible transfer line. It is made of corrugated SS lines and is vacuum insulated.

The regenerator of the GM cryocooler and the check valves are optimized for the cold helium circulation. The cold helium transfer line was redesigned to reduce the thermal losses. The cold finger could provide >110W cooling capacity at 77K at a remote location while the system has a power input of ~8 kW. This new cold helium circulation system features a compact design for the cold finger and vacuum chamber. It results in a smaller size, less vibration, and lower cost than the existing Cryomech cold helium circulation system.

Numerical Simulation of the Effect of Heat Conductivity in a 4K Regenerator [TO4-2]

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In a 4K cryocooler, the performance of the second stage is strongly dependent on the efficiency of the second stage regenerator. In order to improve the efficiency of the second stage regenerator, the effect of the heat conductivity of the regenerator material is analyzed by numerical simulation. It is found that the cooling performance of both the first and second stage can be improved by choosing a material with reasonable heat conductivity at the warm end of the second stage regenerator. The temperature profile of the second stage regenerator with respect to the heat conductivity of the regenerator material and the mass variation in the void volume of the second stage regenerator are also analyzed. The simulation results will be reported in this paper.

High-Capacity and High-Efficiency Stirling Cycle Cryocoolers [TO4-3]

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Infinia Technology Corporation (ITC) has been active in development of low cost high, capacity cryocoolers for a number of years to meet a wide range of user requirements. The use of commercially available, low cost, high efficiency, linear drive motors, and ITC's proven long-life flexural bearing components in the compressor portion of the system results in a compact, high power compressor modules (up to 8+ kW electrical input) that can be utilized for various cold head configurations. This modular nature allows the cold head assembly to be easily adapted to various low temperature refrigeration system requirements. As in the case of the compressor, ITC's flexure bearings are employed in the cold head assembly. The resulting unit is compact, low in mass, low in vibration, very quiet, and uses an integrated power supply/controller ensuring safe operation. Testing of these systems have been carried out for a wide range of cold head operating conditions with an emphasis on supporting liquid oxygen/nitrogen production, LNG production and LNG storage tank boil off prevention, low temperature electronics cooling, and cooling superconducting devices. Cryocooler performance is quite good with demonstrated efficiencies of 30+% of Carnot based on net useful cooling and net electrical power to the drive motors. This paper provides an update and review of the unique technical aspects/challenges in the current and future development of this class of refrigeration systems for situations where the combination of the market constraints and specific end user requirements are significantly different than the classical requirements placed on cryo-refrigeration systems in the past.

Study on a High-Power Stirling Cryocooler [TO4-4]

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Stirling cryocoolers are well-adapted to high temperature superconductivity application and small scale gas liquefaction, due to their high efficiency, wide operating temperature range and fast cool-down process. A high-power Stirling cryocooler driven by a crank-rod mechanism was designed, built and tested systematically. Simulations were done using SAGE-software to find the optimum operating conditions and geometric dimensions. The cooling performance of the cooler is tested and analyzed under various operating conditions. A cooling power of 699.7 W at 77 K with an electrical input power of 11.2 kW has been achieved up to now. The comparison analysis between SAGE-model and experimental results has shown the direction for further design optimization of the high-power Stirling cryocooler.

Energy Smart Compressors for Helium Liquefiers [TO4–5]

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The high degree of control and optimization that is needed in interfacing a cryocooler to a cryogenic instrument requires a careful budgeting of the available cooling power while making the best use of energy. The operational specifications of interest for a cryo-cooled system include cooling time, cooling power, operating temperature, vibration, and operating time between service cycles.

In this paper, we describe a system where the individual speed control of the compressor capsule and the cold head motor provide for intelligent oversight and budgeting of the cooling power delivered in small-scale helium liquefiers. This system provides a new capability for a commercial 4 K Gifford-McMahon cryocooler system to dynamically control the cooling power delivered to the first and second stages based upon the compressor capsule and displacer stroke speeds.

The combination of highest cooling power, provided at full speed, typically required in an “initial cool down” and “fast liquefaction” modes of operation of a helium liquefier, and very low cooling power in “stand-by” mode, to allow operation with minimal power consumption, is described.

A Hybrid Cooling System for HTS Devices [TP1 – 1]

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A hybrid cooling system for HTS devices is a Zero boil-off (ZBO) liquid nitrogen Dewar system, which mainly consists by a pulse tube cryocooler (PTC), a thermosyphon and a liquid nitrogen Dewar. As an integrated cooling source for HTS devices, it has advantages of temperature stable, system reliable, easy to move, without supplement of liquid nitrogen and isolation of vibration and electromagnetic interference. In this paper, the structure form of ZBO system was designed with special insulation technology to reduce the dewar heat leak and also reduce the demand of cryocooler cooling power. By calculating the heat leakage and considering the heat load of HTS devices, a matched PTC was determined. It's a 5W@80K PTC developed by Institute of Physical and Chemical. And a matching designed cryogenic thermosiphon was also developed, which heat transfer performance was tested early. The whole cooling system was tested recently, and the results show that it had achieved the design goals with zero boil-off and it could provide a well cooling for small HTS devices.

Numerical Analysis of Magnetic Refrigeration at Room Temperature with the Refrigerant Materials [TP1-2]

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In recent years, magnetic refrigeration attracts attention as a new type of refrigeration technique for applying to refrigerator and air conditioner because of its little environmental load without using chlorofluorocarbons. Magnetic refrigeration is based on magnetocaloric effect (MCE) of magnetic refrigerant. In room temperature region, the temperature change obtained by applying magnetic field of permanent magnet is too small for general-use of refrigerator. An active magnetic regenerative (AMR) cycle is one of the suitable solutions of that problem. The AMR refrigerator makes temperature gradient inside the AMR bed by MCE and heat transport of flowing fluid. We have accomplished producing below zero degree and more than 40°C of temperature span between hot and cold ends of the bed by AMR cycle operation with Gd-alloy. We also developed a one-dimensional calculation model of AMR cycle in which heat generation by MCE and heat transmission inside the AMR bed and heat release to ambient environment were considered. The results of model calculations are consistent with the experimental results. Recently, various materials such as $\text{La}(\text{Fe},\text{Si})_{13}$, $\text{Gd}_5(\text{Ge},\text{Si})_4$ and $\text{Mn}(\text{Fe},\text{P})$ have been proposed. Therefore, we conduct a numerical analysis on the difference of effect on the refrigeration performance for the refrigeration materials of $\text{La}(\text{Fe},\text{Si})_{13}$ and Gd. In addition to the variation of refrigerant materials, we have also focused on the layered structure of refrigerant.

In this study, we have investigated the refrigeration performance of the AMR cycle with $\text{La}(\text{Fe},\text{Si})_{13}$ compared to Gd, with single-layered /multi-layered model considering several operation parameters such as displacement of heat transfer fluid, cycle frequency and the heat load. As a result, the Gd and $\text{La}(\text{Fe},\text{Si})_{13}$ show the different features of advantages /disadvantages on the refrigeration performance. In particular, optimization of displacement of heat transfer fluid is important. The detail of this study will be discussed on the conference.

Development of a Small Zero-Loss Hydrogen Liquefaction Plant [TP1-3]

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A small scale zero-loss hydrogen liquefaction plant including a cryocooler cooled hydrogen liquefier, vacuum jacketed transfer line, and liquid hydrogen (LH₂) storage tank has been developed to demonstrate a zero loss hydrogen liquefaction, transfer, storage and re-condensation for various LH₂ applications. Boil-off gas from the transfer line and storage tank is re-condensed in the liquefier. The liquefier was designed to liquefy 1 L/hr hydrogen using a single stage Gifford-McMahon cryocooler in a 150 L vacuum and multi-layer insulation (MLI) jacketed tank. A liquid nitrogen precooler, hydrogen purifier, heat pipe and two ortho-para hydrogen converters were integrated into the system. LH₂ in the liquefier is transferred to the 5 L storage vessel using a low loss vacuum insulated transfer line. Evaporated cold hydrogen gas can be returned to the liquefier and recondensed to LH₂ for future use. The system successfully demonstrated its liquefaction, low loss transfer, storage, and recondensation for various operational modes and applications. More detailed system configurations and experiment results are presented in this paper.

Evaluation of Graphite and Metal Foams for Circulated Cryogen Heat Exchangers [TP1-4]

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Metal foams have recently been studied in a variety of heat transfer applications, and could greatly reduce the weight of heat exchanger modules in superconductor cooling systems while simultaneously providing increased heat transfer effectiveness. Superconductors present great potential for weight reduction and increased power delivery when compared to traditional copper power delivery systems, but current systems require cryogenic cooling systems. Traditional superconductor cooling systems consist of helium cooled by helical heat exchangers made of Oxygen Free High thermal Conductivity (OFHC) copper tube.

Aluminum and Copper foams have been available for several years, but more recently, carbon foams, such as PocoFoam™, have been developed which have particularly good heat transfer characteristics. Using 3-D Computational Fluid Dynamics (CFD) to model a cryogenic heat exchanger application, several metal foam heat exchangers are examined and the effectiveness and pressure drop are compared to a more traditional helical coil design. The CFD simulation results show that a heat exchanger with the same heat sink contact area as existing helical heat exchangers weighs up to 95 percent less and can be up to 25 percent more effective, depending on system conditions such as pressure, cryogenic cooler temperature and helium inlet temperature.

Environmental Chamber for Long-Term Cryocooler Performance Assessment [TP1-5]

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Superconducting wind generators for off-shore placement or superconducting bulb hydro machines need a reliable cryogenic environment.

Cryocoolers are installed on MRI and NMR systems in hospitals working under ideal environmental operating conditions. However, we know only little of any possible cooler performance degradation over time with compressor and cryocooler exposed to a harsh saline setting.

The following paper describes the design intent of a low-cost environmental chamber. The environmental chamber features wide-range controllable salt content in water spray at temperature ranges from -40°C to $+60^{\circ}\text{C}$ with an overall humidity of $>90\%$, including rocking motions on both, compressor and cryocooler of $\pm 10\%$. Commissioning is envisaged midyear with preliminary results available by end of 2014.

Experimental Study and Two- Dimensional Numerical Simulation in Two-Cold-Finger Pulse Tube Cooler [TP2-1]

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Due to the demands on multi refrigeration temperature level at different position for infrared devices in space, we do some researches on a two-cold-finger pulse tube cooler (TCFPTC). In this paper, some experimental study and numerical analysis were introduced. We investigate the PV power distribution in TCFPTC and the effects of hot-end temperature on cold-end temperature. The experimental results show that cooling power has more effects on PV power distribution than input electrical power, especially, with the increase of cold-end temperature. The experiments suggest PTCs' size have big effects on PV power distribution. In our further research, the numerical simulation of multi-PTCs was performed in FLUENT. Simulation results reveal that the bigger cold finger gets more PV power, which is a reasonable agreement with the experimental study. Our experiments also show that the cold-end temperature increases 1K when hot-end temperature increases 3K-5K.

Application of Dynamic Absorber in Vibration Controlling of Pneumatically Driven Expander in Split Stirling Cryocooler [TP2-2]

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Vibration characteristics are analyzed based on the theoretical model of Stirling cryocooler. Dynamic absorber meets the requirement of vibration controlling of Stirling cryocooler, application of dynamic absorber in vibration controlling of Stirling cryocooler is shown. Designing method of dynamic absorber is present in theory in this paper. Experiment result is fully agreement with theoretical expeditions.

A Miniature Thermo–Acoustically Driven Pulse Tube Cooler [TP2–3]

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A miniature thermo-acoustically driven pulse tube cooler has the advantage of no moving mechanical components and thus promises a potentially long life time, which is very attractive for space application for its small dimension and high energy density. In this paper, a miniature thermo-acoustically driven pulse tube cooler operating at 250Hz has been developed and constructed, which consists of a miniature thermoacoustic string engine and a single-stage pulse tube cooler, and the total length and height of thermoacoustic cooling system is less than 0.5m and 0.25m respectively. Some efforts had been paid to the miniaturization of the thermoacoustic engine, design of the phase shifter and coupling between the thermoacoustic engine and cooler. To improve the cooling power, the relation between the cooling temperature and the cooling power of the cooler is also analyzed. After the optimization, the experimental results showed that the cold head of the cooler achieves a no-load temperature of below 70K and a cooling power of 1.8 W at 120 K with an input heating power of 400W and a mean pressure of 3.0 MPa, which can meet some demands of the cooling performance in the space applications.

Thermal Testing of an EM Two Stage Coaxial Pulse Tube for Earth Observation Missions [TP2-4]

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In the framework of a Research and Technology program co-funded by the French space agency (CNES), CEA/SBT has developed a two stage coaxial pulse tube in its engineering model version (EM) that fulfils the space requirements. This cold finger has been designed, manufactured and tested at CEA-SBT. The thermal performances are presented in this paper. We tested several rejection temperatures as well as different input PV powers with a tool compressor. Then, the matching of this cold finger with an EM LPTC has been verified leading to a high TRL level cooler. In this configuration, the cooler provides simultaneously 3 W at 125 K on the first stage and 1 W at 42 K on the second stage for 160 W of electrical power and 20°C of rejection temperature. In addition, the impact of the phase shifting on the second stage has been studied by using an active phase shifter compressor and large gains on both stages have been achieved. In this configuration we managed to obtain ultimate's temperatures as low as 16 K on the second stage. Mechanical testing to launch loads has also been performed and will be described.

This cooler is already addressing the cooling needs of detectors of most of the earth observation missions.

Comparative Analysis of Linear Motor Configurations for a Stirling Cryocooler [TP2-5]

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Stirling cryocoolers are becoming more popular in the area of remote sensing and space applications because of their inherent characteristics like long life, high reliability, less weight etc. In order to have a good on board performance, the selection of the drive system for the compressor is critical. Linear motors are simple devices in which axial forces are generated by currents in a magnetic field. Even though a number of studies are going on in the area of linear motor system, the comparative study of various motor configurations are few. In the present work, a comparative study and electromagnetic analysis of different types of moving magnet linear motor configurations have been performed to get an optimal configuration in terms of thrust force, flux density and satisfying the dimensional limits and material availability. The analysis consists of material selection, electromagnetic design and comparison to meet the stringent requirements while in operation. Various geometries are identified and the final optimized configuration is arrived at by trial and error method. The compact size, available permanent magnet sizes, low weight etc. were some of the constraints for design. The comparative analysis is performed to determine the optimal configuration in terms of the thrust force, nil saturation in the inner core and minimum leakage of magnetic flux. The force produced by the motor increases with the reduction in air gap and with the increase in thickness of magnet. The results throw light on the selection criteria and most appropriate geometry of the linear motor for the use in a cryocooler.

Experimental Investigation of a Single Stage Pulse Tube Cryocooler [TP2-6]

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Stirling type pulse tube cryocoolers are very attractive for cooling of diverse application because it has several inherent advantages such as no moving part in the cold end, low manufacturing cost and long operation life.

In an objective to development of the Stirling type pulse tube cryocooler, we need to design a linear compressor to drive the pulse tube cryocooler. A moving magnet type linear motor of dual piston configuration is designed and fabricated, and this compressor could be operated with the electric power of 120W and the frequency up to 60 Hz. A single stage coaxial type pulse tube cold finger aiming at over 1W at 80K is built and tested with the linear compressor.

Experimental investigations have been conducted to evaluate their performance characteristics with respect to several parameters such as the phase shifter, operating pressure and operating frequency of the linear compressor.

Study on Space Environment Adaptability for Stirling Cryocooler [TP2-7]

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This paper describes the design, development, testing of the Lanzhou Institute of Physics 80K/2W long life space cryocooler optimized for the adaptability of space environment and payload. The cryocooler is designed to provide enough cooling for high temperature superconductor filter (HTSF) at 77K. The cryocooler endure the environment effect of launch and on-orbit, the performance is perfect. The cryocooler was launched successfully in 10/2012, till now, the cooler goes on well. The correctness of the design was proved.

The Reliability Development of Miniature Stirling Cryocoolers [TP2–8]

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Miniature Stirling Cryocoolers are more and more widely used in many applications for their merits of high efficiency, small volume, light weight, fast start and low vibration, while reliability is one of the most important performance index of them. In this paper, firstly we introduce some basic conceptions of reliability and the prediction methods of reliability in RICOR Inc., Thales Cryogenics as well as BAE systems. After that the reliability development of the miniature Stirling cryocoolers is presented in detail from the 1950s. Finally some acceleration methods of measuring the reliability are introduced.

Air Force Research Laboratory Spacecraft Cryocooler Endurance Evaluation Update [TP2-9]

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Long-life data is essential for confirming design lifetimes (sometimes 10 years or more) for space cryocoolers. Continuous operation in a simulated environment is the only accepted method to test for degradation failure mechanisms.

The Air Force Research Laboratory (AFRL) has been evaluating life performance of space cryocooler technology for many years providing raw data and detailed evaluations to space designers and cryocooler developers for advancing the technology, correcting discovered deficiencies, and improving cryocooler designs.

At AFRL, units of varying design and refrigeration cycles are instrumented in state-of-the-art experiment stands that provide space-like conditions and are equipped with software data acquisition to track critical cryocooler operating parameters. The collected data allows an assessment of the technology's ability to meet the desired lifetime and documents any long-term changes in performance.

This paper documents performance of AFRL tested coolers over the past decade.

Cobham Microcooler for High Temperature Applications [TP2-10]

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Cobham Mission Systems, Davenport, Iowa, USA

Cobham Mission Systems of Davenport, Iowa is developing a new microscale cryogenic cooler intended for use in high temperature applications (greater than 95 K). This new cooler uses a linear dual opposed compressor and split expander and aims to be the smallest and highest performing cooler in the emerging micro class. This paper will highlight and compare the cooler's performance against its expected performance.

Coaxial Pulse Tube Microcryocooler

[TO5-1]

J.R. Olson, P. Champagne, E. Roth, G. Kaldas, T. Nast,
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We report the successful completion and initial testing of the Lockheed Martin first-article, single-stage, coaxial Pulse Tube Microcryocooler (PTM). This PTM supports cooling requirements for emerging large, high operating temperature (125-150K) infrared focal plane array sensors with nominal cooling loads of ~500mW @125K @290K ambient. We present new coaxial PTM cooling performance test measurements with comparisons to previous in-line pulse-tube measurements and design predictions. The PTM exhibits small size, volume, weight, power and cost features that warrant further component enhancements and manufacturing process maturation for a variety of space and tactical applications.

Development of Single Piston Moving Magnet Cryocooler SX020 [TO5-2]

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AIM INFRAROT-MODULE GmbH, Heilbronn, Germany

State of the art Mid Wave IR-technology has raised up typical FPA temperature from 77K to 130-150K (high operation temperature - HOT). This trend will continue by current developments thus FPA temperature will be in the range of 150-200K for future Mid Wave detectors.

AIM has developed a compact SX030 cooler, optimized for FPA temperatures of about 140K (shown at SPIE conference in 2012). The SX030 cooler incorporates a high efficient single piston driving mechanism with a passive balancer for lowest exported vibration levels. For future HOT application even this cooler will be oversized. Thus AIM has developed the next member of the SX cooler family, the SX020.

With an outer diameter of less than 27mm and a length of less than 60mm SX020 is the smallest compressor AIM has ever developed.

It is a single piston Moving Magnet driving mechanism and an internal passive balancer. AIM has developed a novel passive balancer concept, which is implemented into SX020 housing. Following the modular design principle of SX cooler family the SX020 supports the AIM ¼" displacer but also an upcoming ultra-short 5mm displacer. The cooler is driven by a compact and highly efficient digital cooler electronics DCE025.

This paper gives an overview on the development of this very new compact single piston cryocooler. Technical details and performance data will be shown.

Efficient High Capacity Space Microcooler [TO5-3]

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Northrop Grumman Aerospace Systems, Redondo Beach, CA, USA

The Northrop Grumman space micro pulse tube cooler is a split configuration cooler incorporating a coaxial cold head connected via a transfer line to a vibrationally balanced back to back linear flexure bearing compressor. Scaled from the TRL 9 HEC cryocooler and designed for > 10 year operation with no performance change, the 900 gram mechanical cooler incorporates a new cold head that has substantially increased its efficiency and cooling power over a range of temperatures above 40K. The very small, low vibration, high frequency cooler is designed to be directly integrated into space SWIR, MWIR and LWIR payloads or into an integrated detector cooler assembly (IDCA) similar to those used with shorter lived tactical coolers. Despite its small size the tested cooler is capable of providing up to 4.5W of cooling at 150K or 0.3W at 45K when rejecting heat to 300K. At lower reject temperatures it is more efficient and has even greater cooling power. This paper reports on the performance of this cooler.

Qualification of Lockheed Martin Micro Pulse Tube Cryocooler to TRL6 [TO5-4]

T.C. Nast, E. Roth, J.R. Olson, P. Champagne, D. Frank

Lockheed Martin, Palo Alto, CA, USA

Lockheed Martin has developed a micro pulse tube cryocooler for both Avionics and space applications. This thermal mechanical unit is light weight and compact with high reliability. The technology is based on our space systems and has predicted lifetimes of 10 years or more. System weight is 328 grams, including the 210 gram compressor.

The system utilizes the classic flexure bearing/clearance seal technology with a coaxial pulse tube approach.

This unit recently underwent qualification to a technology readiness level (TRL) of 6, which included launch vibration and temperature cycling for the range of operating and standby conditions. Load lines were obtained over a range of powers and cold tip temperatures.

In addition the unit was cycled and operated down to temperatures at low at 130 K for potential use on hostile planetary environments.

This paper summarizes the operating characteristics over a range of cooling loads and temperature conditions and the response to random launch vibration levels.

150K – 200K Pulse Tube Cooler for Micro Satellites [TO5–5]

C. Chassaing, J. Butterworth, G. Aigouy, A. Gardelein,
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[2] STEEL Electronique, Martres Tolosane, France

Air Liquide is working with the CNES and Steel Electronique in 2013 and 2014 to design, manufacture and test a Pulse Tube cooler to cool infrared detectors for micro-satellite missions.

The cooler is particularly adapted to the needs of the CNES MICROCARB mission to study atmospheric Carbon Dioxide which presents absorption lines in the thermal near infrared, at 1.6 μm and 2.0 μm .

The required cooler temperature is from 150 to 200K with cooling power between 1 and 3Watts. The overall electrical power budget including electronics is less than 20W with a 288-300K rejection temperature. Particular attention is therefore paid to optimizing overall system efficiency. The microvibration and thermal control systems already developed for the AL-AT Large Pulse Tube Cooler have been implemented into a new low power electronics architecture.

The presented work concerns the new cold finger and electronics test results. The cooler uses the compressor already developed for the 80K Miniature Pulse Tube Cryocooler.

This Pulse Tube Cooler addresses the requirements of space missions where extended continuous operating life time (>5 years), low mass and low micro vibration levels are critical.

Development of a Miniature Cryocooler System for Cubesats [TO5-6]

Mike Ellis

Iris Technology Corporation, Irvine, CA, USA

The Microsat Cryocooler System (MCS) is a key enabling technology for a suite of single FPA dewar solutions on microsat and cubesat platforms. The overall effort addresses the entire cryocooler system, i.e., the thermo mechanical unit and the electronics. The focus of this paper is the cryocooler control electronics. The range of missions of interest for the MCS is broad, thus it is essential that the electronics be modular and configurable. By leveraging the fully space-qualified Low Cost Cryocooler Electronics (LCCE) and by employing advanced component technologies, Iris Technology has developed a miniaturized version of the LCCE (mLCCE). The mass of the mLCCE is less than 200 grams and the volume is 90 cm³, representing an 80% reduction in size relative to the LCCE. The mLCCE has been integrated and tested with four (4) different cryocoolers including dual and single compressor piston configurations and pulse-tube and Stirling cold-heads. Although the mLCCE was tested as high as 55 W, it was designed for a nominal output power of 25 W with a measured efficiency higher than 95% in a wide vicinity around its design point. The design and test data are presented.

Micro-Size Cryocooler Control Electronics [T05-7]

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Focal Plane Array cooling for satellites presents a very challenging need for power dense cryogenic refrigeration and drive electronics. Critical performance metrics include small size, low mass, low vibration, high efficiency, and radiation tolerance. In addition to excellent technical performance, universal designs are needed to support a variety of missions with short development time and minimal cost. This paper describes the development and demonstration of Micro-size Cryocooler Control Electronics (MCCE) suitable for small satellites. Our MCCE provides dual, independent drives for pulse tube cryocoolers which can be customized for each application with only software changes. The MCCE package is small and lightweight, with a volume of 140 cm³ and mass of 220 g. We have demonstrated through brassboard tests: (1) operation with three different Cryocoolers; (2) output power levels up to 30 W; and (3) efficiency of 85 to 95%. Our MCCE design has been validated with electrical, thermal and structural design and analysis consistent with requirements such as GSFC-STD-7000.

Raytheon Low Temperature RSP2 Production Program [WO6-1]

**B. Schaefer, T. Conrad, L. Bellis, D. Bruckman, R. Yates, M.
Pillar,
M. Barr**

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

The Low-Temperature Raytheon Stirling / Pulse Tube 2-stage (“LT-RSP2”) hybrid cryocooler is a long-life, robust machine designed to operate efficiently at a first stage temperature of 55K and a capacity of 5W and a second stage temperature of 10K 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. The flight program was executed in 2011 - 2014. 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.

Raytheon Productized High Frequency Cryocooler [WO6-2]

T. Conrad, B. Schaefer, R. Yates, L. Bellis, D. Bruckman,
Y. Im, M. Pillar, M. Barr

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

The Raytheon Dual-Use Cryocooler (DUC) has been packaged into a flight configuration incorporating a surge volume and inertance tube integrated with its cold head. The operating frequency of the DUC has been also been increased to 100 Hz in order to facilitate a reduction in its size and mass and to take full advantage of the performance characteristics of the Raytheon Advanced Regenerator. The operating frequency increase and re-optimization of the cold head for the Advanced Regenerator have resulted in an approximately 20% reduction in size and mass along with a significant increase in predicted performance in comparison with the brassboard DUC. Design information such as mass, package dimensions, and predicted thermodynamic performance for the flight packaged DUC will be presented along with plans for flight qualification testing.

A 30–50K Dual–Stage Pulse Tube Space Cooler [WO6–3]

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[2] Absolut System SAS, Meylan, France

[3] CEA-SBT, Grenoble, France

A Technical Research Program (TRP) has been won by the TCBV/CEA/AS consortium for the development, optimization and testing of a cryostat actively cooled by a 2-Stage High Reliability Pulse Tube cryocooler. The interest of this concept is to allow the operation of detectors – for example QWIP or MCT infrared detectors - at lower temperatures, in the range of 35-40K, for an overall input power similar to the one required by current Earth Observation programs.

The primary objective of the activity is to develop and manufacture a Two-Stage Pulse Tube Cooler able to provide 350mW@33K and 1200mW@120K with 180W input or 800mW@40K and 1500mW@130K with 160W input. This cooler will make use of compressors previously developed for Space applications by Thales Cryogenics.

The secondary objective of the TRP program is to perform a test of this cryocooler mounted into a Breadboard 2-Stage Cryostat in order to verify the possibility to integrate such a system and to test ‘in-situ’ the cooling capabilities of the 2-Stage cryocooler.

The cryostat will be designed to provide adequate mechanical, thermal and electrical interfaces between the 2-stage cryocooler, the detector assembly and the external structure. The key requirements that could critically impact the assembly, integration and testability of the cryostat equipped with the cryocooler will be discussed in this paper.

15K Pulse Tube Cooler for Space Missions [WO6-4]

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M. Linder [2], J.M. Duval [3], I. Charles [3], T. Rijks [4], J.Mullié
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Air Liquide is working with ESA, CEA and Thales Cryogenics since 2009 to design, manufacture and test a 15K Pulse Tube cooler system.

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

For the presented project, the required cooler temperature is from 15 to 18K with cooling power between 0.1 and 0.4watts. The overall electrical power budget is less than 300W (without the electronics) with a 288K rejection temperature. Significant cooling power at an intermediate temperature (typically 80K) will be also available.

Particular attention is therefore paid to optimizing overall system efficiency. To achieve this low temperature, two cold fingers working in parallel have been integrated on one common warm flange and they are connected on one specially developed high power compressor (240W PV power).

The presented work concerns the 15K cooler design and the expected performances in regards of the simulations and the laboratory tests.

This Pulse Tube Cooler addresses the requirements of space missions where temperature lower than 20K, cooling power higher than 0.1W, extended continuous operating life time (>5 years), compactness, low mass and low micro vibration levels are critical.

Development of a Pulse Tube Cooler for an Infrared Aerospace Application

[WO6-5]

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Zhi Lu

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For the purpose of cooling an infrared aerospace application, on one-stage inline pulse tube cooler (PTC) driven by a linear compressor has been designed, manufactured and tested at Shanghai Institute of Technical Physics (SITP), Chinese Academy of Sciences. The PTC consists of an assembly of aftercooler, regenerator, cold heat exchanger, pulse tube and hot heat exchanger. Its optimization has been discussed analytically, which shows that the PTC can offer cooling power between 50K and 180K with over 10W of cooling capacity at 80K with a rejection temperature of 300K.

An experimental setup has been designed and fabricated to carry out experimental investigations on the PTC and the experimental results of its performance have been presented.

In addition, the influence of various parameters, such as operation frequency and charge pressure, has been presented and investigated in detail for a thorough understanding of the PTC system.

Investigation of Visualized Solid-Liquid Phase Equilibria for Mixed Refrigerant [WP3-1]

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Pure refrigerant Joule-Thomson (J-T) refrigerator has constraints of cooling capacity and temperature limit because of their thermodynamic characteristics. Therefore, mixed refrigerant (MR) which efficiently overcomes the limitation of the pure coolant, recently attracted the attention due to its high performance of J-T effect and a variety of cooling temperature. Although the MR has a good acceptability of various requirements of J-T refrigerator, it has a significant operating challenge of the clogging at the J-T expansion part, which caused by freezing of the refrigerant. In this paper, the freezing points, i.e. solid-liquid phase equilibria of MR have been tested by the visualized apparatus and analyzed by several calculation methods in the temperature range from 90K to 180K. The visualized experimental apparatus was developed and tested to observe the freezing point with a camcorder and temperature variation of the glass test tube. The experimental apparatus contains 3 parts which are a cooling part with liquid nitrogen (LN₂), a MR test part fabricated with glass tube, and a helium base part with glass bell jar to prevent frosting on the glass apparatus. The apparatus detected the freezing points of selected pure refrigerants (R14, R218, R125 and N₂O) and the binary mixture of N₂O/R125 with the maximum error of 0.33% and 5%, respectively. Also, the multiple component MR (more than 3-component) with various compositions were tested to find the optimized mole fraction which has the lowest temperature of freezing.

Design and Performance Calculation of the Passive Helium Heat Switch for a Two-Stage Cryocooler [WP3-2]

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A new type of thermal heat switch has been designed and analyzed by numerical approach. A passive helium heat switch using adsorption of helium on activated charcoal is expected to facilitate the rapid cool down of the second stage of the two-stage cryocooler. The heat switch contains vertical fins in staggered array, activated charcoal bed and helium gas. These components are isolated from outside by a thin walled cylinder. The heat switch thermally connects the first and the second stage of a two-stage cryocooler at high temperature in order to utilize large refrigeration capacity of the first stage for second stage cooling. When the second stage reaches a certain low temperature, the heat switch thermally isolates the second stage from the first one. Thermal connections between first and second stage can be determined by pressure of the helium gas which is function of activated charcoal bed temperature.

In this paper, the cooling time of the second stage is calculated by heat transfer analysis which takes into account helium gas adsorption on activated charcoal, flow regimes in vacuum environment, and energy balance. The numerical results show that the cooling time of 9 kg of copper using a two-stage cryocooler with the heat switch can be reduced to 65%. Moreover, the effect of design parameters and the operating conditions on cooling time of two-stage cryocooler such as the cooling capacity of the first and second stage, mass of the first and second stage and heat transfer area of the vertical fins are analyzed and discussed.

Three-Dimensional Steady Simulation of a Zero Boil-Off Cryogenic Storage Tank Using New Conductive Components [WP3-3]

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The pyrolytic graphite at high temperature is a material with high thermal conductivity. A new type of conductive components which are the composition of graphite and copper is concerned after testing the conductivity of graphite, and the components which are coupling with cryocooler are applied to zero-boil-off cryogenic storage tank. Meanwhile, 3D symmetric model is applied to predict temperature field in different geometry parameters, such as different materials' ratio, structure arrangement, length, width, etc. The result above shows that the arrangement of graphite/copper/graphite has a better heat-transfer capacity, and the increased length and width make the temperature decrease, while change thickness is not obvious for the temperature filed in the tank.

Investigation of Inertance Phase Shifting Characteristics in Small Scale Pulse Tube Cryocooler [WP3-4]

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Phase shifting characteristics of inertance tube in small scale pulse tube cryocooler are investigated experimentally. It was found that the length of inertance tube whose diameter is 1mm has a more significant influence on the optimal frequency of the pulse tube cryocooler than the inertance tube with diameter 3mm. The performances of the pulse tube at the each optimal frequency are not great difference whatever the length of inertance tubes with 1mm diameter and 3mm diameter are changed.

Compressor behaviors dynamic behaviors influenced by inertance tube were investigated too. It was found that in the case of that the best performance of the cryocooler occurs dynamic behavior of compressor responds more intensely to the variety lengths of inertance tube.

Application and Research of Heat Coupling Technology for Cryocooler and Zero Boil-Off Storage System [WP3-5]

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Heat Coupling of cryocooler and zero boil-off storage system is a key technology for space cryogenic liquid long-term on-orbit storage. Different kinds of technology schemes of heat coupling applied in ZBO system are introduced. The heat coupling principle and heat-transfer character of heat coupling components which are cryogenic heat pipe, cryogenic heat conduction strap, cryogenic heat exchanger are analyzed. The partial test and numerical simulations are carried out for the future ZBO ground test. The results provide foundation and reference for the ZBO system design.

Study on the Turbo-Expander and Heat Exchanger of a 100K Miniature Reverse Brayton Cryocooler [WP3-6]

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For the demands of space application, the prototype of the reverse Brayton cycle cryocooler was developed. The designed lowest temperature of this cryocooler is 80 K and with a cooling capacity of 10W@100K. The main components of the cryocooler are a woven wire screen matrix heat exchanger and a gas bearing turbo-expander (GBTP). The heat transfer performance of woven wire screen matrix heat exchanger was introduced; especially the overall performance of the miniature high speed turbo-expander was studied experimentally and examined in this paper. A 9 mm diameter radial impeller is applied to drive the rotor of the turbine, and an 11 mm diameter centrifugal supercharger is adopted to absorb the output power of the expander. The rotor of the turbo-expander weighs about 12g with a shaft of 6 mm diameter and 50 mm total length. The normal speed of this GBTP is about 300,000 rpm. The experimental results show that the turbine maintains very stable running, small vibration and high efficiency. The gas bearings used here achieved good performance in a wide speed region up to 350,000 rpm, and the vibration amplitudes of shaft are very small (less than 5 μm) during the whole operation process. In the test, a maximum expander efficiency of 50% is achieved at the nominal working speed of the turbo-expander.

A Novel Approach to Optimize the 2nd Stage Regenerator Configuration of a 4K Gifford–McMahon Cryocooler [WP3–7]

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This paper presents a novel method to optimize the 2nd stage regenerator configuration to improve the cooling efficiency of a 4K Gifford-McMahon (G-M) cryocooler. In general, it is not easy to find out the optimum regenerator configuration by experiments, because changing it should be remade simultaneously with several cryocooler components including stainless steel cylinder. From this point of view, we developed a novel method that can equivalently change the regenerator configuration by using a bakelite rod. The bakelite rod is inserted in the co-axial direction of the 2nd stage regenerator in which a regenerator material of spheres is filled. The inserted bakelite rod is a dummy volume that has no regenerative effect. Therefore the 2nd stage regenerator configuration can be changed by adjusting the geometry of the inserted bakelite.

A conventional two-stage G-M cryocooler (RDK-408D2, SHI) has been used to evaluate this novel method. The electric power consumption is 7.3 kW at 60 Hz. The detailed experimental results and numerical analysis will be discussed in this paper.

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Optimum Cooling Capacity of Two-Stage Thermoelectric Refrigerators Operating at Cryogenic Temperatures [WP3-8]

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Optimization of two-stage thermoelectric refrigerators is considered in this study. Cooling capacity of the refrigerator under a cascade arrangement having different electric currents and numbers of thermocouples at each stage is optimized using the method of Lagrange multipliers. Emphasis is placed on the effect of thermal conductance at the hot side on optimum cooling capacity and the resulting cooling flux at the cold side of the refrigerator. The effects of electric contact resistance, the figure of merit of the thermoelectric material, and the length of the elements at each stage are considered in the analysis. The performance of the refrigerator operating at low temperatures rejecting heat to a reservoir at the cryogenic temperature is evaluated. Important non-dimensional variables convenient for parametric studies and design analysis are developed and their effect on the optimum performance of the refrigerator is presented.

Prospects of Cooling to Cryogenic Temperatures Using Thermoelectric Coolers [WP3-9]

T. Fraser

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The feasibility of using thermoelectric coolers (TECs) to cool to cryogenic temperatures will be examined in this study. Calculations are based on material properties and basic thermoelectric principles. The simulation of an ideal refrigerator, i.e. without any parasitics or other losses, will give lower bounds on what is required of thermoelectric materials' performance metrics in order to be competitive with mechanical cryocoolers. Results are given with varying cooling temperatures. Cascaded staging is examined and optimized. Current research on improving low temperature thermoelectric materials is discussed and compared to the requirements. The possibility of using a TEC in series with a mechanical cryocooler is also examined.

Fabrication of MEMS Linear Actuator

[WP3–10]

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

Highly-Conductive Graphite Thermal Straps Used in Conjunction with Vibration Isolation Mounts for Cryocoolers [WP3-11]

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Despite momentum balancing and active damping methods often utilized to mitigate vibration transmission from mechanically driven cryocoolers, sometimes it is still necessary to incorporate an external mechanical isolation mounting subsystem that will further attenuate coupling of mechanical disturbances into sensitive instruments or electro-optical systems. By incorporating a means for mechanical isolation of cryocooler compressors, a compromise is necessarily made in the elimination of straight-forward heat rejection through solid materials and hard-bolted interfaces. Since the performance of space-borne cryocoolers is highly sensitive to the thermal efficiency of heat rejection from the compressor, it is critical that a method for heat transport be devised without adversely impacting the relevant damping characteristics of the mechanical mounting system. Graphite fiber thermal straps (GFTS) provide an optimum combination of properties including high-thermal conductivity, low-mass, and low-stiffness for a thermal subsystem designed to be used in conjunction with a cryocooler compressor isolation mount. This paper discusses the challenging design parameters and resulting configuration of a GFTS-based heat rejection approach for Dewar mounted cryocoolers that are mechanically isolated from the heat rejection interface. Performance of the thermal subsystem and the interactive aspects with respect to the mechanical damping subsystem are presented.

Parametric Numerical Study of Off-Axis Pulse Tube Losses [WO7-1]

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Recently there has been an emphasis on applying numerical modeling, with varying degrees of complexity, to the study of the notorious sensitivity of the pulse tube cryocooler to off-axis operation. Previous work has demonstrated the suitability of applying multi-dimensional CFD simulation to the pulse tube cryocooler both as a whole and at the component level for qualitative and quantitative analysis of system performance and losses. To date there has been no comprehensive study of the pulse tube losses for a wide range of operating conditions consistent with modern coolers currently used in both the military and civilian sectors. This work presents for the first time a comprehensive loss analysis of the linear pulse tube cryocooler operating at common conditions using full three-dimensional CFD coupled with a real gas model for the working fluid.

The scope of results presented includes both system level models and a pulse tube/heat exchanger component level model. Results from the system level simulations are presented for two pulse tube aspect ratios at tilt angles of 0° , 91° , and 135° . Component level simulation results are presented and discussed for permutations in tilt angle between 0 - 180° , aspect ratios from 4-8, cold tip temperatures from 4-80 K, phases angles between -30° and $+30^\circ$, and an operating frequency range of 25-60 Hz. The entire set of modeling results is compiled and used to show a correlation between the normalized pulse tube cryocooler losses as a function of a non-dimensional pulse tube number. Discussion is also provided regarding the utility of component level simulation compared to system level simulation considering analysis complexity, computational resource requirements, and suitability for cooler design.

Design of a 20 K High Efficiency Stirling/Pulse Tube Hybrid Cryocooler [WO7-2]

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Cryocoolers providing hundreds of milliWatt cooling power around 20 K with features of high efficiency, high reliability, compact structure and long life are urgently demanded to meet the rigorous cooling requirements of detectors and instruments in the fields of aerospace and military applications. Two or three stages are necessary for Stirling or pulse tube cryocoolers to fulfill the above mentioned cooling performance, and the efficiency of those cryocoolers are still very low due to the various losses in regenerator and other parts.

Stirling/pulse tube hybrid cryocooler proposed by Kirkconnell et al consists of a Stirling high temperature module and pulse tube low temperature modules, as the hybrid cryocooler combines the advantages of active control of Stirling cryocoolers with high reliability of pulse tube cryocooler, so it can work at a wide temperature region efficiently and has been verified experimentally.

A two-stage Stirling/pulse hybrid cryocooler working around 20 K was designed based on Sage and the cooling power was about 0.5~1 W, the design process and calculation results are presented in this paper, the results indicate that the hybrid cryocooler can work more efficiently than the current reporting two-stage Stirling or Stirling-type pulse tube cryocoolers.

Pressure Ratio Effect to Warm Displacer Type Pulse Tube Refrigerator [WO7-3]

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In displacer type pulse tube, there is no pressure ratio limitation problem happened in an inertance tube pulse tube refrigerator, so the pressure ratio can be as high as we want. Higher pressure ratio means higher temperature oscillation in compression space, displacer space, and pulse tube, which means higher irreversible loss due to heat transfer. In this paper, pressure ratio effect is discussed with a numerical simulation model.

Study on the Thermodynamic Cycles of the Gas Parcels in the Pulse Tube Cryocooler [WO7-4]

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It's significant to reveal the working mechanism of the pulse tube cryocooler (PTC) in a microcosmic way as the gas parcels at different parts of the PTC all experience different cycles. In this study, the thermodynamic cycles of typical gas parcels in the pulse tube were visualized in a Lagrangian viewpoint by CFD simulation. The influence of the phase angle on the periodic work-heat conversion of the gas parcels was studied intensively. Research shows that the cold end phase angle plays a crucial role on the heat "transfer" direction of the gas parcels in the pulse tube. It determines the gas parcels in the pulse tube where to be compressed meanwhile release heat, and where to expand meanwhile absorb heat. For the phase shifting PTCs, the gas parcels in the pulse tube do not contribute cooling but bring heat losses to the cold end as they expand while absorb heat at the hot side and are compressed and release heat at the cold side during a cycle due to the effect of the phase shifter, which is different with the traditional concept that considers heat at the cold end being taken away by the gas in the pulse tube.

Numerical Simulation of a High Power Stirling Cryocooler [WO7-5]

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High-power Stirling cryocoolers driven by crank-rod mechanisms are promising candidates for small scale gas liquefaction and high temperature superconductivity technologies, due to the features of high efficiency, wide temperature range, fast cool-down and compact structure. A high-power Stirling cryocooler was studied numerically. The numerical simulation conducted by using SAGE-software shows the variation of mass flow rate and working medium pressure, the distribution of acoustic power and enthalpy flow, and the temperature profile of regenerator in the cooler. According to the simulation, the cold head is able to reach no-load refrigeration temperature of 26K and a cooling power of 981.5W at 77.35K with a PV power of 9.5 kW. The simulation has shown a consistent trend with the experimental results, which indicates this SAGE-model will show reasonable directions for the optimization of the high-power Stirling cryocooler.

Low Frequency Linear Compressors for GM- and Pulse Tube Cryocoolers [WO8-1]

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Pressure Wave Systems GmbH, Munich, Germany

Pressure Wave Systems GmbH is developing low frequency linear compressors for GM- and pulse tube cryocoolers. A first 2kW technology demonstrator has confirmed the working principle operating a small two-stage 4K GM-cryocooler. A second generation 6kW technology demonstrator has been built. Results of this system will be presented.

The Phase Shifting Performance of a Cylindrical Adjustable Inertance Tube [WO8-2]

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The length and diameter of the inertance tube plays a significant role in obtaining a desired phase angle for the pulse tube cryocooler. This paper reports the design method and experimental results from the cylindrical adjustable inertance tube, which has the ability to adjust the phase angle of the pulse tube cryocooler in real time during operation. This cylindrical adjustable inertance tube has the ability to change length from 1.25 m to 3.14 m and adjust the diameter from 7.6 mm to 9.1 mm while turning the outer screw from it topmost to its bottommost position. By using this adjustable inertance tube, a 30° phase angle shift can be obtained based on the model prediction. The phase shifting performance is verified in the experiment.

Comparison of Fluid Flow and Heat Transfer for 1D and 2D models of an In-Line Pulse Tube Refrigerator [WO8-3]

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Lower order models are commonly utilized for preliminary designs and optimization of cryocoolers. These models are at most one dimensional and therefore often cannot adequately predict the behaviors of fluid flow and heat transfer in cryocoolers that are inherently multi-dimensional. We simulate a linear pulse tube cryocooler using a two-dimensional axisymmetric computational fluid dynamics (CFD) model and compare it to the results obtained from the SAGE[®] software normally used in the design and optimization of pulse tube and Stirling cryocoolers.

These models are also compared using second-law analysis techniques, specifically examining the losses in the pulse tube region. We compare the results from both models and identify instances where the models disagree.

Developments in Advanced Cooler Drive Electronics [WO8-4]

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Thales Cryogenics BV, Eindhoven, NL

An overview is given of the cooler drive electronics capabilities of Thales Cryogenics and the recent developments with respect to this product range.

For Linear Stirling and Pulse Tube coolers, an update will be given regarding advances in active vibration reduction.

Presently available fully adaptive Active Vibration Reduction electronics are presented and developments in the miniaturization of active vibration reduction are discussed.

Results are presented of tests performed using commercial off-the-shelf drive electronics with low noise force transducers rather than standard accelerometers. Furthermore, an overview is given of possible applications of active vibration reduction.

For Rotary Stirling coolers, recent developments will be presented which have resulted in a new design for high-efficiency digital drive electronics, suitable as a drop-in replacement for legacy analog controllers.

Energy Efficient Operation of 4 K Pulse Tube Cryocoolers [WO9-1]

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A variable speed helium compressor for 4 K pulse tube cryocoolers has been developed and commercialized. The same compressor can be used for both model PT410 (1W at 4.2K) and PT407 (0.7W at 4.2K) cryocoolers. For the PT410, the frequency of the compressor power can be adjusted from 45 Hz to 72 Hz. The frequency adjustment results in a variable cooling capacity from 0.5W to 1.0W at 4.2 K.

In most applications, cryogenic refrigerators produce excess cooling capacity and a heater must be used to take up the unneeded capacity. Using a power inverter, the compressor is able to reduce power consumption by matching the refrigerator cooling capacity with the thermal load. An inverter driven compressor could reduce energy consumption up to 50% in some 4 K systems. The inverter compressors are used in Cryomech helium reliquefiers, liquid helium plants and liquid cryostats. The inverter frequency is regulated by a pressure controller to maintain zero boil off in these applications. In a superconducting magnet cooling application, a PT410 using the inverter driven compressor has demonstrated an energy savings of ~25%.

Development of a 4K Pulse-Tube Cold Finger for Space Applications [WO9-2]

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Sub-kelvin cryogenic chain without helium bath is a challenge for space missions and 4.2K pulse-tube working at high frequency (around 30Hz) is one option to take it up.

A low temperature pulse-tube could be an option for the next astrophysics space missions like ATHENA + (Advanced Telescope for High ENergy Astrophysics), PRISM and TALC that require sub-kelvin temperatures for ultra-sensitive detectors cooling. Several tens of mW in the 4K-5K temperature range is the order of magnitude of the cooling power requirement.

The studied apparatus is composed of two compressors (one main and an active phase shifter) and of a pulse-tube with two regenerators separated by an intercept (heat exchanger) cooled by a Gifford-McMahon.

The work has been focused on the cold part of this cold finger. The impact of the specific heat of the porous media used in the cold regenerator has been studied. Experimental results will be presented, such as load curves, cold end temperature fluctuations, impact of the power of the main compressor, and analyzed. This pulse-tube has been tested and optimized and temperatures near 5K have been obtained at a frequency of 30Hz with an intercept temperature at 20K.

The attempt made to model this cold finger will be also presented.

Sorption-Based Helium-3 Pump for a Closed-Cycle Dilution Refrigerator

[WO9-3]

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At the Néel institute in Grenoble a closed-cycle dilution refrigerator (CCDR) is under development for future long-lifetime missions requiring a cooling power of the order of 1 microWatt at typically 50 mK for at least 5 years. For operating this CCDR, the isotopes He-3 and He-4 are separated in a still that contains the liquid and the gas phase of a mixture of He-3 and He-4. The He-3 is extracted from the still by pumping on the gas phase and it is re-injected into the refrigerator. For this purpose, the University of Twente and Cooll SES are developing a sorption-based pump operating between 5 mbar inlet and 200 mbar outlet pressure. The pump consists of a single sorption-compressor cell of which the sorber container measures 1 cm in diameter and 10 cm in length. It uses passive inlet and outlet valves and is thermally linked to a 15-K platform. Small gas buffers are applied for stabilizing the low pressure and for storing the gas at 300 K thus reducing the filling pressure to below 20 bar. The required input is 90 mW of which 50% is to drive the compressor cell and 50% is for controlling the temperature of the low-pressure buffer. At these conditions, we expect to establish a flow of 20 micromol/s. Compared to mechanical pumps the main advantage is lower mass and less complex interfacing. Both advantages result from the fact that the pump is fully integrated with the cold part of the CCDR, whereas the mechanical alternative pumps need to be operated at the 300 K level. The design of the sorption-based pump will be presented as well as introductory experiments.

Dry Dilution Refrigerator for Experiments on Quantum Effects in the Microwave Regime [WO9-4]

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At the WMI, a new cryogen-free $^3\text{He}/^4\text{He}$ dilution refrigerator (DR) has been completed; the cryostat will be employed to cool experiments on superconducting quantum circuits for quantum information technology and quantum simulations. All major components have been made at the WMI. The DR offers lots of space at the various stages of the apparatus for microwave components and cables. E. g., the usable space at the mixing chamber has a height of more than 60 cm and a diameter of 30 cm (mixing chamber mounting plate). To cool cables and cold amplifiers, the DR is equipped with a separate ^4He -1K-loop which offers a cooling power of up to 100mW near 1K. The refrigeration power of the still is 18mW at 0.9K; the diameter of its mounting plate is 35 cm.

The cryostat rests in an aluminum trestle on air springs to attenuate building vibrations. It is precooled by a Cryomech PT410-RM pulse tube cryocooler (PTC) which is mechanically decoupled from the vacuum can of the cryostat by a bellows assembly. The two stages of the PTC are thermally connected to the DR via copper ropes. There are no nitrogen cooled traps with this DR to purify the gas streams of the ^3He and ^4He loops; instead, charcoal traps are mounted inside the DR at the first stage of the PTC. The dilution unit has three heat exchangers; its base temperature is 11mK and its cooling power is 300 μW at 100mK.

Status of the Closed-Cycle Dilution Refrigerator for Space Applications

[WO9-5]

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We present the development of the closed-cycle dilution refrigerator (CCDR) derived from the open-cycle dilution refrigerator (OCDR) used in Planck mission. Unlike the OCDR, the two isotopes ^4He and ^3He are circulated (with a fountain pump for the ^4He and with a compressor for ^3He) instead of rejecting to space in order to increase the lifetime of the system. Each individual block is working and the full system is under development.

In this work, we discuss the development of the different parts of the CCDR and the next steps to be performed in order to achieve the cryogenic performance of future mission ($1\mu\text{W}$ at 50mK). We address more specifically the ^3He compressor options and the status of one solution identified that is the Holweck compressor. Then, we propose a possible integration according to the constraints given by future space missions.

Characteristics of a VM Type Thermal Compressor for Driving a Pulse Tube Cooler [WO9-6]

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The VM type cryocooler is a classical kind of cryocoolers. It utilizes the temperature difference, typically the temperature difference between liquid nitrogen and the ambient, to generate the pressure wave to drive the coldhead. The subsystem that generates the pressure wave could be viewed as a type of thermal compressor called the VM type thermal compressor herein. From the thermoacoustic viewpoint, the output of the thermal compressor is strongly related to the characteristics of the load. The paper studies the characteristics of the thermal compressor with the simulations based on thermoacoustic theory. Interesting features such as the dependence of local acoustic characteristics on the load, optimal load impedance, etc, have been systematically studied. The study sheds new light into the working mechanism of VM type thermal compressor as well as sets the basis for optimizing a VM type thermal compressor to drive a pulse tube cooler for liquid helium temperature.

Development of a Diaphragm Stirling Cryocooler [THO10-1]

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Callaghan Innovation, formerly Industrial Research Ltd, has developed a novel free piston Stirling cryocooler concept using metal diaphragms. The concept uses a pair of metal diaphragms to seal and suspend the displacer of a free piston Stirling cryocooler. The diaphragms allow the displacer to move without rubbing or moving seals to produce a long-life mechanism. When coupled to a metal diaphragm pressure wave generator, the system produces a complete Stirling cryocooler with no rubbing parts in the working gas space. Initial modeling of this concept using Sage indicates the potential for a useful cryocooler. A proof of concept prototype was constructed and achieved cryogenic temperatures. CFD modeling of the heat transfer in the radial flow fields created by the diaphragms shows the possibility of utilizing the flat geometry for heat transfer, reducing the need for, or the size of, expensive heat exchangers.

A second prototype has been designed and constructed using the experience gained from the first prototype. Further CFD modeling has been used to understand the underlying fluid-dynamic and heat transfer mechanisms and refine the Sage model. The prototype has produces 29W of cooling at 77K and reaches a no-load temperature of 56K. This paper presents details of the development, modeling and testing of the second iteration prototype.

Large Pulse Tube Developments

[THO10-2]

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Callaghan Innovation, formally known as Industrial Research Ltd (IRL), has continued to develop its largest of three high frequency single-stage pulse tubes. The target performance for the pulse tube cooler was 200W @ 77K and was close-coupled to a 200cc metal diaphragm Pressure Wave Generator (PWG). The previous pulse tube achieved 110W of cooling power @ 77K, with an electrical input power of 3.1 kW from a 90cc swept volume PWG. The pulse tubes have all been tuned to operate at 50 Hz, with mean helium working gas pressure of 2.5 MPa. Sage pulse tube simulation software was used to model the latest pulse tube and predicted 280W of cooling power @ 77K. The pulse tube cryocooler was designed to be an intermediate step to up-scale pulse tube technology for our 1000 cc swept-volume PWG, to provide liquefaction of gases and cooling for HTS applications. Details of the modeling, design, development and experimental results are discussed.

Experimental Study on a Stirling Type Cryocooler with High Cooling Capacity [THO10-3]

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Cryocoolers with high cooling capacity around 80 K~120 K play an important role in boil off gas recondensation and power application of superconductivity. Among the cryocoolers, the free piston Stirling cryocooler (FPSC) might be a good candidate due to its attractive virtues of compact size and high thermal efficiency. In this work, an FPSC has been optimized based on thermoacoustic theory, moreover, an experimental system has been built for further validation against the predictions. Considerable experiments were carried out to study the fundamental performance in terms of the operating frequency, the mean pressure and the input acoustic power. In addition, the coupling mechanism between the FPSC and the linear compressor was investigated in detail. Typically, a large cooling power of 250 W was obtained with 3 MPa helium and operating frequency of 50 Hz. The relative Carnot efficiency was as high as 28%.

A Pulse Tube Cryocooler with 1 kW Cooling Capacity at 120K [THO10-4]

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Due to the high reliability, low vibration, and high efficiency, Stirling-type pulse tube cryocoolers are enlarging the cooling capacities for industrial applications. In this paper, a coaxial type pulse tube cryocooler has been developed. The coaxial design philosophy provides an exposed cold head, therefore, shows a convenience in the cold energy utilization especially when liquefying boil-off gas in LNG Tanks. Several methods are taken to reduce loses in both the regenerator and the buffer tube as to push the limitation of refrigerating capacity. Dishes made of low mesh are installed where diameters or flow direction change rapidly to reduce jet-flow as well as turbulent flow. Some copper screens are inserted in the regenerator to prevent the circumference temperature asymmetry. Preliminary experiments have verified a refrigeration capacity of 1030W at 120K, consuming about 6500W PV power supplied by a dual-opposed pressure wave generator from CFIC. The temperature difference detected in the central annulus of regenerator is less than 55K which is acceptable for such a diameter of 180 mm. The current design has shown a promising application value in the cold energy resupplement for LNG stations.

Study on a 300Hz Pulse Tube Cryocooler Driven by a Thermoacoustic–Stirling Heat Engine [THO10–5]

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The pulse tube cryocooler (PTC) driven by a thermoacoustic heat engine is one of the most promising thermoacoustic systems. It has the advantages of high reliability and potentially high thermal efficiency. The miniaturization of the thermoacoustically-driven pulse tube cryocooler is of great importance for a broader application, which means the specific power (i.e. the ratio between power and weight) should be increased. To address it, one effective way is to increase the resonant frequency to several hundred Hertz. In the recent two decades, high frequency thermoacoustically-driven pulse tube cryocoolers have drawn much attention. Our group has made considerable efforts on a 300 Hz pulse tube cryocooler driven by a standing-wave thermoacoustic heat engine and obtained a lowest cold head temperature of 58 K. However, the intrinsic irreversibility of the standing wave thermoacoustic heat engine makes it not as efficient as the thermoacoustic-Stirling heat engine (TAHE). Therefore, a 300Hz pulse tube cryocooler driven by a TAHE was designed and studied in this paper. Experiments were carried out and a no load cooling temperature of 48 K was obtained with heat input of 500 W in the TAHE. Compared with the results on the PTC driven by a standing-wave thermoacoustic heat engine, our new cryocooler driven by a TAHE has higher thermal efficiency and lower cooling temperature.

CFD Simulation of the Gas Flow in a Pulse Tube Cooler with Two Pulse Tubes

[THP4-1]

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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, 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.

Novel Numerical Model for Pulse Tube and Stirling Cooler [THP4-2]

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A novel one-dimension theoretical model of oscillating flow in pulse tube cryocooler and Stirling cryocooler is established. The model is constructed in Lagrange perspective instead of Euler approach. Limited gas amount in the closed system of the cryocooler supplies feasibility for the model.

The model is helpful to explain the mechanism of regenerative cryocooler, even inertance tubes in pulse tube cryocooler. Gas in the cryocooler is divided into finite small elements, and by using this model to calculate the physics of the elements in the regenerative cryocooler, processes of gas flow and heat transfer between gas and solid can be present more exactly. Besides, thermodynamic cycle of each gas element can be achieved. Based on the thermodynamic cycles, loss of each gas element in the cooler can be found out easily and it is helpful to improve performance of cryocooler.

Cooling process, cold end temperature and many other parameters of the regenerative cryocooler can be predicted by this model.

Thermo-Fluid Modeling of a Full Scale Liquid Hydrogen Storage System with Integrated Refrigeration [THP4-3]

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Distribution of liquid hydrogen (LH₂) via tanker trucks is the most direct path towards meeting the delivery requirements in the early phases of the transition to a hydrogen based energy economy. This will use larger, centralized production and liquefaction systems, and tankers to deliver liquid to the distribution stations. Due to the low storage temperature, heat leak into the storage vessel will create boil off and pressurization and may eventually lead to venting and loss of product. Engineers at NASA Kennedy Space Center have been dealing with these issues on a large scale since the 1960's with a normal evaporation rate on their 850,000 gallon LH₂ tanks varying between 600-1,000 gallons per day. NASA KSC is currently developing a Ground Operations Demonstration Unit (GODU) for LH₂, where advanced operations including an integrated cryogenic refrigerator designed to remove heat from the stored liquid will be tested. This will allow for zero loss storage and transfer operations, as well as control of the propellant state to enable conditioning or densification. NASA KSC has partnered with the Florida Solar Energy Center to develop a thermo-fluid model of the integrated refrigeration and storage system to predict behavior in a variety of operating conditions. This model will consider thermo-physical properties and specifications of associated fluids and materials in the GODU for more accurate prediction of behaviors. This paper will discuss details of the GODU LH₂ system and the modeling parameters.

A Numerical Study on Recuperative Finned–Tube Heat Exchangers [THP4–4]

Nir Tzabar

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A recuperative heat exchanger is a crucial element in Joule-Thomson (JT) cryocoolers. The heat exchanger efficiency determines the cryocooler efficiency, and below a certain value of the heat exchanger efficiency the cryocooler is inoperative. Among a few configurations of heat exchangers, the helical finned-tube type is widely in use. In addition to the requirement for high heat transfer efficiency, there is also a demand from the heat exchanger for low pressure drops, especially at the low pressure stream. As JT cryocoolers are commonly integrated in miniature systems, the heat exchangers are required for miniature dimensions as well.

In the current research a numerical model for describing the heat exchanger is developed. The analysis includes the calculations of the heat exchanger performances and provides an insight view to the fluid states and thermal characteristics of the heat exchanger, at steady state conditions. The analysis enables to perform an extensive investigation of the heat exchanger and to optimize the dimensions for any target.

Thermodynamic Analysis of the Cold-End Connection Tube Influence in U-Shape Pulse Tube Cooler [THP4-5]

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The objective of this paper was to demonstrate and analyze the influence of cold-end connection tube in U-shape pulse tube cooler (UPTC). A UPTC was constructed and experimented and the performance was undesirable. According to the experimental results, the temperature difference between the cold-end heat exchangers of the pulse tube and regenerator always existed. This phenomenon was explained by the gas parcel thermodynamic analysis. Through thermodynamic analysis about UPTC and linear pulse tube cooler (LPTC), the influence of the cold-end connection tube was verified. According to the research, the periodical movement of the gas parcel in connection tube experienced a thermodynamic process like pumping heat from pulse tube to regenerator. Such kind of heat-pumping process led to the loss of cooling power of UPTC. The further research showed the quantity of the loss was influenced by the size of connection tube, frequency, the phase angle between mass flow rate and dynamic pressure.

The Design of Embedded-Type Stirling Cryocooler [THP4-6]

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The design method of a new model called embedded-type Stirling cryocooler is presented in this paper in order to make the Stirling cryocooler's volume much smaller and its length much shorter. The designed Stirling cryocooler's expander is embedded into its compressor to shorten the length of complete machine. The sage software was used to test and verify the feasibility of the embedded-type Stirling cycle and to performance optimization had been done simultaneously to get the key factors that will impact cryocooler performance; the design optimization about the electrical machine structure and some parameters had been analyzed by using Ansoft that is electromagnetism analysis software to make the electrical machine meet the design requirements.

Simulation of Thermodynamic Cycles in Linear Type Pulse Tube System [THP4-7]

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In this study, a simulation is built to analyze gas parcels in linear type pulse tube system. Thermodynamics process of gas parcels in compressor, regenerator, heat exchanger, pulse tube and inertial tube are considered in the simulation. Pressure in the pulse tube system is sinusoidal. And the working fluid is assumed to be ideal gas. Length-wise mixing and heat conduction are ignored in the simulation, and process in the pulse tube and inertial tube is considered to be adiabatic. By using Lagrange method, the simulation follows the thermodynamics processes of each gas parcel and gives the thermodynamic parameters of the working fluid throughout the processes. The refrigerating capacity, input power and COP of the pulse tube system are also calculated in the simulation. The results of the simulation can help us to design pulse tube system and study the physical nature of the working fluid in the pulse tube. All simulations are done by a one-dimensional model built by Matlab.

Parametric Investigation of Regenerator of a Miniature Stirling Cryocooler

[THP4-8]

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Miniature Cryogenic coolers working on the reversed Stirling cycle are used for cooling IR detectors in satellites, imaging cameras in battle tanks and applications like HTS devices. They require cryogenic cooling in the range of 60-80 K with cooling power varying from mW to a few Watts. A regenerative heat exchanger is the most vital design component of miniature Stirling cryocooler because the performance of the cooler largely depends on the effectiveness of the regenerator used in the system. A study has been carried out using REGEN 3.3 to optimize the regenerator of a miniature Stirling cryocooler operating with a warm end temperature of 300 K and cold end temperature of 80 K. #200 twill, #250 twill, #400 twill and #200 plain screen regenerators made of Stainless Steel and Phosphor Bronze were considered for investigation. The output given by REGEN 3.3 includes the gross and net cooling power, thermal losses, and associated PV work at the cold and warm ends of the regenerator. Thus the optimization is achieved by maximizing the COP, which is calculated from the net cooling power and PV work at the warm end of the regenerator, as a function of length, mass flow and the phase between the cold end mass flow and pressure. The investigation was conducted for a frequency range of 30 to 80 Hz using an average pressure of 12 bar and pressure ratio of 2. The net cooling power, COP and the optimized parameters of regenerator length, mass flux and phase angle are presented as a function of frequency. The results obtained from the analysis are useful for the complete design of a miniature Stirling cryocooler.

Exergy Flow in Multistage Cryogenic Refrigerators with Application to Multistage Reverse Brayton Cryocoolers [THP4-9]

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Exergy analysis of multistage cryogenic refrigerators is considered in this study using separation of pressure and thermal components of exergy through the thermodynamic cycle. The analysis provides a method for estimating the performance of multistage cryocoolers under a variable load condition in terms of an exergy based figure of merit for each component of the system. A figure of merit for the expansion process is proposed that is convenient for quantifying the irreversibility of the expansion process at each stage and its effect on the performance of multistage refrigerators. The method is applied to multistage reverse Brayton cryogenic refrigerators to evaluate their thermodynamic performance under a variable load condition at each stage. The performance of the reverse Brayton cryocoolers employing auxiliary coolers at the intermediate stages is also analyzed.

CFD Simulation of a Thermoacoustic Cooler with RHVT Effect [THP4–10]

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High frequency and pressure operation conditions are the usual approach for thermoacoustic devices of reduced size and practical feasibility; as result, heat is generated by viscous losses and vorticity, mainly around the stacks. Many different topologies of stacks have been analyzed to reduce these effects and also helium or mixtures He/Ar are employed for this purpose.

This article evaluates the effect of incorporating a Ranque-Hilsch Vortex Tube into a thermoacoustic cooler device, as a way to reduce the dependence on the stack and mimic the behavior of the traveling wave arrangement in a reduced space.

Numerical Simulation and Experimental Study of a Spiral Tube-in-Tube Heat Exchanger Used in Joule-Thomson Cryocooler [THP5-1]

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Due to its compact structure and excellent heat transfer performance, spiral tube-in-tube heat exchanger is widely used in Joule-Thomson (J-T) refrigerator. In previous study, our laboratory has developed a hybrid 4.5K cryocooler by using a two stage GM cooler to precool a J-T system. The spiral tube-in-tube heat exchanger used in the cryocooler is one of the key components which significantly affect the overall performance of the Joule-Thomson circle.

In the present research, a numerical study is carried out to promulgate the distribution of pressure and temperature in spiral tube-in-tube heat exchanger at different operating pressures. Different design dimensions of the counter-flow heat exchanger are simulated numerically. The pressure drop of each condition is calculated and analyzed. And special attention is laid on the optimization analysis of the heat exchanger's structure, for the purpose of building a more compact spiral tube-in-tube heat exchanger with high efficiency. Then, experimental data are presented to verify the numerical results.

Development of 1.5 W 4K Two-Stage Pulse Tube Cryocooler with a Remote Valve Unit [THP5-2]

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SHI has been continuously improving the efficiency and reducing the vibration of a 4K pulse tube cryocooler. A 1.5 W 4 K pulse tube cryocooler with a remote valve unit has been developed. The valve unit of the cryocooler is split from the cold head by one flexible gas line and two stainless pipes. When the valve unit is split with 1 m lines, the cooling capacity is reduced because of increased pressure drop and dead volume. A typical cooling capacity of the prototype unit is more than 30 W at 45 K on the first stage and more than 1.3 W at 4.2 K on the second stage when the compressor is operated at 50 Hz. The performance load map and the performance with respect to orifice openings will be reported in this paper.

Development of Adiabatic Demagnetization Refrigerator for Sensor Cooling [THP5-3]

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In recent years, numerous space scientific missions are being planned which require very low temperatures and very low temperature environments. Among them is cosmic microwave background radiation (CMB). The excellent full resolution of the X-ray detector which is used for CMB observations is obtained by cooling to below 100mK. The adiabatic demagnetization refrigerator (ADR) is cited as a refrigerator for generating temperatures in such a range. ADR boasts high refrigeration efficiency at very low temperatures and further, has the advantage that it is not dependent on gravity since the cooling medium is solid. At present, we are developing an ADR suitable for the CMB project. Its prototype is the four-stage continuous-operation adiabatic demagnetization refrigerator (Continuous ADR) which has been developed previously. First, proof-of-concept experiments of sensor cooling will be conducted using the existing CADR apparatus. Improvements will be made based on the results, and the final goal is set as the development of a three-stage CADR. The overall thermal design and the characteristics of the heat switch will be presented this time.

Simulation Study on a Miniature 4He J-T Cryocooler with Two Stage G-M Cooler as the Pre-Cooler [THP5-4]

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A compact 4He Joule-Thomson (JT) cryocooler using a two-stage Gifford-McMahon (GM) cooler as pre-cooling stages is designed and analyzed numerically. The relationships between the mass flow rate, the diameter of the orifice and the high-side pressure, the cooling capacity of the JT cooler, the state of incoming gas and the temperature of the pre-cooler's second stage are simulated. The trends of JT compressor power with exhaust pressure and the cooling power required from the pre-cooler with the mass flow rate of the refrigerant are also analyzed. Based on these relationships, a design scheme is given with the details of the key components of the system.

Testing of a 1 kW-Class Cryogenic Turboalternator [THO11-1]

D. Deserranno, A. Niblick, M. Zagarola

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Future NASA missions and facilities will require hydrogen liquefaction systems for spaceport, planetary, and lunar surface operations. Cryogenic expansion turbines are critical components of many liquefaction systems. Recently, Creare designed, built and tested several turboalternators suitable for hydrogen liquefaction systems producing 5000 gallons/day. The turboalternator designs were scaled from Creare's space-borne turboalternators which were developed for sensor cooling applications with refrigeration from watts to tens of watts. The hydrogen turboalternators were optimized for operation between 77 and 20 K, and produce up to 1.5 kW of refrigeration, depending on the expansion stage and operating conditions. Testing was performed in cryogenic nitrogen at 140 K and at dynamically equivalent operating conditions as hydrogen. Net efficiencies were demonstrated up to 80%, closely matching our performance predictions. The design and testing of the turboalternator, and the extension of the technology to high-capacity turbo-Brayton cryocoolers are the subjects of this paper.

Testing of a Two-Stage 10 K Turbo-Brayton Cryocooler for Space Applications [THO11-2]

J. Breedlove, K. Cragin, M. Zagarola

Creare Incorporated, Hanover, NH, USA

Future space missions will require active refrigeration for cooling sensor payloads to temperatures as low as 10 K. In addition, this payload will require refrigeration at high temperatures of 60 to 80 K for cooling thermal shields and optics. Stored cryogenes are only suitable for short duration missions and passive radiators are not an option due to the extremely cold sensor operating temperature. Creare recently built and demonstrated a two-stage turbo-Brayton cryocooler suitable for sensor payloads operating at 10 K. The cryocooler was assembled in a brass board configuration comprising a combination of brass board and flight quality components. The cryocooler was operated with cold load temperatures between 10 and 20 K and intermediate load temperatures between 60 and 70 K.

This paper presents the initial test results, describes modifications that were implemented to improve performance, presents the final test results, and provides performance predictions for a fully optimized cryocooler to be built in the future.

Ultra Low Power Cryo-Refrigerator for Space Applications [THO11-3]

M. V. Zagarola, R. W. Hill, J. R. Gagne

Creare Incorporated, Hanover, NH, USA

Future NASA astronomical observatories will require long-life, mechanical cryocoolers for cooling bolometers, detectors, sensors, shields, and telescopes. Some missions are either to the outer planets or to the L2 Lagrange point. Here, the scientific payload can be effectively shielded from the sun and earth which reduces thermal noise and parasitics, but power is more difficult to generate due to the reduced solar flux. Consequently, payload power and mass are even more critical parameters for these observatories than for earth-orbiting satellites.

Creare has developed a reverse Brayton cryocooler design that meets aggressive mass and input power objectives. The cryocooler has been optimized to provide 300 mW of cooling at 35 K and requires 8.9 W of compressor input power at 150 K. The total system mass is 6.2 kg including electronics and cryo-radiator. The cryocooler is designed to operate at cold end temperatures of 30 to 70 K, loads of up to 3 W, and heat rejection temperatures of up to 210 K by changing only the charge pressure and turbomachine operating speeds. On a recent project, a demonstration cryocooler was assembled and tested over a range of cold end temperatures and heat rejection temperatures. The design of the cryocooler and results of the testing are the subjects of this paper.

Switchless Sorption–Compressor Design [THO11–4]

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Sorption coolers are free of vibrations and of EMI, and have the potential of a long lifetime. They are, therefore, attractive for cooling sensitive optical detector systems in space as well as in terrestrial applications. Generally, gas-gap heat switches are applied for reducing the input power in the desorption phase of the compressor sorption cycle. This is specifically required in space applications since the compressor cells are cooled by radiators of which the size is proportional to the compressor input power. In terrestrial applications, such as the METIS instrument in the European Extremely Large Telescope, small input power may, however, not be the major concern. Especially in applications requiring high cooling powers and thus large numbers of compressor cells, complexity and costs may become more important. In order to reduce these, we developed an alternative switchless sorption-compressor design using short-pulse heating. A dynamic thermal model was built for evaluating this concept and for optimizing the compressor-cell dimensions and operating parameters. Introductory experiments were performed for validating the model. The concept is used in the design of the METIS-cooler compressor cells.

Joule–Thomson Cryocoolers Operating with Binary Mixtures [THO11–5]

Nir Tzabar

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Joule-Thomson (JT) cryocoolers operating with mixtures containing 4 – 7 components are widely investigated for reducing the operating pressures and increasing the COP. In addition to exploring multi-component mixtures we also examine mixtures with 2 – 3 components as refrigerants for JT cryocoolers. These mixture performances expected to be inferior relative to multi-component mixtures; however, they are analytically calculated in a more convenient manner. Furthermore, in some scenarios binary and ternary mixtures can be advantageous over multi-component mixtures.

In a previous research we investigated phase diagrams and isothermal JT effects (Δh_T) of binary mixtures that contain nitrogen, argon, methane, ethane, ethylene, and propane. The present paper presents the research progress with nitrogen-ethane and nitrogen-propane mixtures for extended cooling temperature range of 80 – 150 K. The compression power is calculated and the COP of the cryocooler is obtained. Finally, experimental results are presented to verify some of the analytical results.

High Efficiency Cryocooler Performance [THO12-1]

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The Northrop Grumman TRL 9 High Efficiency Cryocooler (HEC) is a pulse tube cryocooler with flexure bearing compressor that has been delivered for flight for a number of different payloads while configured for a variety of cold head temperatures and cryogenic loads extending from $35\text{K} < T < 200\text{K}$. The coolers have been customized for many of the payloads either in one or 2 stage configurations by optimizing the cold heads for temperature and load or with linear or coaxial cold heads or both. Common to all of these coolers is the compressor and flight electronics. The performance of some of these various coolers has previously been published. Recently we have extended the performance of the single stage coolers to much higher cooling power and to lower temperatures, improved the performance of the coaxial cold head integral cooler and extended the performance of the 2 stage cooler to temperatures below 35K. This paper will report the performance of these HEC coolers over their complete range of capability.

Flight Qualification Testing of the Thales LPT9510 Pulse Tube Cooler [THO12-2]

D. Johnson and J. Rodriguez

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

JPL has continued the qualification of the Thales LPT9510 pulse tube cryocooler as a candidate low cost cryocooler for future cost-capped scientific missions. The commercially available cooler can provide refrigeration in excess of 2 W at 100K for 60W of power. JPL purchased the LPT9510 cooler for thermal and dynamic performance characterization, and has completed random vibration dynamics tests and the post-dynamics thermal cycling tests for the flight qualification of the existing cooler design to satisfy near-term JPL needs for this cooler. The cooler was shaken to protoflight dynamics levels in all 3 axes to the 0.16 g^2/Hz level. The LPT9510 cooler was then thermally cycled three times over the heat reject temperature range of $-15^{\circ}C$ to $+55^{\circ}C$ to demonstrate its survival of the dynamics testing. Thermal performance characterization measurements were made at several input voltages at the $-15^{\circ}C$, $+20^{\circ}C$ and $+55^{\circ}C$ reject temperatures. Test results of the Thales LPT9510 cooler thermal and dynamics testing will be presented here.

Characterization Testing of the Thales LPT9310 Pulse Tube Cooler [THO12-3]

D. Johnson, J. Rodriguez, H. Tseng, B. Carroll

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

JPL has identified the Thales LPT9310 pulse tube cryocooler as a candidate low cost cryocooler to provide active cooling on future cost-capped scientific missions. The commercially available cooler can provide refrigeration in excess of 5W at 80K for 160W of compressor power. JPL purchased the LPT9310 cooler for thermal and dynamic performance characterization, and has initiated the flight qualification of the existing cooler design to satisfy near-term JPL needs for this cooler. The cooler has been subjected to random vibration testing and post-vibration thermal cycling. The thermal performance has been characterized as a function of input voltage and as a function of coldtip load and temperature at heat sink temperatures of -20°C, +20°C and +60°C. The cooler will be placed on a force dynamometer to measure the self-generated vibration of the cooler as a function of input power, and the orientation dependence of the cooler performance with respect to the gravity vector will also be explored. Test results of the thermal and dynamic testing of the Thales LPT9310 cooler will be presented here.

Flight Qualification Testing of Cryocooler Electronics [THO12-4]

Carl Kirkconnell

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The Low Cost Cryocooler Electronics (LCCE) has been developed by Iris Technology under United States Air Force (USAF) funding to provide a radiation hard, high performance, modular, affordable set of cryocooler electronics. To date the LCCE has been used to drive and control a wide range of 100W class linear coolers, including the AIM SF100 (pulse tube and Stirling versions), Thales LPT 9510, Lockheed Martin Microcryocooler, Northrop Grumman Micro Pulse Tube Cooler, and the Ricor K527. This paper describes the Flight Qualification Testing to which the LCCE was subjected in the achievement of Technology Readiness Level (TRL) 6. The LCCE survived thermal cycling, thermal vacuum and applied vibration environments without damage or degradation. MIL STD 461F electromagnetic interference (EMI) testing was also successfully completed. Performance testing was performed throughout the test sequence with the AIM SF100 pulse tube and dummy resistive loads to ensure that degradation was not occurring. The test profiles and performance of the LCCE are discussed.

Joule–Thomson Impedance Measurements for Microcryocoolers [THO13–1]

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Compact low power microcoolers are being explored to meet advanced infrared systems requiring 80 K to 150 K operating regimes. In the recent past work has been conducted exploring low pressure (4:1 up to 16:1 pressure ratio) mixed refrigerant JT microcoolers to meet the cooling needs of the latest IR detectors. For JT microcoolers determining the proper JT impedance is difficult to model and predict accurately due to uncertainty in geometry, surface roughness, and fluid properties, thereby leading to an extensive trial and error fabrication process to meet desired flow for a given pressure. Further compounding this uncertainty, flow changes nonlinearly with respect to minor changes in the geometry of the JT impedance further extending trial and error fabrication. To alleviate the trial and error approach room temperature flow measurements with nitrogen were undertaken to narrow selected JT impedance geometry to deliver desired flow rates for given pressures. We present details and results of examples employing flow measurements with singular gases that enables good evaluation and prediction of flow for a given pressure drop for microscale impedances reducing the guess work and extensive iterative repetition required to determine the proper geometry to meet flow rates and cooling capacity desired for a given gas or mixture. Flow rates of nitrogen at room temperature are found to be a factor of up ~ 3 high with respect to expected values for a single gas or mixture.

We present results of measurements made during the course of a program developing low pressure (16:1 down to 4:1) mixed-gas JT microcryocoolers for flows of 0 to 40 SCCM through microscale impedances. While useful for mixed-gases the measurements for single gases such as Isobutane and Propane demonstrate greater applicability for broader implementation and prove more reliable predicting flow rates and cooling capacity especially for cascade JT microcoolers forthcoming.

Cryocooler with Cold Compressor for Deep Space Applications [THO13-2]

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Future NASA Mission will require cryocoolers providing cooling capacities in excess of 0.3 W at 35 K with rejection temperatures as low as 150 K and input powers up to 10 W. Presently there are no qualified cooler systems operating at this low rejection temperature. Madison CryoGroup was awarded a phase 1 SBIR contract to demonstrate this capability. Lockheed Martin's Advanced Technology Center was a subcontractor to provide the compressor for this development using their "Mini" pulse tube cooler which also included the cold head.

Initial concept feasibility tests were conducted with the compressor operating at 150 K; cooling of 0.17 W at a cold tip temperature of 35 K was achieved, although the system was not optimized for the 150 K compressor operation. Predictions of the modifications to optimize the performance were conducted and indicated that the goal of 0.3 W at 35 K with 10 W of power input could be achieved with the reject temperature at 150 K. This paper presents both the early test results and predictions for both the as-tested system and a compressor optimized for 150 K.

A Cryocooler Driven by Electrochemical Compressors with No-Moving Parts

[THO13-3]

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This paper reports on the development of a vibration-free cryocooler for infrared detectors. The cryocooler employs an Electro-Chemical Hydrogen Compressor (EHC) with no-moving parts for reliable, vibration-free operation. The EHC uses an advanced anhydrous proton conducting membrane to compress hydrogen through an electrochemical process. This compressor produces high pressure ratios with no moving parts. The cryocooler also uses a unique single pressure dilution cycle to provide cooling at temperature significantly than the hydrogen J-T inversion temperature. The paper first reports preliminary test data from an open-cycle cryostat using argon as the refrigerant and hydrogen as the diluent. The measured cooling power of the dilution cryostat is compared with predicted value. The paper also reports test data for the compression ratio and compression efficiency of a proof-of-concept EHC with a H₂-Ar mixture. Based on the performance data of the dilution cycle and the EHC, the thermodynamic cycle design of the cryocooler is optimized and then the cryocooler performance is estimated. Preliminary mechanical designs for the EHCs are also developed.

Analytical Investigation on Joule–Thomson Micro–Cryocooler [THO13–4]

Nir Tzabar

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Joule-Thomson (JT) cryocoolers include recuperative heat exchangers (RHE) where a high pressure fluid is cooled by the same fluid in a state of lower pressure and temperature. The pressure difference between the streams varies between 2 - 20 MPa and the temperature difference between the RHE ends can exceed 200 K.

The RHE is the largest component in the JT cryocooler cold-end; therefore, miniaturization of the cooler is achieved with a micro-fabricated RHE. Our preliminary design of a JT micro-cryocooler is based on a plane counter flow RHE that consists of straight micro-channels at both high and low pressure streams. An analytical quasistatic model of the cryocooler has been developed for investigating the micro RHE performances. The analysis calculates five temperature profiles in the RHE; high and low pressure streams, both stream covers, and the buffering material between the streams. The axial heat losses through the buffering material and two covers are also incorporated. This analytical model helps to design the prototypes to be fabricated and tested and facilitates parameter and sensitivity studies. Some preliminary results of the parameter study are presented and discussed.

Design and Analysis of a 150 K Cascade Joule–Thomson Microcooler [THO13–5]

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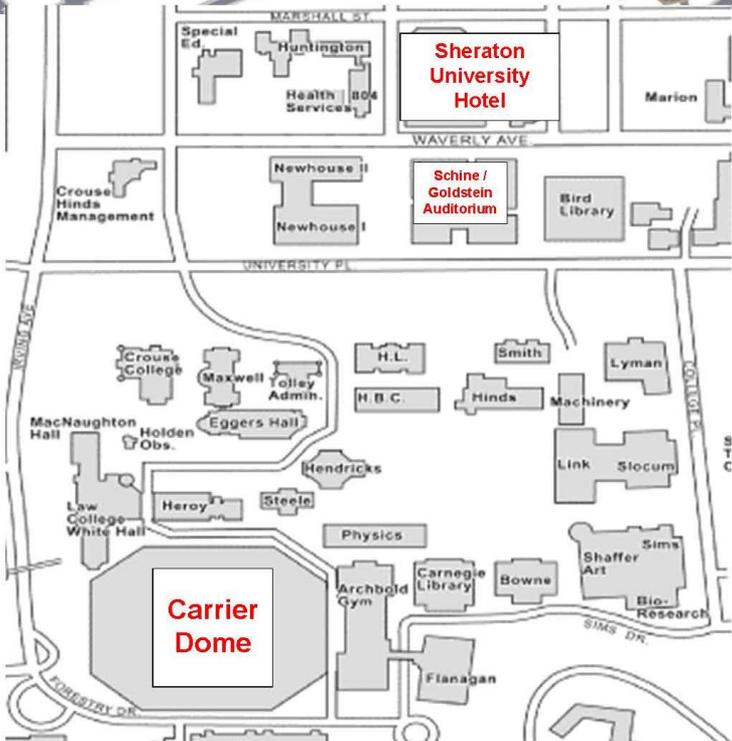
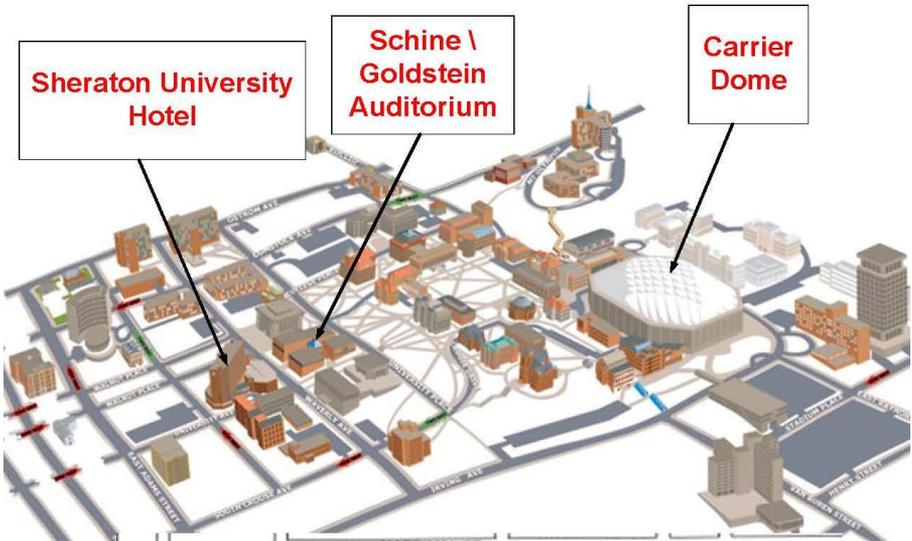
[2] University of Colorado, Boulder, CO, USA

Lightweight and compact microcoolers are needed for advanced, hand-held infrared systems. A temperature of 150 K is adequate for high sensitivity with some of the latest IR detectors, which simplifies the cooling requirements compared to 80 K detectors. The largest and heaviest component of most gas-cycle cryocoolers has been the compressor.

This paper describes how the use of a 150 K, five-stage, cascade Joule-Thomson (JT) cycle significantly reduces the total refrigerant flow rate and total compressor swept volume compared with other types of cryocoolers for this temperature range. The use of vapor compression in each of the five stages results in very high specific refrigeration powers and low flow rates even with no recuperative heat exchangers and with pressure ratios of only about 4:1. Such low pressure ratios are needed for the use of chip-scale compressors.

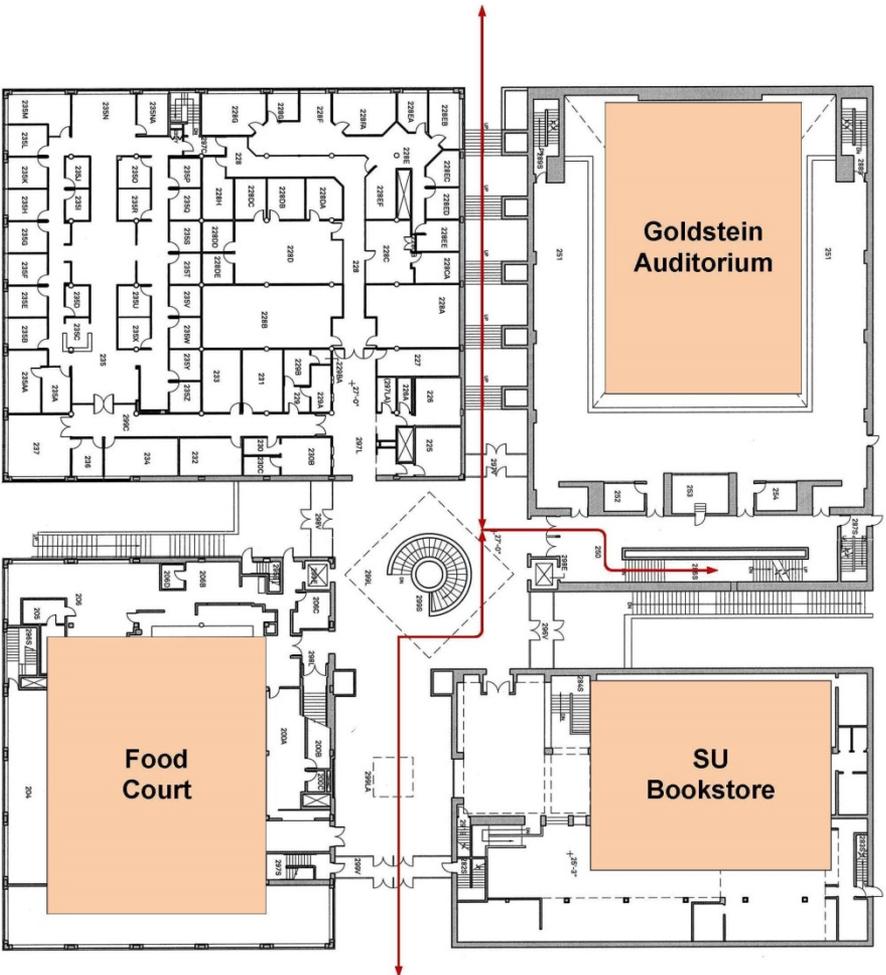
We discuss the thermodynamic design of a five-stage planar polyimide cold head for a range of refrigeration powers up to about 350 mW at 150 K. We compare the use of single-layer and double-layer construction over this range of refrigeration powers. In the double layer construction, the high-pressure fluid streams are on the bottom and the low-pressure fluid streams are on top. Such construction allows for simple recuperative heat exchangers and leads to a compact planar geometry of about 20 mm by 30 mm for 350 mW refrigeration power at 150 K. The ideal fluid input power for the five-stage system at 150 K with no recuperative heat exchangers is 1.5 W per watt of net refrigeration power. The paper describes the geometry of the condensers, evaporators and Joule-Thomson impedances to achieve the high heat flux required for minimum size.

Campus Map



Sheraton University Hotel

Waverly Ave.



University PL

	Monday, June 9	Tuesday, June 10	Wednesday, June 11	Thursday, June 12			
7:00 AM		Session Chair Breakfast Meeting/ Continental Breakfast	Continental Breakfast	Continental Breakfast	7:00 AM		
8:00 AM	Foundations of Cryocoolers Short Course	Welcome to Conference [TO1] Space Missions	[WO6] Aerospace Cryocoolers I	[THO10] Commercial Cryocoolers II	8:00 AM		
8:15 AM					8:15 AM		
8:30 AM					8:30 AM		
8:45 AM					8:45 AM		
9:00 AM			Break	[WP3] Advanced Cryocooler Component Technology	[THP4] Advanced Analysis & Modeling II	[THP5] Very Low Temperature Cryocoolers II	9:00 AM
9:15 AM			[TO2] Regenerators	[WO7] Advanced Analysis & Modeling I	[THO11] Brayton, JT, and Sorption Cryocoolers	9:15 AM	
9:30 AM							
9:45 AM						9:45 AM	
10:00 AM						10:00 AM	
10:15 AM						10:15 AM	
10:30 AM						10:30 AM	
10:45 AM						10:45 AM	
11:00 AM			Lunch	Lunch	Lunch	11:00 AM	
11:15 AM							
11:30 AM							11:30 AM
11:45 AM							11:45 AM
12:00 PM					12:00 PM		
12:15 PM					12:15 PM		
12:30 PM					12:30 PM		
12:45 PM					12:45 PM		
1:00 PM		[TO3] Cryocooler Applications I	[WO8] Advanced Cryosystem Components	[THO12] Aerospace Cryocoolers II	1:00 PM		
1:15 PM		[TO4] Commercial Cryocoolers I	Break	Break	1:15 PM		
1:30 PM							1:30 PM
1:45 PM		[TP1] Cryocooler Applications II	[TP2] Stirling and Pulse Tube Cryocoolers	[THO13] Emerging Cryocooler Technology	1:45 PM		
2:00 PM		[TO5] Miniature Cryocoolers	[WO9] Very Low Temperature Cryocoolers I		2:00 PM		
2:15 PM							2:15 PM
2:30 PM							2:30 PM
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5:00 PM					5:00 PM		
5:15 PM					5:15 PM		
5:30 PM					5:30 PM		
5:45 PM					5:45 PM		
6:00 PM	Welcome Reception & Tour 6:00-9:00 PM Carrier Dome Club 4•4		Conference Dinner Event 6:00PM - 10:00 PM		6:00 PM		
6:15 PM						6:15 PM	
6:30 PM						6:30 PM	
6:45 PM						6:45 PM	
7:00 PM					7:00 PM		