14th International Cryocooler Conference

June 14-16, 2006
Annapolis, Maryland

Final Program

With Complete Technical Abstracts

Loews Hotel
Annapolis, Maryland

INVITATION AND WELCOME

As chairman of Cyrocoolers 14, I would like to welcome you to the 14th International Cryocoolers Conference to be held in Annapolis, Maryland. The planned conference should be as exciting as those in the past with the latest information on new developments in cryocooler technology. The technical topics cover a wide variety of cooler types as well as vital information about components necessary to make them efficient and reliable.

The Conference is being held at the Loews Annapolis on June 14-16, 2006. A welcome reception is planned for Tuesday June 13 from 6-8 pm to allow for registration and renewing old friendships. The Loews Hotel is located in the heart of Annapolis, a short walk to area attractions for after-hours enjoyment and entertainment. Annapolis is located on the shores of the Chesapeake Bay which provides a bountiful supply of seafood to satisfy any seafaring appetite. If it is food you desire, you will find many quaint restaurants and pubs, steakhouses and seafood hot spots in the downtown historic district as well as eateries nestled away in a quiet waterfront cove. Boating abounds with over 3500 miles of navigable waterways for both sail and powerboat enthusiasts. Nightlife is always plentiful here in Annapolis, with live music venues, theaters and pubs providing entertainment every night of the week.

Cryocoolers 4 was held 20 years ago in the town of Easton, Maryland which is directly across the Chesapeake Bay from Annapolis. That conference was attended by 176 scientists representing 11 different countries. Thirty technical papers were presented over a 2-day period. Cryocoolers 14, in contrast, will have more than 100 papers presented over a 3-day period and I am confident it will be just as international as Cryocoolers 4.

On behalf of the conference committee and the Board of Directors, we would like to thank you for participating in Cryocoolers 14 and hope you take home some new and helpful technical information as well as joyful and pleasant memories of Annapolis. Remember, "You all come back, real soon."

Michael Superczynski
Chairman Cryocoolers 14

CONFERENCE COMMITTEE

CHAIRMAN

Michael Superczynski, Jr.
Chesapeake Cryogenics, Inc.
P. O. Box 9771, Arnold, MD 21012 USA
(410) 757-6616, Fax: (410) 757-8010
iccchair@cryocooler,org.

LOCAL ARRANGEMENTS

William Superczynski
Chesapeake Cryogenics, Inc.

TREASURER

Ray Radebaugh, NIST

CO-EDITORS

Saul Miller, Aerospace Corp.
Ron Ross, Jet Propulsion Laboratory

PROGRAM CHAIR

John Brisson, MIT

PROGRAM ADMINISTRATOR

Doris Elsemiller, MIT

PROGRAM COMMITTEE

Geoffrey Green, CCI; Chuck Hannon, AMT, Inc.; Peter Kerney, Consultant; Carl Kirkconnell, Raytheon; Eric Marquardt, Ball Aerospace; John Pfotenhauer, U. of Wisconsin; Ray Radebaugh, NIST; Alain Ravex, Air Liquide; Klaus Timmerhaus, U. of Colorado; Mark V. Zagarola, Creare

BOARD OF DIRECTORS

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GENERAL INFORMATION

ICC14 will be held at the Loews Annapolis Hotel in downtown Annapolis. The technical program consists of 106 oral and poster papers presented over three full days beginning at 8:00AM on June 14th and adjourning at 3:30 PM on June 16th. A welcome reception is scheduled for Tuesday evening at the Loews hotel, starting at 6:00 PM. Registration material will be available at this time.

Technical topics include:
Space Cryocoolers
Tactical Cryocoolers & Magnetic Refrigeration
Stirling Cryocoolers
Regenerators
Pulse Tube Technology
Oscillating Flow Components
Pulse Tube Modeling
Joule Thomson Cryocoolers
MEMS Based and Miniature Cryocoolers
Sub 10K Spacecoolers
Cryocooler Applications
Steady Flow Systems

REGISTRATION

Everyone attending the conference is required to pay a registration fee. The fee includes participation in the technical program, welcome reception, refreshment breaks, Conference Banquet, and a copy of the Conference Proceedings. Companion Banquet tickets are offered at an additional cost.

Conference funds must be in U.S. currency, drawn on a U.S. bank. Purchase orders and payment in foreign currency will not be accepted. The registration fee is $595. Early registration fee, before May 15th, is $495. Registration can be made at http://www.cryocooler.org.

A welcoming reception will be held on Tuesday, June 13, 2006 at 6:00 PM – 8:00 PM at the Loews Annapolis Hotel, in the Atrium which is adjacent to the lobby and registration desk. Pre-registrants may pick up their conference material at the registration desk. Those not registered may register at this time.

Hours of Registration

Tuesday	6:00 PM – 8:00 PM	(Welcome Reception)
Wednesday	7:30 AM – 5:00 PM	
Thursday	7:30 AM – 5:00 PM	
Friday	7:30 AM – 3:30 PM	

CONFERENCE BANQUET

The evening banquet will be held on Thursday June 15, 2006 from 5 to 8 P.M. The banquet will be held at Sandy Point State Park which is on the shores of the Chesapeake Bay about 5 miles from Annapolis. Buses will depart the Loews Hotel starting at 4:15 P.M. with the last bus departing at 4:45. We strongly advise attendees to use the bus transportation. Those not using the buses will have to pay a park entrance fee of $5.00 per person. Buses will leave the park at 8:00 PM for the return trip to the hotel.

We have reserved three large open pavilions, incase of poor weather conditions, adjacent to a lovely beach where you can even take a dip in the bay if you wish. A bath house is available for changing clothes so bring a bathing suit and towel. Water temperature in June is about 70 degrees F. Hors d'oeuvres will be served at 5 PM along with drinks (beer, wine, and soda) and will include many things from the bay including our famous steamed blue crabs. The main course will start at 6 PM to include local cuisine and seafood specials which I'm sure you will enjoy. We'll be entertained by live music and a performance by Middle Eastern Dancers to get you in a festive mood. There will be a photo opportunity with the dancers after their performance so bring your camera. The dress for the "banquet" is very casual. Dress to be comfortable and to enjoy yourself.

WEB SITE

Information on the conference is available through the Internet on the worldwide web at: http://www.crycooler.org.

HOTEL INFORMATION

The Loews Annapolis Hotel
126 West Street
Annapolis, MD 21401
Phone (1-800-526-2593 or 410-263-7777)

The Loews Annapolis Hotel is conveniently located in the heart of Annapolis and a short walk to many fine restaurants, historic district, Naval Academy, and the Annapolis waterfront. There is no need for a car once you arrive in Annapolis for there is ample activities and entertainment close by to enjoy after conference hours.

Annapolis served as the capital of the United States in the late 1700's and has many historic buildings related to the birth of the United States. Tours are also available to all historic places, including the Naval Academy. Additional information is available at our home page "Area Attractions" link.

Reservation Information
In order to insure that rooms are available for all attendees, ICC 2006 has reserved a block of rooms at the Loews Annapolis. You are strongly encouraged to reserve your room(s) at the Loews Annapolis so the conference can meet its room commitment and keep the registration costs from increasing at future conferences. To make reservations, you must call the hotel directly at (1-800-526-2593 or 410-263-7777), and indicate you are attending the "CRYOCOOLER CONFERENCE" in order to get the conference rates. Reservations cannot be made on line. ROOM RESERVATIONS MUST BE MADE BY MAY 14, 2006 IN ORDER TO RECEIVE THE CONFERENCE RATE.

- The room rate is US dollars $185.00 single/double.
- Sales tax 12% and is not included in the room rate.

- These rates are available 3 days prior to the conference and 3 days following the conference.

Government Room Rates

A limited number of government room rates at $104 single/double are available for the conference. These rooms are available on a first come first served basis for government employees only and requires a government ID when checking in. Again you must call the hotel directly indicating you will be attending the "Cryocooler Conference" in order to get the rate before May 14, 2006.

Parking at the Hotel

Those who choose to rent a car should be advised that parking is available at the hotel:

- Self parking $11.00 day maximum
- Valet parking $14.00 day maximum

Other Hotel Information

Additional information about the Loews Annapolis Hotel is available at http://www.LoewsAnnapolisHotel.com/hotels/annapolis.

CLIMATE & WEATHER

The month of June in Annapolis has mild temperatures near 80°F (30 °C), making outdoor activities a pleasant experience. Night can become a little chilly and therefore a light jacket or sweater may be advisable. Humidity is a pleasant 40 to 50 percent.

AUTHOR/PRESENTOR INFORMATION

The finished paper, in an electronic version on CD, or memory stick, and a camera-ready hard copy, must be brought to the conference and turned into the publication/AV staff when you arrive. The conference proceedings will be published as a hardcover book that also contains a CD containing all papers. New also with the 14th ICC, all papers will be freely available as PDF files on the Web following the final editing of the conference proceedings. The paper should be 10 or less pages in length to meet the publication requirements, and must be typed according to the conference's detailed typing format instructions; these instructions, as well as other conference materials, are available on the ICC website.

Each paper must be peer-reviewed for technical and format errors to insure the technical integrity of the proceedings. To expedite this review, please enclose three reduced (8½ x11 or A4) photocopies of your paper with your electronic & camera-ready manuscript, and mark each photocopy and manuscript page with your assigned paper number; this will ease the tracking of your paper during the review and publication cycle. Also be sure to attach a filled-out and signed Copyright Form (available on the conference web site), include a check for any over-page charges, ($50 per page) and obtain any sponsor clearance for publication and an approval for release.

Oral Information

Each oral presenter is permitted 15 minutes. You should arrange your talk so that your presentation lasts 12-13 minutes, with 2-3 minutes available for questions. You are expected to notify the session chair of your presence 10 minutes before the start of the session so that he/she knows you are present. There will be no rearrangement of papers within an oral session to accommodate absences or cancellations, so the time you have been assigned within the oral session is fixed. If you need to make changes or withdraw your presentation from the program on site at the conference, please contact the program administrator, Doris Elsemiller, in the Publication Room located in the atrium of the Loews Hotel.

All oral presenters are required to submit an electronic version of their presentation by 6:00 pm of **the day prior** to their presentation. **Presentations must be submitted in Microsoft Power Point format** (but may be saved as a PDF) and should be turned in at the Publication Room. 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, an overhead projector and a screen. Presenters are not allowed to use their own personal laptops. The laptops in all oral sessions 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 a duplicate copy of their presentation in the form of transparencies. You may also want to bring an additional electronic copy for added security against unanticipated software/hardware anomalies.

If a presenter has failed to submit his/her presentation by 6:00 pm of the day prior to their presentation, he or she will be required to give the presentation using transparencies and the overhead projector. If the first day (June 14) presenters cannot arrive on June 13 with their presentation before 6:00 pm, we suggest you send your electronic version via FedEx, UPS, etc. to:

Chesapeake Cryogenics, Inc.
492 Broadneck Road
Annapolis, Md 21409

Poster Information

Congratulations on your paper being accepted for a poster presentation at our upcoming 14th International Cryocooler Conference. Poster sessions will be held each day of the conference in the morning and afternoon. The exact times are listed in the program. We encourage morning session papers to be posted before 10:00 AM and removed during the lunch break. Afternoon papers should be posted before 3:00 PM and removed at the end of the day. Papers not removed in a timely manner will be discarded.

Each poster presenter will be provided with a poster mounting area 48" (1.22 m) wide by 48" (1.22 m) tall. The poster boards are a foam core 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. Tables will be provided to allow for display materials, however electrical power will not be available to operate computers, lights, etc.

Detailed Questions

If you have detailed questions concerning the poster presentations, or the board or mounting format, feel free to contact

Michael Superczynski, ICC14
Chesapeake Cryogenics, Inc.
Annapolis, MD 21401 USA
(410) 757-6616 or Fax (410) 757-8010
e-mail: icc14@earthlink.net

TECHNICAL PROGRAM

The Technical Program for the 14th ICC is organized into 14 sessions containing 106 papers. The technical sessions begin at 8:00 AM on Wednesday, Thursday, and Friday. The conference ends at 3:30 PM on Friday.

The entire conference will be held at the Loews Annapolis Hotel. All oral technical sessions will be held in the Ballroom. The poster sessions will be held in the Atrium, adjacent to the Ballroom. The poster sessions are schedule to coincide with mid-morning and mid-afternoon breaks and should provide an excellent opportunity for close personal interaction with authors of specialized topical subjects. Light refreshments will be served in the Atrium during the poster sessions.

Authors and presenters should submit their manuscripts and presentations to conference staff in the Publications Room, located in the Atrium. Presentations will be loaded on a separate laptop for use during the conference presentations. Technical papers will also be distributed by the publications staff for peer review.

CONFERENCE PROCEEDINGS

A copy of the proceedings containing all of the presented papers will be mailed to each registrant approximately 6 months after the conference. Proceedings will also be available on the internet. Go to http://www.cryocoolers.org for instructions on how to access the proceedings.

SESSION 1: SPACE CRYOCOOLERS I
Wednesday, June 14, 2006 8:00 – 10:00 AM

Co Chairs: Paul Whitehouse, NASA/Goddard Space Flight Center
Saul Miller, The Aerospace Corporation

8:00 An Overview of NASA Space Cryocooler Programs in 2006 [1-106]
R.G. Ross, Jr., Jet Propulsion Laboratory, Pasadena, CA, and R.F. Boyle, NASA Goddard Space Flight Center, Greenbelt, MD

8:15 Cryogenic Refrigeration Systems as an Enabling Technology in Space Sensing Missions [1-43]
T. Roberts and F. Roush, Air Force Research Laboratory AFRL/VSSS, Kirtland AFB, NM

8:30 Thermal/Mechanical System Level Test Results of the GIFTS 2-Stage Pulse Tube Cryocooler [1-77]
S. M. Jensen (1), G. Hansen (1), T. Nast (2), E. Roth(2), and B. Clappier (2)
(1)Space Dynamics Laboratory, North Logan, UT , (2)Lockheed Martin Advance Technology Center, Palo Alto, CA

8:45 Active Cooling for the Advanced Baseline Imager [1-68]
R. F. Boyle, NASA Goddard Space Flight Center, Greenbelt, MD

9:00 Aerospace Cryocooler Selection for Optimum Payload Performance [1-63]
C.S. Kirkconnell, Raytheon Space and Airborne Systems, El Segundo, CA

9:15 Thermal Model for a Mars Instrument with Thermo-Electric Cooled Focal Plane: CCD Subsystem Results [1-49]
D. R. Ladner and J. P. Martin, N-Science Corporation, Arvada, CO

9:30 HIRDLS Cooler Subsystem On-Orbit Performance-A Second Year In Space [1-46]
J. Lock, R. Stack, D. S. Glaister, W. Gully, Ball Aerospace and Technologies Corp, Boulder, CO

SESSION 2: – TACTICAL CRYOCOOLERS & MAGNETIC REFRIGERATION
POSTER SESSION
Wednesday, June 14, 2006 10:00 – 11:00 AM

Co Chairs: Brad Ross, Raytheon Vision Systems
Ir. T. Benschopo, Thales Cryogenics
Peter Shirron, NASA/Goddard Space Flight Center
Dan Hoch, University of Wisconsin

Miniature Pulse Tube Research [2-32]
Y. Luwei, Technical Institute of Physical and Chemistry of CAS, Beijing, China

Pulse Tube Cryocooler for IR Applications [2-64]
I. Ruehlich, M. Mai, J. Petrie and G. Thummes, AIM INFRAROT-MODULE GmbH, Heilbronn, Germany

Microminiature Linear Split Stirling Cryogenic Cooler for Portable Infrared Applications[2-12]
A. Veprik and H. Vilenchik, RICOR, En Harod Ihud, Israel

Gas Bearing Technology for Long Life Tactical Coolers[2-40]
D. T. Kuo, A. S. Loc, and M. Hanes, L-3 Communications Cincinnati Electronics, Pasadena, CA

STI's Next Generation of Cryocoolers[2-80]
A. Fiedler, A. Soto, A. Karandikar, Superconductor Technologies Inc., Santa Barbara, CA

Rotary Stirling Cycle Cooler With Optimized Expander Stroke and Phase[2-30]

U. Bin-Nun, Flir Systems Inc., North Billerica, MA

A Study on the Refrigeration Cycle of Active Magnetic Regeneration[2-87]
S. Kito(1), H. Nakagome(1), T. Kobayashi(2), A.T. Saito(2), H. Tsuji(2)
(1)Dept. of Urban Environment System, Chiba University, Chiba, Japan, (2)Corporate R&D Center, Toshiba Corporation, Kawasaki, Japan

Research of Magnetic Refrigeration Cycle for Hydrogen Liquefaction[2-65]
T. Utaki, K. Kmiya, T. Nakagawa, T. Yamamoto,T. Numazawa, Graduate School of Engineering, Osaka University, Osaka, Japan

Session 2: Continued

Cooling Capabilities of Adiabatic Demagnetization Refrigerators for Space Missions[2-81]
P. Shirron and P. Whitehouse, NASA/Goddard Space Flight Center, Greenbelt, MD

A Study on the Formation of Magnetic Refrigerant $La(Fe,Si)_{13}$ Compounds by Spark Plasma Sintering[2-98]
H. Tsuji, A. T. Saito, T. Kobayashi, S. Sakurada, Corporate R&D Center, Toshiba Corp., Kawasaki, Japan

Hydrogen Liquefaction by Magnetic Refrigeration[2-41]
K. Kamiya, T. Numazawa and H. Takahashi, National Institute for Materials Science, Ibaraki,Japan

SESSION 3: STIRLING CRYOCOOLERS

Wednesday, June 14, 2006 11:00-12:15 PM

Co Chairs: David Curran, The Aerospace Corporation
Eric Marquardt, Ball Aerospace and Technologies Corporation

11:00 Ball Aerospace Next Generation 2-Stage 35 K Coolers: The SB235 and SB235E [3-48]

V. Kotsubo, D. S. Glaister, W. Gully, P. Hendershott, E. Marquardt, Ball Aerospace & Technologies Corp., Boulder, CO

11:15 Multistage Stirling Cycle Refrigeration Performance Mapping of the Ball SB235 [3-44]

T. Roberts and A. Razani, Air Force Research Laboratory AFRL/VSSS, Kirtland AFB, NM

11:30 Development of Single-Stage Stirling Cycle Cryocooler at ISRO [3-31]

A. Ramasamy, Padmanabhan, C.S.Gurudath, P.P.Gupta, D. R. Bhandari and H. Narayanamurthy, Thermal Systems Group, ISRO Satellite Centre Bangalore, India

11:45 Thermodynamic Comparison on Two Types of Stirling Refrigerators [3-99]

E. C. Luo, Z. H. Wu, W. Dai, and S. F. Li, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China

12:00 A High Frequency Thermoacoustically Driven Thermoacoustic-Stirling Cryocooler [3-100]

E. Luo, W. Dai, S. Zhu, G. Yu, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China

SESSION 4: REGENERATORS

Wednesday, June 14 , 2006 2:00 – 3:00 PM

Co Chairs: Tom Roberts, Air Force Research Laboratory – VSSS
Mostafa Ghiaasiaan, Georgia Institute of Technology

2:00 **Photoetched Regenerator for Use in a High Frequency Pulse Tube** [4-94]

W.F. Superczynski and G.F. Green, Chesapeake Cryogenics, Inc., Arnold, MD

2:15 **Cooling Performance of Multilayer Ceramic Regenerator Materials** [4-61]

T. Numazawa, K. Kamiya, *Y.Hirastuka, *T. Satoh, **H. Nozawa and **T. Yanagitani, National Institute for Materials Science, *Sumitomo Heavy Industries, **Konoshima Chemical Co., Japan

2:30 **Ribbon Regenerator Performance in Single Stage GM Cryocooler** [4-69]

Geoffrey Green and William Superczynski, Chesapeake Cryogenics Inc., Annapolis, MD

2:45 **A Numerical CFD Model for Reciprocating Laminar Flow in a Channel** [4-103]

M. Raizner, I. Garaway and G. Grossman, Faculty of Mechanical Engineering, Technion-Israel Institute of Technology, Haifa, Israel

SESSION 5: PULSE TUBE TECHNOLOGY - COMPONENTS & INTERFACES
POSTER SESSION
Wednesday, June 14, 2006 3:00 – 4:00 PM

Co Chairs: John Pfotenhauer, University of Wisconsin
Alain Ravex, Air Liquide
E. Tward, Northrop Grumman Space Technology

Performance Results of Microplate Heat Exchangers [5-47]
E.D. Marquardt and J. Fryer, Ball Aerospace and Technologies Corporation, Boulder, CO

Investigation of Materials for Long Life, High Reliability Flexure Bearing Springs for Stirling Cryocooler Applications [5-38]
C.J. Simcock, Honeywell Hymatic / University of Birmingham, England

Development and Testing of a Multi-Plate Recuperative Heat Exchanger for Use in a Hybrid Cryocooler [5-72]
D.W. Hoch(1), G.F. Nellis(1), J.R. Maddocks(2), T. Davis(3), (1) University of Wisconsin-Madison Madison, WI, (2) Atlas Scientific San Jose, CA, (3) Air Force Research Laboratory, Kirtland AFB, NM

Development of a Practical Cryogenic Heat Switch [5-6]
M. F. Wang (1,2), J.H. Cai (1), L. W. Yang (1), and J. T. Liang(1)
(1) Technical Institute of Physics and Chemistry, C A S, Beijing , China, (2) Graduate University of Chinese Academy of Sciences, Beijing , China

Comparison Test of Rotary Valve and Solenoid Valves for Single Stage G-M Type Pulse Tube Refrigerator [5-95]
Z. H Gan, Z. H. Zhang, L .M Qiu, and G. B. Chen, Cryogenics Lab., Zhejiang University, Hangzhou, China

A Hybrid Counter-Flow Pulse-Tube Refrigerator [5-55]
W. Liang, M.E. Will and A.T.A.M. de Waele, Department of Applied Physics, Eindhoven University of Technology, The Netherlands

High Capacity Staged Pulse Tube Cooler [5-84]
C. Jaco, T. Nguyen, D. Durand, E. Tward, Northrop Grumman Space Technology (NGST), Redondo Beach, CA

Fluid Flow and Heat Transfer in Pulse Tube in Double-Inlet GM Type Pulse Tube Refrigerators [5-33-]
B. Y. Du(2), L. W. Yang(1), J. H. Cai (1) and J. T. Liang(1), (1)Technical Institute of Physics and Chemistry, Chinese Academic of Sciences, Beijing, China , (2)Graduate University of Chinese Academy of Sciences, Beijing, China

Session 5: Continued

Visualization of Secondary Flow in an Inclined Double-Inlet Pulse Tube Refrigerator [5-21]
M. Shiraishi(1), M. Murakami(2) A. Nakano and T. Iida(3), (1)National Institute of AIST, Ibaraki, Japan; (2)University of Tsukuba, Ibaraki, Japan (3)Orbital-Engineering, Yokohama, Japan

Gravity Effect in a High Frequency Coaxial Pulse Tube Cryocooler [5-15]
X. F. Hou, L. W. Yang, J. H. Cai and J. T. Liang, Technical Institute of Physics and Chemistry ,Chinese Academic of Sciences, Beijing, China

Parametric Study of Stirling Cycle Cryocooler by Using Cyclic Analysis [5-17]

M. M. Lele(1), S.L. Bapat(1), and K. G. Narayankhedkar(1,2), (1) I. I. T. Bombay, Mumbai, India, (2) V.J.T.I. Mumbai, India

Analysis on a Stirling-Type Pulse Tube Refrigerator Considering the Dynamics of a Linear Compressor [5-24]
J. Ko, S. Jeong, Cryogenic Engineering Laboratory, Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea

Development of a Compressor for a Miniature Pulse Tube Cryocooler of 2.5 W at 65 KN [5-35]
M. Y. Yasukawa, K. Ohshima, T. Takeuchi, K. Yoshizawa, T. Matsushita, Y. Mizoguchi and A. Ikura, Fuji Electric Systems Co., Ltd., Tokyo, Japan

SESSION 6: OSCILLATING FLOW COMPONENTS
Wednesday, June 14, 2006   4:00 – 5:30 PM

Co Chairs: Zhihua Gan, Zhejiang University
Ray Radabaugh, NIST

4:00 **Development of a Simple Cryocooler to Provide Remote Cooling for Infrared Astronomy Systems** [6-91]
T. Nast, J. Olson, E. Roth, B. Evtimov, D. Frank, P. Champagne and J. Jensen, Lockheed Martin Space Systems, Palo Alto, CA

4:15 **Characterization of Inertance Tubes Using Resonance Effects** [6-58]
M. A. Lewis, P. E. Bradley, R. Radebaugh and Z. Gan, National Institute of Standards and Technology, Boulder, CO

4:30 **Long Transfer Lines Enabling Large Separations Between Compressor and Coldhead for High-Frequency Acoustic-Stirling ("Pulse-Tube") Coolers** [6-79]
P. S. Spoor and J. A. Corey, CFIC Inc., Troy, NY

4:45 **Evaluation of Total Pressure Oscillator Losses** [6-75]
P. E. Bradley, M. A. Lewis, R. Radebaugh, Z. Gan, and J. Kephart, National Institute of Standards and Technology, Boulder, CO

5:00 **Modified Oil-Lubricated Compressors for Regenerative Cryocoolers by Using a Simple Elastic Membrane** [6-16]
E. Luo, Z. Wu, G. Yu, J. Hu and W. Dai, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China

5:15 **Gas Spring Losses in Linear Clearance Seal Compressors** [6-56]
P.B. Bailey(1), M.W. Dadd(1), J.S.Reed(2), C.R. Stone(1), and T.M. Davis(3)
(1)Department of Engineering Science Oxford University, United Kingdom, (2)Cryogenic Systems Group EADS Astrium Ltd, United Kingdom , (3)Air Force Research Laboratory, Kirtland AFB, NM

SESSION 7: PULSE TUBE MODELING
Thursday, June 15, 2006 8:00 – 10:00 AM

Co Chairs: Peter Kittel, Consultant
Alphons DeWaele, Eindhoven University of Technology

8:00 One-Dimensional Analytical and Numerical Models of the Pulse-Tube Cooler [7-57]
M.A. Etaati, R.M.M. Mattheij, A.S. Tijsseling and A.T.A.M. de Waele, Eindhoven University of Technology, The Netherlands

8:15 A New Type of Streaming in Pulse Tubes [7-54]
W. Liang and A.T.A.M.de Waele, Department of Applied Physics, Eindhoven University of Technology, The Netherlands

8:30 A Model for Parametric Analysis of Pulse Tube Losses in Pulse Tube Refrigerators [7-5]
C. Dodson, A. Razani and T. Roberts, Air Force Research Laboratory, Kirtland AFB, NM

8:45 Comparison of Three Different Configurations of Pulse Tube Cooler [7-2]

W. Dai, E. Luo Z. Guan, C. Bei, Y. Tiao, Technical Institute of Physics and Chemistry, CAS Beijing, China

9:00 Non-Zero Time-Averaged Thermoacoustic Effects, Linear or Nonlinear? [7-14]
E. Luo, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China

9:15 Validation of an Integrated Modeling Tool for the Study of Pulse Tube Coolers [7-67]
A.S. Gibson (1) H. Elmrini (2) D. Nikanpour (1), (1) Canadian Space Agency, Longueuil, Canada (2) MAYA Heat Transfer Technologies Ltd., Montreal, Canada

9:30 The Second-Law Based Thermodynamic Optimization Criteria for Pulse Tube Refrigerators [7-3]
A. Razani, T. Roberts and B. Flake, The University of New Mexico, Albuquerque, NM , Air Force Research Laboratory Kirtland AFB, NM, European Office of Aerospace Research and Development, London, UK

9:45 A Dimensionless Analysis Model of a Regenerator [7-90]
J. Shi, J. Pfotenhauer, and G. Nellis, University of Wisconsin-Madison, Madison, WI

SESSION 8: –REGENERATORS & JOULE THOMSON CRYOCOOLERS POSTER SESSION

Thursday, June 15, 2006 10:00 – 11:00 AM

Co Chairs: Martin Nisenoff. Consultant
Sangkwon Jeong, KAIST
Marcel ter Brake, University of Twente

Numerical Simulation of Regenerator in a Two-Stage Pulse Tube Refrigerator [8-36]
B.Y. Du,(2), L.W. Yang(1), J.H. Cai(1) and J.T. Liang(1); (1) Technical Institute of Physics and Chemistry, Chinese Academic of Sciences, Beijing, China; (2) Graduate University of Chinese Academy of Sciences, Beijing, China

Dynamic Analysis of Oscillating Flow Regenerators [8-29]
H.L. Chen, L.W. Yang , J.H. Cai and J.T. Liang, Technical Institute of Physics and Chemistry, CAS Beijing, China

Results of Tests of Etched Foil Regenerator Material [8-86]
M. P. Mitchell (1), D. Gedeon(2), G. Wood(3), and M. Ibrahim (4); (1) Mitchell/Stirling, Berkeley, CA, (2)Gedeon Assoc., Athens, OH; (3) Sunpower Inc., Athens, OH; (4) Cleveland State University, Cleveland, OH

Hydrodynamic Parameters of Pulse Tube or Stirling Cryocooler Regenerators for Periodic Flow [8-62]
J. Cha, S.M. Ghiaasiaan, P.V. Desai, J. P. Harvey (2) and C.S. Kirkconnell(2); G.W. Woodruff School of Mechanical Engineering Georgia Institute of Technology, Atlanta, GA; (2) Raytheon Space and Airborne Systems, El Segundo, CA

On the Differential and Integral Inversion States of the Joule-Thomson Effect and their Interrelation [8-1]
B-Z. Maytal, Rafael, Ltd. Haifa, Israel

Throttle-Cycle Flow Control Using Shape Memory Alloy [8-74]
J.M. Pfotenhauer(1), A.J. Marconnet(1), and B-Z. Maytal(2), (1)University of Wisconsin – Madison; (2) Rafael, Ltd., Israel

Progress Towards a Low Power Mixed Gas Joule-Thomson Cryocooler for Electronic Current Leads [8-76]
J. F. Pettitt, J. M. Pfotenhauer, G. F. Nellis, and D. W. Hoch, University of Wisconsin, Madison, WI

Session 8: Continued

Metal Hydride Sorbent Beds in the Planck Sorption Cryocooler: Performance, Degradation and Lifetime Issues [8-8]
R. C. Bowman, Jr.(1), J. W. Reiter 2, P. B. Karlmann(1), M. Prina(1); (1) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; (2) Swales Aerospace, Pasadena, CA

A Numerical Study on the Performance of the Miniature Joule-Thomson Refrigerator [8-50]
Y-J Hong, S-J Park and Y-D Choi*, Korea Institute of Machinery and Materials Taejeon, Korea, *Korea University, Seoul, Korea

Compositions Shift of a Mixed-Gases Joule-Thomson Refrigerator Driven by an Oil-Free Compressor [8-10]
M. Gong, Z. Deng and J. Wu, Technical Institute of Physics ,CAS, Beijing, China

Composition Shifts Due to Different Solubility with the Lubricant Oil for Multi-component Mixtures
[8-11]
M. Gong, W. Zhou and J. Wu, Technical Institute of Physics and Chemistry, CAS, Beijing, China

Microfabricated Microchannel Regenerators for Cryocoolers [8-109]
C. Becnel, Mezzo Technologies, Baton Rouge, LA

SESSION 9: MEMS BASED AND MINIATURE CRYOCOOLERS

Thursday, June 15, 2006   11:00 – 12:15 PM

Co Chairs: Willy Gully, Ball Aerospace & Technologies Corp.
Chuck Hannon, AMTI

11:00 Micromachined Regenerator: Pressure Drop and Heat Exchange [9-23]

S. Vanapalli, H. J. M. ter Brake, H. V. Jansen, J. F. Burger, H. J. Holland and M. Elwenspoek, University of Twente, Enschede, Netherlands

11:15 All-Micromachined Joule-Thomson Cold Stage [9-22]
P. P. M. Lerou, H. V. Jansen, J. F. Burger, T. T. Veenstra, H. J. Holland, G. C. F. Venhorst, H. J. M. ter Brake and H. Rogalla, University of Twente, Enschede, Netherlands

11:30 Progress Towards a Micromachined Heat Exchanger for a Cryosurgical Probe [9-66]
D. W. Hoch(1), W. Zhu(2), G.F. Nellis(1), S. A. Klein(1), Y. B. Gianchandani(2); (1)University of Wisconsin, Madison, WI; (2)University of Michigan, Ann Arbor, MI

11:45 CVD Diamond-Based Miniature Stirling Cooler [9-25]
D. E. Patterson (1), K. D. Jamison (1), M. Durrett (1), A. Kashani (2), and D. Gedeon(3), (1) Nanohmics, Inc., Austin, TX, (2) Atlas Scientific, San Jose, CA, (3) Gedeon Associates, Athens, OH

12:00 All-Solid-State Optical Coolers: History, Status, and Potential [9-70]
C. E. Mungan(1), M. I. Buchwald(2), and G. L. Mills(3); (1) Physics Dept, U.S. Naval Academy, Annapolis, MD; (2) Buchwald Consulting, Bethesda, MD; (3) Ball Aerospace & Technologies Corp, Boulder, CO

SESSION 10: SINGLE STAGE PULSE TUBES

Thursday, June 15, 2006 2:00 – 3:30 PM

Co Chairs: Carl Kirkconnell, Raytheon
Ercang Luo, Technical Institute of Physics and Chemistry, CAS

2:00 **A Pulse Tube Cryocooler with 300W Refrigeration at 80K with Operating Efficiency of 19% Carnot** [10-102]
J. H. Zia, Praxair, Inc., Tonawanda, NY

2:15 **Prototyping of a Large Capacity High Frequency Pulse Tube Cryocooler** [10-20]
J. Tanchon(1), T. Trollier(1), A. Ravex(1) and E. Ercolani(2); (1) Air Liquide Advanced Technology Division, AL/DTA, Sassenage, France; (2) CEA/DSM/DRFMC, Service des Basses Temperatures, Grenoble, France

2:30 **Design of a Large Heat Lift 40 to 80 K Pulse Tube Cooler for Space Applications** [10-19]
T. Trollier(1), J. Tanchon(1), J. Buquet, A. Ravex (1), I. Charles(2), A. Coynel(2), L. Dub(2), E. Ercolani(2) L. Guillemet(2), J. Mullie(3), J.Dam(3), T. Benschop(3) and M. Linder(4); (1)Air Liquide Advanced Technology Division, AL/DTA, Sassenage, France; (2) CEA/DSM/DRFMC, Service des Basses Temperatures, Grenoble, France; (3) THALES Cryogenics B.V., Eindhoven, The Netherlands; (4) European Space Agency, ESA/ESTEC, Noordwijk, The Netherlands

2:45 **Sunpower's CPT60 Pulse Tube Cryocooler** [10-73]
K. Wilson(1), D. Gedeon(2) and M. Yoshida(3); (1) Sunpower, Inc., Athens,OH; (2) Gedeon & Associates, Athens, OH; (3) Smach Co. Ltd, Osaka, Japan

3:00 **Pulse Tube Microcooler for Space Applications** [10-85]
M. Petach, M. Waterman, E. Tward and P. Bailey(1), Northrop Grumman Space Technology (NGST) Redondo Beach, CA; (1)Department of Engineering Science, University of Oxford, UK

3:15 **Proposed Rapid Cooldown Technique for Pulse Tube Cryocoolers** [10-93]

R. Radebaugh, A. O'Gallagher, M.A. Lweis, and P.E. Bradley, National Institute of Standards and Technology, Boulder, CO

SESSION 11: SUB 10K SPACECOOLERS
Friday, June 16, 2006 8:00 – 9:30 AM

Co Chairs: Ron Ross, Jet Propulsion Laboratory
Ted Nast, Lockheed Martin Missiles & Space

8:00 Successful Qualification of the First PFM Model Space Dilution Refrigerator [11-39]
S. Triqueneaux(1), J. Delmas(1), P. Camus(2) and G. Guyot(3); (1) Air Liquide/DTA (2) CNRS/CRTBT; (3) IAS

8:15 Development of 4K-Class Mechanical Cooler for SPICA [11-96]
S. Tsunematsu, Sumitomo Heavy Industries, Niihama Ehime, Japan

8:30 Ball Aerospace 4-6 K Space Cryocooler [11-45]
D. S. Glaister, W. Gully, R. Ross, P. Hendershott, E. Marquardt, V. Kotsubo, Ball Aerospace and Technologies Corporation, Boulder, CO

8:45 NGST Advanced Cryocooler Technology Development Program (ACTDP) Cooler System [11-82]
D. Durand, R. Colbert, C. Jaco, M. Michaelian, T. Nguyen, M. Petach, and E. Tward, Northrop Grumman Space Technology (NGST) Redondo Beach, CA

9:00 Vibration Free 4.5 K Sorption Cooler [11-53]
J.F. Burger, H.J. Holland, G.C.F. Venhorst, R.J. Meijer, T.T. Veenstra, H.J.M. ter Brake, H. Rogalla, P. M.Coesel(1), D. Lozano-Castello (2), A. Sirbi (3); University of Twente, The Netherlands; (1) Dutch Space, The Netherlands; (2) University of Alicante, Spain; (3) ESA-ESTEC, The Netherlands

9:15 Flight Acceptance Testing of the Two JPL Planck Sorption Coolers [11-4]

D. Pearson(1), B. Zhang(1) M. Prina(1), C. Paine(1) G. Morgante, P. Bhandari(2), R. Bowman(2) and A. Nash(2); (1)Jet Propulsion Laboratory California Institute of Technology, Pasadena, CA; (2) INAF/ISAF-Sezione, Bologna, Italy

SESSION 12: CRYOCOOLER APPLICATIONS POSTER SESSION

Friday, June 16, 2006 9:30 – 11:00 AM

Co Chairs: William Superczynski, CCI
Toru Koriyama, Toshiba Corp.
Mark Zagarola, Creare Inc.

Optimal Control Strategies for a Rectified Continuous Flow Loop Interfaced with a Distributed Load [12-28]
D. Hoch; H. Skye(1), Greg Nellis(1), S.Klein(1), J. Maddocks(2); (1) Cryogenic Engineering Lab University of Wisconsin, Madison, WI; (2) Atlas Scientific, San Jose, CA

Cryocooler Performance Estimator [12-9]
Peter Kittel, Consultant, Palo Alto, CA

Multistage Stirling Cycle Refrigeration Performance Mapping of the Northrup Grumman High Capacity Cooler [12-88]
E. Pettyjohn and T. Roberts, Air Force Research Laboratory AFRL/VSSS Cryogenics Laboratory, Kirtland AFB, NM

Development of a Cryocooler System to Provide Zero Boil-Off of a Propellant Tank [12-97]
D. Frank, E. Roth, B. Sompayrac, J. Olson and T. Nast, Lockheed Martin Space Company, Palo Alto, CA

G-M Type Two-Stage Pulse Tube Cryocooler for Cryopump [12-52]
S-J Park, Y-J Hong and H-B Kim, Korea Institute of Machinery & Materials, Daejeon, Korea

Helium-Liquefaction by Cryocooler for High-Field Magnets Cooling [12-71]

Y-S. Choi, D-L. Kim, B-S. Lee, H-S. Yang, T. A. Painter, A. J. Trowell, and J. R. Miller, KBSI-NHMFL RCC, Tallahassee, FL

Air Force Research Laboratory Space Cryogenic Technology Research Initiatives [12-42]
F. Roush and T. Roberts, Air Force Research Laboratory, AFRL/VSSS, Kirtland AFB,NM

Session 12: Continued

Development of a 0.5W/40K Pulse Tube Cryocooler for Infrared Detector [12-7]
G. P. Wang(1,2), J. H.Cai(1), Ning Li(3), Wei.Jing(1), L. W.Yang(1), J. T.Liang(1); (1) Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China; (2) Graduate University of Chinese Academy of Sciences, Beijing, China; (3)National Lab. for Infrared Physics, Shanghai Institute of Techinical Physics, Chinese Academy of Sciences, Shanghai, China

Cryogenic Refrigeration Cycle for Re-Liquefaction of LNG Boil-off Gas [12-27]
J. W. Moon(1), Y-.W. Jin(2), Y. P. Lee(1), E-.S. Hong(3) and H. M. Chang(4); (1) Thermal Flow Control Reasearch Center, KIST, Seoul, Korea; (2) School of Mechanical Engineering, Korea University of Technology and Education, Chungnam, Korea; (3) Shinyoung Heavy Industries CO.,LTD., Junnam, Korea; (4) Mechanical System & Design Engineering, Hong Ik University, Seoul, Korea

Development of Detachable Cooling System for HTS Floating Coil [12-104]
T.Kuriyama, Y. Ohtani, T. Tosaka, M. Ono, S. Mizumaki, N. Tachikawa, J. Morikawa, Y. Ogawa, and Z. Yoshida, Toshiba Corporation /University of Tokyo, Japan

Research on Improvement in the Efficiency of the GM Refrigerator [12-92]
H. Nakagome(1) and T. Okamura(2); (1)Department of Urban Environment System, Chiba University, Japan; (2)Department of Energy Sciences, Tokyo Institute of Technology, Japan

Design and Analysis of Distributed Cooling Networks [12-89]
J.R. Feller(1), P. Kittel(2), A. Kashani(3), B. Helvensteijn(3) and L.J. Salerno(1); (1) NASA-Ames Research Center, Moffett Field, CA; [(2) University of California, University Affiliated Research Center, Moffett Field, CA; (3) Atlas Scientific, San Jose, CA

SESSION 13: STEADY FLOW SYSTEMS AND COMPONENTS
Friday, June 16, 2006 11:00 – 12:15 PM

Co Chairs: Peter Gifford, Cryomech, Inc.
Peter Kerney, Consultant

11:00 Modeling, Development and Testing of a Small-Scale Collins Type Cryocooler [13-26]
C.L.Hannon, B.Krass and J. Gerstmann(1) G.Chaudhry, J.G.Brisson and J.L. Smith Jr.(2)
(1)Advanced Mechanical Technology, Inc., Watertown, MA, (2)Massachusetts Institute of Technology, Cambridge, MA

11:15 Demonstration of a Novel Brayton Cycle Cryogenic Expander [13-105]

S. Nieczkoski, B. Nguyenphu, D. Petrick and R. Mohling, Technology Applications Inc. Boulder CO

11:30 A Recuperative Heat Exchanger for Space-Borne Turbo-Brayton Cryocoolers [13-78]
R. W. Hill and M. V. Zagarola, Creare Incorporated, Hanover NH

11:45 Thermoacoustic Expansion Valve: A New Type of Expansion Component to Enhance Performance of Recuperative Cryocooler Systems [13-59]
Z. Hu, CryoWave Advanced Technology, Inc., Pawtucket, RI

12:00 Carbon Dioxide Flash-Freezing Process Applied to Ice Cream Production [13-108]
T. Baker, J.G Brisson and J.L. Smith, Jr.
Massachusetts Institute of Technology, Cambridge, MA

SESSION 14: MULTI STAGE PULSE TUBES

Friday, June 16, 2006 2:00– 3:30 PM

Co Chairs: Takenori Numazawa, Tsukuba Magnet Laboratory CHECK BOTH chairs
Gunther Thummes, Transmit GmbH

2:00 **A Novel Three-Stage 4 K Pulse Tube Cryocooler** [14-37]
C. Wang, Cryomech, Inc., Syracuse, NY

2:15 **Free Third Stage Cooling for Two Stage 4K Pulse Tube** [14-18]
A. Ravex and T. Prouve, Air Liquide, Division Techniques Avancees B.P.15, Sassenage, France

2:30 **Compact Two-Stage Pulse Tube Refrigerator in Coaxial Configuration Reaching Temperatures Below 7 K** [14-51]
T. Koettig, R. Nawrodt, M.Thuerk, and P. Seidel, Friedrich-Schiller Universitaet Jena, Institut fuer Festkoerperphysik, Jena, Germany

2:45 **10K Pulse Tube Cooler** [14-83]
T. Nguyen, R. Colbert, D. Durand, C. Jaco, M. Michaelian and E. Tward, Northrop Grumman Space Technology (NGST), Redondo Beach, CA

3:00 **Investigation of Two-Stage High Frequency Pulse Tube Cryocoolers** [14-13]

L. W. Yang(1), M. G. Zhao(1), M. Dietrich(2), J. T. Liang(1), Y. Zhou(1) and G.Thummes(2);
(1) Technical Institute of Physical and Chemistry, CAS, Beijing, China, (2) Institute of Applied Physics, University of Giessen, Giessen, Germany

3:15 **A Thermoacoustically Driven Pulse Tube Cooler Working Below 20K** [14-101]
J.Y. Hu, E.C. Luo and W. Dai, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China

An Overview of NASA Space Cryocooler Programs in 2006 [1-106]

R.G. Ross, Jr.
Jet Propulsion Laboratory
Pasadena CA
R.F. Boyle
NASA Goddard Space FlightCenter
Greenbelt MD

Mechanical cryocoolers represent a significant enabling technology for NASA's Earth and Space Science Enterprises. An overview is presented of ongoing cryocooler activities within NASA in support of current flight projects, near-term flight instruments, and long-term technology development. NASA programs in Earth and space science observe a wide range of phenomena, from crop dynamics to stellar birth. Many of the instruments require cryogenic refrigeration to improve dynamic range, extend wavelength coverage, and enable the use of advanced detectors. Although, the largest utilization of coolers over the last decade has been for instruments operating at medium to high cryogenic temperatures (55 to 150 K), reflecting the relative maturity of the technology at these temperatures, important new developments are now focusing at the lower temperature range from 6 to 20 K in support of studies of the origin of the universe and the search for planets around distant stars. NASA's development of a 20K cryocooler for the European Planck spacecraft and a 6K cryocooler for the James Webb Space Telescope (JWST) are examples of the thrust to provide low temperature cooling for this class of missions.

Cryogenic Refrigeration Systems as an Enabling Technology in Space Sensing Missions [1-43]

T. Roberts and F. Roush
Air Force Research Laboratory
Kirtland AFB, NM

Infrared (IR) space sensing missions of the future depend on low mass, highly capable imaging technologies. Limitations in visible imaging due to the earths shadow drive the use of IR surveillance methods for a wide variety of applications for Intelligence, Surveillance, and Reconnaissance (ISR) or for Ballistic Missile Defense (BMD) applications. Utilization of IR sensors greatly expands and improves mission capabilities including target discrimination and target behavioral discrimination. Background IR emissions and electronic noise that is inherently present in Focal Plane Arrays (FPAs) and surveillance optics bench designs obviates their use unless they are cooled to cryogenic temperatures. This paper describes the role of cryogenic coolers as an enabling technology for generic ISR and BMD missions and provides ISR and BMD mission and requirement planners with a brief glimpse of this critical technology implementation potential. Practical alternatives to active refrigeration systems for certain mission types are also described. The interaction between cryogenic refrigeration component performance and the IR sensor optics and FPA can be seen as not only mission enabling but also as mission performance enhancing when the refrigeration system is considered as part of an overall optimization problem.

Thermal/Mechanical System Level Test Results of the GIFTS 2-Stage Pulse Tube Cryocooler [1-77]

S. M. Jensen , G. Hansen
Space Dynamics Laboratory
North Logan, UT
T. Nast, E. Roth, B. Clappier
Lockheed Martin Advance Technology Center
Palo Alto, CA

The Space Dynamics Laboratory (SDL), in partnership with NASA Langley Research Center is building the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument. The GIFTS focal plane assemblies (FPAs) must operate below 60 K to work properly. The aft optics and interferometer of the instrument must operate below 150K. These two temperature zones will be cooled by a 2-stage pulse tube cryocooler built by Lockheed Martin. This cryocooler was designed to cool 1.5 watts at 55 K and 8.0 watts at 140 K with a 300 K reject temperature. System power consumed was to be less than 160 watts. SDL recently completed system level testing of the 2-stage cryocooler integrated into the GIFTS system. The thermal performance of the cryocooler as well as mechanical vibration characteristics observed during these tests will be presented. Preliminary analysis of the thermal data shows that cooling performance was achieved on both stages of the cryocooler with adequate thermal margin. Mechanical vibrations from the cryocooler were also found to be sufficiently low in that the perturbations did not prevent the instrument from meeting NESR requirements. This paper will discuss the effects of the cryocooler vibration on the performance of the GIFTS interferometer, which is highly susceptible to even the smallest vibration inputs. This paper will also discuss the thermal performance data obtained during these tests.

Active Cooling for the Advanced Baseline Imager [1-68]

R. F. Boyle
NASA/GSFC
Greenbelt, MD

The Advanced Baseline Imager (ABI) is being developed for use on the next generation of Geostationary Operational Environmental Satellite (GOES-N) spacecraft. A redundant pair of two-stage pulse tube cryocoolers will be used to operate the ABI mid and long-wave IR detectors at 60K, with the visible and near-IR detectors operating near 200K. The cooler housing will be mechanically decoupled from the detector housing, with a set of flexible aluminum foil straps for thermal coupling. The NGST cooler electronics employs a single axis vibration cancellation scheme (in the compressor axis) to minimize exported forces from the cooler. Exported forces depend on the efficacy of the cryocooler electronics cancellation and cryocooler power. There are some uncertainty regarding the precise relation of cryocooler power and exported forces. GOES-R is currently seeking to measure exported forces using an NGST single axis HEC cryocooler and to characterize the relationship. We hope to go forward with this test and report our findings.

SESSION 1: SPACE CRYOCOOLERS I

Wednesday, June 14, 2006 8:00 – 10:00 AM

Aerospace Cryocooler Selection for Optimum Payload Performance [1-63]

C.S. Kirkconnell
Raytheon Space and Airborne Systems
El Segundo, CA

As evidenced by the wide variety of aerospace cryocooler designs presently deployed in space and in development for future deployment, widely variable payload requirements drive the need for a broad selection of cryocooler types and sizes. Reverse Brayton, Stirling, pulse tube, and Joule-Thomson are the most common types, along with hybrid combinations of these, such as the Raytheon Stirling / Pulse Tube Two-Stage (RSP2) line of cryocoolers. Each of these types embodies its own unique advantages, the relevance and importance of which are strongly payload-dependent functions. Operating temperatures, heat loads, number of refrigeration stages, payload physical configuration, and maximum allowable emitted vibration are examples of key payload requirements that drive the selection of the optimum cryocooler type and size. Another critical factor is procurement cost, particularly for the emerging class of "responsive space" infrared sensors requiring cryogenic refrigeration. This paper discusses the strengths and weaknesses of the various cryocooler types, how these characteristics can be aligned for the user's greatest advantage against the payload requirements, and how Raytheon is addressing this broad requirements space through our various development activities. The maturity and development status of Raytheon Stirling, pulse tube, and turbo Brayton (collaborative with Creare) cryocoolers and hybrid combinations of these is discussed.

Thermal Model for a Mars Instrument with Thermo-Electric Cooled Focal Plane: CCD Subsystem Results [1-49]

D. R. Ladner and J. P. Martin
N-Science Corporation
Arvada, CO

The Mineral Identification and Composition Analyzer (MICA) is a miniature instrument that employs X-ray scattering and visual imaging to determine nondestructively the mineralogy of a rock sample in-situ. Results for the System Thermal Model, including one special case for the CCD Subsystem Model, were previously reported. The CCD subsystem comprises the CCD focal plane, the thermoelectric cooler (TEC), the TEC heat sink, a passive heat switch, and the subsystem radiator. The TEC is used to hold the CCD focal plane at or below 208 K during instrument operation. The inclusion of the heat switch and TEC are found to significantly extend instrument observation times and to enable schedule flexibility during extreme Martian diurnal temperature excursions, including atmosphere (~175 K to 255 K), sky (~130 K to 200 K), and convection (wind) effects. The CCD Subsystem Model includes all parasitic and dissipative heat sources, such as heat leaks from MICA electronics, CCD and TEC dissipation during active status, and parasitic heat loads to the focal plane and heat sink. The model incorporates logic that allows the heat switch to provide heat sink cool-down by night and isolation by day if a sufficient temperature difference exists between the radiator and the sink, which must not exceed 258 K for efficient cooler performance. Model parameter variation allows the instrument designer to optimize the subsystem thermal capacities and thermal resistances to minimize input power to the TEC and maximize instrument observation periods. This paper extends previous results to include various combinations of the heat switch status (open / closed), the TEC status (active / inactive), and the ambient environmental condition (warm / cold), for various input parameters.

HIRDLS Cooler Subsystem On-Orbit Performance-A Second Year In Space [1-46]

J. Lock, R. Stack, D. S. Glaister and W. Gully
Ball Aerospace & Technologies Corporation
Boulder, CO

This paper describes the HIRDLS (High Resolution Dynamic Limb Sounder) Cryocooler Subsystem and its on-orbit flight performance. The HIRDLS Instrument was launched on July 15, 2004 as part of the NASA GSFC EOS Aura platform. Ball Aerospace provided the Cryocooler Subsystem (CSS) which included the long life Stirling cryocooler (cooling at 57 K), cold plumbing to connect the cooler to the instrument Detector Subsystem, an ambient radiator to reject the cooler dissipation, and a vacuum enclosure system that enabled bench top ground testing. As of January 2006, the cooler subsystem has over 12,000 of continuous operation with performance that exceeds requirements. Of note is that the cryogenic and cooler subsystem has experienced no change in performance including no indication of external contamination related degradation that has been evident on several other cooler space flights. This steady performance can be attributed to the MLI based insulation design which will be described in the paper. The HIRDLS mission has had an instrument anomaly in which Kapton is blocking the aperture. The undegraded performance provided by the CSS has allowed the development of operational and data processing techniques to alleviate this issue resulting in 75-80% of the science mission.

Miniature Pulse Tube Research [2-32)

Y. Luwei
Technical Institute of Physical and Chemistry of CAS
Beijing, China

High frequency pulse tube coolers have gained great progress in the past ten year. In this research, coaxial structure is the most attractive version to customers because its structure is just like that of normal Stirling cold finger. For some application such as military, not only coaxial structure but the diameter of PTC cold finger is also an important parameter; and very small diameter such as 6mm is needed. This has been introduced in one of Dr. Radebaugh's paper and there were some simulation and test for such a dimension like BAE. For high frequency coaxial PTC research, pulse tube research group at Technical Institute of Physical and Chemistry, former Cryogenic Lab, has gained much progress. One dia.7mm coaxial PTC has been finished with good performance. Now we have make dia.9mm co-axial PTC for actual application and the performance is enough for customer. In this paper, we are going to introduce our design and test of dia.6mm coaxial PTC. Based on our performance evaluation program, we have finished the design. According to simulation, the temperature could be lower that 60K with 30W input power and more than 0.4W cooling power could be gained. We hope it could provide the cooling of 0.1-1W/80K. Detail results about simulation and future test will be introduced in the paper.

Pulse Tube Cryocooler for IR Applications [2-64]

I. Ruehlich, M. Mai, J. Petrie and G. Thummes
AIM INFRAROT-MODULE GmbH
Heilbronn, Germany

AIM has developed in co-operation with TransMIT a coax-pulse tube cooler with cooling capacities ranging from about 0.8W to 3W @80K, depending on the type compressor. Carnot efficiencies of up to 10% are achieved. The outer diameter is about 14mm. A split configuration was chosen to be compatible to typical IR requirements. General design aspects, performance data and specific design requirements for compatibility with IR applications will be presented. Recent improvements include adaptations to smaller compressors with lower input power and the operation at higher operating frequency with typical miniature cryocoolers. AIM has also developed an Integrated Detector Cooler Assembly (IDCA) based on the pulse tube coldfinger. This PT design is foreseen for high reliability IR applications and also for space applications with AIM IR detectors, when operated with a flexure bearing compressor. Technical issues like implementation of customer specific coldfinger top material, adaptation of warm end to customer specific dewar design, solution for adaptation of IR-Detector, size and location of buffer volume etc. will be discussed.

Microminiature Linear Split Stirling Cryogenic Cooler for Portable Infrared Applications [2-12]

A. Veprik and H. Vilenchik
RICOR
En Harod IHUD, Israel

New tactics for carrying out military and antiterrorist operations call for the development of modern combat technologies where surveillance, reconnaissance, targeting and navigation rely upon sophisticated portable infrared (IR) imagers. The superior performance of such imagers is achieved by using high-end optronic technologies along with cooling the IR focal plane arrays (FPA) down to liquid nitrogen temperatures (77K) using closed cycle Stirling cryogenic engines, possessing a long life expectancy, as well as being compact and light mechanical devices, consuming little electrical power and producing no aural noise and vibration export. Traditionally, integral rotary coolers are used for maintaining the FPA of the portable IR imagers at optimal cryogenic temperature. As compared to their off-the- shelf available linear rivals they are lighter, more compact and normally consume less electrical power. However, they are inherently noisier (especially when mounted directly upon the camera optical bench or enclosure), have a limited life-time and, due to the oscillations of the gasodynamic torque, produce high low-frequency vibration export affecting the line of sight stability. Recent technological advances initialized industrial development of a new generation of high- performance IR detectors enabling higher operating temperatures in the region of 90-110K. This, in turn, necessitated the development of low-power micro-miniature cryogenic coolers. However, on this occasion, because of their inherently lower idle losses (as compared to the rotary drive) and the availability of highly efficient "moving magnet" linear motors, linear cryogenic coolers appear to have superior performance. The author reports on the development of a novel Ricor model K527 micro-miniature split Stirling linear cryogenic cooler designed especially for portable infrared imagers. From experimentation, such a long-life cryocooler has better electromechanical and thermo-dynamical performance, is smaller, lighter and has an essentially better noise and vibration signature as compared to the best examples of similar integral rotary coolers.

Gas Bearing Technology for Long Life Tactical Coolers [2-40]

D. T. Kuo, A. S. Loc, and M. Hanes
L-3 Communications Cincinnati Electronics, Pasadena, California

L-3 Communications is investigating gas bearing technology to extend life of tactical coolers into the range that is typically associated with strategic space coolers. This paper discusses the interim progress towards that goal.

STI's Next Generation of Cryocoolers [2-80]

A. Fiedler, A. Soto and A. Karandikar
Superconductor Technologies Inc.
Santa Barbara, CA

STIs Next Generation of Cryocoolers Andreas Fiedler, Arturo Soto, Abhijit Karandikar Superconductor Technologies Incorporated (STI) Santa Barbara, CA 93111 Superconductor Technologies Incorporated (STI) has developed 2 new coolers using its current, highly reliable, field proven Sapphire cooler design as their baseline. The first was developed for the next generation of the SuperLinkTM product family. It was part of on-going cost reduction programs at STI, which are necessary to compete in the highly competitive wireless market The new cost targets dictated a complete revision of STIs cooler design. An analysis showed that major changes to some of the existing cooler components were necessary to reduce the cooler production costs significantly. The second cooler is a 2.6 Watt version designed for applications which demand high reliability and performance in a small package. It was developed as part of a DOD program. The paper describes the development results regarding new technologies chosen by STI for realizing these cost optimized, reliable, high performance cryocoolers. It discusses the tradeoff between cost reduction and performance, in comparison to Sapphire of which over 5000 units have been deployed since 1999.

Rotary Stirling Cycle Cooler With Optimized Expander Stroke and Phase [2-30]

Uri Bin-Nun
Flir Systems Inc.
North Billerica, MA

FLIR Systems developed a displacer drive system which is fundamentally different and is a hybrid of both the common pneumatic and positive mechanical drive. A cable and pulley system drive mechanism with one end coupled to the drive crank and the other end to the displacer base. The displacer is spring loaded against a hard stop at a certain threshold load. The displacer pulled by the cable toward the crank assisted by the working gas pressure pulse during the expansion cycle. During the compression and precooling portion of the cycle the spring energized displacer movement is made possible by a spring and the gas pressure. By careful selection of the spring and the preload amount the gas pressure can be made to overcome the spring and begin expansion at the most desired phase. A detailed description of this device combined with test results will be presented.

SESSION 2: – TACTICAL CRYOCOOLERS & MAGNETIC REFRIGERATION
POSTER SESSION 1
Wednesday, June 14, 2006 10:00 – 11:00 AM

A Study on the Refrigeration Cycle of Active Magnetic Regeneration [2-87]

S. Kito, H. Nakagome
Dept. of Urban Environment System, Chiba University
Chiba, Japan
T. Kobayashi, A.T. Saito, H. Tsuji
Corporate R&D Center, Toshiba Corporation
Kawasaki, Japan

In recent years, the study of magnetic refrigeration techniques based on the magnetocaloric effect (MCE) have been the focus of much attention due to its potential technological applications such as high cooling performance and environment-friendly cooling system without chlorofluorocarbons. Especially, a new type of refrigeration cycle, the Active Magnetic Regeneration (AMR) cycle, makes it possible to attain high efficiency and wide temperature spans. A rotary magnetic refrigerator of AMR type using permanent magnets instead of superconducting magnets has been demonstrated advantages of practical applications in compact design and its performance [1]. However, there are a few reports on the AMR, and the AMR cycle has been not fully discussed. In the AMR refrigeration cycle, control of the heat exchange between the magnetic refrigerant and heat transfer fluid or between refrigerant themselves is one of most important problems. In this paper, we present a design of magnetic refrigerant and discuss the heat exchanges mentioned above in AMR cycle, in view of the MCE profile of magnetic refrigerant, the heat capacity and thermal conductivity of the magnetic refrigerant or the heat transfer fluid, the shape and size of the magnetic refrigerant, in the case of some magnetic refrigerants of Gd-R alloys with different Curie temperatures. In practically, sphere is a suitable shape of the magnetic refrigerant for the AMR, because it can be easily controlled heat exchange area and packing density with varying particle size. In this presentation, the temperature span of the magnetic refrigerants between at the cold end and the hot end in AMR cycle using Gd-R alloys refrigerants will be described.

Research of Magnetic Refrigeration Cycle for Hydrogen Liquefaction [2-65]

T. Utaki, K. Kmiya, T. Nakagawa, T. Yamamoto and T. Numazawa
Graduate School of Engineering, Osaka University
Osaka, Japan

For upcoming the hydrogen society, there are several technological key issues such as hydrogen generation, liquefaction, storage and transportation. Magnetic refrigeration systems based on the magnetocaloric effect involve intrinsically higher energy efficiency than conventional refrigeration systems at cryogenic temperatures, so they attract the attention as hydrogen liquefaction method. However, there is little report that faithfully calculates the refrigeration performance of the magnetic refrigeration as a hydrogen liquefier. So, we have evaluated system parameters required for optimum design of magnetic refrigerator and estimated the coefficient of performance of it by a numerical simulation. We have constructed a model of hydrogen magnetic refrigerator which consisted of multi-stage active magnetic regenerative (AMR) cycle. In our current model, an ideal magnetic material with constant magnetocaloric effect is employed as magnetic working substance. Maximum applied field is 5 T. Liquid hydrogen production rate is 0.01 t/day. When hydrogen assumed to be cooled from liquid nitrogen temperature (77 K), four separate stages are needed. The result of the simulation shows that magnetic refrigerator for hydrogen liquefaction is possible more efficient than conventional liquefaction methods. There are several models to realize the magnetic liquefaction cycles starting from room temperature (300 K) and liquid natural gas temperature (120 K).We will show trial results on efficiency and cooling power.

Cooling Capabilities of Adiabatic Demagnetization Refrigerators for Space Missions [2-81]

P. Shirron and P. Whitehouse
NASA/Goddard Space Flight Center
Greenbelt, MD

With recent advances in mechanical cryocoolers and adiabatic demagnetization refrigerators (ADR), it will soon be possible to construct a cooler that operates at any temperature down to the millikelvin regime. Most instruments will require the cooler to provide different temperatures for various components like detectors, amplifiers, telescopes, etc., and the stages that provide this cooling must have certain minimum cooling powers and temperature stability. While it is believed that any set of cooling requirements can be met, doing so may require changes to the ADR/cryocooler configuration, reoptimization of each system, and even additional technology development. This paper will present an assessment of state-of-the-art ADRs and cryocoolers in terms of temperature and cooling power capabilities, including limitations of present systems and technology developments that may be needed to meet an arbitrary set of requirements.

A Study on the Formation of Magnetic Refrigerant $La(Fe,Si)_{13}$ Compounds by Spark Plasma Sintering [2-98]

H. Tsuji, A. T. Saito, T. Kobayashi and S. Sakurada
Corporate R&D Center, Toshiba Corp.
Kawasaki, Japan

Magnetic refrigeration using permanent magnets is attractive as an alternative cooling technology to conventional gas-compression cycle refrigeration. Recently, Fe-based compounds with a cubic NaZn13- type structure such as La(Fe,Si)13 have been proposed as suitable for the magnetic refrigeration application in view of their large magnetic entropy change in low magnetic fields. However, long annealing time (10days to 1 month) is necessary to form a NaZn13-type structure because the coarse α-Fe is likely to segregate in the arc-melted bulk alloys. That is, the course α -Fe dendrites make the formation of a NaZn13-type structure slows because of long range diffusion of the elements. The dendrite width of the α -Fe phase is estimated about 10-30 μm. In this presentation, we study on the formation of a NaZn13-type structure by the solid state reaction of fine elemental powder using the spark plasma sintering (SPS) technique. It is noted that we use the elemental powder which have smaller particle size (3-5μm) than that of the dendrite width of α -Fe phase in the arc- melted bulk alloy. From the XRD analysis and the microstructure analysis, a NaZn13-type phase was observed remarkably in a sample fabricated by SPS, whereas some amount of La-rich phase and α;-Fe phase were also detected. These results indicate that the homogenous distribution of the elements and short range atomic diffusion are important to form a NaZn13-type structure efficiently. The solid state reaction of the fine elemental powder using the SPS technique leads to rapid formation of a NaZn13-type structure compared with the conventional annealing for the arc-melted bulk alloy.

Hydrogen Liquefaction by Magnetic Refrigeration [2-41]

K. Kamiya, T. Numazawa and H. Takahashi
National Institute for Materials Science
Ibaraki Japan

For hydrogen infrastructure aiming at fuel cell society, development of hydrogen liquefaction technology is urgent necessity. Among several techniques, magnetic refrigeration is considered most promising method. NIMS and Kanazawa University have been designing and building hydrogen magnetic refrigerator (HMR) reaches 20K and liquefies the hydrogen. Magnetic refrigeration makes use of magneto-carolic effect and the HMR originally came up as substitute for conventional mechanical coolers since the HMR essentially has better cooling performance around this temperature range. Aiming at practical cooling power requirement, we have been developing a test machine to evaluate performance as a first step. Our first model, subsequently, aims at 5W, which is the maximum cooling power with GM refrigerator at 20K. This study describes basic concept of our experimental set-up, measurement and numerical simulation for comparison. HMR consists of 2 stages, a precooling stage and a liquefaction stage. Kanazawa University is in charge of the precooling stage cools from N2 temperature (77K) down to H2 liquefaction temperature (20K) removing sensible heat. NIMS in charge of a liquefaction stage works at 20K removing latent heat. Liquefaction stage is called ADR (adiabatic demagnetization refrigeration) stage because psudo Carnot cycle is made use of. In the framework of our design of engineering ADR stage, a magnetic material goes in and out of 6 tesla magnetic field to generate magnetocaloric effect. In the first experiment, cooling performance is planned to be measured precisely, then hydrogen liquefaction will be confirmed in the next phase. These detailed measurements will be announced in the conference. HMR consists of 2 stages, a precooling stage and a liquefaction stage. Kanazawa University is in charge of the precooling stage cools from N2 temperature (77K) down to H2 liquefaction temperature (20K) removing sensible heat. NIMS in charge of a liquefaction stage works at 20K removing latent heat. Liquefaction stage is called ADR (adiabatic demagnetization refrigeration) stage because psudo Carnot cycle is made use of. In the framework of our design of engineering ADR stage, a magnetic material goes in and out of 6 tesla magnetic field to generate magnetocaloric effect. In the first experiment, cooling performance is planned to be measured precisely, then hydrogen liquefaction will be confirmed in the next phase. These detailed measurements will be announced in the conference. HMR consists of 2 stages, a precooling stage and a liquefaction stage. Kanazawa University is in charge of the precooling stage cools from N2 temperature (77K) down to H2 liquefaction temperature (20K) removing sensible heat. NIMS in charge of a liquefaction stage works at 20K removing latent heat. Liquefaction stage is called ADR (adiabatic demagnetization refrigeration) stage because psudo Carnot cycle is made use of. In the framework of our design of engineering ADR stage, a magnetic material goes in and out of 6 tesla magnetic field to generate magnetocaloric effect. In the first experiment, cooling performance is planned to be measured precisely, then hydrogen liquefaction will be confirmed in the next phase. These detailed measurements will be announced in the conference.

Ball Aerospace Next Generation 2-Stage 35 K Coolers: The SB235 and SB235E [3-48]

V. Kotsubo, D. S. Glaister, W. Gully, P. Hendershott and E. Marquardt
Ball Aerospace & Technologies Corp.,
Boulder, CO

This paper describes the design, development, testing and performance of the Ball Aerospace SB235 and its model derivative the SB235E; long life, 2-stage space cryocoolers that have been optimized for 2 cooling loads. The SB235 and the SB235E are 2-stage coolers designed to provide simultaneous cooling at 35 K (typically for HgCdTe detectors) and 85 K (typically for optics). The SB235 qualification unit was delivered to AFRL for life testing and has accrued more than 13,000 hours as of 1/15/06. The SB235E is a higher capacity model derivative of the SB235. It is the precooler for a Stirling/Joule- Thomson (J-T) hybrid cooler under development at Ball Aerospace for the DoD 35 K High Capacity Variable Load Cryocooler program. Initial testing of the SB235E has shown performance of 2.49 W at 35 K and 10.3 W at 85 K for 202 W powers. These data equate to Carnot efficiency of 0.222 or about twice that of other published cryocooler data. Mass of the SB235E cooler is 14.4 kg for the compressor and displacer.

Multistage Stirling Cycle Refrigeration Performance Mapping of the Ball SB235 [3-44]

T. Roberts and A. Razani
Air Force Research Laboratory
Kirtland AFB, NM

The performance mapping of a multistage Stirling cycle refrigeration system has been performed on the Ball Aerospace SB235 cryocooler by the Air Force Research Laboratory. The results are presented in terms of primitive variables such as temperature, work inputs, and cooling load supported. It is then restated in terms of composite variables such as available work (exergy) inputs, the individual and composite exergies of the cooling loads supported, and system efficiency. The results of this mapping when stated in terms of these composite variables shows that overall cooling performance follows discernable, distinct paths as external environmental conditions such as work input, rejection temperature, or imposed cooling load change. This composite performance is analogous to how cooling performance of a real single stage refrigerator is determined by its functional performance manifold with respect to these same environmental variables. Further analysis of this performance of the SB235 suggests theoretical approaches to the question of how multistage Stirling refrigeration systems proportion available work to the discrete stages as a function of cooling load temperature, total available work input to the system, and rejection temperature. The data provided by this mapping would therefore form the basis for a theoretical first order model of how practical application environments alter the relative refrigeration performances of multistaged cold ends which now has to be empirically measured or predicatively modeled using high order composite component models.

SESSION 3: STIRLING CRYOCOOLERS
Wednesday, June 14, 2006 11:00-12:15 PM

Development of Single-Stage Stirling Cycle Cryocooler at ISRO [3-31]

A.Ramasamy, Padmanabhan, C.S.Gurudath, P.P.Gupta, D.R.Bhandari and H.Narayanamurthy
Thermal Systems Group, ISRO Satellite Centre
Bangalore, India

For onboard applications, components such as IR Detectors and low noise amplifier devices require cooling to low temperatures ranging from 100K down to within a couple degrees of absolute zero, for which a number of techniques exist. Stirling cycle cryocooler is one of the cooling devices, which can provide cooling capacity of 1watt load at 80K for long life applications has been developed and flight proven by other space agencies. The need of such cooler for Indian satellites was envisaged and development of the same was taken up. Split Stirling cycle cryocooler compressor mounted head to head with single stage expander is developed to meet the requirement of cooling IR Detector of a payload to 80K with 1watt load with less than 30watts input power. The concept of the cryocooler is based on the Oxford type Stirling cycle cryocooler. A Laboratory Model was fabricated, assembled and tested at ISRO Satellite Centre. Detailed performance studies were conducted and have shown that this unit can provide 1watt cooling at 80K for an input power of 47watts.

To improve the performance further, studies were conducted and certain modifications like sizing of regenerator, achieving close clearance seal between piston and cylinder, displacer and cryocylinder are incorporated in the Development Model. With these modifications, the performance has improved considerably. For the same cooling capacity, the input power required by the unit is 25watts. Also, the unit can handle 1watt at 60K for an input power of 43watts. This paper presents the overall system configuration, thermal performance, present status, future plan and conclusions.

Thermodynamic Comparison on Two Types of Stirling Refrigerators [3-99]

E.C. Luo, Z.H. Wu, W.Dai, and S.F. Li
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing, China

The pulse tube type of two-piston Stirling refrigerator can improve the reliability by moving the displacer from cold end to ambient temperature end. More recently, the thermoacoustic-Stirling refrigerator further improves the reliability by eliminating the displacer. The thermoacoustic-Stirling refrigerator uses a traveling-wave loop to help realize Stirling cycle. Both the refrigerators have a pulse tube. By thermodynamic analysis on the two refrigerators, this paper has made the following conclusions. Firstly, though flowing resistance (especially of the regenerator), compliance and inertance effects of different thermodynamic components make contributions to phase shifting of pressure and velocity waves, the pulse tube type of Stirling refrigerator can readily achieve any phase shifting by controlling the displacer, not relying on the flowing resistance of the regenerator. On the contrary, the thermoacoustic-Stirling refrigerator is not able to achieve any phase shifting, and its phase shifting mechanism is passive and somewhat dissipative due to the flowing resistance of the regenerator is necessary for the passive phase shifting. As a result of fact, the pulse tube type of two piston Stirling refrigerator may achieve a higher efficiency by deceasing the flowing resistance of the regenerator, whereas the thermoacoustic- Stirling refrigerator not. Secondly, the standingwave acoustical field in the compression space of the thermoacoustic-Stirling refrigerator is predominant, resulting in smaller power flow for the same pressure wave amplitude and swept volume; in other word, the thermoacoustic-Stirling refrigerator may give smaller cooling power with the same working conditions and component sizes. Typically, the two-piston Stirling refrigerator may be 10% to 30% higher in efficiency and 20%-50% larger in cooling capacity than the thermoacoustic-Stirling refrigerator in efficiency.

A High Frequency Thermoacoustically Driven Thermoacoustic-Stirling Cryocooler [3-100]

E. Luo, W. Dai, S. Zhu, G. Yu
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing, China

A thermoacoustically driven pulse tube cryocooler is expected to be highly reliable due to no any moving parts, showing a good potential applications in aerospace cryogenic cooling. Mature pulse tube cryocoolers usually operate below 100Hz so that previously developed thermoacoustically driven pulse tube cryocoolers are too large and heavy for aerospace cooling. One way to solve this deadlock can be realized by increasing operating frequency of the thermoacoustic heat engine, for instance, up to about 500Hz or even higher. To match the high frequency thermoacoustic pressure wave generator, a high frequency cryocooler is also required to develop. In the paper, a thermoacoustically driven thermoacoustic-Stirling cryocooler operating around 500Hz is studied theoretically and experimentally. Our thermoacoustic-Stirling cryocooler is a traveling-wave thermoacoustic refrigerator with acoustical recovery, mainly including an inertance tube, a compliance cavity, an ambient heat exchanger, a regenerator, a thermal buffer (pulse tube) and a secondary ambient heat exchanger. We choose the thermoacoustic-Stirling refrigerator because it has a higher thermodynamic efficiency over conventional pulse tube cryocoolers. Our thermodynamic design shows that the high frequency thermoacoustic- Stirling cryocooler can achieve a no-load temperature around 60K.On the other hand, a coaxial high frequency thermoacoustic-Stirling heat engine is designed to function as a pressure wave generator. Unlike the thermoacoustic-Stirling cryocooler, the two heat exchangers of the heat engine are elegantly designed to meet the requirement of both high compactness and high heat transfer efficiency. Moreover, a special membrane with a little mass is used to fulfill the functions of Dc-flow suppression and feedback inertance. Both theoretical and experimental work has been done and will be given in details during ICC14.

Photoetched Regenerator for Use in a High Frequency Pulse Tube [4-94]

W.F. Superczynski and G.F. Green
Chesapeake Cryogenics, Inc.
Arnold, MD

To produce refrigeration at 20K in a single stage regenerative cryocooler requires a combination of materials that possess high heat capacity within its operational temperature range. This has typically been accomplished using woven screens made of stainless steel or phosphorous-bronze operating in the 300K to 50K range followed by a packed bed of spheres made of lead or other rare earth material. However, screens and particularly spheres produce high pressure losses within the regenerator. In pulse a tube operating at higher frequencies, (40 to 60Hz) where the pressure ratio is on the order of 1.3, the pressure loss becomes a more significant factor and prevents achieving 20K. Therefore, Chesapeake Cryogenics, Inc. (CCI) is investigating the use of a gap-type regenerator employing both conventional materials and rare earths. The flow channels are created by a photochemical etching process to generate slots in disks. The disks are then stacked in the regenerator aligning the slots to produce parallel channels in the axial direction. The photochemical machining process may provide sufficient dimensional tolerances and repeatability resulting in uniform channels with heat transfer surface area approaching that of screens and spheres. Furthermore, this etching process can be applied to rare earth materials making the disks suitable for use at temperatures below 50K. CCI has performed preliminary test to determine the pressure loss under steady flow conditions, thermal conduction and cryocooler performance using photoetched disks made of phosphorous-bronze and stainless steel to determine their suitability as replacements of screens and spheres. Results of these tests as well as a quantitative analysis of the flow channel geometry are presented.

Cooling Performance of Multilayer Ceramic Regenerator Materials [4-61]

T. Numazawa, K. Kamiya
National Institute for Materials Science
Ibaraki, Japan
Y.Hirastuka, T. Satoh
Sumitomo Heavy Industries
Tokyo, Japan
H. Nozawa, T. Yanagitani
Konoshima Chemical Co.
Kangawa, Japan

Recently we developed the multilayer magnetic regenerator particles consisting of different heat capacity peak temperatures of (GdxTb1-x) 2O2S=GTOS system to cover the higher cooling temperature range above 6 K. This is a very useful method to control the heat capacity of regenerator materials. The heat capacity curve could be controlled easily by changing the magnetic transition temperature and the volumetric ratio of magnetic layers. Our newly developed fabrication method showed that the magnetic layers in the particles were bound firmly with good thermal connection keeping the small size of 0.2 mm in diameter. However, optimum conditions of the heat capacity curves with the concentration x have not been found for 4K cryocoolers. This paper will show recent experimental results for cooling test with 4K GM refrigerator (1 W and 0.1 W at 4.2 K) by using GTOS + GOS magnetic regenerator materials including several types of heat capacity curves controlled by the various volumetric ratio of magnetic layers. Some simulation results also will be reported.

SESSION 4: REGENERATORS

Wednesday, June 14 , 2006 2:00 – 3:00 PM

Ribbon Regenerator Performance in Single Stage GM Cryocooler [4-69]

G. Green and W. Superczynski
Chesapeake Cryogenics Inc.
Annapolis, MD

The need to operate a single stage, regenerative cryocooler near 20K with some significant capacity is of great interest to the high temperature superconductivity industry. One method is to improve the performance of the regenerative heat exchanger. A regenerator was fabricated as a ribbon with embossed ridges across the width of the ribbon and coiled in a jelly- roll configuration. These thin pancakes are then stacked one on top of the other to provide the desired length of the regenerator. Materials used to fabricate these regenerators were Bronze, Lead, and Holmium for high heat capacity at the lower temperatures. Performance of these regenerators was measured using a CTI 350, single stage GM cryocooler and compared to the screen and sphere geometries. Results indicated that the screen geometry performed slightly better than the ribbon, and the ribbon performed better than the spheres. A 13% improvement was measured using a lead ribbon regenerator compared to the lead sphere geometry. The fabrication of the Holmium ribbon proved to be difficult and therefore the increase in performance using Holmium was predicted using REGEN 3. A predicted performance of a Bronze screen/ Holmium ribbon regenerator was compared to the measured performance of a Bronze screen/ Lead sphere regenerator in a single stage GM cryocooler.

A Numerical CFD Model for Reciprocating Laminar Flow in a Channel [4-103]

M. Raizner, I. Garaway and G. Grossman
Faculty of Mechanical Engineering, Technion-Israel Institute of Technology
Haifa, Israel

A CFD solution is presented for the flow and heat transfer in laminar flow in a channel subject to an oscillating pressure difference. An analysis of compressible flow, such as that of Helium, is preceded by that of an incompressible case; the results of the incompressible model have been compared with those of an analytical solution and found to be in excellent agreement. Thus, the analytical model provides a calibration for the numerical one. The CFD solution helps determine the effects of compressibility on the flow and heat transfer. The velocity profiles created by a reciprocating pressure difference are described. The heat transfer has been studied for a situation of a channel with insulated walls and two extreme temperatures at both ends, simulating the conditions of a pulse tube. Temperature profiles are calculated and found to depend on the flow Valensi (Va) number, on the fluids Prandtl (Pr) number, the Eckert (Ec) number and the ratio of tidal displacement to the channel length. The convective axial heat loss was calculated and found to be non-zero despite the periodic nature of the flow. The geometrical effect of a tapered channel is also considered. The results of this study further our understanding of the flow and heat transfer processes occurring in the channel and should help to improved pulse tube design.

Performance Results of Microplate Heat Exchangers [5-47]

E.D. Marquardt and J. Fryer
Ball Aerospace & Technologies Corporation
Boulder, CO

High effectiveness heat exchangers are required for recuperative cycles such as Brayton and Joule-Thomson cryocoolers. System efficiency is greatly improved by higher exchanger effectiveness. An improvement of the effectiveness from 98% to 99% can reduce the input power by 24% for a typical Brayton cryocooler. The compact heat exchangers tested use a parallel plate geometry and could provide mass reductions of up to 80% compared to the most advanced exchangers built today. A new manufacturing method has been developed allowing the use of titanium alloys significantly decreasing mass and volume which is an important advancement particularly for aerospace coolers. We have manufactured and tested the performance of three heat exchangers. The first is a baseline design similar to heat exchangers we have built in the past. The other two use different methods to improve the heat exchanger effectiveness. The heat exchanger effectiveness has been measured, and these experimental results will be presented. While there is still much to be learned to be able to reliably design and build these exchangers, this work shows important improvements in performance from those previously presented.

Investigation of Materials for Long Life, High Reliability Flexure Bearing Springs for Stirling Cryocooler Applications [5-38]

C.J. Simcock
Honeywell Hymatic/University of Birmingham
Worcestershire, England

Flexure bearing disc springs are installed in linear cryocoolers to support the Motor Assembly within the compressor and the displacer within the Stirling Cryocooler. Such spring components are photo-etched in stainless steel. As spring fatigue failure would be critical; time consuming batch tests are performed. Research has been carried out to identify an acceptable factor of safety for the component, establish material mechanical properties and improve understanding of failure and its causes. Operating within a safe limit and inspecting for intolerable defects may remove the need for extended batch testing. In the testing of thin-sheet material; multiple grades of stainless steel were investigated. A superior grade demonstrated improved fatigue properties over the current composition; offering the opportunity of an increased spring stroke and improved cooler efficiencies. Electroformed nickel was found not to be a viable alternative material for high stress applications. Rolling direction of sheet material was investigated. Improved fatigue performances were evident when the component was stressed with the grain running longitudinally. Due to the multi-axial symmetry of the springs, failure was found to occur parallel to rolling direction, in the high stress region at the mid-point of the arm. Inconsistencies were evident between stresses provided from strain gauged components and FEA modelling. The modelling indicated that springs in some product variants are operating at limit. The multiple spring-stack arrangement varied with both movement and stresses experienced by a single component. The etching process was found not to compromise surface finish integrity. However, pits (likely result of etch defect) in test samples have been identified as initiation points for failure.

Development and Testing of a Multi-Plate Recuperative Heat Exchanger for Use in a Hybrid Cryocooler [5-72]

D.W. Hoch, G.F. Nellis
University of Wisconsin-Madison
Madison, WI
J.R. Maddocks
Atlas Scientific
San Jose, CA
T. Davis
Air Force Research Laboratory
Kirtland AFB, NM

Current available crycooler technology operating at sub-10 K load temperatures is too massive and inefficient to be considered for future space-based systems. High vibrations and low reliability often cause these systems to lack the required long-life expectations for space flight hardware. A compact and innovative hybrid crycooler is being developed with the potential to provide a more efficient means of cooling future space-based systems. The cooler directly interfaces a recuperative, reverse-Brayton, low-temperature stage with a regenerative, pulse-tube upper stage. Four components of the PT/RB are critical to its performance: the pulse-tube coldhead, the rectification system, the cryogenic turbine and the high effectiveness recuperator. The focus of this paper will be on the recuperative heat exchanger, which uses chemically etched copper plates interleaved with stainless steel axial conduction barriers. A model of the recuperative heat exchanger is described; the model is used to optimize the geometry subject to constraints associated with fabrication and mass. A sub- scale module was built in order to verify the model and develop the fabrication techniques. The experimentally measured ineffectiveness of the sub-scale module compared favorably with the predicted value. Based on the success of the sub-scale version, two full-scale modules have been fabricated, assembled and tested at the component level. The performance of the full-scale modules is compared with the model prediction.

Development of a Practical Cryogenic Heat Switch [5-6]

M. F. Wang(1,2) J.H. Cai(1), L. W. Yang(1), and J. T. Liang(1)
(1) Technical Institute of Physics and Chemistry, C A S, Beijing, China;
(2)Graduate University of Chinese Academy of Sciences Beijing , China

The cryogenic heat switch, which is one of the key technologies for connecting several cryocoolers in parallel, is mainly used to couple redundant cryocoolers to cryogenic components with minimal parasitic heat load from the off-cryocoolers. Based on comparing the performance of many types of heat switches for aerospace application, a passively operated heat switch devised by Technical Institute of Physics and Chemistry was presented in this paper. The cryogenic heat switch works on the principle of differential thermal expansion which has only three parts. Its total length is between 20mm and 40mm. The performance of switch gap varying from 0.15mm to 0.40mm was studied carefully. The effect of the contact stress on the "on" resistance of heat switch has also been analyzed. In addition, an automatic test platform for long duration life time testing was designed and its reliability was successfully testified by running for 1500 times on/off repetitively. The experimental results obtained from this test platform showed that the heat switch has an "on" resistance of less than 1.1K/W, and an "off" resistance of more than 1410K/W. Furthermore, the device could be kept on "off" condition if it is connected with the off-cryocooler, which is in accord with the unidirectional request for the heat switch during the working process.

Comparison Test of Rotary Valve and Solenoid Valves for Single Stage G-M Type Pulse Tube Refrigerator [5-95]

Z. H Gan, Z. H. Zhang, L. M Qiu and G. B. Chen
Cryogenics Lab., Zhejiang University
Hangzhou, China

Without moving parts at the cold end, pulse tube refrigerators (PTRs) are better than Stirling and G-M cooler in the aspects of reliability. It is important to generate pressure wave for G -M type PTRs. Comparison test on both a rotary valve and a pair of solenoid controlled by a computer to generate the pressure wave in a single stage pulse tube refrigerator setup are carried out in this paper. Both of them could let the cooler down to below 20K.

A Hybrid Counter-Flow Pulse-Tube Refrigerator [5-55]

W. Liang, M. E. Will and A. T. A. M. de Waele
Department of Applied Physics, Eindhoven University of Technology, The Netherlands

Counter-flow pulse tube refrigerators (CFPTR) are a special type of pulse tube refrigerators (PTR). They use two identical PTRs which run in opposite phase. When one PTR is in the charging phase the other one is in the discharging phase. The gases of the two PTRs exchange heat by a counter-flow heat exchanger. Thus HCFPTRs have the possibility of avoiding expensive regenerator materials. In order to provide a low starting temperature for the CFPTR a hybrid system is constructed which consists of two subsystems, one CFPTR and one conventional PTR. The latter is used to precool CFPTR. The two subsystems work independently and have their own running parameters. The results of the first experiments on the hybride system will be described in this paper. Our setup has great potential and improvements will be made to optimize the performance both in cooling power and temperature range.

High Capacity Staged Pulse Tube Cooler [5-84]

C. Jaco, T. Nguyen, D. Durand, E. Tward
Northrop Grumman Space Technology (NGST)
Redondo Beach, CA

The High Capacity Cryocooler (HCC) has been designed to provide large capacity cooling at 35K (2 Watts) and 85 K (18.5 Watts) for space applications in which both cold focal planes and optics require cooling. The compressor is capable of using input powers up to 700 W. The two linear pulse tube cold heads are integrated with the compressor into an integral cryocooler. Flight qualification of this novel cryocooler includes thermal performance mapping over a range of reject temperatures, launch vibration testing, self induced vibration and thermal cycling testing. The Air Force Research Laboratory (AFRL) is conducting a life test of the cooler.

SESSION 5: PULSE TUBE TECHNOLOGY & COMPONENTS & INTERFACES
POSTER SESSION 2

Wednesday, June 14, 2006   3:00 – 4:00 PM

Fluid Flow and Heat Transfer in Pulse Tube in Double-Inlet GM Type Pulse Tube Refrigerators [5-33]

B.Y. Du,(1,2), L.W. Yang(1), J.H. Cai(1), J.T. Liang(1)
(1)Technical Institute of Physics and Chemistry, Chinese Academic of Sciences, Beijing, China (2)Graduate University of Chinese Academy of Sciences, Beijing, China

Pulse tube refrigerators have demonstrated many advantages with respect to temperature stability, vibration, reliability and lifetime among cryocoolers. Double-inlet type pulse tube refrigerators are popular in GM type pulse tube refrigerators. The mass flow rate through the double -inlet is caused by the pressure drop through the regenerator, which improves the performance of pulse tube refrigerator. However, single double-inlet valve may introduce DC flow in refrigerator, which deteriorates the performance of pulse tube refrigerator, so it is crucial to control the DC flow. Experiments and numerical simulations are carried on to investigate the double-inlet characters GM type pulse tube refrigerators. Two parallel-placed needle valves with opposite flow direction named double-valve configuration, instead of single double-inlet valve, are used in our experiment to reduce the DC flow. Without double-inlet operating, the lowest cold end temperature of 30.2K has been obtained while the refrigerator is driven by compressor of 1.1KW power at 1.7Hz. Moreover, a numerical model is made to analyze the characters of double-inlet. The model is based on 2 -dimensional thermodynamic equations for the pulse tube and 1-dimensional ones for the others. The simulation results show the temperature field and velocity field of pulse tube with and without the double-inlet. Double-inlet is a key factor for a double-inlet type pulse tube refrigerators. It is important to understand the characters of double-inlet. Deep research on characters of double-inlet will be very helpful to reveal the mechanics of pulse tube refrigerator.

SESSION 5: PULSE TUBE TECHNOLOGY & COMPONENTS & INTERFACES
POSTER SESSION 2
Wednesday, June 14, 2006 3:00 – 4:00 PM

Visualization of Secondary Flow in an Inclined Double-Inlet Pulse Tube Refrigerator [5-21]

M. Shiraishi), A. Nakano
National Institute of AIST
Ibaraki, Japan
M. Murakami
University of Tsukuba
Tsukuba, Japan
T. Iida
Orbital-Engineering
Yokohama, Japan

An oscillating flow in an inclined double-inlet pulse tube refrigerator was observed to clear the cause for the effect of inclination angle on the performance. Here, the inclination angle of 0° was defined as the angle where the refrigerator was in vertical orientation with the cold end lower. The performance of the refrigerator at 0° was evaluated and the magnitude of DC was adjusted at the optimum level. By changing an inclination angle from 0° to 180°, the performance of the refrigerator was evaluated and the occurrence of the effect was confirmed. Based on the result of the performance, visualization was done at the typical inclination angles of 0°, 60°, 90°, 120°, 150° and 180° by using a smoke-wire flow visualization technique. At the angle of 0°, the gravity-driven convective flow was not induced so that the overall secondary flow in the core region was decreased to almost zero, but the flow near the peripheral wall flowed to the hot end due to the DC flow at the optimum level. At the angle over 60° except at 180°, the velocity in the core region, which went toward the cold end, was increased from almost zero with increasing of angle and the velocity profile deformed from an axisymmetric profile at 0° to an asymmetric one due to the induction of the gravity-driven convective flow. At the angle of 180°, the profiles restored to an axisymmetric profile again, but the velocity in the core region was reached to the maximum velocity due to the induced gravity-driven convective flow. This visualization result proved that the gravity- driven convective flow was induced as the secondary flow in the inclined double-inlet pulse tube refrigerator and the flow was the cause for the effect of inclination angle.

Gravity Effect in a High Frequency Coaxial Pulse Tube Cryocooler [5-15]

X. F. Hou, L. W. Yang, J. H. Cai, and J. T. Liang
Technical Institute of Physics and Chemistry, Chinese Academic of Sciences
Beijing, China

Pulse tube cryocooler (PTC) has no moving parts, thus has the advantages of structural simplicity, high reliability, and low cost. Because of the big end-to-end temperature gradient along the pulse tube, there exists convective heat loss caused by gravity-driven convective flow and the cooling performance of PTC may change drastically when the angle between pulse tube and gravity direction changes. This phenomenon exists not only at ground testing of low-frequency PTC, but also at ground testing of high-frequency PTC. To clarify the gravity effect of inclination angle for high frequency PTC, a series of tests and simulation have been conducted. A high frequency coaxial PTC is tested with the tilt angle from 0° to 180°. A commercial computational fluid dynamics (CFD) software package is used to model the oscillation flow inside PTC, where the gravity is considered in the control equations. The tests show that increasing the operating frequency of PTC can not reduce the gravity effect but exacerbate the gravity effect, while the gravity effect becomes smaller at the higher input power. In simulation, the flow pattern inside pulse tube is changed with the inclination angle. This change affects the convective heat loss inside pulse tube and then affects the performance of PTC. The loss is calculated in simulation.

Parametric Study of Stirling Cycle Cryocooler by Using Cyclic Analysis [5-17]

M. M. Lele, S.L. Bapat
I. I. T. Bombay, Mumba, India
K. G Narayankhedkar
V.J.T.I.
Mumbai, India.

The cyclic analysis used as a tool for designing Stirling cycle cryocooler. The analysis takes care of all possible losses (viz. temperature swing loss; regenerator ineffectiveness loss; shuttle conduction loss; pumping loss; conduction loss etc.) for prediction of refrigerating capacity and input power. Further it is possible to study effect of various geometric parameters (viz. displacer diameter; piston diameter; regenerator length; etc.) and operating parameters (viz. operating pressure; operating frequency etc.) on refrigerating capacity and input power to the system. Based on this a Cryocooler for 3W at 80 K has been designed. Design of matching linear compressor is also reported in this paper.

Analysis on a Stirling-Type Pulse Tube Refrigerator Considering the Dynamics of a Linear Compressor [5-24]

J. Ko and S. Jeong
Cryogenic Engineering Laboratory Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology
Daejeon, Korea

This paper describes two analysis models (linear and nonlinear) for the performance analysis of Stirling-type pulse tube refrigerator (PTR) in conjunction with the dynamics of a linear compressor. The linear compressor under this study is a moving coil type and the inertance tube is incorporated as a phase control device in the pulse tube refrigerator. The dynamic behavior of the piston in the linear compressor is directly influenced by the load condition of the pulse tube refrigerator. In this paper, the dynamic equation of the piston is simultaneously solved with the thermodynamic governing equations of the pulse tube refrigerator. The piston displacement, the pressure wave and the mass flow rate are calculated for the electric input current, and then the PV power, the cooling capacity, the input electric power and the efficiency are also predicted. This model can explain the characteristics of cryocooler more accurately than the usual models with assumed piston displacement or pressure wave at the compression space of a linear compressor. Each optimum frequency for the compressor or the pulse tube refrigerator is derived and the design method to match those two optimum frequencies is discussed. Nonlinear effect, which is noticeable in the vicinity of the resonant frequency, is not negligible and fully discussed through the comparison of the linear and the nonlinear models.

Development of a Compressor for a Miniature Pulse Tube Cryocooler of 2.5 W at 65 KN [5-35]

**M., Y. Yasukawa, K. Ohshima, T. Takeuchi, K. Yoshizawa, T. Matsushita,
Y. Mizoguchi, A. Ikura**
Fuji Electric Systems Co., Ltd.
Tokyo, Japan

Fuji Electric group has established main technologies for high reliability in some Stirling cryocoolers for space satellite systems. We also have developed and started selling a miniature pulse tube cryocooler from 2 W to 3 W at 70 K with 100 W electric power input for any commercial applications. In development of a new compressor, we introduce a moving magnet to a driving system in order to achieve moreover compactness and higher efficiency, not a moving coil that is a conventional system with about 65% efficiency. The compressor requires total compression work of 75 W with 90% efficiency and longer than 50,000 hour. This development is for cooling a high temperature superconductive device in a wireless telecommunication system. We just start designing a motor structure with a simple method and running experiments in basic elements, because a moving magnet system is a new technology for us. At first the magnetic circuit for element tests is evaluated by basic formula, and computed by general-purpose FEM software. The results both element tests and calculated data are used for next designing. As a bearing supporting magnets, various ways are considered. This paper describes development status of the compressor including the motor design and the primary test results.

Development of a Simple Cryocooler to Provide Remote Cooling for Infrared Astronomy Systems [6-91]

T. Nast, J. Olson, E. Roth, B. Evtimov, D. Frank, P. Champagne and J. Jensen
Lockheed Martin Space Systems
Palo Alto, CA

Lockheed Martin has been developing advanced technology to provide very low temperature cooling for remote payloads. These cryocooler systems are designed for high reliability, and hence minimize the number of parts and components. Our selected approach is based on our JPL-funded advanced cryocooler technology development program (ACTDP) four-stage pulse tube cryocooler, which has demonstrated cooling to 3.8 K (no-load temperature) in combination with an integral flow loop using the same working gas as the pulse tube. This flow loop is driven by the same compressor which provides the pressure wave to the pulse tube cold head, an approach that adds very little complexity to the overall system. The flow loop utilizes constant (DC) flow to provide cooling at temperatures near 6 K at the remote cooling location. All cooling is provided by the pulse tube cooler, so that the remote cooling is provided directly by the cold gas stream. No Joule Thomson expansion is utilized in this approach, greatly simplifying the hardware and reducing number of components. This paper describes the results from our cryocooler combined with the flow loop developed as a technology demonstration. We utilize an overall loop length of 22 meters length to transport the flow to and from the remote location. This length is sufficiently long to allow for on-orbit deployment of the cold observatory to separate it from the warm portion of the satellite. The remote location includes two heat exchangers to provide the simulated instrument cooling. The paper includes values for the parasitic heat input into the remote flow loop and the temperature distribution along the flow path. The four stage pulse tube cryocooler and the compressor utilized were developed under the very successful advanced cryocooler technology development program (ACTDP) under contract to the Jet Propulsion Laboratory, which were made available for this technology advancement.

SESSION 6: OSCILLATING FLOW COMPONENTS

Wednesday, June 14, 2006 4:00 – 5:30 PM

Characterization of Inertance Tubes Using Resonance Effects [6-58]

M. A. Lewis, P. E. Bradley, R. Radebaugh and Z. Gan
National Institute of Standards and Technology
Boulder, CO

Inertance tubes can be characterized by their inertance, compliance, and resistance. All three of these impedance components are present during normal measurements of inertance tube impedance. As a result, in comparing experimental results with models it is often difficult to find the fundamental cause of any disagreement. In previous inertance tube measurements we have observed resonance conditions when the reservoir volume is properly sized. The resonance is analogous to an LC resonance of electrical systems with L analogous to the inertance and C analogous to the compliance of the reservoir volume. This paper discusses how we make use of this resonance to separate the various impedance components of the inertance tube and compare them with models. Frequency is varied about the resonance frequency for fixed pressure amplitude to find the resonance frequency, the minimum impedance, and the half-width of the resonance peak. Other measurements are made with zero reservoir volume and with a large reservoir volume. With this set of measurements we show how to separate the impedance components to compare them with models. Various methods for mass flow measurement at the inlet to the inertance tube are compared. These include hot-wire anemometry, pressure drop across stacked screen, and pressure drop across a laminar flow element. The inertance tubes investigated here are 5.70 mm and 9.53 mm in diameter with lengths about 2 m. Average pressures ranges from 1.5 to 2.5 MPa and pressure ratios extend up to 1.3 to give acoustic powers ranging from about 200 W to 1500 W. The reservoir volumes are sized to produce resonance frequencies near 60 Hz.

Long Transfer Lines Enabling Large Separations between Compressor and Coldhead for High-Frequency Acoustic-Stirling ("Pulse-Tube") Coolers [6-79]

P. S. Spoor and J. A. Corey
CFIC Inc.
Troy, NY

One of the chief advantages of Joule-Thompson or Gifford- McMahon cooling systems over the more recently developed acoustic Stirling variety (e.g. high-frequency “pulse-tube" coolers) is the large separation distance between the compressor and coldhead, which are connected by long, flexible transfer lines. This permits insertion of the coldhead into locations where the complete system would never fit, and isolates the coldhead from the vibrations of the compressor. High-frequency "split" Stirling and acoustic Stirling systems are not uncommon, but the separation distance is usually quite small, with a significant penalty on system efficiency. The usual approach has been to minimize the "dead volume" in the transfer line, making it relatively short and very small diameter. Recently, we have explored a different approach, using a fairly large transfer line diameter to lower the flow velocity (and hence the viscous loss), and increasing the length to over 1 meter, to allow these coolers to be used in the same applications as JTs and GMs. For small systems, this means using slightly larger compressor pistons to create the extra volume flow. The increase in compressor power required is small, because while there are losses in the transfer line, a long transfer line acts like an acoustic transformer, lowering the dynamic pressure at the compressor pistons for a given dynamic pressure at the coldhead. This lowers the seal loss in the compressor, which at least partially cancels the losses in the transfer line. In large systems, the increase in power is proportionally less, because the surface-to-volume ratio of the transfer lines is lower, and seal loss is a bigger fraction of the total input power. We will present simulations for various size systems, and data for one or two prototype systems, comparing capacity and efficiency with and without a long transfer line

Evaluation of Total Pressure Oscillator Losses [6-75]

P. E. Bradley, M. A. Lewis, R. Radebaugh, Z. Gan, and J. Kephart
National Institute of Standards and Technology
Boulder, CO

The ratio of piston PV power to the electrical input power typically has been used to define compressor efficiency for regenerative cryocoolers. This definition ignores blowby, irreversible heat transfer, and flow losses within the compressor. A new total loss method redefines compressor efficiency by subtracting the mechanical losses from the PV power at the piston face. The total loss method consists of a set of simple measurements. One measurement accounts for pressure losses within the compressor by measuring the electrical and PV power required for a blanked-off compressor for a given pressure ratio. The second accounts for flow losses by measuring the electrical and PV power for a given stroke with the compressor connected to a large reservoir. The sum of these mechanical losses subtracted from the PV power measured at the piston face gives the estimated PV power delivered to an attached load. In this work we evaluate the total loss method for some small and large pressure oscillators with swept volumes ranging from 4 cm3 to 25 cm3. We compare these estimates with system measurements using hot wire anemometry at the compressor outlet to determine the PV power delivered by the compressor to a load. We also determine the significance and scaling of these losses as they relate to compressor size and operating frequency. We report on measurements for mean pressures from 1.5 to 2.5 MPa, pressure ratios from 1.0 to 1.3, and corresponding mass flows.

Modified Oil-Lubricated Compressors for Regenerative Cryocoolers by Using a Simple Elastic Membrane [6-16]

E. Luo, Z. Wu, G. Yu, J. Hu and W. Dai
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing, China

Regenerative machines including refrigerators and heat engines operate on oscillating flowing. Lubricated oil for moving parts is not allowed to go into thermodynamic components such as heat exchangers and regenerators because the lubricated oil will deteriorate their heat transfer performance and block flowing passages So far, there has been no an easy, cost-effective and reliable solution to solve the problem of lubricated-oil separation in the oscillating systems. In this paper, the authors propose an innovative way to attack the difficult problem. The critical point of the way is based on the fact that the oscillating flow never flows through every thermodynamic component. The mechanical work for cold box is transported in the form of acoustical wave, and the flow particles only oscillate nearby their counter-balanced positions. Accordingly, an elastic rubber membrane can be used to fulfill two-fold important functions: acoustical power transportation and lubricated oil separation. Some important rules and considerations for designing such a device are given. The operating schematics of two types of oil-lubricated compressors are proposed, corresponding valve-less oil-lubricated compressors and valved oil-lubricated compressors. In addition, three compressors are modified to drive a two-staged pulse tube refrigerator, a pulse-tube-typed Stirling refrigerator and a four-valve pulse tube refrigerator. The preliminary experiments show that the solution could be very hopeful to provide a pressure wave generator by using plenty of commercial oil-lubricated compressors and by using a simple elastic membrane.

Gas Spring Losses in Linear Clearance Seal Compressors [6-56]

P. B. Bailey, M. W. Dadd, C. R. Stone
Department of Engineering Science Oxford University
United Kingdom,
J. S. Reed
Cryogenic Systems Group EADS Astrium Ltd
United Kingdom
T. M. Davis
Air Force Research Laboratory
Kirtland Air Force Base, New Mexico

A fundamental loss mechanism in cryocoolers is associated with compression and expansion processes, and the simplest demonstration of this can be observed in a gas spring. Our understanding of these gas spring losses is largely based on work by Kornhauser, Smith and others who carried out a series of thorough investigations on conventional crank driven reciprocating compressors, where the use of normal sliding seals would minimize seal losses. The widespread use of clearance seals in linear compressor has raised the question of how applicable the Kornhauser correlations are to these compressors which have significant flow through the seals and consequent seal losses. This paper describes experiments carried out with a clearance seal linear compressor attached to a plain gas spring volume. The static flow through the clearance seal in the compressor was measured over a range of piston positions, and this information was used to estimate the seal loss for specific strokes. Calculation of the gas spring losses from electrical power measurements was found to be unreliable due to uncertainties in the internal losses within the compressor. The P-V work done by the piston on the gas was measured, taking into account the small phase shifts in the instrumentation. By subtracting out the estimated seal loss, the gas spring loss was derived. Results are presented for a number of gasses over a range of frequencies and strokes.

One-Dimensional Analytical and Numerical Models of the Pulse-Tube Cooler [7-57]

M. A. Etaati, R. M. M. Mattheij, A. S. Tijsseling and A. T. A .M. de Waele
Eindhoven University of Technology,
The Netherlands

The results of three different one-dimensional models of the pulse-tube cooler are compared and explained. The first analytical model assumes that pressure, density, flow and temperature vary harmonically in time at the operating frequency of the cooler. The second analytical model provides an exact solution based on the method of characteristics. The third model is numerical and uses a finite- difference method with flux limiters to account for steep pressure gradients. The first and second models neglect viscosity and thermal conduction, so that the driving pressure is spatially uniform. The third model offers the possibility to study the effects of (temperature-dependent) viscosity and conduction. New elements in the numerical model are the inclusion of unsteady friction effects (based on two-dimensional analytical solutions obtained in the frequency domain) and heat exchange with the tube wall. Matters discussed in the paper are: DC flow, temperature peaks and gradients, numerical and physical dispersion, viscous and thermal boundary layers, orifice models, boundary conditions. Results of the three different models are compared and explained. The validity of assumptions is checked. The models presented will be used in the development of two-dimensional models and in the design of a 4K three-stage pulse-tube refrigerator operating at high frequencies and low pressure-amplitudes.

SESSION 7: PULSE TUBE MODELING

Thursday, June 15, 2006   8:00 – 10:00 AM

A New Type of Streaming in Pulse Tubes [7-54]

W. Liang and A. T. A. M.de Waele
Department of Applied Physics, Eindhoven University of Technology
The Netherlands

By numerical simulation a new type of streaming has been found in pulse tubes. The geometry in the simulation consists of the pulse tube and with its flow straighteners. The straighteners are described as a porous medium with the directional momentum loss. Viscous effects are taken into account, but heat transfer with the wall is not considered. In this simulation a stable model is used. The gas flow in the pulse tube is periodic. Positive and negative boundary conditions are imposed on the geometry which results in flow fields with opposing directions. The net flow field is obtained by the superposition of these two flow fields. It turns out that the net velocity is not equal to zero. Four loops are formed in the tube. This paper analyzes this phenomenon and explains how the flow resistance of the straightener and the viscous effect of the tube wall result in this new type of streaming.

A Model for Parametric Analysis of Pulse Tube Losses in Pulse Tube Refrigerators [7-5]

C. Dodson, A. Razani and T. Roberts
Air Force Research Laboratory
Kirtland AFB, New Mexico

In order to quantify the pulse tube irreversibility, a loss parameter is introduced into the first order thermodynamic model of a pulse tube that consists of a hot, a cold, and an adiabatic section. The entire pulse tube is assumed to be adiabatic while the loss parameter simulates its irreversibility. It is shown that the primary effect of the parameter is to modify the temperature as a function of time in the cold and hot sections of the pulse tube as well as having a secondary effect on the mass flow rate as a function of time at both ends of the pulse tube. The model is incorporated into a first order model of an Inertance Tube Pulse Tube Refrigerator (ITPTR). A distributed parameter model of the inertance tube is developed to simulate the fluid flow in the tube and to quantify the phase shift between the mass flow rate and the pressure at the tube's entrance. The effect of the loss parameter in the pulse tube on the energy and exergy flow in the ITPTR is investigated. The irreversibility distribution of the ITPTR, including the pulse tube, is quantified and the effect of the loss parameter on its cooling capacity is presented.

Comparison of Three Different Configurations of Pulse Tube Cooler [7-2]

W. Dai, E. Luo, Z. Guan, C. Bei and Y. Tiao
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing, China

Pulse tube cooler has undergone great development within the last twenty years. In case of high frequency Stirling type pulse tube coolers, three configurations are very famous the double inlet type, the inertance tube type and most recently the loop type with work recovery capability. All of them can realize traveling wave acoustic field inside the regenerator to ensure a relatively high efficiency operation. However, no systematic comparisons between them have been made to show respectively the advantages or disadvantages of each type. In this article, with the help of phasor analysis or numeric calculation, careful comparison of their characteristics is made. This comparison is important because it helps to set up some selection criteria when building a practical cooler system.

Non-Zero Time-Averaged Thermoacoustic Effects, Linear or Nonlinear? [7-14]

E. Luo
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing, China

Classical regenerative machines or recently developed thermoacoustic machines operate on complicated interactions between oscillating flow and its contacted solids, the so-called thermoacoustic effects. N.Rott et al have developed linear thermoacoustic theory to explain the effects and the working mechanism of related machines. One of the main viewpoints of the linear thermoacoustic theory is that the non-zero time-averaged thermoacoustic effects such as time-averaged enthalpy flow, heat flow and acoustical workflow, are linear thermoacoustic effects under acoustical approximation. However, the author of this paper presents a different viewpoint. In the first part of the paper, the author argues that the energy effects in the regenerative or thermoacoustic systems can be the zero-th order, the first-order, the second-order and the higher order. For commonly-used regenerative or thermoacoustic systems, the zero-th order energy flows do not exist due to the particle velocity does not achieve sound velocity. The first-order energy flows do exist and are huge, but their time-averaged values are equal to zero! From physical essence and mathematical viewpoint, the first-order energy flows are really linear. For the second-order energy flows, they are the products of two acoustical or thermodynamic variables and are nonlinear. Usually, the second-order energy flows are composed of two parts: non-zero time- averaged item and time-dependent item. It is the second-order non-zero time-averaged item that the regenerative or thermoacoustic machines operate on. In the second part of the paper, the author gives an important proof to support the newly developed standpoints. The proof is based on a traveling-wave thermoacoustic heat engine/ refrigerator with a closed loop. Here, the author shows that no matter how the oscillating wave is small, the classical linear theory is unable to give an accurate prediction for the machine's time-averaged thermoacoustic effects. To solve this problem, the author develops a weakly nonlinear theory to describe the non-zero time-averaged thermoacoustic effects for small perturbation wave, and the author suggest that the CFD method is a last and practical tool to accurately describe the non-linear time-averaged effects under large-amplitude waves.

SESSION 7: PULSE TUBE MODELING
Thursday, June 15, 2006 8:00 – 10:00 AM

Validation of an Integrated Modeling Tool for the Study of Pulse Tube Coolers
[7-67]

A. S. Gibson, D. Nikanpour
Canadian Space Agency
Longueuil, Canada
H. Elmrini
MAYA Heat Transfer Technologies Ltd.
Montreal, Canada

Cryocooler research at CSA is exploring techniques to more rapidly develop scaled versions of pulse tube coolers, while provided new opportunities to optimize performance. The study explores a computational fluid dynamics approach, with validation of a simple prototype cooler. Despite the heritage accumulated by space borne cryocoolers, there are a limited number of products available to suit particular mission constraints. This is particularly apparent in the case of long-life pulse tube coolers for small-sat platforms. The trend to deploy scientific instruments on smallsats has continued, as has the related demands for pulse tube cooling. However, there is a prevailing gap in terms of cost and availability of proven, low-mass cooling technology. It is surmised that such development can be hastened with the application of higher-fidelity simulation tools. Given that 1-D and 2-D tools have been applied in different forms, it has become interesting to explore the feasibility of 3-D modeling with the intent to achieve greater optimization and enable mass reductions through less restrictive geometric constraints. Flow parameters from testing of a prototype pulse tube cryocooler are compared with analytical results obtained using 3-D computational fluid dynamics software. The analysis incorporates coupled solutions of conductive and convective heat transfer in a realistic in-line pulse tube configuration, with consideration for compressibility and turbulence of the helium gas. Initial correlation studies focus on phase relationships of pressure observed across the inertance tube section of the cryocooler. Mass flow phase effects are predicted using the fluid model. An interpretation of the results demonstrates the usefulness of the model in diagnosis of key performance issues with the prototype.

The Second-Law Based Thermodynamic Optimization Criteria for Pulse Tube Refrigerators [7-3]

A. Razani, T. Roberts and B. Flake
The University of New Mexico Albuquerque, NM
Air Force Research Laboratory Kirtland AFB, NM
European Office of Aerospace Research and Development London, UK

The second-law based thermodynamic optimization criteria with application to Stirling and pulse tube cryogenic refrigerators are investigated and compared. New ecological criteria for optimization and characterization of cryogenic refrigerators are proposed and a model based on the exergy flow interpretation of the criteria is developed. It is shown that the conventional ecological criteria used in the analysis and optimization of energy systems is not suited for application to cryogenic refrigerators. The criteria must be modified due to the fact that practical cryogenic refrigerators have high internal irreversibilities. This high internal irreversibility exists despite the fact that the external irreversibility due to heat transfer is quite low in the cryogenic refrigerators. It is shown how the proposed ecological criteria simulate the condition where a compromise between exergy delivered and exergetic efficiency in design space is obtained. The optimization criteria is applied to experimental data generated for a high efficiency cooler by assuming a linear load curve for the cooler while appropriate parameter models are chosen to simulate other cooler characteristics. Numerical example for the effect of different parameters including the heat rejection temperature, no load temperature and other important system parameters are presented. Finally, application of the criteria to thermodynamic optimization of multistage cryocoolers is discussed.

A Dimensionless Analysis Model of a Regenerator [7-90]

J. Shi, J. Pfotenhauer, and G. Nellis
University of Wisconsin-Madison
Madison, WI

Regenerative heat exchangers represent a crucial component in the design of single and multi-stage cryocoolers. Both the heat transfer and fluid dynamics that occur in the regenerator influence its performance significantly, and dictate the need for mass, energy, and momentum conservation equations to adequately characterize its operation. However, because of the inherent sophistication required, numerical solutions describing regenerator performance can require extensive time for convergence. This report investigates the usefulness of dimensionless analysis to extrapolate the performance of a regenerator from a known, or base case to conditions removed from the base case. The base case performance is determined using REGEN3.2, and the extrapolated performance via dimensionless analysis is compared to the performance also predicted directly by REGEN3.2. Correlations are developed using the dimensionless analysis to predict the mass flow rate and phase at the warm end of the regenerator, as well as the heat exchanger ineffectiveness and pressure drop. The correlations are integrated with the other components of a two-stage pulse tube model (previously described) and comparisons of the integrated model using REGEN3.2 and using the correlation-description of the regenerator performance are presented.

Numerical Simulation of Regenerator in a Two-stage Pulse Tube Refrigerator [8-36]

B. Y. Du(1,2), L. W. Yang(1), J. H. Cai(1) and J. T. Liang(1)
(1)Technical Institute of Physics and Chemistry, Chinese Academic of Sciences, Beijing, China (2)Graduate University of Chinese Academy of Sciences, Beijing, China

Pulse tube refrigerators have demonstrated many advantages with respect to temperature stability, vibration, reliability and lifetime among cryocoolers. It is easier to obtain between 20K for two-stage high frequency pulse tube refrigerator than that of one-stage. The regenerator is one of the key components in two-stage pulse tube. Program REGEN3.2 developed at NIST is a very useful tool to simulate the performance of regenerator of pulse tube regenerator, and it is used to simulate second-stage regenerator of two -stage pulse tube refrigerator. The regenerator operates with a warm end temperature of 80~100K, a cold end temperature of 10~30K. The effects of the geometry of regenerator is achieved and analyzed to get optimized conclusion for different operate condition. The operating parameters, such as frequency, mean pressure, are also investigated. The commonly used stainless steel matrix is not suitable when the cold end temperature is below 30K, so different material is used to improve the performance of the regenerator. The results of the simulation show that the new material is useful to get lower cold end temperature and higher COP. It is important to simulate regenerator to get a more efficient pulse tube refrigerator. Deep research on characters of regenerator will be helpful to improve the performance of pulse tube refrigerator.

Dynamic Analysis of Oscillating Flow Regenerators [8-29]

H. L. Chen, L. W. Yang, J. H. Cai and J. T. Liang
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing,China

Regenerator is the most important component in a pulse tube cryocooler. Because of oscillating flow, heat transfer and flow resistance in the regenerator are complex. Regenerator research is a fundamental work for cryocoolers. Simulating the pulse-tube cooler, experiments are performed to test five regenerators of different length at different operating conditions in terms of frequency, orifice opening and input power. Two fine hot wire anemometers are used to measure the instantaneous velocities at the inlet and outlet of the regenerators, and the pressure waves are measured by piezoelectric pressure transducers at the same positions. Phase shift characteristics between velocities and pressures at both ends of the regenerator are studied. Different from some other work, the phase shift of the same parameter at different ends is analyzed. It's developed that the phase shift between the velocities at the two ends is caused by the volume of the regenerator mesh, and the phase shift between the pressures is caused by the resistance of the mesh. Further more, instantaneous pressure difference through the whole regenerator is composed by pressure drops, which has different values, of each tiny section of the mesh. The integrate result is, as shown in experimental results, the average velocity always has the same phase with the total pressure drop under different conditions. Resistance characteristics of oscillating flow regenerator do not vary much from that of steady flow.

Results of Tests of Etched Foil Regenerator Material [8-86]

M. P. Mitchell
Mitchell/Sterling, Berkeley, CA
D. Gedeon
Gedeon Assoc., Athens, OH
G. Wood
Sunpower Inc., Athens, OH
M. Ibrahim
Cleveland State University, Cleveland, OH

Results of Tests of Etched Foil Regenerator Material Matthew P. Mitchell, Mitchell/Stirling, Berkeley, California, USA David Gedeon, Gedeon Associates, Athens, Ohio, USA Gary Wood, Sunpower, Inc., Athens, Ohio, USA Mounir Ibrahim, Cleveland State University, Cleveland, Ohio, USA A parallel- plate regenerator fabricated by Mitchell/Stirling from flat-stacked layers of etched stainless steel foil was tested at Sunpower, Inc., under a grant from NASA Glenn Research Center to Cleveland State University, in a regenerator test rig on loan from NASA. Test data were analyzed by Gedeon Associates. The tests of the etched stainless steel foil regenerator were part of a program of tests of a variety of regenerator materials and geometries. The figure of merit ("FOM") for the etched stainless steel foil was higher at 0.22 than for 30 micron random fiber of 90% porosity at about 0.20. That FOM was, in turn, higher than for random fiber of lesser porosity, woven screens of 70% porosity, or any other material so far tested. Porosity of the foil regenerator was 55%. The FOM measures the heat-transfer effectiveness per unit of flow resistance. The etched foil regenerator achieved its highest FOM at about Re = 600 as compared to random fiber, which peaked at about Re = 400. The larger thermal mass of the foil regenerator, and the higher Reynolds number at which its performance peaks, suggest possible advantages for cryocooler design, operation or both. The flow path through the foil regenerator as tested was straight-through. Another foil regenerator with similar porosity but with a zigzag flow path remains to be tested. Previous work under less rigorous conditions suggests possible advantages of the zigzag flow path. Since the theoretical FOM for a parallel plate regenerator is about 0.50, there is substantial room for improvement.

Hydrodynamic Parameters of Pulse Tube or Stirling Cryocooler Regenerators for Periodic Flow [8-62]

J. Cha, S. M. Ghiaasiaan and P. V. Desai
G.W. Woodruff School of Mechanical Engineering Georgia Institute of Technology
Atlanta, GA
C. S. Kirkconnell and J. P. Harvey
Raytheon Space and Airborne Systems
El Segundo, CA

Recent studies have shown that computational fluid dynamics (CFD) techniques can be applied for modeling cryocooler systems in their entirety in order to capture their operation under steady periodic flow. However, the results of CFD simulations can only be fully trusted if they are based on correct closure relations. Among the most important closure relations are the hydrodynamic and heat transfer parameters. The regenerator is typically a microporous structure that is subject to a periodic flow of a cryogenic fluid (gas). The hydrodynamic and heat transfer parameters of microporous structures under oscillatory flow are not well understood, however, and current state-of-art modeling methods are based upon using constant cycle-average friction factor and heat transfer coefficients. The preliminary results of a research program on the measurement and correlation of instantaneous anisotropic hydrodynamic parameters of some widely-used cryocooler regenerator fillers under steady, as well as periodic oscillatory, flow conditions are presented. An experimental apparatus consisting of test sections for the measurement of axial and lateral (radial) permeability and Forchheimer coefficients is used. The test section for the radial hydrodynamic parameter measurements is annular. It is connected to a compressor through its inner boundary and to a constant-volume chamber through its outer boundary. The instrumentation includes pressure transducers and anemometers that measure the local and instantaneous fluid mass flux and temperature. Time histories of local pressures, temperatures, mass fluxes at points near the entrance and exit are measured under steady- periodic conditions. A CFD-assisted methodology is then used for the analysis and interpretation of the measured data. The permeability and Forchheimer parameter values obtained in this way are then correlated in terms of relevant dimensionless parameters. The test section for the axial parameter measurements is cylindrical. It is subjected to experimental and CFD-assisted analytical methods similar to those for the radial flow test section.

On the Differential and Integral Inversion States of the Joule-Thomson Effect and their Interrelation [8-1]

B.-Z. Maytal
Rafael, Ltd.
Haifa, Israel

The differential inversion curve (DIC) is the loci of thermodynamic states of vanishing Joule-Thomson coefficient. The integral inversion curve (IIC) is the loci of states of vanishing integral isenthalpic Joule-Thomson effect. While the former one was intensively studied since the discovery of this effect in 1852 the second one was significantly less studied. However, the interrelation between the two inversion curves was not studied at all. This is the first objective of the present study while adapting the following approach. The van der Waals (vdW) equation of state is applied to derive closed form interrelations between the differential and integral inversion states. The predicting power of these interrelations was examined and demonstrated versus real gases data. For the same reduced density, the two inversion states have common residual entropy (at the same volume and temperature). The inversion temperatures are normalized by the maximum inversion temperature. The normalized differential inversion temperature is a square of the normalized integral inversion temperature. However, at the same normalized temperature the residual entropy on the IIC is twice as on the DIC. The second objective of this study is to examine the behavior of some thermodynamic functions along the DIC and the IIC, by the same approach. The temperature along IIC is a linear function of the density. The compressibility is bounded and peaks along the DIC but is not bounded along the IIC. The differences between the isobaric and isochoric heat capacities peaks and is bounded along the IIC but is not bounded and increase monotonically along the DIC. The Joule-Thomson coefficient along the IIC increases monotonically but is bounded. The integral isothermal Joule-Thomson effect along the DIC is bounded but increases monotonically.

Throttle-Cycle Flow Control Using Shape Memory Alloy [8-74]

J. M. Pfotenhauer and A. J. Marconnet
University of Wisconsin – Madison
Madison, WI
B-Z. Maytal
Rafael, Ltd.
Israel

We report on the use of a shape memory alloy within the structure of a throttle-cycle cooler to provide a passive flow control mechanism. The experimental investigation includes measurements using both pure nitrogen gas and pure argon gas as the working fluid in the throttle-cycle, or Joule-Thomson cryocooler. The mass flow rates varied during the experiments from as low as 0.1 SLPM in very well controlled situations, and up to 38 SLPM in the wide-open throttle operation. The operating characteristics of the cooler are described for inlet pressures ranging from 55 bar to 235 bar and for resulting temperatures ranging from 94 K to 275 K (not respectively). The flow regulating mechanism is described and its operation is correlated with the reversible, temperature dependent properties of the shape memory alloy. A secondary feature of the data reveals that the mass-flow dependence of the heat exchanger efficiency agrees with expected behavior based on an Ntu-effectiveness analysis.

SESSION 8: –REGENERATORS & JOULE THOMSON CRYOCOOLERS POSTER SESSION 3

Thursday, June 15, 2006   10:00 – 11:00 AM

Progress Towards a Low Power Mixed Gas Joule-Thomson Cryocooler for Electronic Current Leads [8-76]

J. F. Pettitt, J. M. Pfotenhauer, G. F. Nellis and D. W. Hoch
University of Wisconsin – Madison
Madison WI

This paper describes the progress towards a single-stage; low power (< 1 W) mixed gas Joule-Thomson (MGJT) cryocooler for cooling current leads associated with superconducting electronics. By thermally integrating the leads with the recuperative heat exchanger of the MGJT, it is possible to intercept the electrical dissipation and conductive heat leak of the wires at a relatively high temperature which provides a thermodynamic advantage. Also, the cooling of the leads may provide advantages relative to thermal integration. The composition of the gas mixture was optimized using a genetic optimization technique. The thermal-fluid behavior of the mixed gas refrigerant was measured in a cryogenic test facility. These results were incorporated into a numerical model of a Hampson style recuperative heat exchanger which was used to design the system. A demonstration device was fabricated and integrated with a thermal vacuum test facility, gas handling equipment, precision jewels which acted as fixed orifice expansion valves, and appropriate instrumentation. The system was tested using high pressure (9.745 MPa) pure Argon in an open cycle configuration in order to verify the model under relatively simple operating conditions. Further experiments using gas mixtures were performed in a closed loop configuration. The test results illustrate issues relative to liquid management that constrain the performance. The specific factors that influence the liquid management issue are explored systematically through a parametric variation of the orifice size and mixture composition.

SESSION 8: –REGENERATORS & JOULE THOMSON CRYOCOOLERS POSTER SESSION 3

Thursday, June 15, 2006 10:00 – 11:00 AM

Metal Hydride Sorbent Beds in the Planck Sorption Cryocooler: Performance, Degradation and Lifetime Issues [8-8]

R. C. Bowman, Jr., P. B. Karlmannand M. Prina
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA
J. W. Reiter
Swales Aerospace
Pasadena, CA

Recently developed hydrogen sorption cryocoolers will provide continuous ~19 K cooling to instruments on the Planck spacecraft in a mission to measure the temperature anisotropy of the cosmic microwave background (CMB) at radio and infrared wavelengths. These Planck Sorption Coolers (PSC) use six individual compressor elements (CEs) filled with the hydriding alloy LaNi4.78Sn0.22 to provide high-pressure (~50 bar) hydrogen gas to a Joule-Thomson (J-T) expander and to absorb low-pressure (~0.3 bar) gas from liquid hydrogen reservoirs cooled to ~19K. Thermal control of the hydrogen storage sorbent beds in each of the CEs is managed by a closed-cycle Gas Gap Heat Switch (GGHS) with a small independent hydride actuator containing ZrNiHx. Each GGHS functions as a variable vacuum dewar with an on/off heat conduction ratio >200, allowing the reduction of nominal input power to each CE by ~80% over a lifetime exceeding 20,000 heating/cooling cycles without the use of any moving parts. As these heat switches are sensitive to residual pressure in the off state, gas accumulation in the GGHS volume will impact performance. This accumulation was found to be a combination of hydrogen outgassing from metallic components and permeation through the walls of the high-pressure hydride bed when heated up to ~670 K as well as formation of small amounts of methane. Long term performance of the CEs is also limited by degradation of the LaNi4.78Sn0.22 hydride during its temperature cycling. Extensive results from laboratory testing on engineering models as well as the flight versions of the CE-GGHS components will be presented along with pressure- and temperature-dependent hydrogen accumulation rates in the GGHS. Finally, a regeneration process that restores the behavior of the degraded LaNi4.78Sn0.22 hydride will be described.

A Numerical Study on the Performance of the Miniature Joule-Thomson Refrigerator [8-50]

Y-J Hong, S-J Park
Korea Institute of Machinery and Materials
Taejeon, Korea
Y-D Choi
Korea University
Seoul, Korea

Miniature Joule-Thomson refrigerators have been widely used for rapid cooling of infrared detectors, probes of cryosurgery, thermal cameras, missile homing head and guidance system, due to their special features of simple configuration, compact structure and rapid cool-down characteristics. The cool-down time, the temperature at the cold end, the running time and the gas consumption are the important indicators of the performance of the Joule-Thomson refrigerator. Limited experimental and theoretical studies on the performance of the refrigerator were performed due to the complexity of the geometry of the recuperative heat exchanger of the Joule-Thomson refrigerator. In this study, a simplified transient one-dimensional model of momentum and energy transport for the recuperative heat exchanger was adopted to predict the transient behaviors of the refrigerator. In the analysis, to consider the thermal interactions of the each of component of the refrigerator, the momentum and energy equations for the high pressure gas, the low pressure gas, the tube, the Dewar, the mandrel were simultaneously solved. The thermodynamic properties from REFPROP were used to account the real gas effects of the gas. The results show the effects of the initial supply pressure on the transient behaviors of the temperature at the cold end and the thermal performance of the recuperative heat exchanger.

Compositions Shift of a Mixed-Gases Joule-Thomson Refrigerator Driven by an Oil-Free Compressor [8-10]

M. Gong, Z. Deng and J. Wu
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing, China

The mixed-gases Joule-Thomson refrigerator (MJTR) has distinct advantages compared with other kind of cryocoolers for operating over a large temperature range from 80 to 230 K. One of the most obvious merits is that the commercial oil-lubricated single-stage compressor can be utilized to drive the low temperature MJTR. The utilizing of the commercial compressor can reduce the cost, achieve high reliability and easily be built in industry scale because of its several decades' commercial applications in the commercial and domestic refrigeration fields. However, the utilizing oil-lubricated compressor also brings disadvantage. One obvious disadvantage is that different solution of components with oil lubricant is one main contribution to the composition shift. Concerning the composition shift, the liquid hold-up of the two-phase flow in the cryostat also makes a very important contribution. The accurate composition variation prediction is quite difficult because of the lack of fundamental research both on the gas-lubricant phase equilibrium and the two-phase flow of multicomponent mixtures, especially at low temperature ranges. So in order to get a deep understanding of the composition shift caused by phase holdup in the two-phase flow of multicomponent mixtures, an experimental apparatus was built to investigate the composition variation characteristic of the MJTR. This prototype was driven by an oil-free compressor. Extensive measurements were conducted for different mixed-gases utilizing this apparatus. The detail composition shift features were presented in this paper. Some active methods for controlling the composition shift were also discussed.

Composition Shifts Due to Different Solubility with the Lubricant Oil for Multi-Component Mixtures [8-11]

M. Gong, W. Zhou and J. Wu
Technical Institute of Physics and Chemistry, Chinese Academy of Sciences
Beijing, China

For a typical mixed-gases Joule-Thomson refrigerator, the mixed-refrigerants used consist of from 4 to more than 7 components, which have different boiling temperatures from cryogenic to ambient temperatures. Different gases have different gas (vapor)-liquid equilibria with the lubricating oil in the system. That is, different substance has different solubility with the lubricant oil in the multi-component mixed-refrigerant Joule-Thomson refrigerators. This is an important factor that cause the circulating composition different from the initial charged one. In this paper, this composition shift due to the different solubility of different component with oils was studied. Squalane is treated as a kind of mineral oil. PR equation of state is selected from several thermodynamic models to predict the solubilities. A group contribution method was used to predict the binary interaction coefficient, which is crucial in the prediction of Gas (Vapor) - Liquid equilibria with squalane. The equilibria for squalane and multi-component mixtures were studied to know the influence of the solubility on the composition shift. The results show that the solubility with oil will greatly decrease the concentrations of those components with high boiling point. The composition variation can reach -70% for the highest boiling component, and about 160% for the lowest boiling component. The work presented in this paper is very useful in the modification of the existing simulation model of the mixture refrigeration cycle as well as the fabrication of such systems.

SESSION 8: -REGENERATORS & JOULE THOMSON CRYOCOOLERS POSTER SESSION 3

Thursday, June 15, 2006 10:00 – 11:00 AM

Microfabricated Microchannel Regenerators for Cryocoolers [8-109]

Charles Becnel
Mezzo Technologies
Baton Rouge, LA

Advances in the field of microfabrication have resulted in the ability to fabricate advanced geometries in various materials for use as regenerators in cryocoolers. Microchannels have been produced in nickel, stainless steel, lead and erbium, and these microfabrication techniques can also be applied to other rare-earth materials. Regenerators produced by this method will greatly benefit the cryocooler industry due to the fact that the power efficiency and the attainable cold end temperature are strongly influenced by the geometry of the regenerator. These new fabrication techniques allow the designer to reduce the pressure drop across the regenerator and optimize the regenerator performance by varying the porosity, channel shape, and channel size. The resulting regenerators support lower NPH/NTU values over the screens and powders currently in use. Models that have been developed for microchannel regenerator designs indicate that cryocooler efficiencies can be significantly improved relative to packed powder and screen regenerators. Both DC and oscillating testing systems are being developed to experimentally determine the performance of microchannel regenerators. Improvements in the thermal performance of regenerators will result in an overall improvement in cryocoolers, especially at the lower temperature ranges.

Micromachined Regenerator: Pressure Drop and Heat Exchange [9-23]

S. Vanapalli, H.J.M. ter Brake, H.V. Jansen, J.F. Burger, H.J. Holland and M. Elwenspoek
University of Twente, Enschede
The Netherlands

As part of the microcooling research project at the University of Twente, micro-regenerator test structures were machined in silicon. These structures consist of continuous channels having a width of 25 micron and a height of 250 micron, or matrix structures with different shapes of pillars. The latter also typically have a size of 25 micron and a height of 250 micron. The high aspect ratio was realized by means of dry etching. The structures were characterized at around room temperature on pressure drop and heat exchange, both with flow rates in the range of 1 to 10 mg/s. The pressure drop over parallel channels has been modeled taking into account inlet and exit losses. For the same rectangular cross-section, a sine shaped channel exhibits a higher pressure drop due to transformation of the flow into turbulence. Pressure losses in an aligned pattern of square pillars have been modeled and it is found that the fluid in the gaps between the pillars contributes to an extra viscous loss, which can be taken into account as an effective viscous length. The compression and expansion losses in the square pillar matrix appear to be relatively small, whereas those in an aligned circular pillar matrix are quite significant. Staggered patterns have a higher pressure drop due to the flow becoming turbulent. An ellipsoid pillar matrix appeared to have the lowest pressure drop for the same porosity of the matrix. In the paper, these pressure-drop experiments will be discussed and compared to theoretical analysis. In addition, we hope to present data on heat exchange, so as to enable an optimization of the micro-regenerator geometry.

All-Micromachined Joule-Thomson Cold Stage [9-22]

P. P. M. Lerou, H. V. Jansen, J. F. Burger, T. T. Veenstra, H. J. Holland, G. C. F. Venhorst, H. J. M. ter Brake and H. Rogalla
University of Twente, Enschede
The Netherlands

As part of the microcooling research project at the University of Twente, a micro Joule-Thomson cold stage was designed, realized and tested. The cold stage consists of a stack of three glass wafers. In the top wafer, the high-pressure line is etched as a rectangular channel with supporting pillars. The high-pressure line ends in a flow restriction and an evaporator volume that crosses the center wafer into the bottom wafer. This bottom wafer contains the low- pressure line, again etched as a rectangular channel containing supporting pillars, thus forming a counter-flow heat exchanger. A design aiming at a net cooling power of 10 mW at 96 K and operating with nitrogen as the working fluid was optimized based on the minimization of entropy production. The optimum cold finger measures 28 mm x 2.2 mm x 0.8 mm (max dimensions). It should be able to generate a net cooling power of 10 mW at 96 K at a nitrogen flow of 1 mg/s at a high pressure of 80 bar and a low pressure of 6 bar. A batch of 14 prototype coolers was made in 7 different designs, among which the theoretical optimum. One of these is currently under test. Based on mass-flow measurements we conclude that liquid nitrogen is collected in the evaporator, and since the low pressure is 6 bar, the temperature should be 96 K. However, probably because of some thermal resistance the thermocouple attached top the cold tip measured 105 K minimum. A net cooling power of 5 mW was measured. In the paper, the design of these coolers will be discussed along with experimental results.

Progress Towards A Micromachined Heat Exchanger For A Cryosurgical Probe
[9-66]

D. W. Hoch, G.F. Nellis, S. A. Klein
University of Wisconsin
Madison, WI
W. Zhu, Y. B. Gianchandani
University of Michigan
Ann Arbor, MI

This paper describes developments towards a lithography- based microfabricated recuperative heat exchanger intended to be a component within a cryosurgical probe. A cryosurgical probe must achieve a temperature below -50C in order to be clinically useful for the treatment of cancer. Cryosurgical probes based on the mixed gas Joule-Thomson (JT) cycle require only a recuperative heat exchanger and an expansion valve in the cold-head. Therefore, this cycle has the potential for high reliability and miniaturization. The objective of this project is to explore the application of micromachining techniques to the recuperative heat exchanger. The heat exchanger must maintain high stream-to-stream thermal conductance while restricting axial conduction losses through the base plate. The 1st generation heat exchanger consists of rows of fins composed of high conductivity silicon that are bonded onto a single 100m base plate composed of low conductivity Pyrex glass. This design minimizes the number of wafers that must be bonded compared to more favorable designs based on interleaving many high conductivity silicon plates with low conductivity Pyrex spacers. However there are several disadvantages associated with the design, most notably the fragility of the thin Pyrex separating plate which limits the ability to withstand the relatively large pressure difference between fluid streams associated with the proposed Joule-Thomson cooling cycle. The 1st generation heat exchanger was fabricated and tested. Results of these tests will be provided in the paper. In parallel, a bonding technique has been developed that shows the potential to allow multiple plates to be hermetically joined using a metallization layer. Therefore, a 2nd generation heat exchanger design is presented which will be more robust and will also provide enhanced thermal performance. Preliminary design specifications for this heat exchanger will be provided.

CVD Diamond-Based Miniature Stirling Cooler [9-25]

D.E. Patterson, K.D. Jamison, M. Durrett
Nanohmics, Inc.
Austin, TX
A. Kashani
Atlas Scientific
San Jose, CA
D. Gedeon
Gedeon Associates
Athens, OH

To help fulfill NASA's Earth Science Enterprise mission objectives and to provide a solution to the growing demand for miniature, high efficiency cooling devices, Nanohmics and its partners are developing a compact Stirling refrigerator. The refrigerator measures 1 cm x 1 cm x 3 mm and incorporates several novel components that are not found in other previously described MicroElectroMechanical Systems (MEMS) Stirling coolers. The Nanohmics diamond-based cooler includes the use of high thermal conductivity CVD diamond components for the heat exchange plates and compressor/expansion diaphragms and a proprietary high heat capacity, low thermal conductivity regenerator. The miniature refrigerator is operated by piezoelectric crystal drivers that are internally attached to the two diamond diaphragms. The diaphragms are driven at several kilohertz frequency approximately 90 degrees out of phase with each other to establish the appropriate Stirling refrigeration cycle for an alpha-design Stirling engine. The working stroke of the cooler diaphragms is approximately 5 microns. In order to improve the coolers' performance, the device is charged to an internal working pressure of 500 kPa. The device can theoretically provide a lift of 68 mW with a temperature difference of 20 K between the hot and cold heat exchange faces of the device. Details of the device model, device construction, and actual device performance will be presented.

SESSION 9: MEMS BASED AND MINIATURE CRYOCOOLERS

Thursday, June 15, 2006   11:00 – 12:15 PM

All-Solid-State Optical Coolers: History, Status, and Potential [9-70]

C.E. Munganand
Physics Dept, U.S. Naval Academy
Annapolis, MD
M. I. Buchwald
Buchwald Consulting
Bethesda, MD
G. L. Mills
Ball Aerospace & Technologies Corp
Boulder, CO

Laser cooling of a bulk solid was first demonstrated in 1995 with a net temperature drop of 0.3 C at room temperature. The sample was a sliver of ytterbium-doped ZBLAN, a heavy-metal fluoride glass developed as a low-loss optical fiber material. The ideal cooling efficiency was calculated to be as large as 3% relative to the laser power, assuming all the pump light is absorbed. A step in this direction was achieved by coating a cylindrical sample with mirrors having high reflectivity at the pump wavelength, resulting in more that 100 C of cooling in the lab. Laser calorimetric measurements of the actual cooling nevertheless shows that less than 25% of the predicted performance was realized compared with a detailed model including the effects of fluorescence reabsorption and the angle-dependent reflectivity of the coatings. The sources of the nonidealities in the cooler are believed to result from trace impurities in the ZBLAN that act as heating traps. Small concentrations of nonradiative impurities may dramatically reduce the cooling. An ytterbium excitation can migrate to those defects via energy transfer and a quenching site thereby leads to heating even if direct laser absorption does not take place at that site. We report on measurements that promise improved cooling of detectors based on a compact system package weighing only a few grams. Specifically, we have prepared new high- purity samples using ytterbium from different sources and compared their performance with the glasses used in earlier demonstrations. We consider design aspects such as higher efficiency fiber-optic-coupled diode pump lasers, fluorescence recycling, radiative shielding, and thermal linking. We contrast this with the disappointing results to date for alternative cooling materials such as dyes and semiconductors.

A Pulse Tube Cryocooler with 300W Refrigeration at 80K with Operating Efficiency of 19% Carnot [10-102]

J. H. Zia
Praxair, Inc.
Tonawanda, NY

An electrically driven pulse tube cryocooler that produces 300W of refrigeration at 80K is now available from Praxair Inc. The unit reflects efforts by Praxair R&D to toward higher operating efficiencies required by commercial HTS applications. A unique in-line design philosophy along with proprietary technology developed at Praxair allows losses in the regenerator and pulse tube to be minimized, thus achieving an efficiency of 19% of Carnot. A dual opposed 'pressure wave generator' from CFIC, Inc. supplies the acoustic power to the cold head. Experimental results from refrigeration performance tests and load curves will be presented. A brief overview of continuing efforts to enhance performance, efficiency and cryocooler geometry will also be provided.

SESSION 10: SINGLE STAGE PULSE TUBES
Thursday, June 15, 2006   2:00 – 3:30 PM

Prototyping of a Large Capacity High Frequency Pulse Tube Cryocooler [10-20]

J. Tanchon, T. Trollier and A. Ravex
Air Liquide Advanced Technology Division, AL/DTA
Sassenage, France
E. Ercolani
CEA/DSM/DRFMC, Service des Basses Temperatures
Grenoble, France

A very large heat lift Pulse Tube Cooler (VLPTC) is currently under development in partnership between AL/DTA and CEA/SBT. This pulse tube cold head prototype is based on an In-Line configuration to ease the prototyping and makes use of an inertance and a buffer volume as phase shifter. The pulse tube is driven by a 8 kW flexure bearing linear compressor. The current performances will be presented and discussed for various configurations and input power.

Design of a Large Heat Lift 40 to 80 K Pulse Tube Cooler for Space Applications [10-19]

T. Trollier, J. Tanchon, J. Buquet and A. Ravex
Air Liquide Advanced Technology Division, AL/DTA
Sassenage, France;
I. Charles, A. Coynel, L. Duband E. Ercolani and L. Guillemet
CEA/DSM/DRFMC, Service des Basses Temperatures
Grenoble, France;
J. Mullie, J.Dam and T. Benschop
THALES Cryogenics B.V
Eindhoven, The Netherlands
M. Linder
European Space Agency, ESA/ESTEC
Noordwijk, TheNetherlands

A Large heat lift Pulse Tube Cooler (LPTC) is currently under development in partnership between AL/DTA, CEA/SBT and THALES Cryogenics. The Engineering Model is expected to provide 2.3 W at 50 K at 10°C rejection temperature and 160 watts electrical input power to the motors of the compressor. The split coaxial design of the pulse tube cold finger and the moving magnet linear motor compressor design will be presented. The expected thermal and mechanical performances will be discussed. An Engineering Model will be delivered to ESA/ESTEC in October 2006 after completion of a qualification levels test campaign. This work is funded by the European Space Agency (ESA/ESTEC Contract N°18433/04/NL/AR) in the frame of future Earth Observation instruments development.

Sunpower's CPT60 Pulse Tube Cryocooler [10-73]

K. Wilson
Sunpower, Inc.
Athens,Ohio
D. Gedeon
Gedeon & Associates
Athens, Ohio
M. Yoshida
Smach Co. Ltd
Osaka,Japan

Sunpower, Inc. in collaboration with Gedeon Associates has developed a new model of single stage, coaxial pulse tube cryocooler, the CPT60, through funding from Smach (SMArt teCHnologies) Co., Ltd. of Osaka, Japan. The CPT60 achieves 2 W of cooling power at 60 K with 100 W of input power and 37 C reject temperature using forced air cooling in cold-end-up orientation. A dual-opposed piston configuration minimizes vibration and the coaxial cold head configuration results in a compact package and the appearance of a Stirling-style cold finger. This design uses proprietary half-wave inertance tubes for acoustic tuning that eliminates the need for a buffer volume at the end of the inertance tube. An overriding goal in the development program was to make use of Sunpowers successful Stirling cryocooler technology in two ways, 1) to use components directly available from the CryoTel MT Stirling cryocooler manufacturing line, and 2) to make customer interfaces (mainly the cold tip and vacuum flange) and the overall cryocooler appearance as similar as possible to the CryoTel MT. After successfully testing a water-cooled prototype, the CPT60 was redesigned for hermetic sealing and air cooling. Three hermetic units were produced, tested and delivered to Smach.

Pulse Tube Microcooler for Space Applications [10-85]

M. Petach, M. Waterman, E. Tward, P. Bailey*
Northrop Grumman Space Technology (NGST) Redondo Beach, CA and
*Department of Engineering Science, University of Oxford

This paper describes a new small, low mass, fast cool down pulse tube cryocooler designed for space flight cooling. The compressor is a scaled down version of Northrop Grumman Space Technology's existing line of flight qualified compressors with a mass of 600 grams. Because it is scaled from NGST's larger space compressors it has all their characteristics which result in very high reliability and low vibration, including the use of Oxford flexure springs and vibrationally balanced back to back compressor modules driven by voice coil motors. The cooler uses a split configuration with a remote coaxial cold head, although it can be readily reconfigured for an integral coldhead. The coaxial pulse tube coldhead was optimized to utilize the small swept volume of this compressor. It was also thermodynamically and mechanically optimized for rapid cool down, and it has a very low inherent thermal mass at the cold end. At 298K reject, this cooler can lift 1.1W at 77K. This paper describes this cooler, its components and interfaces and presents test data over a range of input power and reject temperature.

Proposed Rapid Cooldown Technique for Pulse Tube Cryocoolers [10-93]

R. Radebaugh, A. O'Gallagher, M.A. Lweis, and P.E. Bradley
National Institute of Standards and Technology
Boulder, CO

Some cryocooler applications, such as those for tactical military operations dealing with high temperature superconducting (HTS) magnets or generators, require faster cooldown times than what can normally be provided with a cryocooler designed to accommodate a relatively small steady-state heat load. The current approach to achieve fast cooldown is to use a cryocooler oversized for steady-state operation. This paper proposes a new method applicable only to pulse tube cryocoolers that may decrease cooldown times a factor of two or three when cooling to 50 K to 80 K from room temperature without increasing the size of the cryocooler. Such temperatures are appropriate for HTS magnets or generators. The proposed method makes use of the resonance phenomena that occurs with an appropriately sized inertance tube and reservoir volume combination. With a small reservoir, an LC resonance effect can occur, with C being the compliance (volume) of the reservoir and L being the inertance of the inertance tube. At or near resonance the input acoustic impedance to the inertance tube is low, which allows for a high acoustic power flow at the pulse tube cold end for a given pressure amplitude. When the reservoir volume is increased to its normal size, the impedance increases to the value optimized for steady-state operation. A simple ball valve can then be used to change the reservoir volume and to switch from the fast cooldown mode to the steady-state mode. The higher acoustic power flow can be accommodated by the pulse tube and regenerator when they are at or near room temperature. In most cases the higher acoustic power in the fast cooldown mode does not require additional input power to the pressure oscillator because the load impedance is a closer match to that of the oscillator compared to that of the normal load during cooldown.

Successful Qualification of the First PFM Model Space Dilution Refrigerator [11-39]

S. Triqueneaux
Air Liquide/DTA, France
J. Delmas P. Camus
CNRS/CRTBT, France
G. Guyot
IAS, France

We report the successful qualification down to 100mK of the first space dilution refrigerator. This dilution refrigerator will cool down the bolometers of the high frequency instrument (HFI) of the Planck Satellite for 18 months. For HFI, the required sensitivity (DT/T ~ 2.10-6) is achieved by using an array of bolometers cooled down to 100mK by an open-cycle dilution cooler. To achieve the temperature of 100mK the isotopes are pre-cooled with external cryocoolers down to 4.5K. Further cooling to less than 1.6K is achieved through an internal Joule Thomson (JT) expansion process on the mixture return line. The results obtained on the proto-flight model at JT and dilution cooler levels are compared to those obtained with the qualification model. Also discussed is the influence of the pre-cooling temperature on the performance of the dilution cooler. Potential applications of this cooler or of an upgraded version for other missions are presented.

Development of 4K-Class Mechanical Cooler for SPICA [11-96]

S. Tsunematsu
Sumitomo Heavy Industries
Niihama Ehime, Japan

SPICA (Space Infrared Telescope for Cosmology and Astrophysics) is a future mission to launch a large infrared observatory to the second Sun-Earth Lagrangian liberation point as an orbit by H-IIA rocket.A unique feature of its cryogenic system is a warm launch system using radiative cooling and closed-cycle mechanical cooler in orbit to cool down its detectors and mirrors to about 4.5K and 1.7K.4K-class cooler, which consists of two-stage Stirling cycle cooler and Joule Thomson cycle cooler with 4He as the working fluid, has been developed for cooling the Telescope to 4.5K. Designed cooling capacity of the cooler is 50 mW at 4.5K and total input power to the cooler is about 160W without driver electronics. This presentation describes the results from preliminary test of the prototype cooler for the 4K-class cooler.

SESSION 11: SUB 10K SPACECOOLERS

Friday, June 16, 2006   8:00 – 9:30 AM

Ball Aerospace 4-6 K Space Cryocooler [11-45]

D. S. Glaister, W. Gully, R. Ross, P. Hendershott, E. Marquardt, V. Kotsubo

Ball Aerospace & Technologies Corporation

Boulder, CO

This paper describes the design, development, testing and performance at Ball Aerospace of a long life, 4-6 K temperature space cryocooler. For temperatures to 4 K and below, Ball has developed a hybrid Stirling/J-T (Joule-Thomson) cooler. The hybrid cooler has been verified in test to 3.5 K on a Ball program to study the J-T system, and a complete system test with the Stirling precooler and J-T cooling loop has been completed on the NASA/JPL ACTDP (Advanced Cryocooler Technology Program). This system test has shown that the Ball 4-6 K cooler can meet all the requirements of the JWST Mid-Infrared Instrument (MIRI) cooler including a minimum 70 mW at 6 K and 77 mW at 18 K. The ACTDP cooler provides simultaneous cooling at 6 K (typically, for either doped Si detectors or as a sub-Kelvin precooler) and 18 K (typically, for optics or shielding) with cooling stages also available at 40 and 180 K (typically, for thermal shields or other components). In the last year, the ACTDP cooler has become the baseline cooling method for the NASA JWST MIRI mission in addition to uses on several other future NASA missions. The 4-6 K Cooler is highly leveraged off previous Ball space coolers including multiple life test and flight units.

SESSION 11: SUB 10K SPACECOOLERS
Friday, June 16, 2006 8:00 – 9:30 AM

NGST Advanced Cryocooler Technology Development Program (ACTDP) Cooler System [11-82]

D. Durand, R. Colbert, C. Jaco, M. Michaelian, T. Nguyen, M. Petach and E. Tward
Northrop Grumman Space Technology (NGST)
Redondo Beach, CA

The NGST ACTDP cooler features a 5-6 K Joule-Thomson (JT) cooler pre-cooled by a three-stage Pulse Tube (PT) cryocooler. Our design provides remote cooling of ~60 mW at 5 to 6 K and optional remote cooling at ~18 K. The NGST ACTDP cooler was developed under contract with the Jet Propulsion Laboratory to enable active cooling of instruments including large space telescopes, in particular the Mid Infra Red Instrument (MIRI) of the James Webb Space Telescope (JWST). This paper describes the design of the NGST ACTDP cooler and presents test results, including the integrated tests of the two major subsystems making up the thermal-mechanical cryocooler, the closed loop JT cooler and the PT pre-cooler. Both the JT and PT subsystems have been demonstrated to provide the cooling required for MIRI in laboratory tests using flight like hardware with considerable margin. The performance and high efficiency of the pulse tube pre-cooler and the integrated cooler system will be reported.

Vibration Free 4.5 K Sorption Cooler [11-53]

J. F. Burger, H. J. Holland, G. C. F. Venhorst, R. J. Meijer, T. T. Veenstra, H. J. M. ter Brake, H. Rogalla, P. M.Coesel(1), D. Lozano-Castello(2) and A. Sirbi(3)
University of Twente, The Netherlands
(1) Dutch Space, The Netherlands
(2) University of Alicante, Spain
(3) ESA-ESTEC, The Netherlands

At the University of Twente, a breadboard 4.5 K sorption cooler is being developed which has no moving parts and, therefore, is essentially vibration-free. Moreover, it has the potential of a very long life. This cooler is a favorite option for missions such as ESA's Darwin mission, which is a future space interferometer consisting of a few free flying telescopes and a central beam combiner. Because of the optics involved, hardly any vibration can be tolerated. The cooler consists of a hydrogen stage cooling from 80K to 14.5K and a helium stage establishing 10mW at 4.5K. Both stages use micro-porous activated carbon as the adsorption material. The two cooler stages need 8W of input power and are heat sunk at two passive radiators at temperatures of about 50 and 80K. We developed and built a demonstrator of the helium stage under an ESA-TRP contract. This demonstrator has four sorption compressor cells in stead of the eight cells in the full design and, therefore, has a cooling power of 5mW. In the paper, the design of the cooler system and its components will be summarized. Also, some attention will be paid to the demonstrator integration. After that, the test experiments on the 4.5K helium stage will be presented and discussed.

Flight Acceptance Testing of the Two JPL Planck Sorption Coolers [11-4]

D. Pearson, B. Zhang, M. Prina, C. Paine, G. Morgante
Jet Propulsion Laboratory California Institute of Technology
Pasadena, CA
P. Bhandari, R. Bowman, A. Nash
INAF/ISAF-Sezione
Bologna, Italy

The Jet Propulsion Laboratory has built and delivered two continuous closed cycle hydrogen Joule-Thomson (JT) cryocoolers for the ESA Planck mission, which will measure the anisotropy in the cosmic microwave background. The sorption cooler provides cooling in two different locations: it directly cools the Planck Low Frequency Instrument (LFI) below 22.5K while providing a pre-cooling stage for a 4 K JT cooler for the High Frequency Instrument (HFI) below 19 K. The temperature stability at the LFI interface is required to be less than 100 mK while that of the HFI must be below 450 mK. The two coolers have been designed to provide 650 mW and 200 mW for the LFI and HFI respectively, with a total input power of 470 W, excluding electronics. The performance of these coolers is mainly a function of the compressor interface and final pre-cooling stage temperatures. We present results from the testing of these two coolers for the input power, cooling power, temperature, and temperature fluctuations over the flight allowable ranges for these interfaces.

Optimal Control Strategies for a Rectified Continuous Flow Loop Interfaced with a Distributed Load [12-28]

H. Skye, G. Nellis, S. Klein,
Cryogenic Engineering Lab University of Wisconsin
Madison, WI
J. Maddocks
Atlas Scientific
San Jose, CA

Distributed loads are frequently encountered in large deployable structures used in space applications such as optical mirrors, actively cooled sunshades, and focal plane electronics. An innovative mechanism for providing distributed cooling is investigated experimentally and analytically that uses an oscillatory pulse-tube cryocooler that is integrated with a fluid rectification system consisting of check-valves and buffer volumes in order to extract a small amount of continuous flow. This continuous flow allows relatively large loads to be accepted over a long distance with a small temperature difference and has advantages relative to vibration and electrical isolation. The same working fluid, helium, can be used throughout the entire system, reducing complexity and simplifying the contamination control process. It is possible to provide rapid and precise temperature control via modulation of the flow rate; this paper specifically investigates the capability of the rectifying interface to control the temperature of a distributed load in the face of various disturbances. The temperature regulation is enabled using a temperature feedback control of a throttle valve placed in the loop. The control parameters are selected using root locus and Bode plot techniques. The predicted and measured controlled transient behaviors are compared. The experimental data are used to demonstrate the thermal management concept and illustrate how it can be used for rapid and precise automatic temperature control of distributed loads.

Cryocooler Performance Estimator [12-9]

Peter Kittel
Consultant
Palo Alto, CA

Recently several studies were published that made use of a simple cryocooler model to perform trades between active and passive cryogenic propellant storage systems for space missions. This paper described the cryocooler model. The model is based on published databases and performance correlations of actual commercial, space flight, and flight-like cryocoolers. The objective was to develop a tool to estimate the cryocooler requirements and performance for a concurrent engineering based feasibility study. This environment only permits rapid (time scale of seconds to minutes) analyses. This precludes using full cryocooler optimization tools that typically require hours to days to run or using the real performance of the flight coolers that do not yet exist. These options are reserved for the more detailed analyses that occur in later stages of developing a mission. The approach is to combine the underlying physics of coolers with experience based correlations. There is extensive experience with coolers for liquid oxygen (LOx, 80 K nominal). Unlike the LOx coolers, there is only limited data on low temperature flight-like liquid hydrogen (LH2, 20 K nominal) coolers. Hence, we will use data from detailed cryocooler models and from commercial coolers to supplement the available database. The experienced base correlations and model results will be interpolated based on the Carnot efficiency relation. While the models discussed here were developed for the storage of the cryo-propellants, LOx and LH2, the models are quite general and can be easily extended to other applications requiring single or multistage coolers. These models were based on the current state-of-the-art. As cooler technology progresses, the correlations used here will need to be updated to keep current.

Multistage Stirling Cycle Refrigeration Performance Mapping of the Northrup Grumman High Capacity Cooler [12-88]

E. Pettyjohn and T. Roberts
Air Force Research Laboratory, Cryogenics Laboratory
Kirtland AFB, NM

The performance mapping of a multistage Stirling-Pulse Tube cycle refrigeration system has been performed on the Northrop Grumman High Capacity Cooler (NG HCC) cryocooler by the Air Force Research Laboratory. This cooler design uses two pulse tube cold ends in parallel. The 85 K cold end is thermally strapped to the regenerator housing of the 35 K cold end in order to boost 35 K cooling capacity. The as delivered performance was tailored to support long wave infrared (LWIR) HgCdTe focal plane arrays and their associated optical systems, but this particular refrigeration system can also support a variety of short or medium wave infrared sensing as well as high temperature superconducting electronics applications. The results are presented for both steady state and transient performance envelopes for this cooler which has an as delivered design point of 2 Watts of cooling at 35 K and 17 Watts at 85 K. These results are presented both as empirical data and as interpolating function estimates of the entire performance envelope. Results are also given for a mapping of the heat rejection interface performance to support a redesign of that refrigeration system component.

Development of a Cryocooler System to Provide Zero Boil-off of a Propellant Tank [12-97]

D. Frank, E. Roth, B. Sompayrac, J. Olson and T. Nast
Lockheed Martin Space Company
Palo Alto, CA

Lockheed Martin has been developing advanced technology to provide cooling of a cryogenic propellant tank in order to achieve zero boil-off during orbital storage periods. Present plans for long duration flights show large amounts of propellant loss due to parasitic heat loads during long in-flight storage periods. A single stage Pulse Tube cryocooler has been integrated with a cryogenic methane tank at Lockheed Martin in Denver. The cryocooler provides a flow loop of cold gas that circulates in the storage tank and is used to absorb the parasitic heat load thus allowing the tank to remain non-vented. The cryocooler is remote from the cooling loop simplifying system integration. The integral flow loop uses the same working gas as the pulse tube. This flow loop is driven by the same compressor, which is used to provide the pressure wave to the pulse tube cold head, an approach that adds very little complexity to the overall system. The flow loop utilizes unidirectional (dc) flow to provide cooling at temperatures near 110 K at the remote cooling location. All cooling is provided by the pulse tube cooler, so that the remote cooling mechanism is forced convection. This paper describes the results from a flow loop developed and tested on a 635 liter cryogenic methane tank as a technology demonstrator.

G-M Type Two-Stage Pulse Tube Cryocooler for Cryopump [12-52]

S-J Park, Y-J Hong and H-B Kim
Korea Institute of Machinery & Materials,
Daejeon, Korea

The small cryocooler is being widely applied to the areas of superconducting, infrared detector, satellite communication and cryopump. The pulse tube cryocooler, which has no moving parts at its cold section, is attractive in obtaining higher reliability, simpler construction, and lower vibration than any other small cryocoolers. Many efforts have been made world-wide over more than 15 years in developing pulse tube cryocoolers in place of conventional Stirling and G-M cryocoolers for applications in which cooling to low temperature less than 80 K is necessary for many sensors, device and systems. Korea Institute of Machinery & Materials (KIMM) has developed G-M type and Stirling type pulse tube cryocooler since 1992. The developments in KIMM on the pulse tube cryocooler systems have focused primarily on refrigeration capacity, efficiency and performance reliability as well as mechanical reliability. The purpose of this study is to provide reliable, efficient and long life cryocoolers for cooling systems in cryopump and other applications. The G-M type two-stage pulse tube cryocooler consists of a helium compressor, a pulse tube, regenerator, orifice, double inlet valve, a buffer (reservoir) volume and vacuum chamber. This paper describes the two-stage pulse tube cryocoolers designed for cooling arrays of the cryopump and their performance characteristics.

Helium-Liquefaction by Cryocooler for High-Field Magnets Cooling [12-71]

Y-S. Choi, D-L. Kim, B-S. Lee, H-S. Yang, T. A. Painter, A. J. Trowell, J. R. Miller
KBSI-NHMFL RCC
Tallahassee, FL

An experiment to liquefy helium by two-stage pulse-tube cryocooler is performed. This study is motivated mainly by our recent development of closed-loop cooling system for 21 T Fourier Transform Ion Cyclotron Resonance (FT-ICR) superconducting magnets without any replenishment of cryogen. Since the cold surface of a cryocooler is very limited, a cylindrical shape of copper fin is thermally anchored to the first and second stage coldhead in order to serve as an extended surface. A heat exchanger tube is attached on the outer surface of each copper cylinder and heat exchange occurs between tube and helium gas which is passing through the tube. The temperature distributions along the copper cylinder and heat exchanger tube are measured in steady state and compared with the numerical analysis. The effect of mass flow rate of helium and cooling capacity (or heating power to coldhead) of cryocooler on the liquefaction rate is also investigated.

Air Force Research Laboratory Space Cryogenic Technology Research Initiatives [12-42]

F. Roush and T. Roberts
Air Force Research Laboratory,
Kirtland AFB, NM

The Air Force Research Laboratory (AFRL) Space Vehicles Directorate actively pursues cryogenic refrigeration system and system integration technology research to support the research needs of the Air Force, Missile Defense Agency, and Department of Defense. This effort takes place using a technology development strategy emphasizing definition of current requirements to support these customers, procurement of the needed technology, and evaluation of the delivered hardware and software so that the future customer requirements can be anticipated and technically satisfied. The balance between research into refrigeration performance, refrigeration capability envelope enhancement, and integration facilitation methods critically affects the short and immediate term results of this long term strategy. Incorporation of supplier suggestions on nascent technology development opportunities into long term development planning completes this technology management process. This process is shown in its historical context and extrapolated into the future by projecting current trends and near term customer projected needs.

Development of a 0.5W/40K Pulse Tube Cryocooler for Infrared Detector [12-7]

G. P. Wang(1,2), J. H. Cai(1), N. Li(3), W. Jing(1) L. W. Yang(1) and J. T. Liang(1)

(1) Technical Institute of Physics and Chemistry, CAS, Beijing, China; (2)Graduate University of Chinese Academy of Sciences, Beijing , China; (3) National Lab. for Infrared Physics, Shanghai Institute of Techinical Physics, CAS, Shanghai, China

Along with the commercialization of High Temperature Superconductors (HTS) devices in fields such as mobile communications, and the development of very long wavelength infrared devices for space and military applications, it arises a strong demand for simple and high reliable cryocoolers working at 40-80K.The Stirling-type pulse tube cryocooler (PTC) has the potential to achieve high reliability and long-life time because it operates without a moving displacer at cold end. Based on the linear Oxford type compressor, it generally operates at frequencies from 30 to 60Hz and provides cooling power from 30-100K temperature range. Cryocoolers for cooling normal long wave infrared detector usually work at 80K or at slightly higher temperature and the cooling power is usually from scores of milliWatts to a few watts. With the development of very long wavelength infrared devices such as Quantum Well Infrared Photodetectors, lower temperatures such as 40K is necessary for these devices to work properly. It is reported that the development of pulse tube cryocooler that was designed for operation on an existing linear compressor (Leybold Polar SC 7). Its maximum swept volume is 10cm3. A U-shaped PTC has reached a minimum no-load temperature of 34.8K, and achieved cooling power of 420mW at 40K with inertance tube and double-inlet configuration. Several matching experiments between the PTC and the infrared device have been done. The results of these experiments showed that the infrared devices could work at 38.5K temperature stably. It is proved that the infrared focal plane array can be cooled down and kept working at 40K with the single-stage Stirling-type pulse tube cryocooler.

Cryogenic Refrigeration Cycle for Re-Liquefaction of LNG Boil-off Gas [12-27]

J. W. Moon(1), Y. W. Jin(2), Y. P. Lee(1), E. S. Hong(3), H. M. Chang(4)
(1) Thermal Flow Control Reasearch Center, KIST, Seoul, Korea; (2) School of Mechanical Engineering, Korea University of Technology and Education, Chungnam, Korea: (3) Shinyoung Heavy Industries CO.,LTD., Junnam, Korea; (4) Mechanical System & Design Engineering, Hong Ik University, Seoul, Korea

In recent years, there has been a significant increase in the level of interest on environmentally friendly and economically viable solutions for the transport of liquid Natural Gas (LNG). Actually, The LNG is shipped on vessels propelled by steam turbines and the LNG boil- off gas (BOG) burned on the boiler or vented. The LNG process chain has been optimized in the last years whilst the LNG Tankers design remained installing conventional steam turbines. The steam turbine high consumption compared to last-generation diesel engines will eventually motivate their replacement encouraged also by environmental concerns and future regulation.' As a result of the improvements on the insulation techniques, the BOG produced as a result of natural vaporization has been reduced, and the amount of BOG is therefore insufficient to satisfy the vessel consumption motivated by the existing power generation system. Further to LNG forced vaporization and the use of HFO as auxiliary fuel, the design and construction of new LNG tankers with different propulsion system such as diesel electric engine the use of BOG re-liquefaction plants is herewith proposed as the way forward. The objective of the present paper is to address the development of liquefaction processes for BOG plants in order to provide environmentally friendly and cost effective solutions for gas transport. Cycle analyses were performed for Brayton, Claude and Kaptiza refrigeration cycles by a numerical method. It was found out that there exist unique optimum values for the ratio of expanded mass through the turboexpanders to the total mass.

SESSION 12: CRYOCOOLER APPLICATIONS
POSTER SESSION 4

Friday, June 16, 2006 9:30 – 11:00 AM

Development of Detachable Cooling System for HTS Floating Coil [12-104]

T.Kuriyama, Y.Ohtani, T.Tosaka, M.Ono, S.Mizumaki, N.Tachikawa, J.Morikawa, Y.Ogawa and Z.Yoshida
Toshiba Corporation /University of Tokyo
Japan

This paper describes a design and test results of a detachable cooling system for an HTS floating coil in the RT (Ring Trap)-1 project at the University of Tokyo. RT-1 is an experimental device for the purpose of a high-beta plasma confinement research. The HTS coil in a persistent current mode is levitated in a plasma vacuum chamber during a plasma experiment for several hours. A cooling device such as cryocoolers or liquid helium can not be installed on the coil for the purpose of a reduction of weight. The cooling system which consists of two stage GM cryocoolers and helium gas circulation pumps must be detached from the coil when it is floating. The HTS coil and a radiation shield were initially cooled down to 20 K level by the circulated helium gas cooled by GM cryocoolers. Then the cooing system is detached and the HTS coil is levitated. During the experiments, the coil and the thermal shield temperatures increased because of the thermal loads from room temperature. The HTS coil can be energized in a persistent current mode until the coil temperature reaches the critical temperature of 32 K for about 8 hours Cryocoolers performances and the detachable cooling system are introduced. The experiment results of the cooling characteristics of the floating HTS coil are also presented.

SESSION 12: CRYOCOOLER APPLICATIONS
POSTER SESSION 4
Friday, June 16, 2006 9:30 – 11:00 AM

Research on Improvement in the Efficiency of the GM Refrigerator [12-92]

H. Nakagome
Department of Urban Environment System, Chiba University
Japan
T. Okamura
Department of Energy Sciences, Tokyo Institute of Technology
Japan

Conversion into Hydrogen Energy Society is advanced focusing on the application to a fuel cell electric vehicle. As volume and weight density of liquid hydrogen are large, it is the method which was most excellent as the storage method of hydrogen. However, in order to store liquid hydrogen stably over a long period of time, decreasing the loss of energy, development of an efficient small cryocooler becomes important. On the other hand, progress of a superconducting system in recent year is remarkable. Therefore, improvement in the refrigeration efficiency of 4K cryocooler is called for strongly. This paper reports the research about improvement in the refrigeration efficiency of a two-stage GM cryocooler. In order that the GM cryocooler may operate by the Simon expansion, it carries out asymptotic of the COP of the GM cryocooler to the Carnot COP as a compression ratio is lowered. When experimented according to this view, it was checked that refrigeration efficiency rises with reduction in a compression ratio. Furthermore, if the compression ratio is lowered, refrigeration efficiency will fall rapidly it was verified by optimization of the compression ratio of the GM cryocooler that refrigeration efficiency can be improved significantly. Therefore, by applying the result of this research, sharp reduction of the energy consumption of a liquid hydrogen system and a superconducting system will be attained.

Design and Analysis of Distributed Cooling Networks [12-89]

J. R. Feller L. J. Salerno
NASA-Ames Research Center
Moffett Field, CA
P. Kittel
University of California, University Affiliated Research Center
Moffett Field, CA,
A. KashaniB. Helvensteijn
Atlas Scientific
San Jose, CA

Future NASA missions will require long-term storage of cryogenic propellants. In certain scenarios cryocooler integration, enabling reduced boil-off (RBO) or zero boil-off (ZBO) propellant storage, becomes a viable design option. Distributed cooling networks capable of conveying heat to the cryocooler cold head from remote areas of a spacecraft would further extend the applicability of active cooling. Various distributed cooling strategies will be discussed. Of particular interest is the concept of the broad area cooling (BAC) network. A BAC network consists of one or more loops of small-diameter tubing within which cold gas is circulated. Heat exchange takes place over the entire length of each loop; this allows for efficient cooling of large surface areas, such as propellant tank walls and thermal radiation shields. The primary focus of this paper is a description of the design and analysis of a ZBO subsystem for a ground-based cryogenic propellant storage test bed that employs a BAC network to actively cool a low-mass thermal shield. The viability, in terms of mass and power requirements, of this technology for in-space use will be examined.

Modeling, Development and Testing of a Small-Scale Collins Type Cryocooler [13-26]

C. L. Hannon, B. Krass and J. Gerstmann
Advanced Mechanical Technology, Inc.
Watertown, MA
G. Chaudhry, J. G. Brisson and J. L. Smith Jr.
Massachusetts Institute of Technology
Cambridge, MA

A multi-stage 10K cryocooler is under development that is based upon a novel modification of the Collins cycle, a cycle commonly used in many large-scale high-efficiency cryogenic machines. This cryocooler design achieves compactness and reliability by using modern microelectronics to enable complex valve timing in a mechanically simple yet efficient cold head design. This cycle is particularly well suited for cryocoolers operating in a temperature range from 4K up to about 30K. The modular nature of this design enables the configuration of application specific two stage (30 K), three stage (10 K), and four stage (4 K) cryocoolers. Innovations of the design include floating piston expanders and electromagnetic smart valves, which eliminate the need for mechanical linkages and thereby reduce the input power, size, and weight of the cryocooler in an affordable modular design. A sophisticated LabView based control algorithm enables electronic control of the expansion cycle. Software based control enables variable valve timing and adaptive control logic. An engineering prototype has been built that integrates a floating piston expander and recuperative heat exchanger as a functional cryocooler stage. This prototype cryocooler stage has been tested in two configurations. Initial testing was as a balanced flow single stage cryocooler. The second configuration represented the third (lowest temperature) stage of a three stage 10K cryocooler. In this configuration a precooling stream was added to the low temperature side of the heat exchanger to create the unbalanced flow condition that characterizes the Collins cycle. This paper will review the design of the engineering prototype, the results of analytical modeling, prototype development testing, and the direction of future development.

Demonstration of a Novel Brayton Cycle Cryogenic Expander [13-105]

S. Nieczkoski, B. Nguyenphu, D. Petrick, and R. Mohling
Technology Applications Inc.
Boulder CO

A direct-flow reciprocating expander has been developed and demonstrated for use in a Brayton cycle cryocooler. The cryocooler development effort focused on a novel cryogenic expansion device to achieve highly efficient cooling at target temperatures of 35 K and below. The expansion device is a reciprocating piston which cools the circulating refrigerant by extracting energy through electrostatic discharge. Extremely high-precision manufacturing steps were employed to construct an electrical structure capable of generating the variable capacitor features necessary to perform energy extraction in the expansion process. Electrostatic valves regulate refrigerant flow into and out of the expander. These devices also rely upon unique dielectric and micro-machining processes to enable operation at cryogenic temperatures. Fabrication and test results describe a method of producing expander components by employing micro-fabrication methods to achieve miniaturization and high reliability. Advancements include high capacitance thin films, electrostatic flow control valves, and rapid high-voltage switching of dynamic capacitive structures. Micro- machining processes developed for the expander include laser ablation, ceramic grinding, chemical mechanical polishing, and micron-scale thermal expansion matching of materials. Results indicate a revolutionary advancement in providing a low vibration, low mass method of generating cooling at remote locations when the expander is combined with a recuperative heat exchanger. A new generation of Brayton cycle cryocooler technology is now available through micro-scale extraction of fluid energy using the reciprocating expander device. Complete integration of the expander with a circulating compressor and recuperative heat exchanger will enable high efficiency cryocoolers capable of larger heat lift at remote locations than existing regenerative cryocooler technology.

A Recuperative Heat Exchanger for Space-Borne Turbo-Brayton Cryocoolers
[13-78]

R. W. Hill and M. V. Zagarola
Creare Incorporated
Hanover NH

The recuperative heat exchanger in turbo-Brayton cryocoolers is often the largest and heaviest cryocooler component, and its performance has a direct impact on the available cooling, and consequently, the cycle efficiency. The design of this component is also quite challenging as structural constraints associated with vibration loads are often in conflict with thermal constraints for low axial conduction. Creare has developed the only space qualified recuperator for turbo-Brayton cryocoolers. This recuperator is currently installed on the Hubble Space Telescope as part of the NICMOS cryocooler, which has operated on-orbit for over 4 years without degradation. The NCS recuperator technology has demonstrated extremely high thermal performance and structural robustness. The recuperator went through extensive structural tests prior to installation including two random vibration tests, two shuttle launches, and one shuttle landing. Under support from NASA and MDA, Creare has been developing the next generation recuperator technology. The advanced recuperator technology is based on silicon slotted plates as the heat transfer elements to provide high stream-to-stream conductance and lightweight. An innovative core construction minimizes axial conduction and supports the core against launch vibrations. The resulting recuperator is predicted to provide the same high thermal performance as the NCS recuperator for a fraction of the size and weight. This paper reviews the recuperator design, and the results of vibration and thermal tests.

Thermoacoustic Expansion Valve: A New Type of Expansion Component to Enhance Performance of Recuperative Cryocooler Systems [13-59]

Z. Hu
CryoWave Advanced Technology, Inc.
Pawtucket, Rhode Island

The new thermoacoustic expansion technology and its device, thermoacoustic expansion valve (TEV), are introduced in this paper. Distinguished from existing thermoacoustic refrigeration technologies which drive noble gas such as helium by heat or mechanical pistons in the closed cycle, this technology directly removes heat from cold stage expansion in recuperative cooler systems without moving parts and limit on the expansion gases. Stringent requirements on reliability and free of vibrations raise challenges to fabricate cryocoolers running efficiently. Thus the cryocoolers that have no moving parts at the cold stage, such as pulse tube cooler, Joule-Thomson cooler, and sorption cooler systems, are the ideal alternatives to satisfy the long term mission target. Recuperative cryocooler systems intrinsically rely on expander components at the cold end to produce refrigeration by the reduction of cycle pressure. Ultimately, only two types of expander components can be used in all recuperative cryocooler: "Isenthalpic types of expander components such as J-T valve, capillary tubes, and porous plugs, "Isentropic types of expander components such as turbine-expanders The former has no moving parts and the worst efficiency yet it has high reliability and simplicity. The latter can extract the energy to obtain higher efficiency than J-T valves but it requires precise moving structures which could penalize its reliability and efficiency gains. The both expanders have shortfalls to meet the efficiency and reliability goals of cryocoolers for space applications. Thermoacoustic expansion valves (TEVs) integrate the merits of both devices (no moving parts and heat extraction), to provide the new solution that enable to enhance cooling performance by extracting heat from cold stage in recuperative cryocoolers while retaining the simplicity and reliability of its structure. TEVs mechanism, the refrigeration cycle to use TEV, and the preliminary experiments on its cooling performance vs. JT valves are presented in this paper.

Carbon Dioxide Flash-Freezing Process Applied to Ice Cream Production [13-108]

T. Baker, J. G. Brisson and J. L. Smith, Jr.
Massachusetts Institute of Technology
Cambridge, MA

Ice cream can be flash-frozen using carbon dioxide as a direct-contact refrigerant. An emulsion of ice cream mix and liquid carbon dioxide are throttled to the saturated carbon dioxide pressure associated with the desired temperature of the frozen ice cream. A proof-of-principle apparatus was built to test the process. In the apparatus, the emulsion is formed and throttled by atomizing fuel nozzles. A powdery, carbonated ice cream product is obtained. The process and resulting product will be described and compared to ice cream frozen by conventional methods. Potential advantages of the flash-freezing process include energy savings, novel texture and consistency, and opportunities to produce ice cream in new venues. The product characteristics can be changed by varying the inlet and outlet conditions applied to the process. For example, the ice cream-carbon dioxide emulsion can be flashed to atmospheric pressure in the presence of excess carbon dioxide. Under these conditions the initial ice cream product may contain powdered dry ice formed at 194 K.

A Novel Three-Stage 4 K Pulse Tube Cryocooler [14-37]

C. Wang
Cryomech, Inc.
Syracuse, NY

A three-stage pulse tube cryocooler has been successfully developed at Cryomech, Inc. to provide three cooling capacities at the temperatures around 45K, 15K and 4K. The three-stage PTC uses a new configuration which makes it simple for the design and manufacture than traditional three-stage PTC. The room temperature parts and flow control unit of this three stage PTC are the same as our standard two- stage PTC, Model PT410. The three stage pulse tube cryocooler reaches the bottom temperatures of 28K, 8.8K and 2.41K on three stages in 70 min. It provides 40W@45K, 15W@15K and 0.32W@4.2K simultaneously while consuming 11.7 kW electrical powers. It has demonstrated very stable operation during all tests.

Free Third Stage Cooling for Two Stage 4K Pulse Tube [14-18]

A. Ravex and T. Prouve
AIR LIQUIDE Division Techniques Avancees
Sassenage, France

The Helium enthalpy variation with temperature and pressure in the operation range of 4K cryocoolers is by far different from ideal gas. This real gas behavior leads to large irreversibility in the regenerator operation. It is theoretically possible to reduce the associated losses and recover some "free" cooling power by implementing appropriate heat intercepts in the regenerator. We have experimentally confirmed this capability with a commercial 4K Pulse Tube cooler. Several hundreds mW of "free" cooling power in the temperature range of 6K to 20K have been obtained without any degradation of 4K performances. Experimental set-up will be described and experimental results presented and discussed. A patent is pending on this technological improvement and potential applications.

Compact Two-Stage Pulse Tube Refrigerator in Coaxial Configuration Reaching Temperatures Below 7 K [14-51]

T. Koettig, R. Nawrodt, M.Thuerk, and P. Seidel
Friedrich-Schiller Universitaet Jena, Institut fuer Festkoerperphysik
Germany

We report on an all-coaxial two-stage pulse tube refrigerator for practical applications. The specific knowledge of the internal heat loss generated by the thermal contact between the pulse tube and the regenerator encouraged us to combine the two-stage arrangement with an all-coaxial design. We arranged two needle valves at the hot end of each pulse tube to create a valve controlled active type of phase shifting. The second stage regenerator matrix is composed of a lead coated screen material. Stainless steel screens with a wire diameter of 36 μm (158 meshes) were electroplated to a resulting wire diameter from 105 μm to 125 μm. using this material we designed an inhomogeneous regenerator for the second stage altering the regenerator porosity from 0.43 to 0.35. The refrigerator reaches a no load temperature well below 7 K and provides a cooling capacity of 2 W at 9.5 K limited by an electrical input power of 6.2 kW (Compressor Leybold RW 6000). The design parameters and the influencing variables to optimize the cryocooler will be discussed.

SESSION 14: MULTI STAGE PULSE TUBES

Friday, June 16, 2006 2:00– 3:30 PM

10K Pulse Tube Cooler [14-83]

T. Nguyen, R. Colbert, D. Durand, C. Jaco, M. Michaelian and E. Tward
Northrop Grumman Space Technology (NGST)
Redondo Beach, CA

This paper presents the development of a 3-stage pulse tube cooler designed to operate at 10K. The staged cooler uses the parallel staging configuration for the 1st and 2nd stages. The 2nd and 3rd stage is in a serial configuration precooled by the first stage. The 3 stage 10K cooler is based on the previous 2 stage High Capacity Cooler (HCC). The first stage uses a coaxial cold head. The second stage is a coaxial cold head. The 3rd stage uses a u-tube configuration. The 3rd stage was designed and tested as a component and then integrated into the complete cooler. The cooler was characterized under different operating conditions and test data will be presented.

SESSION 14: MULTI STAGE PULSE TUBES

Friday, June 16, 2006 2:00– 3:30 PM

Investigation of Two-Stage High Frequency Pulse Tube Cryocoolers [14-13]

L.W.Yang, M.G.Zhao, J.T.Liang, Y.Zhou
Technical Institute of Physical and Chemistry of CAS
Beijing, China;
M. Dietrich, G.Thummes
Institute of Applied Physics, University of Giessen
Germany

Multi-stage high frequency pulse tube refrigerator is one of the newest developments of pulse tube research. Its target is to provide cooling power at very low temperature such as 20K, 10K, 4K that single- stage pulse tube refrigerator could not satisfied, or to provide cooling power at two or more temperature scope, such as 150K/80K, 60K/30K, 80K/10K/5K. In the past several years, theory and experimental research have been conducted on two-stage high frequency PTCs and some results are introduced here. At the beginning, a code based on thermal physics method is developed to optimize the parameter and design. The optimized dimension is used to setup a two stage PTC cooler. Based on this PTC, the lowest temperature of 19.6K has been acquired in 2003 in Germany. This two-stage cooler is further optimized by increase the second stage pulse tube dimension and this change further lowers the temperature and also increases the cooling power. Further, the first stage of the two-stage PTC is changed to be co-axial version for further test in China. With further improvement, this two stage PTC has reached the lowest temperature of 16K. The effects of different parameters are also investigated. The most important part of two-stage PTC is the regenerative materials for low temperature operation. We have tested different stainless steel mesh, lead spheres and lead meshes. The performance is best with SS mesh in our tests; this is different to other research group. This question has been investigated by different simulation program. Detail results will be introduced in the paper.

SESSION 14: MULTI STAGE PULSE TUBES
Friday, June 16, 2006   2:00– 3:30 PM

A Thermoacoustically Driven Pulse Tube Cooler Working Below 20K [14-101]

J. Y. Hu, E. C. Luo, W. Dai
Technical Institute of Physics and Chemistry, CAS
Beijing, China

We previously reported a thermoacoustically driven two-stage pulse tube cryocooler that was capable of achieving a lowest temperature of about 40 K. To obtain a lower temperature around 20K, we have designed a new two-stage pulse tube cryocooler. Driven by a valveless mechanical compressor, the new two-stage pulse tube cryocooler successfully achieved a lowest temperature below 20K. The optimum operating frequency for the cryocooler was found below 40Hz. However, our currently available thermoacoustic heat engine usually operates a resonant frequency of up to 70Hz when using helium gas as its working medium. To match the cryocooler, we have used an innovative configuration, which was demonstrated in a single stage pulse tube cryocooler driven by a thermoacoustic heat engine. In the current 20K thermoacoustically driven two-stage pulse tube cryocooler, a thermoacoustic-Stirling pressure wave generator uses nitrogen-helium mixture as its working gas. By adjusting the nitrogen concentration, it is readily to achieve a frequency ranging from about 20Hz to 70Hz. However, the two-stage pulse tube cryocooler must use pure helium gas. Therefore, an elastic membrane was used as the interface between the thermoacoustic engine and the cryocooler. The membrane can transport acoustic work transparently from the engine to the cooler and meanwhile allow them use different working gases. In order to protect the membrane, a delicate configuration was specially designed. Furthermore, to totally eliminate DC-flow via double-inlet passage, an innovative double-inlet with an elastic membrane was introduced with these modifications; the system could well operate below 20K.

	Tuesday June 13, 2006	Wednesday June 14, 2006	Thursday June 15, 2006	Friday June 16, 2006
7:00		Registration Begins at 7:00 AM	Registration Begins at 7:00 AM	Registration Begins at 7:00 AM
8:00 9:00		Session 1 Space Coolers 1 8:00 – 10:00 AM	Session 7 Pulse Tube Modeling 8: 00 – 10:00 AM	Session 11 Sub 10K Spacecoolers 8:00 – 9:30
10:00		Session 2 - Poster Tactical Cryocoolers – Magnetic Refrigeration 10:00 – 11:00 AM	Session 8 - Poster Regenerators – Joule Thomson Cryocoolers 10:00 – 11:00 AM	Session 12 - Poster Cryocooler Applications 9:30 – 11:00 AM
11:00		Session 3 Stirling Cryocoolers 11:00 – 12:15 PM	Session 9 Mems Based and Miniature Cryocoolers 11:00 – 12:15 PM	Session 13 Steady Flow Systems and Components 11:00 – 12:15 PM
12:15 2:00		Lunch 12:15 – 2:00 PM	Lunch 12:15 – 2:00 PM	Lunch 12:15 – 2:00 PM
2:00		Session 4 Regenerators 2:00 – 3:00 PM	Session 10 Single Stage Pulse Tubes 2:00 – 3:30 PM	Session 14 Multi-Stage Pulse Tubes 2:00 – 3:30 PM
3:00 3:30		Session 5 - Poster Pulse Tube Technology & Components and Interfaces 3:00 – 4:00 PM		
4:00 5:00		Session 6 Oscillating Flow Components 4:00 – 5:00 PM	**Conference Banquet** **Buses leave Loews starting at 4:15 PM – Last bus leaves at 4:45 PM**	
6:00 8:00	**Conference Registration and Reception at Loews Hotel** **6:00 PM – 8:00 PM**			