Contents

Space Stirling Cryocooler Developments 1

Development for Space Use of BAe's Improved Single-Stage Stirling Cycle Cooler for Applications in the Range 50-80 K 1
B.G. Jones, British Aerospace Space Systems, Bristol, ENGLAND

Space Cryogenic Refrigerator System (SCRS) Thermal Performance Test Results 13
I.E. Spradley and W.G Foster, Lockheed, Palo Alto, CA

Test Results for the Single-Stage Ball Flight Prototype Cooler 23
W.J. Horsley, E.F. Hicks, W.C. Kiehl, D.W. Simmons, D.J. Taylor, E.E. Wells and J A. Wells, Ball Aerospace, Boulder, CO

Long-Life Cryocooler Development Program for ASTER 35
M. Kawada and H. Fujisada, Electrotechnical Laboratory, Ibaraki, JAPAN

Development of a Stirling Cryocooler Using Hydrodynamic Gas Bearings 47
L. Duband, A. Ravex and P. Rolland, CEA, Grenoble, FRANCE

Design, Performance, and Testing of the Lockheed-Developed Mechanical Cryocooler 55
T.C. Nast, P.J. Champagne, D Isaac, G.M. Pryor, R L. von Savoye and L G. Naes, Lockheed MSC, Palo Alto, CA

Improved Standard Spacecraft Cryocooler Life Test for Space-Based Infrared Surveillance 69
J.M. Wakugawa, H Haque and K.D. Price, Hughes Aircraft Company, El Segundo, CA

Development of Stirling Cryocooler for Use In Space 77
T. Fukuda, T. Tsuchiya, M. Ishii and T. Takakusagi, Hitachi, Ltd., Ibaraki, JAPAN; M. Furukawa, National Space Devel. Agency of Japan, Ibaraki, JAPAN

NASA/GSFC 80 K Long-Life, Low Vibration Mechanical Cryocooler Performance Test Program Results 85
L.G. Naes, G.M. Pryor, I.A. Spradley, D. Isaac and R.L. von Savoye, Lockheed MSC, Palo Alto, CA; L.M. Sparr NASA GSFC, Greenbelt, MD

20-50K Two-Stage Stirling Cryocoolers 93

Multi-Stage Cryocooler for Space Applications 93
H. Carrington, W.J. Gully, M. Hubbard and C. Varner, Ball Aerospace, Boulder, CO; P. Arter, NCAR, Boulder, CO

30 K Diaphragm Stirling Cryocooler Demonstration 103
W.D. Stacy and W.R. Baschnagel, Creare, Hanover, NH; D. Lussier, Fairchild Space, Greenbelt, MD

Low-Cost Tactical Stirling Cryocoolers 113

Hughes Long-Life Linear Stirlings: A Status Report 113
G.R. Pruitt, Hughes Electron Dynamics Div., Torrance, CA

Linear Drive Stirling Cryocoolers: Qualification and Life Testing Results 121
R.M. Rawlings, C.E. Granger, III and G.W. Hinrichs, Texas Instruments, Inc., Dallas, TX

Dual Opposed Piston Stirling Cryocoolers for IR Systems 129
R. Narayan, Magnavox Electro-Optics, Mahwah, NJ

Space Qualification Program of a Signaal USFA Tactical Cooler for the Mars 1996 Space Mission 137
A. Chardin, Inst. D'Astrophysique Spatiale, Orsay, FRANCE; D. Féger, Cryotechnologies, Blagnac, FRANCE; and D. Verbeek, Signaal USFA, Eindhoven, The Netherlands

Performance Characterization of the Sunpower Cryocooler 149
G.T. Smedley and R.G. Ross, Jr., JPL, Pasadena, CA; D.M. Berchowitz, Sunpower, Inc., Athens, OH

Adaptation of Tactical Cryocoolers for Short Duration Space-Flight Missions 163
L. Sparr, M. Sartor and R. Boyle, NASA/GSFC, Greenbelt, MD; S. Banks and E. James, McDonnell Douglas Corp., Seabrook, MD

Stirling Cryocooler Performance Comparisons 173

JPL Cryocooler Development and Test Program Overview 173
R.G. Ross, Jr., JPL, Pasadena, CA

Thermal Performance of Stirling-Cycle Cryocoolers: A Comparison of JPL-Tested Coolers 185
G.T. Smedley, G.R. Mon, D.L. Johnson and R.G. Ross, Jr., JPL, Pasadena, CA

Vibration Characteristics of Stirling-Cycle Cryocoolers for Space Application 197
G.R. Mon, G.T. Smedley, D.L. Johnson and R.G. Ross, Jr., JPL, Pasadena, CA

Cryocooler Electromagnetic Compatibility 209
D.L. Johnson, G.T. Smedley, G.R. Mon, R.G. Ross, Jr. and P. Narvaez, JPL, Pasadena, CA

NASA/GSFC Cryocooler Test Program Results for FY93/94 221
L. Sparr, M. Sartor, R. Boyle, S. Castles and T. Cygnarowicz, NASA/GSFC, Greenbelt, MD; S. Banks and E. James, McDonnell Douglas Corp., Seabrook, MD; and V. Arillo and R. Cory, Hughes-STX, Greenbelt, MD

BAe 80 K Cryocooler Life Test for Space-Based Infrared Surveillance 233
J M Wakugawa and H. Haque, Hughes Aircraft Co., El Segundo, CA, and R.A Orsini, TRW, Redondo Beach, CA

Stirling Cryocooler Components and Theory 241

A Method for Intrinsic Temperature Regulation of Miniature Stirling Coolers 241
M Bareiss, A. Fiedler, H Laschutza and G. Schellenberger, AEG Aktiengesellschaft, Heilbronn, GERMANY

Regenerator Optimization for Stirling Cycle Refrigeration, II 247
S.A. Colgate, LANL, Los Alamos, NM

Friction Factors of Stacks of Perforated Regenerator Plates 259
S. Yoshida, K.V. Ravikumar and T H.K. Frederking, UCLA, Los Angeles, CA

Experimental Analysis of Heat Transfer Characteristics and Pressure Drop through Screen Regenerative Heat Exchangers 269
J.L. Wiese, USAF Phillips Lab, Kirtland AFB, NM; and W.J. Bowman, Air Force Inst. of Tech., Wright-Patterson AFB, OH

Sage: Object-Oriented Software for Cryocooler Design 281
D Gedeon, Gedeon Assoc., Athens, OH

Design Optimization of Linear-Arm Flexure Bearings 293
E. Marquardt and R Radebaugh, NIST, Boulder, CO

Spiral Flexure Bearing 305
T.E. Wong, R.B. Pan, H.D. Marten, C. Sve, L. Galvan and T S. Wall, The Aerospace Corp , El Segundo, CA

Pulse Tube Cryocooler Developments 313

Demonstration of a High Performance 35 K Pulse Tube Cryocooler 313
W.W. Burt and C.K. Chan, TRW, Redondo Beach, CA

Experimental Investigation of a Linear, Orifice Pulse Tube Expander 321
S C. Soloski and F N. Mastrup, Hughes Aircraft Co., El Segundo, CA

Miniature Long-Life Space-Qualified Pulse Tube and Stirling Cryocoolers 329
E. Tward, C.K. Chan, J. Raab, R Orsini, C. Jaco and M Petach, TRW, Redondo Beach, CA

Two-Stage Pulse Tube Refrigerator for 20 K Operation 337
Y Ohtani, M. Takahashi, T Kuriyama and H. Nakagome, Toshiba R&D, Kanagawa, JAPAN; J. Gao, H. Tanida and Y. Matsubara, Nihon University, Chiba, JAPAN; and M Narita, H. Murakami and H Okuda, Inst. of Space and Astron. Science, Kanagawa, JAPAN

Multi-Stage Pulse Tube Refrigerator for Temperatures below 4 K 345
Y. Matsubara and J.L. Gao, Atomic Energy Research Institute, Nihon University, Funabashi, JAPAN

Cooling Performance of a Prototype Miniature Pulse Tube Refrigerator with a Flexure Spring Compressor 353
T. Haruyama and H. Inoue, KEK, Ibaraki, JAPAN

Pulse Tube Cryocooler Components and Theory 359

Steady Secondary Momentum and Enthalpy Streaming in the Pulse Tube Refrigerator 359
J.M. Lee and P. Kittel, NASA Ames Research Center, Moffett Field, CA; K.D. Timmerhaus, Univ. of Colorado, Boulder, CO; R. Radebaugh, NIST, Boulder, CO

A Model for Analyzing Ideal Double Inlet Pulse Tube Refrigerators 371
A. Hofmann, Kernforschungszentrum Karlsruhe, GERMANY; S. Wild, Universitat Karlsruhe, GERMANY

Effect of Pressure Wave Form on Pulse Tube Refrigerator Performance 383
F. Giebeler, G. Thummes and C. Heiden, Justus-Liebig-Univ., Giessen, GERMANY

Compact Four-Valve Pulse Tube Refrigerator in Coaxial Configuration 395
J. Blaurock, R. Hackenberger, P. Seidel and M. Thurk, Friedrich Schiller University, Jena, GERMANY

Pressure and Temperature Oscillations of Working Gas in a Pulse Tube Refrigerator 403
M. Shiraishi, Mechanical Engineering Lab, MITI, Ibaraki, JAPAN; K. Seo and M. Murakami, Univ. of Tsukuba, Ibaraki, JAPAN

Analytical Model and Experimental Results of a Miniature Pulse Tube Refrigerator 411
M. David and J-C. Maréchal, Ecole Normale Supérieure, Paris, FRANCE

Cryocooler Vibration Control and Drive Electronics 417

MOPITT Stirling Cycle Cooler and Cooler Drive Electronics Evaluation 417
E.L. Cook, COM DEV Atlantic, Moncton, CANADA; J.R. Drummond and G.S. Mand, Univ. of Toronto, Toronto, CANADA; R. Colley, Canadian Space Agency, Ottawa, CANADA; and B. Clappier and T. McGinnis, Lockheed, Palo Alto, CA

Development and Test of Low Vibration Cryocooler Electronics 425
G.D. Salapski, Z.F. Backovsky and T.H. Weight, Rockwell International, Anaheim, CA

Active Multi-Axis Vibration Cancellation for Split-Stirling Cryocoolers 437
S.A. Collins and J.D. Paduano, MIT, Cambridge, MA; and A.H. von Flotow, Hood Technology Corp., Hood River, OR

Flight Hardware Implementation of a Feed-Forward Vibration Control System for Space Flight Cryocoolers 449
R. Boyle, L. Sparr and T. Gruner, NASA/GSFC, Greenbelt, MD; E. James and S. Banks, McDonnell Douglas, Seabrook, MD; J. Wilmot and V. Arillo, Hughes-STX, Greenbelt, MD; and T. Gibboney, Fairchild Space Corp., Greenbelt, MD

STRV Cryocooler Tip Motion Suppression 455
R.J. Glaser, R.G. Ross, Jr. and D.L. Johnson, JPL, Pasadena, CA

Reduction of the Vibration Generated by Stirling Cryocoolers Used for Cooling a High-Tc SQUID Magnetometer 465
J.F.C. Verberne, P.C. Bruins, P.J. van den Bosch and H.J.M. ter Brake, Univ. of Twente, The Netherlands

Implementation and Test of the Control Algorithms for a Diaphragm Stirling 30 K Cryocooler 475
C. Konkel, T. Gibboney and K. Ha, Fairchild Space, Greenbelt, MD; and R. Boyle, NASA/GSFC, Greenbelt, MD

NASA IN-STEP Cryo System Experiment Flight Electronics for Spacecraft Cryocooler Control and Characterization 487
P.M. Mayner and B.F. Wolf, Hughes Aircraft Co., El Segundo, CA

Brayton and J-T Cryocooler Developments 499

Single-Stage Reverse Brayton Cryocooler: Performance of the Engineering Model 499
W.L. Swift, Creare, Hanover, NH

Miniaturization of Components for Low Capacity Reverse Brayton Cryocoolers 507
J.A. McCormick, W.L. Swift and H. Sixsmith, Creare, Hanover, NH

Development Status of a 2.5 K - 4 K Closed-Cycle Cooler Suitable for Space Use 517
A.H. Orlowska, T.W. Bradshaw and J. Hieatt, Rutherford Appleton Laboratory, ENGLAND

Qualification of a 4 K Mechanical Cooler for Space Applications 525
B.G. Jones and D.W. Ramsay, British Aerospace Space Systems, Bristol, ENGLAND

80 K Closed-Cycle Throttle Refrigerator 537
R.C. Longsworth, M.J. Boiarski and L.A. Klusmier, APD Cryogenics Inc., Allentown, PA

Joule-Thomson Cryocooler Development at Ball Aerospace 543
R. Levenduski and R. Scarlotti, Ball Aerospace, Boulder, CO

Phase Equilibria in Cryogenic Mixtures: Part II 559
L.B. Robinson, UCLA, Los Angeles, CA

Sorption Cryocooler Developments 569

Development of an Advanced Sorption Compressor and Its Application in a 125 K Cryocooler 569
J.A. Alvarez, R J. Krylo, R.D. Snapp, C. Weston, P. Sywulka and G.C Abell, Aerojet Electronics Plant, Azusa, CA

Dynamic Simulation of a Periodic 10 K Sorption Cryocooler 581
P. Bhandari, J. Rodriguez, S Bard and L. Wade, JPL, Pasadena, CA

Fabrication and Testing of the Metal Hydride Sorbent Bed Assembly for a Periodic 10 K Sorption Cryocooler 601
R.C. Bowman, Jr., D.R. Gilkinson, R.D. Snapp, G.C. Abell, B.D. Freeman and E.L. Ryba, Aerojet Electronics Plant, Azusa, CA; and L.A. Wade, JPL, Pasadena, CA

Ground Testing of a 10 K Sorption Cryocooler Flight Experiment (BETSCE) 609
S. Bard, J. Wu, P. Karlmann, P. Cowgill, C. Mirate and J. Rodriguez, JPL, Pasadena, CA

Component Reliability Testing of Long-Life Sorption Cryocoolers 623
S. Bard, J. Wu, P. Karlmann, C. Mirate and L. Wade, JPL, Pasadena, CA

Magnetic Refrigerators and Low-Temperature Regenerators 637

Development of a Magnetic Refrigerator Operating between 2 K and 10 K 637
A. Kashani, Atlas Scientific, Sunnyvale, CA; B P.M. Helvensteijn, Sterling Federal Systems, Palo Alto, CA; F.J. McCormack and A.L. Spivak, Trans-Bay Electronics, Richmond, CA; and P. Kittel, NASA ARC, Moffett Field, CA

Investigation of a Magnetically Augmented Cryogenic Refrigerator 647
J.L. Smith, Jr. and G.F. Nellis, MIT, Cambridge, MA

Design of Active Magnetic Regenerative Stage Interfacing to a G-M Cryocooler 657
C.B. Zimm, A.G. Jastrab and J W. Johnson, Astronautics Tech. Center, Madison, WI

Experimental Results of an Efficient Active Magnetic Regenerator Refrigerator 665
A.A. Wang, J.W. Johnson, R.W. Niemi, A A. Sternberg and C.B. Zimm, Astronautics Tech. Center, Madison, WI

Excellent Character of Multi-Layer Type Magnetic Regenerator near 4.2 K 677
T. Hashimoto, T. Tsukagoshi, H. Nitta and M. Yabuki, Tokyo Institute of Technology, Tokyo, JAPAN; T. Kuriyama and H. Nakagome, Toshiba R&D Center, Kanagawa, JAPAN

New Ternary Magnetic Lanthanide Regenerator Materials for the Low-Temperature Stage of a Gifford-McMahon (G-M) Cryocooler 685
K A. Gschneidner, V.K. Pecharsky and M. Gailloux, Ames Lab, Iowa State University, Ames, IA

Generic Cryocooler Integration Technologies 695

Cryogenic Systems Integration Model (CSIM) 695
M. Donabedian, D.S. Glaister and M.D. Bernstein, The Aerospace Corp., El Segundo, CA

Cryocooler Coldfinger Heat Interceptor 709
D.L. Johnson and R.G. Ross, Jr., JPL, Pasadena, CA

Cryogenic Capillary Pumped Loops: A Novel Cryocooler Integration Technology 719
B. Cullimore, Cullimore and Ring Tech., Littleton, CO; E. Kroliczek, OAO Corp., Greenbelt, MD; and J Ku, NASA/GSFC, Greenbelt, MD

A Thermal Switch for Use at Liquid Helium Temperature in Space-Borne Cryogenic Systems 731
L. Duband, CEA, Grenoble, FRANCE

Emerging Technologies for Cryocooler Interfaces 743
J.H. Rosenfeld, Thermacore, Inc., Lancaster, PA; D.A. Wolf, Dynatherm Corp., Hunt Valley, MD; and M.T. Buchko, NASA GSFC, Greenbelt, MD

Modeling Thermal Contact Resistance 755
P. Kittel, NASA Ames Research Center, Moffett Field, CA

Perpendicular Loading as a Solution to the Problem of Building an All Purpose Cryogenic Interface 765
J. Hess, Cryostar Assoc., Tucson, AZ

Cryocooler Applications Experience in the 2-20K Range 777

The Test Results of On-Board Refrigeration System with Low-Temperature Buffer Tank 777
T Herai and K. Nagashima, Railway Tech. Research Inst., Tokyo, JAPAN

A 4 K G-M Refrigerator for Direct Cooling of a 6 T NbTi Superconducting Magnet System 785
T Kuriyama, Y. Ohtani, M Takahashi and H. Nakagome, Toshiba R&D Center, Kanagawa, JAPAN

Improved Seal for a 4 K Gifford-McMahon Cryocooler 795
R L. Plambeck, Univ. of California, Berkeley, CA

Shock and Vibration Test of a Two Stage Gifford-McMahon Cryocooler for Use in a U.S. Navy Magnetic Minesweeping System 803
E. Roth, Vector Research Co , Rockville, MD; G. Green and J. Chafe, NSWC, Annapolis, MD

Finite Element Shock Analysis of a Cryogenic Refrigerator 815
E.A Schroeder and G. Green, NSWC Div., Bethesda, MD; G. Green, NSWC, Annapolis, MD

Variable Temperature Thermal Conductivity and Conductance Measurements Using a Gifford-McMahon Cryocooler 823
J.D. Walters, T H. Fikse and T L. Cooper, Annapolis Detachment, CDNSWC, Annapolis, MD

Application of Boreas Cryocoolers 835
A G. Liepert and J.A. Crunkleton, Boreas, Inc., Burlington, MA

Active Refrigeration for Space Astrophysics Missions 845
L A. Wade, JPL, Pasadena, CA

Cryocooler Applications Experience in the 50-100K Range 855

Design and Verification of Stirling Cooler Interfaces Suitable for Long-Lifetime,Space-Borne Sensor Systems 855
R.F. Arentz, F.A Eriksen, R A. Hopkins, S.J Nieczkoski, D.A. Payne and J F. Siebert, Ball Aerospace, Boulder, CO

Lessons Learned during the Integration Phase of the NASA IN-STEP Cryo System Experiment 869
R.S. Sugimura, JPL, Pasadena, CA; S.C. Russo and D.C. Gilman, Hughes Aircraft Co., El Segundo, CA

Ricor K506B Cryocooler Performance during the Clementine Mission and Ground Testing: A Status Report 883
R.E. Priest, J.A. Robinson, T.L. Clark, D.R. Hadley and N.R. Sewall, LLNL, Livermore, CA

High-Temperature Superconducting Space Experiment II (HTSSE II) Overview and Preliminary Cryocooler Integration Experience 893
T. Kawecki, Naval Research Lab, Washington, DC

The Application of Cryocoolers for Cooling a High-Tc SQUID Magnetometer 901
P.J. van den Bosch, W.A.M. Aarnink, H.A. de Boer, H.J. Holland, H.J.M. ter Brake and H. Rogalla, Univ. of Twente, The Netherlands

Cryocoolers and High-Temperature Superconductors: Advancing toward Commercial Applications 913
M. Nisenoff, NRL, Washington, DC

NASA Advanced Refrigerator/Freezer Technology Development Project Overview 919
J.E. Cairelli, NASA LeRC, Cleveland, OH

The Development and Verification of a Cryogenic Phase Change Thermal Storage Unit for Spacecraft Applications 927
D.S. Glaister, K.D. Bell and M. Bello, The Aerospace Corp , El Segundo, CA; and M. Stoyanof, USAF Phillips Lab, Albuquerque, NM

ICE (Integrated Cooler Experiment) for COOLSAT 941
B.G. Williams and J.C. Batty, Utah State Univ., Logan, UT

Commercial Low Cost Cryogenic Packaging for Linear Micro-Coolers 949
T.H. Clynne, J.R. McCoy and M. Kimak, Infrared Components Corp., Utica, NY

Indexes **953**

Proceedings Index 953

Author Index 955

Subject Index 957