

Contents

Government Cryocooler Development Programs 1

- An Overview of Air Force Phillips Laboratory Cryocooler Programs** 1
*L.D. Crawford and C.M. Kalivoda, Phillips Laboratory, Kirtland AFB, NM;
D.S. Glaister, Aerospace Corp., Albuquerque, NM*
- A Case Study of a Successful Cryogenic Cooler Development Program** 11
S. Castles, NASA/GSFC, Greenbelt, MD
- The DOD Family of Linear Drive Coolers for Weapon Systems** 17
H. Dunmire and J. Shaffer, Night Vision & Electronic Sensors, Fort Belvoir, VA
- And What about Cryogenic Refrigeration?** 25
M. Nisenoff, NRL, Washington, DC; F. Patten and S.A. Wolf, DARPA, Arlington, VA

Space Stirling Cryocooler Developments 29

- Prototype Spacecraft Cryocooler Progress** 29
K.D. Price, M.C. Barr, and G. Kramer, Hughes Aircraft Co., El Segundo, CA
- Hughes Aircraft Company SSC I & II Performance Mapping Results** 35
*T. Roberts, Phillips Laboratory, Kirtland AFB, NM; J. Bruning, NRC Consultant,
Leasburg, MO*
- Development and Demonstration of the Creare 65 K Standard Spacecraft Cryocooler** 45
W.D. Stacy, Creare, Hanover, NH; T. Pilson, A. Gilbert and J. Bruning, Phillips Laboratory, Kirtland AFB, NM
- Test Results for the Ball Single-Stage Advanced Flight Prototype Cryocooler** 55
W.J. Horsley, D.W. Simmons and J.A. Wells, Ball Aerospace, Boulder, CO
- The Batch Manufacture of Stirling-Cycle Coolers for Space Applications Including Test, Qualification, and Integration Issues** 59
B.G. Jones, S.R. Scull, Matra Marconi Space, UK; and C. Jewell, ESA, The NETHERLANDS
- System Test Performance for the Ball Two-Stage Stirling-Cycle Cryocooler** 69
D. Berry, H. Carrington, W.J. Gully, M. Luebbert and M. Hubbard, Ball Aerospace, Boulder, CO

Improvements to the Cooling Power of a Space Qualified Two-Stage Stirling Cycle Cooler	79
<i>T.W. Bradshaw, A.H. Orłowska, RAL, UK; C. Jewell, ESA, The NETHERLANDS; B.G. Jones and S. Scull, MMS, UK</i>	
Design and Development of a 20 K Stirling-Cycle Cooler for FIRST	89
<i>S.R. Scull, B.G. Jones, Matra Marconi Space, UK; T.W. Bradshaw, A.H. Orłowska, Rutherford Appleton Laboratory, UK; and C.I. Jewell, ESA, The NETHERLANDS</i>	
Tactical/Commercial Stirling Cryocoolers	97
Path to Low Cost and High Reliability Stirling Coolers	97
<i>V. Loung, A. O'Baid and S. Harper, Superconductor Technologies, Inc., Santa Barbara, CA</i>	
Miniature Long Life Tactical Stirling Cryocoolers	109
<i>C.R. Aubon and N.R. Peters, The Hymatic Engineering Co., Worcestershire, UK</i>	
Experimental and Predicted Performance of the BEI Mini-Linear Cooler	119
<i>D.T. Kuo, A.S. Loc and S.W.K. Yuan, BEI Sensors and Systems Co., Sylmar, CA</i>	
Space Qualification Test Plan Development, Implementation, and Results for the STRV-2 1.0-watt Tactical Cryocooler	127
<i>K.S. Moser, NRC, Albuquerque, NM; T.P. Roberts, Phillips Laboratory, Kirtland AFB, NM; and R.M. Rawlings, Texas Instruments, Dallas, TX</i>	
Stirling Cryocooler Research and Theory	139
Reduction of Surface Heat Pumping Effect in Split-Stirling Cryocoolers	139
<i>A.A.J. Benschop, F.C.v. Wordragen and P.C. Bruins, Signaal-USFA, Eindhoven, The NETHERLANDS</i>	
A Stirling Cycle Analysis with Gas-Wall Heat Transfer in Compressor and Expander	147
<i>J.S. Park, H.-M. Chang, Hong Ik University, Seoul, KOREA</i>	
Cyclic Simulation of Stirling Cryogenerator with Two-Component Two-Phase Fluid	157
<i>K.P. Padwardhan and S.L. Bapat, Indian Institute of Technology, Bombay, INDIA</i>	
Cryocooler Transient Performance Modeling	163
<i>T. Roberts, Phillips Laboratory, Kirtland AFB, NM</i>	
Pulse-tube Cryocooler Developments	173
New Mid-Size High Efficiency Pulse Tube Coolers	173
<i>W.W. Burt and C.K. Chan, TRW, Redondo Beach, CA</i>	
Performance Characterization of the TRW 3503 and 6020 Pulse Tube Coolers	183
<i>D. L. Johnson, S. A. Collins, M. K. Heun, and R. G. Ross, Jr., JPL, Pasadena, CA</i>	

Performance of the AIRS Pulse Tube Engineering Model Cryocooler	195
<i>C.K. Chan, C. Carlson, R. Colbert, T. Nguyen, J. Raab and M. Waterman, TRW, Redondo Beach, CA</i>	
Advanced Pulse Tube Cold Head Development	203
<i>C.K. Chan, C. Jaco, and T. Nguyen, TRW, Redondo Beach, CA</i>	
50-80 K Pulse Tube Cryocooler Development	213
<i>L. Duband, A. Ravex, CENG/SBT, FRANCE; T. Bradshaw, A. Orłowska, Rutherford Appleton Laboratory, UK; C. Jewell, ESA, The NETHERLANDS; B. Jones, Matra Marconi Space, UK</i>	
80 K Miniature Pulse Tube Refrigerator Performance	223
<i>M. David, Air Liquide, Sassenage, J-C Maréchal, Ecole Normale Supérieure, Paris, FRANCE</i>	
Development of a Low-Cost Cryocooler for HTS Applications	229
<i>S.C. Russo, G.R. Pruitt, Hughes Aircraft Co., El Segundo, CA</i>	
An Experimental Investigation of the Pulse Tube Refrigerator	239
<i>D.Y. Koh, S.J. Park, S.J. Lee, H.K. Yeom, Y.J. Hong and S.K. Jeong, Korea Institute of Machinery and Materials, Daejeon, KOREA</i>	
Pulse Tube Refrigerator and Nitrogen Liquefier with Active Buffer System ...	247
<i>Y. Kakimi, S.W. Zhu, T. Ishige, K. Fujioka, Daido Hoxan, JAPAN; and Y. Matsubara, Nihon Univ., JAPAN</i>	
Two-Stage Double-Inlet Pulse Tube Refrigerator down to 10 K	255
<i>S. Wild, L.R. Oelrich, Univ. Karlsruhe; and A. Hofmann, Forschungszentrum Karlsruhe, GERMANY</i>	
 Pulse Tube Cryocooler Configuration Investigations	 261
Early Pulse Tube Refrigerator Developments	261
<i>R.C. Longworth, APD Cryogenics, Allentown, PA</i>	
Phase Shift Effect of the Long Neck Tube for the Pulse Tube Refrigerator	269
<i>S.W. Zhu, Daido Hoxan, Ibaraki, JAPAN; S.L. Zhou, N. Yoshimura and Y. Matsubara, Nihon Univ., Chiba, JAPAN</i>	
Experimental Study on the Pulse Tube Refrigerator with Two Relief Valves ...	279
<i>Y. Hagiwara, S. Yatuzuka, and S. Ito, Advanced Mobile Telecommunication Technology Inc., JAPAN</i>	
Experiments on the Effects of Pulse Tube Geometry on PTR Performance	285
<i>C.S. Kirkconnell, S.C. Soloski, and K.D. Price, Hughes Aircraft Co., El Segundo, CA</i>	
An Experimental Investigation of a Single-Stage Two-Pulse-Tube Refrigerator	295
<i>J. Yuan, J.M. Pfothenhauer, Univ. of Wisconsin, Madison, WI</i>	
UCLA Pulse Tube Investigations	301
<i>K.V. Ravikumar, S. Yoshida, N.S. Myung, P. Karlmann, S. Sapida, B. Dransart, T. Nguyen and T.H.K. Frederking, UCLA, Los Angeles, CA</i>	

Reversible Cycle Piston Pulse Tube Cryocooler	309
<i>A.L. Johnson, Electro Thermo Associates, Deer Harbor, WA</i>	
Isothermal Model of a Warm Expander Pulse Tube	319
<i>M.M. Peters, G.D. Peskett, and M.C. Brito, University of Oxford, UK</i>	
Pulse-tube Modeling and Diagnostic Measurements	327
A Simple Modeling Program for Orifice Pulse Tube Coolers	327
<i>P.R. Roach, NASA/ARC, Moffett Field, CA; A. Kashani, Atlas Scientific, Sunnyvale, CA</i>	
A One-Dimensional Model of High-Frequency Pulse Tube Heat and Mass Flows	335
<i>C.S. Kirkconnell, Hughes Aircraft Co., El Segundo, CA; G.T. Colwell, Georgia Institute of Technology, Atlanta, GA</i>	
Higher Order Pulse Tube Modeling	345
<i>J.M. Lee, P. Kittel, NASA/ARC, Moffett Field, CA; K.D. Timmerhaus, Univ. of Colorado; and R. Radebaugh, NIST, Boulder, CO</i>	
Visualization Study of Velocity Profiles and Displacements of Working Gas Inside a Pulse Tube Refrigerator	355
<i>M. Shiraishi, MITI, JAPAN; N. Nakamura, K. Seo, and M. Murakami, Univ. of Tsukuba, JAPAN</i>	
Investigation of Radial Temperature and Velocity Profiles in Oscillating Flows Inside a Pulse Tube Refrigerator	365
<i>K. Seo, N. Nakamura, and M. Murakami, Univ. of Tsukuba; and M. Shiraishi, MITI, JAPAN</i>	
An Experimental Investigation of How the Heat Pumping Mechanism in a Pulse Tube Changes with Frequency	375
<i>B.E. Evans and R.N. Richardson, Univ. of Southampton, UK</i>	
DC Gas Flows in Stirling and Pulse Tube Cryocoolers	385
<i>D. Gedeon, Gedeon Assoc., Athens, OH</i>	
Convective Heat Losses in Pulse Tube Coolers: Effect of Pulse Tube Inclination	393
<i>G. Thummes, M. Schreiber, R. Landgraf and C. Heiden, Univ. of Giessen, GERMANY</i>	
Generic Stirling/PT Components Development	403
Advanced Compressor for Long-Life Cryocoolers	403
<i>P.W. Curwen, Consultant, and W.D. Waldron, MTI, Latham, NY</i>	
Flexure Bearing Analysis Procedures and Design Charts	413
<i>C.C. Lee and R.B. Pan, Aerospace Corp., Los Angeles, CA</i>	
Investigation of Gas Effects on Cryocooler Resonance Characteristics	421
<i>M.K. Heun, S.A. Collins, D.L. Johnson, and R.G. Ross, Jr., JPL, Pasadena, CA</i>	

Thermodynamic Comparison between the Orifice Pulse Tube and the Stirling Refrigerator	431
<i>P. C.T. de Boer, Cornell University, Ithaca, NY</i>	
Application of the Periodic Temperature Variation Technique to the Measurement of Heat Transfer Coefficients in High-NTU Matrices	441
<i>J.A. Ramirez, K.D. Timmerhaus, Univ. of Colorado; and R. Radebaugh, NIST, Boulder, CO</i>	
3-D Flow Model for Cryocooler Regenerators	451
<i>J.S. Nigen, K.C. Karki and S.V. Patankar, Innovative Research, Minneapolis, MN; R. Yaron, Yaron Consulting, Los Altos, CA; and R. Radebaugh, NIST, Boulder, CO</i>	
Measurement of Heat Conduction through Stacked Screens	459
<i>T. Kuriyama, Toshiba, JAPAN; F. Kuriyama, Ebara, JAPAN; M. Lewis and R. Radebaugh, NIST, Boulder, CO</i>	
Brayton Cryocooler Developments	465
A Single Stage Reverse Brayton Cryocooler: Performance and Endurance Tests on the Engineering Model	465
<i>F.X. Dolan, W.L. Swift, Creare, Hanover, NH; Lt B.J. Tomlinson, A. Gilbert and J. Bruning, Phillips Laboratory, Kirtland AFB, NM</i>	
Progress on the Development of Miniature Turbomachines for Low-Capacity Reverse-Brayton Cryocoolers	475
<i>J.A. McCormick, W.L. Swift, and H. Sixsmith, Creare, Hanover, NH</i>	
Experimental Study of the Isentropic Efficiency of the Pulse Tube Expansion Process	485
<i>J. Liang, C.Q. Zhang, and Y. Zhou, Chinese Academy of Sciences, Beijing, CHINA</i>	
J-T and Throttle-cycle Cryocooler Developments	493
Joule-Thomson Cryocooler Development at Ball Aerospace	493
<i>R. Levenduski and R. Scarlotti, Ball Aerospace, Boulder, CO</i>	
Low Cost Cryocoolers for Cryoelectronics	509
<i>W.A. Little and I. Sapozhnikov, MMR Technologies, Mountain View, CA</i>	
A Throttle Cycle Cryocooler Operating with Mixed Gas Refrigerants in 70 K to 120 K Temperature Range	515
<i>A. Khatri, M. Boiarski, APD Cryogenics, Allentown, PA</i>	
80 K Throttle-Cycle Refrigerator Cost Reduction	521
<i>R.C. Longworth, APD Cryogenics, Allentown, PA</i>	
Experimental Investigation of an Efficient Closed-Cycle Mixed-Refrigerant J-T Cooler	529
<i>E. C. Luo, J. Liang and Y. Zhou, Chinese Academy of Sciences, Beijing, PRC; and V.V. Yakuba and M.P. Lobko, V. Berkin Institute for Low Temp. Physics and Engin., Ukraine</i>	

65 K Two-Stage MR/O₂ Throttle Cycle Refrigerator	537
<i>R.C. Longworth and D. Hill, APD Cryogenics, Allentown, PA</i>	
Closed-Cycle Neon Refrigerator for High-Temperature Superconducting Magnets	547
<i>P.E. Blumenfeld, J.M. Pfothenhauer, Univ. of Wisconsin, Madison, WI</i>	
Design and Testing of a Combined Stirling-Cycle Joule-Thomson Cryocooler System	557
<i>L.B. Penswick and D.C. Lewis, Jr., Stirling Technology Co., Kennewick, WA</i>	
 Sorption Cryocooler Developments	 567
Flight Demonstration of a 10 K Sorption Cryocooler	567
<i>S. Bard, P. Karlmann and P. Cowgill, JPL, Pasadena, CA</i>	
Continuous and Periodic Sorption Cryocoolers for 10 K and Below	577
<i>L.A. Wade and S. Bard, JPL, Pasadena, CA; and A.R. Levy, UCSB, Santa Barbara, CA</i>	
Preliminary Test Results for a 25 K Sorption Cryocooler Designed for the UCSB Long Duration Balloon Cosmic Microwave Background Radiation Experiment	587
<i>L.A. Wade, JPL, Pasadena, CA; A.R. Levy, UCSB, Santa Barbara, CA</i>	
Experiments on a Charcoal/Nitrogen Sorption Compressor and Model Considerations	597
<i>S.A.J. Huinink, J.F. Burger, H.J. Holland, E.G. van der Sar, J.G.E. Gardeniers, H.J.M. ter Brake, and H. Rogalla, Univ. of Twente, The NETHERLANDS</i>	
 G-M Refrigerators and Low-Temperature Regenerators	 607
Low Cost Gifford-McMahon Cryocooler Development Program	607
<i>J.S. Kurtak, CTI-Cryogenics, Mansfield, MA</i>	
Development of a 2 W Class 4 K Gifford-McMahon Cycle Cryocooler	617
<i>T. Inaguchi, M. Nagao, K. Naka and H. Yoshimura, Mitsubishi Electric Corp., Hyogo, JAPAN</i>	
Geometric Scaling of a 4.2 K Gifford-McMahon Refrigerator	627
<i>J.N. Chafe, G.F. Green, and J.W. Stevens, CDNSWC, Annapolis, MD</i>	
The Effect of Pressure Loss at Intake/Exhaust Valve on Performance of a 4 K G-M Cryocooler	637
<i>T. Satoh, R. Li, A. Onishi, Y. Kanazawa, and Y. Ikeya, Sumitomo Heavy Industries, Ltd., JAPAN</i>	
The Valve Timing Effect on Cooling Power of 4 K Gifford-McMahon Cryocooler	643
<i>M. Nagao, T. Inaguchi, N. Kouki, and H. Yoshimura, Mitsubishi Electric Co., Hyogo, JAPAN</i>	

A Neodymium Plate Regenerator for Low Temperature Gifford-McMahon Cycle Refrigerators	653
<i>J.N. Chafe, G.F. Green, CDNSWC, Annapolis, MD; and J.B. Hendricks, Alabama Cryogenic Engineering, Huntsville, AL</i>	
Influence of Alloying on the Behavior and Properties of Er₃Ni	663
<i>V.K. Pecharsky, K.A. Gschneidner, Jr., W.R. McCallum, and K.W. Dennis, Ames Laboratory-DOE, Iowa State Univ., Ames, IA</i>	
Processing and Testing of the Low-Temperature Stage Er₆Ni₂Sn Cryogenic Regenerator Alloy	669
<i>K.A. Gschneidner, Jr., V.K. Pecharsky, M.G. Osborne, J.O. Moorman, I.E. Anderson, D. Pasker, Ames Laboratory-DOE, Iowa State Univ., Ames, IA; M.L. Eastwood, Eastwood Assoc., South Pasadena, CA</i>	
Promising Refrigerants for the 4.2 - 20 K Region	675
<i>L.P. Bozkova, A.M. Tishin, Moscow State Univ., Moscow, RUSSIA</i>	
Advanced Refrigeration Cycles and Developments	681
The Los Alamos Solid-State Optical Refrigerator	681
<i>R.I. Epstein, B.C. Edwards, C.E. Mungan and M.I. Buchwald, LANL, Los Alamos, NM</i>	
Microcooling: Study on the Application of Micromechanical Techniques	687
<i>J.F. Burger, H.J.M. ter Brake, M. Elwenspoek and H. Rogalla, Univ. of Twente, The NETHERLANDS</i>	
Cryocooler Vibration Characterization and Control	697
Investigation into Vibration Issues of Sunpower M77 Cryocoolers	697
<i>E.F. James, S. Banks, McDonnell Douglas Aerospace, Seabrook, MD; S. Castles, NASA/GSFC, Greenbelt, MD</i>	
Summary and Results of Hughes Improved Standard Spacecraft Cryocooler Vibration Suppression Experiment	705
<i>M. Kieffer, A. Wu and S. Champion, Hughes Aircraft Co., El Segundo, CA</i>	
MOPITT Stirling Cycle Cooler Vibration Performance Results	711
<i>E.L. Cook, J. Hackett, COMDEV Ltd.; J.R. Drummond, G.S. Mand, Univ. of Toronto, CANADA; and L. Burriesci, Lockheed-Martin, Palo Alto, CA</i>	
Summary and Results of a Space-Based Active Cryocooler Vibration Suppression Experiment	719
<i>C.E. Byvik, W.J. Schafer Assoc., Arlington, VA; and J. Stubstad, BMDO, Washington, D.C.</i>	
Vibration Reduction in a Set-Up of Two Split Type Stirling Cryocoolers	727
<i>A.P. Rijpma, J.F.C. Verberne, E.H.R. Witbreuk, and H.J.M. ter Brake, Univ. of Twente, The NETHERLANDS</i>	
Throttle Cycle Cooler Vibration Characterization	737
<i>D. Hill, APD Cryogenics, Allentown, PA</i>	

Cryocooler Integration and Test Technologies	747
Development of a 60 K Thermal Storage Unit	747
<i>D.C. Bugby, R.G. Bettini, C.J. Stouffer, Swales and Assoc., Beltsville, MD; M. Stoyanof, Phillips Laboratory, Kirtland AFB, NM; and D.S. Glaister, Aero- space Corp., Albuquerque, NM</i>	
Temperature Stabilization on Cold Stage of 4 K G-M Cryocooler	765
<i>R. Li, A. Onishi, T. Satoh, and Y. Kanazawa, Sumitomo Heavy Industries, Ltd., Kanagawa, JAPAN</i>	
Reduction of Parasitic Heat Loads to Cryogenically Cooled Components	773
<i>S. Jensen, J.C. Batty, and D. McLain, Space Dynamics Laboratory, Logan, UT</i>	
Cryocooler Heat Interceptor Test for the SMTS Program	783
<i>D.C. Gilman, Hughes Aircraft Co., El Segundo, CA</i>	
Feasibility Demonstration of a Thermal Switch for Dual Temperature IR Focal Plane Cooling	795
<i>D.L. Johnson and J.J. Wu, JPL, Pasadena, CA</i>	
An Advanced Solderless Flexible Thermal Link	807
<i>B. Williams, S. Jensen, and J.C. Batty, Utah State Univ., Logan, UT</i>	
Development and Testing of a Demountable Cryocooler Thermal Interface	813
<i>A.R. Langhorn, Startech, Solana Beach, CA; J.D. Walters, CDNSWC, Annapolis, MD; and H. Heiberger, General Atomics, San Diego, CA</i>	
Thermal Conductance of Multilam Make and Break Cryocooler Thermal Interface	823
<i>J.D. Walters, T.H. Fikse, and T.L. Cooper, CDNSWC, Annapolis, MD</i>	
Heat Pipes for Enhanced Cooldown of Cryogenic Systems	831
<i>F.C. Prenger, D.D. Hill, D.E. Daney, M.A. Daugherty, LANL, Los Alamos, NM; G. Green, J. Chafe, CDNSWC, Annapolis, MD; M. Heiberger, General Atomics, San Diego, CA; and A. Langhorn, Startech, Solana Beach, CA</i>	
Control Electronics Development for Space-Based Cryocoolers	841
<i>P.M. Mayner, Hughes Aircraft Co., Goleta, CA</i>	
Cooler Test Data Acquisition and Environmental Control Software	853
<i>S. Arwood, T. Roberts, Phillips Laboratory, Kirtland AFB, NM</i>	
Cryogenic Systems Integration Model (CSIM)	861
<i>M. Donabedian, S.D. Miller, and D.S. Glaister, Aerospace Corp., El Segundo, CA</i>	
Cryocooler Applications Experience	873
Spacecraft Cryocooler System Integration Trades and Optimization	873
<i>D.S. Glaister, Aerospace Corp., Albuquerque, NM; and D.G.T. Curran, Aerospace Corp., El Segundo, CA</i>	

AIRS Cryocooler System Design and Development 885
R.G. Ross, Jr., JPL, Pasadena, CA; K.E. Green, Lockheed Martin IR Imaging Systems, Lexington, MA

AIRS Pulse Tube Cryocooler System 895
C.K. Chan, J. Raab, A. Eskovitz, R. Carden III, M. Fletcher and R. Orsini, TRW, Redondo Beach, CA

The Qualification and Use of Miniature Tactical Cryocoolers for Space Applications 905
K.S. Moser, NRC, Albuquerque, NM; A. Das, Phillips Laboratory, Kirtland AFB, NM; and M.W. Obal, Obal Technologies Group, Woodbridge, VA

The Design, Development and Qualification of the SCIAMACHY Radiant Cooler 917
I.J.G. Wigbers, Fokker Space B.V., The NETHERLANDS

Integration of HTS SQUIDS with Portable Cooling Devices for the Detection of Materials Defects in Non-Destructive Evaluation 925
R. Hohmann, H. Soltner, H.-J. Krause, W. Wolf, H. Bousack, and M.I. Faley, Forschungszentrum Jülich, GERMANY; M.L. Lucia, UCM, Madrid, SPAIN; G. Spörl, A. Binneberg, ILK, Dresden, GERMANY

Stirling Cooler Magnetic Interference Measured by a High-Tc SQUID Mounted on the Cold Tip 935
H.J.M. ter Brake, H.J. Holland and H. Rogalla, Univ. of Twente, The NETHERLANDS

Cryocooler Integration with High Temperature Superconducting Motors 943
B.X. Zhang, D.I. Driscoll, B.A. Shoykhet and A.A. Meyer, Reliance Electric Co., Cleveland, OH

Integration of a Photoconductive Detector with a 4 K Cryocooler 949
R.S. Bhatia, A.G. Murray, M.J. Griffin, P.A.R. Ade, Queen Mary & Westfield College; and T.W. Bradshaw and A.H. Orłowska, Rutherford Appleton Laboratory, UK

Indexes **959**

Proceedings Index 959

Author Index 961

Subject Index 963