

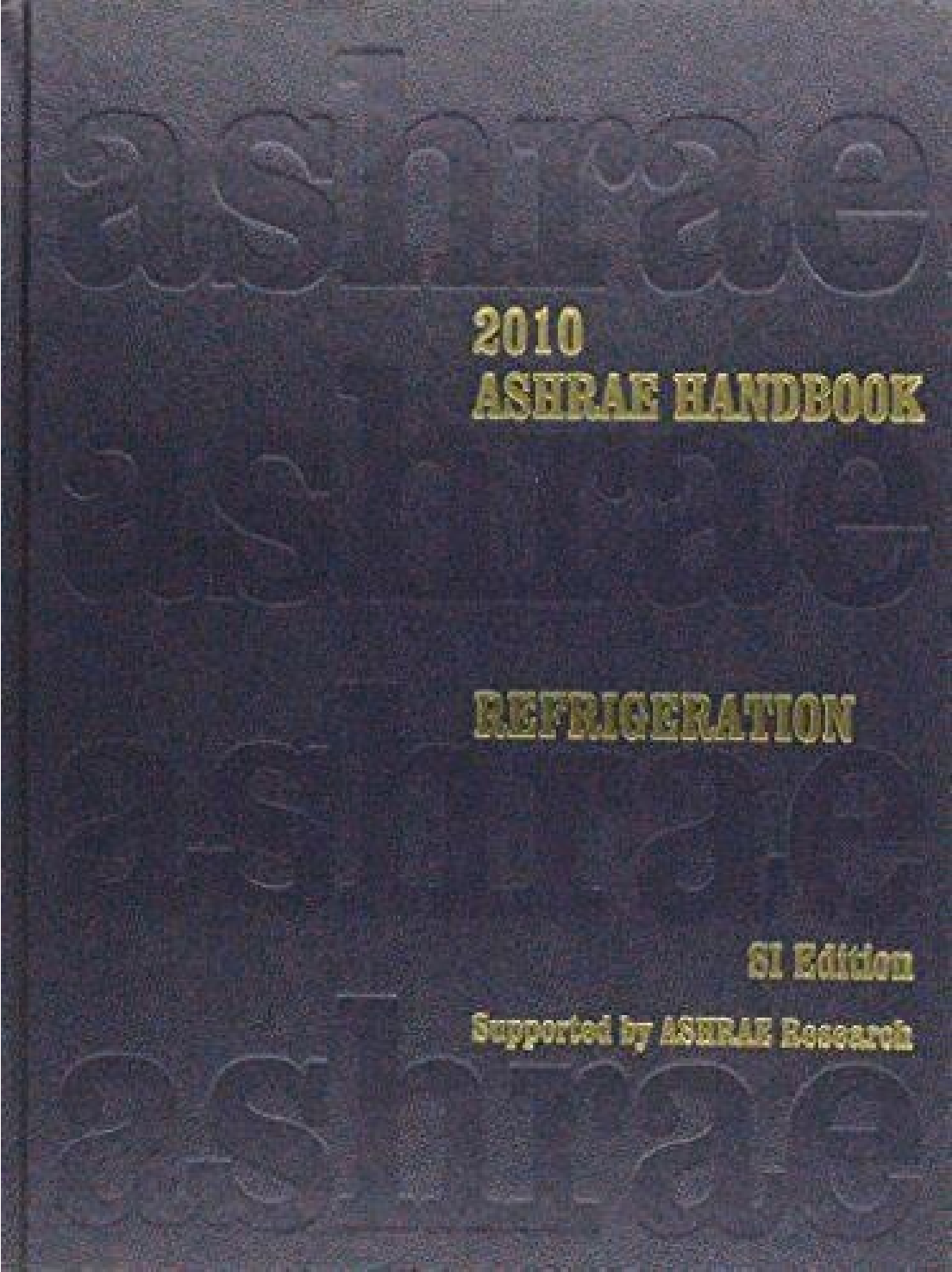
☐

I'm not robot


reCAPTCHA

I am not
robot!

Want more? Advanced embedding details, examples, and help! Licensed for single user. © 2018 ASHRAE, Inc. Licensed for single user. © 2018 ASHRAE, Inc. 2018 ASHRAE HANDBOOK REFRIGERATION SI Edition ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA 30329 www.ashrae.org © 2018 ASHRAE. All rights reserved. DEDICATED TO THE ADVANCEMENT OF THE PROFESSION AND ITS ALLIED INDUSTRIES No part of this publication may be reproduced without permission in writing from ASHRAE, except by a reviewer who may quote brief passages or reproduce illustrations in a review with appropriate credit; nor may any part of this book be reproduced, stored in a retrieval system, or transmitted in any way or by any means—electronic, photocopying, recording, or other—without permission in writing from ASHRAE. Requests for permission should be submitted at www.ashrae.org/permissions. Volunteer members of ASHRAE Technical Committees and others compiled the information in this handbook, and it is generally reviewed and updated every four years. Comments, criticisms, and suggestions regarding the subject matter are invited. Any errors or omissions in the data should be brought to the attention of the Editor. Additions and corrections to Handbook volumes in print will be published in the Handbook published the year following their verification and, as soon as verified, on the ASHRAE Internet website. DISCLAIMER ASHRAE has compiled this publication with care, but ASHRAE has not investigated, and ASHRAE expressly disclaims any duty to investigate, any product, service, process, procedure, design, or the like that may be described herein. The appearance of any technical data or editorial material in this publication does not constitute endorsement, warranty, or guaranty by ASHRAE of any product, service, process, procedure, design, or the like. ASHRAE does not warrant that the information in this publication is free of errors. The entire risk of the use of any information in this publication is assumed by the user. ISBN 978-1-939200-98-3 ISSN 1930-7217 The paper for this book is both acid- and elemental-chlorine-free and was manufactured with pulp obtained from sources using sustainable forestry practices.



Comments, criticisms, and suggestions regarding the subject matter are invited. Any errors or omissions in the data should be brought to the attention of the Editor. Additions and corrections to Handbook volumes in print will be published in the Handbook published the year following their verification and, as soon as verified, on the ASHRAE Internet website. DISCLAIMER ASHRAE has compiled this publication with care, but ASHRAE has not investigated, and ASHRAE expressly disclaims any duty to investigate, any product, service, process, procedure, design, or the like that may be described herein. The appearance of any technical data or editorial material in this publication does not constitute endorsement, warranty, or guaranty by ASHRAE of any product, service, process, procedure, design, or the like. ASHRAE does not warrant that the information in this publication is free of errors. The entire risk of the use of any information in this publication is assumed by the user. ISBN 978-1-939200-98-3 ISSN 1930-7217 The paper for this book is both acid- and elemental-chlorine-free and was manufactured with pulp obtained from sources using sustainable forestry practices. CONTENTS Contributors ASHRAE Technical Committees, Task Groups, and Technical Resource Groups ASHRAE Research: Improving the Quality of Life Preface SYSTEMS AND PRACTICES Chapter 1. 2. 3. 4. 5. 6. 7. Halocarbon Refrigeration Systems (TC 10.3, Refrigerant Piping, Controls and Accessories) Ammonia Refrigeration Systems (TC 10.3) Carbon Dioxide Refrigeration Systems (TC 10.3) Liquid Overfeed Systems (TC 10.1, Custom Engineered Refrigeration Systems) Component Balancing in Refrigeration Systems (TC 10.1) Refrigerant System Chemistry (TC 3.2, Refrigerant System Chemistry) Control of Moisture and Other Contaminants in Refrigerant Systems (TC 3.3, Refrigerant Contaminant Control) 8. Equipment and System Dehydrating, Charging, and Testing (TC 8.1, Positive Displacement Compressors) 9. Refrigerant Containment, Recovery, Recycling, and Reclamation (TC 3.8, Refrigerant Containment) COMPONENTS AND EQUIPMENT Chapter 10. 11. 12. 13. 14. 15. Insulation Systems for Refrigerant Piping (TC 10.3) Refrigerant Control Devices (TC 8.8, Refrigerant System Controls and Accessories) Lubricants in Refrigerant Systems (TC 3.4, Lubrication) Secondary Coolants in Refrigeration Systems (TC 10.1) Forced-Circulation Air Coolers (TC 8.4, Air-to-Refrigerant Heat Transfer Equipment) Retail Food Store Refrigeration and Equipment (TC 10.7, Commercial Food and Beverage Refrigeration Equipment) 16. Food Service and General Commercial Refrigeration Equipment (TC 10.7) 17. Household Refrigerators and Freezers (TC 8.9, Residential Refrigerators and Food Freezers) 18. Absorption Equipment (TC 8.3, Absorption and Heat Operated Machines) FOOD COOLING AND STORAGE Chapter 19. 20. 21. 22. 23. 24. Thermal Properties of Foods (TC 10.5, Refrigerated Processing and Storage) Cooling and Freezing Times of Foods (TC 10.5) Commodity Storage Requirements (TC 10.5) Food Microbiology and Refrigeration (TC 10.5) Refrigerated-Facility Design (TC 10.5) Refrigerated-Facility Loads (TC 10.8, Refrigeration Load Calculations) REFRIGERATED TRANSPORT Chapter 25. Cargo Containers, Rail Cars, Trailers, and Trucks (TC 10.6, Transport Refrigeration) 26. Marine Refrigeration (TC 10.6) 27.

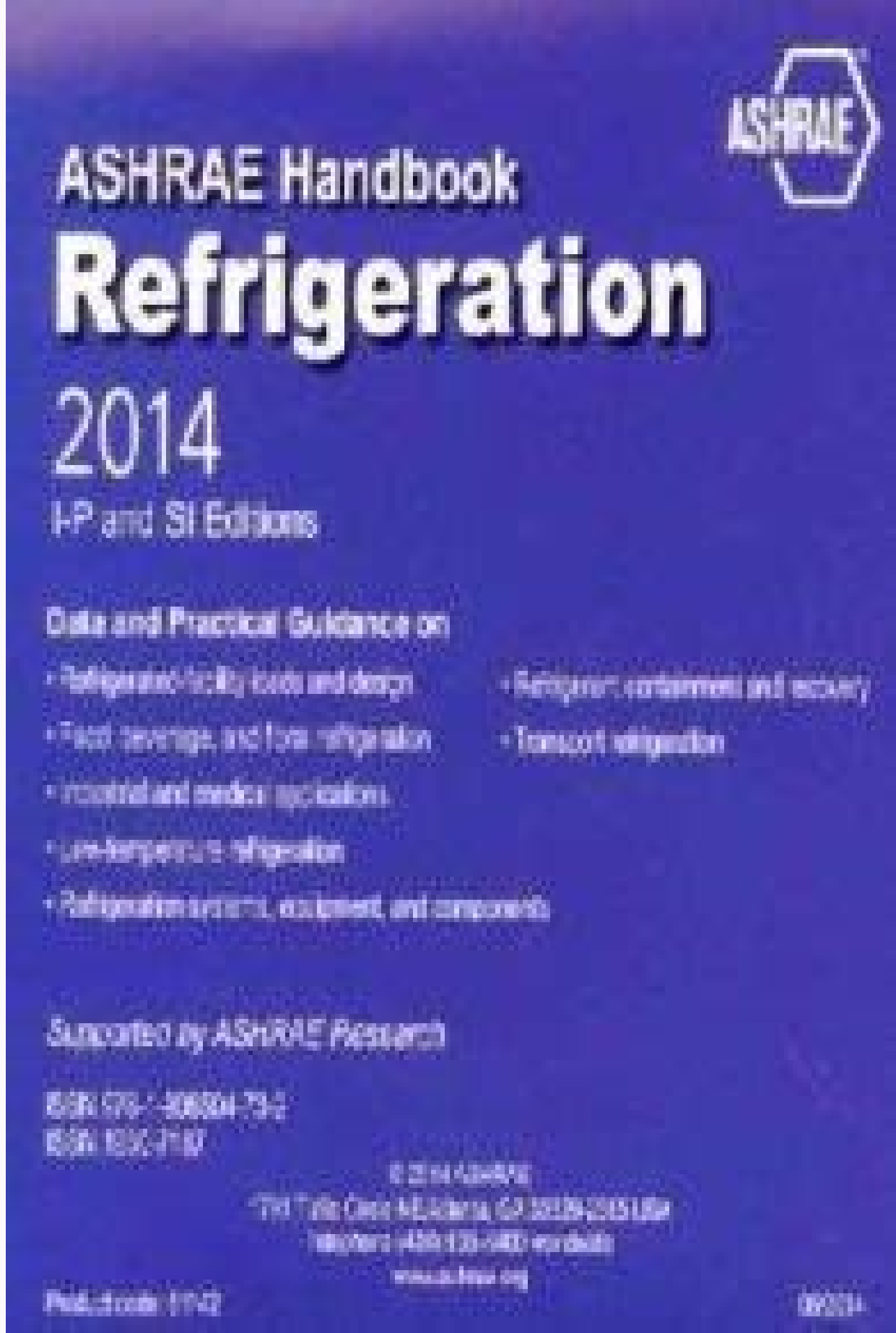
2006 ASHRAE Handbook
Refrigeration



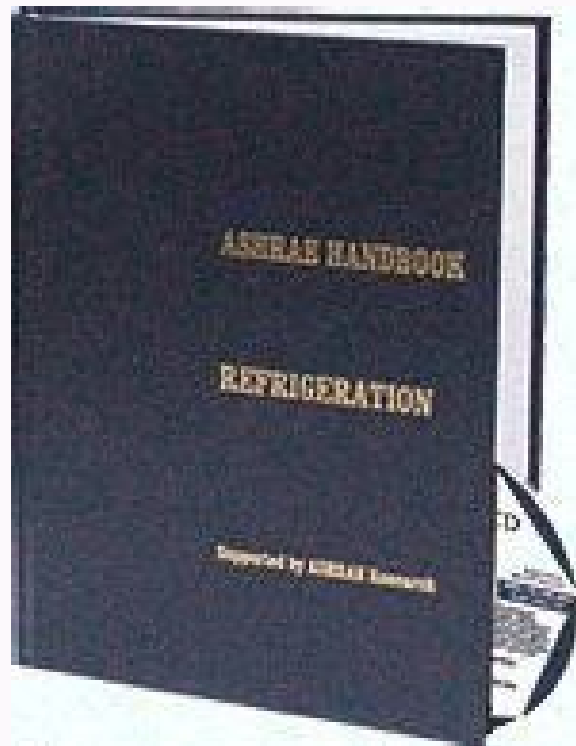
- I-P Edition
- SI Edition

Disclaimer
Licensing Information
Help
Commercial Resources
Feedback on the Handbook

Licensed for single user. © 2018 ASHRAE, Inc. 2018 ASHRAE HANDBOOK REFRIGERATION SI Edition ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA 30329 www.ashrae.org © 2018 ASHRAE. All rights reserved. DEDICATED TO THE ADVANCEMENT OF THE PROFESSION AND ITS ALLIED INDUSTRIES No part of this publication may be reproduced without permission in writing from ASHRAE, except by a reviewer who may quote brief passages or reproduce illustrations in a review with appropriate credit; nor may any part of this book be reproduced, stored in a retrieval system, or transmitted in any way or by any means—electronic, photocopying, recording, or other—without permission in writing from ASHRAE.



Requests for permission should be submitted at www.ashrae.org/permissions. Volunteer members of ASHRAE Technical Committees and others compiled the information in this handbook, and it is generally reviewed and updated every four years. Comments, criticisms, and suggestions regarding the subject matter are invited. Any errors or omissions in the data should be brought to the attention of the Editor. Additions and corrections to Handbook volumes in print will be published in the Handbook published the year following their verification and, as soon as verified, on the ASHRAE Internet website. DISCLAIMER ASHRAE has compiled this publication with care, but ASHRAE has not investigated, and ASHRAE expressly disclaims any duty to investigate, any product, service, process, procedure, design, or the like that may be described herein. The appearance of any technical data or editorial material in this publication does not constitute endorsement, warranty, or guaranty by ASHRAE of any product, service, process, procedure, design, or the like. ASHRAE does not warrant that the information in this publication is free of errors. The entire risk of the use of any information in this publication is assumed by the user. ISBN 978-1-939200-98-3 ISSN 1930-7217 The paper for this book is both acid- and elemental-chlorine-free and was manufactured with pulp obtained from sources using sustainable forestry practices.



DEDICATED TO THE ADVANCEMENT OF THE PROFESSION AND ITS ALLIED INDUSTRIES No part of this publication may be reproduced without permission in writing from ASHRAE, except by a reviewer who may quote brief passages or reproduce illustrations in a review with appropriate credit; nor may any part of this book be reproduced, stored in a retrieval system, or transmitted in any way or by any means—electronic, photocopying, recording, or other—without permission in writing from ASHRAE. Requests for permission should be submitted at www.ashrae.org/permissions. Volunteer members of ASHRAE Technical Committees and others compiled the information in this handbook, and it is generally reviewed and updated every four years. Comments, criticisms, and suggestions regarding the subject matter are invited. Any errors or omissions in the data should be brought to the attention of the Editor. Additions and corrections to Handbook volumes in print will be published in the Handbook published the year following their verification and, as soon as verified, on the ASHRAE Internet website. DISCLAIMER ASHRAE has compiled this publication with care, but ASHRAE has not investigated, and ASHRAE expressly disclaims any duty to investigate, any product, service, process, procedure, design, or the like that may be described herein. The appearance of any technical data or editorial material in this publication does not constitute endorsement, warranty, or guaranty by ASHRAE of any product, service, process, procedure, design, or the like. ASHRAE does not warrant that the information in this publication is free of errors. The entire risk of the use of any information in this publication is assumed by the user. ISBN 978-1-939200-98-3 ISSN 1930-7217 The paper for this book is both acid- and elemental-chlorine-free and was manufactured with pulp obtained from sources using sustainable forestry practices. CONTENTS Contributors ASHRAE Technical Committees, Task Groups, and Technical Resource Groups ASHRAE Research: Improving the Quality of Life Preface SYSTEMS AND PRACTICES Chapter 1. 2. 3. 4. 5. 6. 7. Halocarbon Refrigeration Systems (TC 10.3, Refrigerant Piping, Controls and Accessories) Ammonia Refrigeration Systems (TC 10.3) Carbon Dioxide Refrigeration Systems (TC 10.3) Liquid Overfeed Systems (TC 10.1, Custom Engineered Refrigeration Systems) Component Balancing in Refrigeration Systems (TC 10.1) Refrigerant System Chemistry (TC 3.2, Refrigerant System Chemistry) Control of Moisture and Other Contaminants in Refrigerant Systems (TC 3.3, Refrigerant Contaminant Control) 8. Equipment and System Dehydrating, Charging, and Testing (TC 8.1, Positive Displacement Compressors) 9. Refrigerant Containment, Recovery, Recycling, and Reclamation (TC 3.8, Refrigerant Containment) COMPONENTS AND EQUIPMENT Chapter 10. 11. 12. 13. 14. 15. Insulation Systems for Refrigerant Piping (TC 10.3) Refrigerant Control Devices (TC 8.8, Refrigerant System Controls and Accessories) Lubricants in Refrigerant Systems (TC 3.4, Lubrication) Secondary Coolants in Refrigeration Systems (TC 10.1) Forced-Circulation Air Coolers (TC 8.4, Air-to-Refrigerant Heat Transfer Equipment) Retail Food Store Refrigeration and Equipment (TC 10.7, Commercial Food and Beverage Refrigeration Equipment) 16. Food Service and General Commercial Refrigeration Equipment (TC 10.7) 17. Household Refrigerators and Freezers (TC 8.9, Residential Refrigerators and Food Freezers) 18. Absorption Equipment (TC 8.3, Absorption and Heat Operated Machines) FOOD COOLING AND STORAGE Chapter 19. 20. 21. 22.



Volunteer members of ASHRAE Technical Committees and others compiled the information in this handbook, and it is generally reviewed and updated every four years. Comments, criticisms, and suggestions regarding the subject matter are invited. Any errors or omissions in the data should be brought to the attention of the Editor. Additions and corrections to Handbook volumes in print will be published in the Handbook published the year following their verification and, as soon as verified, on the ASHRAE Internet website. DISCLAIMER ASHRAE has compiled this publication with care, but ASHRAE has not investigated, and ASHRAE expressly disclaims any duty to investigate, any product, service, process, procedure, design, or the like that may be described herein. The appearance of any technical data or editorial material in this publication does not constitute endorsement, warranty, or guaranty by ASHRAE of any product, service, process, procedure, design, or the like. ASHRAE does not warrant that the information in this publication is free of errors. The entire risk of the use of any information in this publication is assumed by the user. ISBN 978-1-939200-98-3 ISSN 1930-7217 The paper for this book is both acid- and elemental-chlorine-free and was manufactured with pulp obtained from sources using sustainable forestry practices. CONTENTS Contributors ASHRAE Technical Committees, Task Groups, and Technical Resource Groups ASHRAE Research: Improving the Quality of Life Preface SYSTEMS AND PRACTICES Chapter 1. 2. 3. 4. 5. 6. 7. Halocarbon Refrigeration Systems (TC 10.3, Refrigerant Piping, Controls and Accessories) Ammonia Refrigeration Systems (TC 10.3) Carbon Dioxide Refrigeration Systems (TC 10.3) Liquid Overfeed Systems (TC 10.1, Custom Engineered Refrigeration Systems) Component Balancing in Refrigeration Systems (TC 10.1) Refrigerant System Chemistry (TC 3.2, Refrigerant System Chemistry) Control of Moisture and Other Contaminants in Refrigerant Systems (TC 3.3, Refrigerant Contaminant Control) 8. Equipment and System Dehydrating, Charging, and Testing (TC 8.1, Positive Displacement Compressors) 9. Refrigerant Containment, Recovery, Recycling, and Reclamation (TC 3.8, Refrigerant Containment) COMPONENTS AND EQUIPMENT Chapter 10. 11. 12. 13. 14. 15. Insulation Systems for Refrigerant Piping (TC 10.3) Refrigerant Control Devices (TC 8.8, Refrigerant System Controls and Accessories) Lubricants in Refrigerant Systems (TC 3.4, Lubrication) Secondary Coolants in Refrigeration Systems (TC 10.1) Forced-Circulation Air Coolers (TC 8.4, Air-to-Refrigerant Heat Transfer Equipment) Retail Food Store Refrigeration and Equipment (TC 10.7, Commercial Food and Beverage Refrigeration Equipment) 16. Food Service and General Commercial Refrigeration Equipment (TC 10.7) 17. Household Refrigerators and Freezers (TC 8.9, Residential Refrigerators and Food Freezers) 18. Absorption Equipment (TC 8.3, Absorption and Heat Operated Machines) FOOD COOLING AND STORAGE Chapter 19. 20. 21. 22. 23. 24. Thermal Properties of Foods (TC 10.5, Refrigerated Processing and Storage) Cooling and Freezing Times of Foods (TC 10.5) Commodity Storage Requirements (TC 10.5) Food Microbiology and Refrigeration (TC 10.5) Refrigerated-Facility Design (TC 10.5) Refrigerated-Facility Loads (TC 10.8, Refrigeration Load Calculations) REFRIGERATED TRANSPORT Chapter 25. Cargo Containers, Rail Cars, Trailers, and Trucks (TC 10.6, Transport Refrigeration) 26. Marine Refrigeration (TC 10.6) 27. Air Transport (TC 10.6) FOOD, BEVERAGE, AND FLORAL APPLICATIONS Chapter 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. Methods of Precooling Fruits, Vegetables, and Cut Flowers (TC 10.5) Industrial Food-Freezing Systems (TC 10.5) Meat Products (TC 10.5) Poultry Products (TC 10.5) Fishery Products (TC 10.5) Dairy Products (TC 10.5) Eggs and Egg Products (TC 10.5) Deciduous Tree and Vine Fruit (TC 10.5) Citrus Fruit, Bananas, and Subtropical Fruit (TC 10.5) Vegetables (TC 10.5) Fruit Juice Concentrates and Chilled Juice Products (TC 10.5) Beverages (TC 10.5) Processed, Precooked, and Prepared Foods (TC 10.5) Bakery Products (TC 10.5) Chocolates, Candies, Nuts, Dried Fruits, and Dried Vegetables (TC 10.5) INDUSTRIAL APPLICATIONS Chapter 43. 44. 45. 46. Ice Manufacture (TC 10.2, Automatic Icemaking Plants and Skating Rinks) Ice Rinks (TC 10.2) Concrete Dams and Subsurface Soils (TC 10.1) Cryogenics (TC 10.1) 48. Ultra-low-Temperature Refrigeration (TC 10.1) 49. Biomedical Applications of Cryogenic Refrigeration (TC 10.1) GENERAL Chapter 50. Terminology of Refrigeration (TC 10.1) 51. Codes and Standards ADDITIONS AND CORRECTIONS INDEX Composite index to the 2015 HVAC Applications, 2016 HVAC Systems and Equipment, 2017 Fundamentals, and 2018 Refrigeration volumes Comment Pages CONTRIBUTORS In addition to the Technical Committees, the following individuals contributed significantly to this volume. The appropriate chapter numbers follow each contributor's name. Caleb Nelson (1) Azane, Inc. Jim Caylor (2) Caylor Engineering & Associates, PLLC Greg Scrivener (2) Cold Dynamics Todd Jekel (2, 24) Industrial Refrigeration Consortium, University of Wisconsin-Madison Brad Boggess (6) Emerson Climate Technologies, Inc. Warren Clough (6) UTC Climate, Controls & Security Ed Hessel (6) Lanxess Solutions U.S., Inc. Ngoc Dung (Rosine) Rohatgi (6) Spauschus Associates, Inc. Greg Smith (6) Honeywell International Jorge Cabrera (7) Emerson Angel Mendez (7) CPI Fluid Engineering, The Lubrizol Corporation Ellyse Sorenson (7) Ingersoll Rand Alexander D. Leyderman (8) Triumph Group Daniel J. Miles (9) Vacuum Technology, Inc. Gordon Hart (10) Artek Engineering Jim Young (10, 46) ITW Insulation Systems Willis J. Brayman (10, 46, 47, 48) Brayman Insulation Consultants, LLC Wendell Cornetel (11) Sanhua International Michael Ditello (11) Sanhua International Kirk Stifle (11) Fujikoki America, Inc. Julie Majumr (12) CPI Fluid Engineering Brian Fricke (14) Oak Ridge National Laboratory Kashif Nawaz, Ph.D. (14) Oak Ridge National Laboratory Kishan Padakannaya (14) Johnson Controls, Inc. Michael Chieffo (15, 16) Zero Zone, Inc. Dave Demina (15, 16) United Refrigeration Bruce R. Heilmeyer (15, 16) Zero Zone, Inc. Carl Roberts (15, 16) Zero Zone, Inc. John Diekmann (17) TLAX Detlef Westphalen (17) Navigator Consulting, Inc. David Yashar (17) National Institute of Standards and Technology Wayne K. Borrowman (23, 41, 44, 46, 47, 48) CIMCO Refrigeration Doug Scott (24) VaCom Technologies Casey Briscoe (25) Ingersoll-Rand Robert Chopko (25) Carrier Transicold Corporation Keonwoo Lee (25) Carrier Transicold Corporation William E. Murphy (25, 27) Qiao Lu (27) B/E Aerospace Division, Rockwell Collins Richard Rusich (27) UTC Aerospace Igor Vaisman (27) Thermal Product Solutions James F. Thompson (28) University of California-Davis Don Fenton (28, 32, 35, 36) Kansas State University Michael Jahnce (32) Virginia Polytechnic Institute William Lape (33) Dean Foods Eric Smith (33, 37) IAR Elhadi Yahia (35, 36) Universidad Autonoma de Queretaro Don Tragethon (37) Western Precooling Greg Schrivener (41) Peter Morris (43) North Star Ice Equipment Corporation John Scott (43, 44) Natural Resources Canada Ronald H. Strong (44) Arthur G. Sutherland (44) Accent Refrigeration Systems, Ltd. Daniel Detmers (46, 47, 48, 50) Industrial Refrigeration Consortium, University of Wisconsin James W. Young, Jr. (47, 48) ITW Insulation Ryan McGuine (50) Industrial Refrigeration Consortium, University of Wisconsin Tom D. Wolgamot (50) DC Engineering ASHRAE HANDBOOK COMMITTEE Kelley P. Cramm David P. Yuill, Chair 2018 Refrigeration Volume Subcommittee: Donald L. Fenton, Chair Harry J. Enck D. Scott Fisher ASHRAE HANDBOOK STAFF W. Stephen Comstock, Publisher Director of Publications and Education Mark S. Owen, Editor Heather E. Kennedy, Managing Editor Nancy F. Thysell, Typographer/Page Designer David Solits, Group Manager, and Jayne E. Jackson, Publication Traffic Administrator Electronic Products and Publishing Services William E. Murphy ASHRAE TECHNICAL COMMITTEES, TASK GROUPS, AND TECHNICAL RESOURCE GROUPS SECTION 1.0—FUNDAMENTALS AND GENERAL 1.1 Thermodynamics and Psychrometrics 1.2 Instruments and Measurements 1.3 Heat Transfer and Fluid Flow 1.4 Control Theory and Application 1.5 Computer Applications 1.6 Terminology 1.7 Business, Management & General Legal Education 1.9 Mechanical Systems Insulation 1.9 Electrical Systems 1.10 Cogeneration Systems 1.11 Electric Motors and Motor Control 1.12 Moisture Management in Buildings 1.13 Optimization SECTION 2.0—ENVIRONMENTAL QUALITY 2.1 Physiology and Human Environment 2.2 Plant and Animal Environment 2.3 Gaseous Air Contaminants and Gas Contaminant Removal Equipment 2.4 Particulate Air Contaminants and Particulate Contaminant Removal Equipment 2.5 Global Climate Change 2.6 Sound and Vibration 2.7 Seismic, Wind, and Flood Resistant Design 2.8 Building Environmental Impacts and Sustainability 2.9 Ultraviolet Air and Surface Treatment TG2 Heating Ventilation and Air-Conditioning System (HVAC) SECTION 3.0—MATERIALS AND PROCESSES 3.1 Refrigerants and Secondary Coolants 3.2 Refrigerant System Chemistry 3.3 Refrigerant Contaminant Control 3.4 Lubrication 3.6 Water Treatment 3.8 Refrigerant Containment SECTION 4.0—LOAD CALCULATIONS AND ENERGY REQUIREMENTS 4.1 Load Calculation Data and Procedures 4.2 Climatic Information 4.3 Ventilation Requirements and Infiltration 4.4 Building Materials and Building Envelope Performance 4.5 Penetration 4.7 Energy Calculations 4.10 Indoor Environmental Modeling TRG4 Indoor Air Quality Procedure Development SECTION 5.0—VENTILATION AND AIR DISTRIBUTION 5.1 Fans 5.2 Duct Design 5.3 Room Air Distribution 5.4 Industrial Process Air Cleaning (Air Pollution Control) 5.5 Air-to-Air Energy Recovery 5.6 Control of Fire and Smoke 5.7 Evaporative Cooling 5.9 Enclosed Vehicular Facilities 5.10 Kitchen Ventilation 5.11 Humidifying Equipment SECTION 6.0—HEATING EQUIPMENT, HEATING AND COOLING SYSTEMS AND APPLICATIONS 6.1 Hydronic and Steam Equipment and Systems 6.2 District Energy 6.3 Central Forced Air Heating and Cooling Systems 6.5 Radiant Heating and Cooling 6.6 Service Water Heating Systems 6.7 Solar and Other Renewable Energies 6.8 6.9 6.10 Geothermal Heat Pump and Energy Recovery Applications Thermal Storage Fuels and Combustion SECTION 7.0—BUILDING PERFORMANCE 7.1 Integrated Building Design 7.2 HVAC&R Construction & Design Build Technologies 7.3 Operation and Maintenance Management 7.4 Exergy Analysis for Sustainable Buildings (EXER) 7.5 Smart Building Systems 7.6 Building Energy Performance 7.7 Testing and Balancing 7.8 Owning and Operating Costs 7.9 Building Commissioning SECTION 8.0—AIR-CONDITIONING AND REFRIGERATION SYSTEM COMPONENTS 8.1 Positive Displacement Compressors 8.2 Centrifugal Machines 8.3 Absorption and Heat Operated Machines 8.4 Air-to-Refrigerant Heat Transfer Equipment 8.5 Liquid-to-Refrigerant Heat Exchangers 8.6 Cooling Towers and Evaporative Condensers 8.7 Variable Refrigerant Flow (VRF) 8.8 Refrigerant System Controls and Accessories 8.9 Residential Refrigerators and Food Freezers 8.10 Mechanical Dehumidification Equipment and Heat Pipes 8.11 Unitary and Room Air Conditioners and Heat Pumps 8.12 Desiccant Dehumidification Equipment and Components SECTION 9.0—BUILDING APPLICATIONS 9.1 Large Building Air-Conditioning Systems 9.2 Industrial Air Conditioning and Ventilation 9.3 Transportation Air Conditioning 9.4 Justice Facilities 9.6 Healthcare Facilities 9.7 Educational Facilities 9.8 Large Building Air-Conditioning Applications 9.9 Mission Critical Facilities, Data Centers, Technology Spaces and Electronic Equipment 9.10 Laboratory Systems 9.11 Clean Spaces 9.12 Tall Buildings SECTION 10.0—REFRIGERATION SYSTEMS 10.1 Custom Engineered Refrigeration Systems 10.2 Automatic Icemaking Plants and Skating Rinks 10.3 Refrigerant Piping, Controls, and Accessories 10.5 Refrigerated Processing and Storage 10.6 Transport Refrigeration 10.7 Commercial Food and Beverage Refrigeration Load Calculations SECTION MTG—MULTIDISCIPLINARY TASK GROUPS MTG.ACR Air Change Rate MTG.ASEC Avoided Sources Energy Consumption Due to Waste Heat Recovery and Heat Pump Technologies MTG.BD Building Dampness MTG.BIM Building Information Modeling MTG.EBO Effective Building Operations MTG.HCDG Hot Climate Design Guide MTG.IAST Impact of ASHRAE Standards and Technology on Energy Savings/Performance MTG.LowGWP Lower Global Warming Potential Alternative Refrigerants MTG.OBB Occupant Behavior in Buildings ASHRAE Research: Improving the Quality of Life ASHRAE is the world's foremost technical society in the fields of heating, ventilation, air conditioning, and refrigeration. Its members worldwide are individuals who share ideas, identify needs, support research, and write the industry's standards for testing and practice. The result is that engineers are better able to keep indoor environments safe and productive while protecting and preserving the outdoors for generations to come. One of the ways that ASHRAE supports its members' and industry's need for information is through ASHRAE Research. Thousands of individuals and companies support ASHRAE Research annually, enabling ASHRAE to report new data about material properties and building physics and to promote the application of innovative technologies. Chapters in the ASHRAE Handbook are updated through the experience of members of ASHRAE Technical Committees and through results of ASHRAE Research reported at ASHRAE conferences and published in ASHRAE special publications, ASHRAE Transactions, and ASHRAE's journal of archival research, Science and Technology for the Built Environment. For information about ASHRAE Research or to become a member, contact ASHRAE, 1791 Tullie Circle N.E., Atlanta, GA 30329; telephone: 404-636-8400; www.ashrae.org. Preface The 2018 ASHRAE Handbook—Refrigeration covers the refrigeration equipment and systems for applications other than human comfort. This volume includes data and guidance on cooling, freezing, and storing food; industrial and medical applications of refrigeration; and low-temperature refrigeration. Some of this volume's revisions are described as follows: • Chapter 1, Halocarbon Refrigeration Systems, has added history, background, and application information, and copper piping tables were modified to remove sizes that are not feasible for field-sweated installations. • Chapter 6, Refrigerant System Chemistry, has been updated with new research and new refrigerants, as well as added content on lubricants. • Chapter 7, Control of Moisture and Other Contaminants in Refrigerant Systems, has added content on how to determine required water capacity, and on desiccant heating during ams for Refrigerant Piping, has new content on the use of low-permeance vapor retarder materials in various combinations. • Chapter 11, Refrigerant Control Devices, has revised content on four-way reversing valve operation. • Chapter 15, Retail Food Store Refrigeration and Equipment, contains extensive updates covering industry statistics, current operational practice, standards, optimum temperature difference (TD) for humidity control, refrigerant regulations, and new types of equipment. • Chapter 16, Food Service and General Commercial Refrigeration Equipment, has been updated for currently available equipment features. • Chapter 17, Household Refrigerators and Freezers, has been updated for current test standards and equipment types, with added content on refrigerants and foam-blowing agents. • Chapter 18, Absorption Systems, has been updated throughout and includes many new figures to show system configurations. • Chapter 24, Refrigerated-Facility Loads, has new guidance on vapor retarder design approaches. • Chapter 25, Cargo Containers, Rail Cars, Trailers, and Trucks, has updated references and guidance reflecting current technologies, including data transmission. • Chapter 27, Air Transport, has a major new section on hybrid environmental control systems. • Chapter 44, Ice Rinks, updated for current practice, also has new information on heat recovery design. • Chapter 46, Refrigeration in the Chemical Industry, contains new guidance on insulation design and standards. • Chapter 47, Cryogenics, has an update on insulation used for cryogenic systems. • Chapter 48, Ultra-low-Temperature Refrigeration, has an update on insulation used for ultra-low-temperature systems. • Chapter 50, Terminology of Refrigeration, has been updated for changes in definitions from IAR, OSHA, and EPA sources. • Chapter 51, Codes and Standards, has been updated to list current versions of selected publications from ASHRAE and others. Publications are listed by topic, and full contact information for publishing organizations is included. This volume is published as a bound print volume, in PDF format, and online, in two editions: one using inch-pound (I-P) units of measurement, the other using the International System of Units (SI). Corrections to the 2015, 2016, and 2017 Handbook volumes can be found on the ASHRAE website at www.ashrae.org and in the Additions and Corrections section of the 2018 volume. Corrections for the 2018 volume will be listed in subsequent volumes and on the ASHRAE website. Reader comments are enthusiastically invited. To suggest improvements for a chapter, please comment using the form on the ASHRAE website or write to Handbook Editor, ASHRAE, 1791 Tullie Circle, Atlanta, GA 30329, or fax 678-539-2187, or e-mail (email protected). Mark S. Owen Editor Related Commercial Resources CHAPTER 1 HALOCARBON REFRIGERATION SYSTEMS Application..... 1.1 System Safety..... 1.2 Basic Piping Principles 1.2 Refrigerant Line Sizing 1.3 Piping at Multiple Compressors 1.20 Piping at Various System Components..... 1.22 Discharge (Hot-Gas) Lines..... 1.24 Defrost Gas Supply Lines 1.27 Heat Exchangers and Vessels Refrigeration Accessories Pressure Control for Refrigerant Condensers Keeping Liquid from Crankcase During Off Cycles Hot-Gas Bypass Arrangements Minimizing Refrigerant Charge in Commercial Systems..... Refrigerant Retrofitting Temperature Glide R degree of toxicity and/or flammability. These first-generation refrigerants were an impediment to Frigidaire's plans to expand into refrigeration and air conditioning, so Frigidaire and DuPont collaborated to develop safer refrigerants. In 1928, Thomas Midgley, Jr., of Frigidaire and his colleagues developed the first commercially available CFC refrigerant, dichlorodifluoromethane (R-12) (Gunta 2006). Chlorinated halocarbon refrigerants represent the second generation of refrigerants (Calm 2008). Concern about the use of halocarbon refrigerants began with a 1974 paper by two University of California professors, Frank Rowland and Mario Molina, in which they highlighted the damage chlorine could cause to the ozone layer in the stratosphere. This publication eventually led to the Montreal Protocol Agreement in 1987 and its subsequent revisions, which restricted the production and use of chlorinated halocarbon (CFC and HCFC) refrigerants. All CFC refrigerant production was phased out in the United States at the beginning of 1996. Replacement HFC, third-generation refrigerants were developed following these restrictions (Calm 2008). Although HFC refrigerants do not contain chlorine and thus have no effect on stratospheric ozone, they have come under heavy scrutiny because of their global warming potential (GWP): like CFCs and HCFCs, they are greenhouse gases, and can trap radiant energy (IPCC 1990). In October 2016, in Kigali, Rwanda, the 1987 Montreal Protocol Agreement was revised to also include regulation of HFC refrigerants as controlled substances. This Kigali Agreement marks a commitment from a significant portion of the world to deal with the global warming consequences of HFC gases. As phasedown begins, interest in the future cost and availability of these refrigerants is likely to increase. Indeed, portions of the United States and Europe already had HFC regulations that predated the Kigali Agreement. The latest fluorinated greenhouse gas (F-gas) regulation in Europe adopted in 2014 (revised from the initial adoption in 2006) aims to reduce HFC refrigerant sales to one-fifth of 2014 levels by 2030. Some HFCs have already been banned where suitable alternatives are widely available, and all systems require specific maintenance checks, servicing, and refrigerant reclamation when the system is decommissioned. In the United States, California's Global Warming Solutions Act (Assembly Bill 32; www.arb.ca.gov/cc/ab32/ab32.htm) went into effect in 2011; this bill's early adoption measures began regulating HFC refrigerants to reduce the environmental consequences of greenhouse gases. These early adoption measures were designed as the prelude to a proposed HFC phaseout, and include required service practices; leak inspection; charge monitoring and record keeping; system retrofit and retrofit plans; and refrigerant distributor, wholesaler, and reclaimer prohibitions. HFO refrigerants have significantly lower GWP values than HFCs, and are being developed and promoted as alternatives to HFC refrigerants. However, HFOs are classed as mildly flammable, which is an obvious barrier to adoption. Safety measures must be fully EFRIGERATION is the process of moving heat from one location to another by use of refrigerant in a closed cycle. Oil management; gas and liquid separation; subcooling, superheating, desuperheating, and piping of refrigerant liquid, gas, and two-phase flow are all part of refrigeration. Applications include air

should be at least 2.3 m above the floor. Locate pipes carefully in relation to other piping and structural members, especially when lines are to be insulated. The distance between insulated lines should be at least three times the thickness of the insulation for screwed fittings, and four times for flange fittings. The space between the pipe and adjacent surfaces should be three-fourths of these amounts.

Hangers located close to the vertical risers or from and compressors keep the piping weight off the compressor. Pipe hangers should be placed no more than 2.4 to 3 m apart, depending on pipe size, and within 0.6 m of a change in direction of the piping. Hangers should be designed to bear on the outside of insulated lines.

Sheet metal sleeves on the lower half of the insulation are usually sufficient. Where piping penetrates a wall, a sleeve should be installed, and where the pipe penetrating the wall is insulated, it must be adequately sealed. Piping to and from compressors and to other components must provide for expansion and contraction. Sufficient flange or union joints should be located in the piping so components can be assembled easily during installation and also disassembled for servicing. Fittings Pipe Sizing Couplings, elbows, and tees for threaded pipe are for a minimum of 21 MPa design pressure and constructed of forged steel. Fittings for welded pipe should match the type of pipe used (i.e., standard fittings for standard pipe and extra-heavy fittings for extra-heavy pipe). Tongue-and-groove or ANSI flanges should be used in ammonia piping. Welded flanges for low-side piping can have a minimum 1 MPa design pressure rating.

Standard fittings for high and medium pressure piping are designed for a minimum 1.6 MPa design pressure. The high and medium pressure piping design charts, Tables 1 and 2, provide practical suction line sizing data based on 0.005 K and 0.01 K differential pressure drop equivalent per meter of total equivalent length of pipe, assuming no liquid in the suction line. For data on equivalent lengths of valves and fittings, refer to Tables 10, 11, and 12 in Chapter 1 for design suction and discharge lines. At 0.02 K differential pressure drop equivalent per metre equivalent length of pipe, and for sizing liquid lines at 0.5 m/s. Charts prepared by Wile (1977) present pressure drops in saturation temperature equivalents. For a complete discussion of the basis of these line sizing charts, see Timm (1991). Table 3 presents line sizing information for pumped liquid lines, high-pressure liquid lines, hot-gas defrost lines, equalizing lines, and thermosiphon lubricant cooling ammonia lines.

should be at least 2.3 m above the floor. Locate pipes carefully in relation to other piping and structural members, especially when lines are to be insulated. The distance between insulated lines should be at least three times the thickness of the insulation for screwed fittings, and four times for flange fittings. The space between the pipe and adjacent surfaces should be three-fourths of these amounts.

Hangers located close to the vertical risers or from and compressors keep the piping weight off the compressor. Pipe hangers should be placed no more than 2.4 to 3 m apart, depending on pipe size, and within 0.6 m of a change in direction of the piping. Hangers should be designed to bear on the outside of insulated lines.

Sheet metal sleeves on the lower half of the insulation are usually sufficient. Where piping penetrates a wall, a sleeve should be installed, and where the pipe penetrating the wall is insulated, it must be adequately sealed. Piping to and from compressors and to other components must provide for expansion and contraction. Sufficient flange or union joints should be located in the piping so components can be assembled easily during installation and also disassembled for servicing. Fittings Pipe Sizing Couplings, elbows, and tees for threaded pipe are for a minimum of 21 MPa design pressure and constructed of forged steel. Fittings for welded pipe should match the type of pipe used (i.e., standard fittings for standard pipe and extra-heavy fittings for extra-heavy pipe). Tongue-and-groove or ANSI flanges should be used in ammonia piping. Welded flanges for low-side piping can have a minimum 1 MPa design pressure rating.

Standard fittings for high and medium pressure piping are designed for a minimum 1.6 MPa design pressure. The design pressure for the piping and components should be at least 1.6 MPa minimum for air-cooled and condensing. Use Table 1 presents practical suction line sizing data based on 0.005 K and 0.01 K differential pressure drop equivalent per meter equivalent length of pipe, assuming no liquid in the suction line. For data on equivalent lengths of valves and fittings, refer to Tables 10, 11, and 12 in Chapter 1 for design suction and discharge lines. At 0.02 K differential pressure drop equivalent per metre equivalent length of pipe, and for sizing liquid lines at 0.5 m/s. Charts prepared by Wile (1977) present pressure drops in saturation temperature equivalents. For a complete discussion of the basis of these line sizing charts, see Timm (1991). Table 3 presents line sizing information for pumped liquid lines, high-pressure liquid lines, hot-gas defrost lines, equalizing lines, and thermosiphon lubricant cooling ammonia lines.

When joining pipes between lengths of pipe or fittings can be threaded if the pipe size is 32 mm or smaller, pipe 40 mm or larger should be welded. An all-welded piping system is superior. Threaded joints. Many sealants and compounds are available for sealing threaded joints. The manufacturer's instructions cover compatibility and application methods. Do not use excessive amounts or apply on female threads because an excess can contaminate the system. Welded joints. Pipe should be cut and beveled before welding. Use pipe alignment guides, and provide a proper gap between pipe ends so that a full penetration weld is obtained. The weld should be made by a qualified welder, using proper procedures as specified in the Welding Procedure Specifications, prepared by the National Certified Pipe Welding Bureau (NCPWB). Gasketed Joints. A compatible fiber gasket should be used with flanges. Before tightening flange bolts to valves, controls, or flange unions, properly align pipe and bolt holes.

When flanges are used to straighten pipe, they put stress on adjacent valves, compressors, and controls, causing the operating mechanism to bind. To prevent leaks, flange bolts are drawn up evenly when connecting the flanges.

Flanges at compressors and other system components must not move or indicate stress when all bolts are loosened. Union Joints. Steel (21 MPa) ground joint unions are used for gage and pressure control lines with screwed valves and for joints up to 20 mm. When tightening this type of joint, the two pipes 1.7 CONTROLS Refrigerant flow controls are discussed in Chapter 11. The following precautions are necessary in the application of certain controls in low-temperature systems.

Liquid Feed Control Many controls available for single-stage, high-temperature systems may be used with some discretion on low-temperature systems. If the liquid level is controlled by a low-side float valve (with the float in the chamber where the level is controlled), low pressure and temperature have no appreciable effect on operation. External float valves, however, should be used with caution. If the float valve is installed in the float chamber, the float chamber must be vented to the atmosphere. Equalizing lines to external float chambers, particularly in the upper line, must be sized generously so that liquid can reach the float chamber, and gas resulting from any evaporation may be returned to the vessel without appreciable pressure loss.

The superheat-controlled (thermostatic) expansion valve is generally used in direct-expansion evaporators. This valve operates on the difference between bulb pressure, which is responsive to suction temperature, and pressure below the diaphragm, which is the actual suction pressure. This file is licensed to Osama Khayata ). Copyright ASHRAE 2018. 2.16 2018 ASHRAE Handbook—Refrigeration (SI) Table 1.1 Suction Line Capacities in Kilowatts for Ammonia with Pressure Drops of 0.005 and 0.01 K/microns Saturated Suction Temperature, °C -50 Steel Nominal Line Size, mm 10 15 20 25 32 40 50 65 80 100 125 150 200 250 300 t = 0.005 K/m p = 12.21 Pa/m -40 t = 0.01 K/m p = 24.2 Pa/m 2018 0.19 0.37 0.80 1.55 2.39 3.68 9.74 15.67 28.08 57.95 105.71 172.28 356.67 649.99 1045.27 t = 0.005 K/m p = 19.2 Pa/m 0.29 0.55 1.18 2.28 3.51 5.41 14.22 22.83 40.81 84.10 153.05 248.91 514.55 937.58 1504.96 -30 t = 0.01 K/m p = 38.4 Pa/m 0.36 0.65 1.41 2.72 4.43 6.85 16.89 27.13 48.36 96.90 181.16 294.74 609.20 1107.64 1777.96 0.51 0.97 2.08 3.97 6.74 9.94 24.50 39.27 69.99 143.84 261.22 424.51 874.62 1589.51 2550.49 t = 0.005 K/m p = 29.1 Pa/m t = 0.01 K/m p = 58.2 Pa/m 0.58 1.09 2.34 4.48 7.66 11.77 27.57 44.17 78.68 161.77 293.12 476.47 981.85 1782.31 2859.98 0.85 1.60 3.41 6.51 11.14 17.48 30.82 63.77 113.20 232.26 420.63 683.18 1402.03 2545.46 4088.54 Saturated Suction Temperature, °C Licensed for single user. © 2018 ASHRAE, Inc. -20 Steel Nominal Line Size, mm 10 15 20 25 32 40 50 65 80 100 125 150 200 250 300 t = 0.005 K/m p = 42.2 Pa/m 0.91 1.72 3.66 6.98 12.47 19.08 42.72 68.42 121.52 249.45 452.08 733.59 1506.11 2731.90 4378.84 t = 0.01 K/m p = 84.4 Pa/m 1.15 2.15 4.30 8.14 14.19 25.02 52.32 82.16 142.27 286.19 515.27 842.92 1569.45 2499.81 4016.24 6381.19 0.85 1.60 3.41 6.51 11.14 17.48 30.82 63.77 113.20 232.26 420.63 683.18 1402.03 2545.46 4088.54 Saturated Suction Temperature, °C Licensed for single user. © 2018 ASHRAE, Inc. -20 Steel Nominal Line Size, mm 10 15 20 25 32 40 50 65 80 100 125 150 200 250 300 t = 0.005 K/m p = 138.3 Pa/m 2.41 4.50 9.53 18.09 28.67 42.27 109.28 174.30 308.91 631.24 1139.74 1846.63 3784.58 6851.91 10 973.55 t = 0.005 K/m p = 92.6 Pa/m 2.37 4.42 9.38 17.79 28.32 43.27 107.61 171.62 304.12 621.94 1124.47 1819.59 3735.65 6759.98 10 810.65 t = 0.01 K/m p = 185.3 Pa/m 3.42 6.37 13.46 25.48 36.02 54.88 105.66 245.00 433.79 885.81 1598.31 2590.21 5303.12 9589.56 15 360.20 Note: Capacities are in kilowatts of refrigeration resulting in a line friction loss per unit equivalent pipe length (p in Pa/m), with corresponding change in saturation temperature per unit length (t in K/m). The thermostatic expansion valve is designed to maintain a preset superheat in suction gas. Although the pressure-sensing part of the system responds almost immediately to a change in conditions, the temperature-sensing bulb must overcome thermal inertia before its effect is felt on the power element of the valve. Thus, when compressor capacity decreases suddenly, the expansion valve may overfeed before the bulb senses the presence of liquid in the suction line and reduces the feed. Therefore, a suction accumulator should be installed on direct-expansion low-temperature systems with multiple expansion valves. Controlling Load During Pulldown System transients during pulldown can be managed by controlling compressor capacity.

Proper load control reduces compressor capacity so that energy requirements stay within motor and condenser capacities. On larger systems using screw compressors, a current-sensing device reads motor amperage and adjusts the capacity control device appropriately. Cylinders on reciprocating compressors can be unloaded for similar control. Alternatively, a downstream, outlet, or crankcase pressure regulator can be installed in the suction line to throttle suction flow if the pressure exceeds a preset limit. This regulator limits the compressor's suction pressure during pulldown. The disadvantage of this device is the extra pressure drop it causes when the system is at the desired operating condition. To overcome some of this, the designer can use external forces to drive the valve to be held fully open when the pressure is below the maximum allowable. Systems using downstream pressure regulators and compressor unloading must be carefully designed so that the two controls complement each other. Operation at Varying Loads and Temperatures Compressor and evaporator capacity controls are similar for multi- and single-stage systems. Control methods include compressor capacity control, hot-gas bypass, or evaporator pressure regulators. Low pressure can affect control systems by significantly increasing the specific volume of the refrigerant gas and the pressure drop. A small pressure reduction can cause a large percentage capacity reduction. System load usually cannot be reduced to near zero, because this results in little or no flow of gas through the compressor and consequent overheating. Additionally, high pressure ratios are detrimental to the compressor if it is required to run at very low loads. If the compressor cannot be allowed to cycle off during low load, an acceptable alternative is a hot-gas bypass. High-pressure gas is fed to the lowpressure side of the system through a downstream pressure regulator. This file is licensed to Osama Khayata ). Copyright ASHRAE 2018. Ammonia Refrigeration Systems Table 2.1.7 Suction, Discharge Line, and Liquid Capacities in Kilowatts for Ammonia (Single- or High-Stage Applications) Discharge Lines t = 0.02 K/m p = 684.0 Pa/m Suction Lines t = 0.02 K/m Licensed for single user. © 2018 ASHRAE, Inc. Steel Saturated Suction Temperature, °C Nominal Line Size, -40 -30 -20 -5 +5 mm 3/8 1/2 3/4 1 1 1/4 1 3/4 2 2 1/2 3 3 1/2 4 4 1/2 5 6 6 3/4 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 54 58 62 66 70 74 78 82 86 90 94 98 102 106 110 114 118 122 126 130 134 138 142 146 150 154 158 162 166 170 174 178 182 186 190 194 198 202 206 210 214 218 222 226 230 234 238 242 246 250 254 258 262 266 270 274 278 282 286 290 294 298 302 306 310 314 318 322 326 330 334 338 342 346 350 354 358 362 366 370 374 378 382 386 390 394 398 402 406 410 414 418 422 426 430 434 438 442 446 450 454 458 462 466 470 474 478 482 486 490 494 498 502 506 510 514 518 522 526 530 534 538 542 546 550 554 558 562 566 570 574 578 582 586 590 594 598 602 606 610 614 618 622 626 630 634 638 642 646 650 654 658 662 666 670 674 678 682 686 690 694 698 702 706 710 714 718 722 726 730 734 738 742 746 750 754 758 762 766 770 774 778 782 786 790 794 798 802 806 810 814 818 822 826 830 834 838 842 846 850 854 858 862 866 870 874 878 882 886 890 894 898 902 906 910 914 918 922 926 930 934 938 942 946 950 954 958 962 966 970 974 978 982 986 990 994 998 1002 1006 1010 1014 1018 1022 1026 1030 1034 1038 1042 1046 1050 1054 1058 1062 1066 1070 1074 1078 1082 1086 1090 1094 1098 1102 1106 1110 1114 1118 1122 1126 1130 1134 1138 1142 1146 1150 1154 1158 1162 1166 1170 1174 1178 1182 1186 1190 1194 1198 1202 1206 1210 1214 1218 1222 1226 1230 1234 1238 1242 1246 1250 1254 1258 1262 1266 1270 1274 1278 1282 1286 1290 1294 1298 1302 1306 1310 1314 1318 1322 1326 1330 1334 1338 1342 1346 1350 1354 1358 1362 1366 1370 1374 1378 1382 1386 1390 1394 1398 1402 1406 1410 1414 1418 1422 1426 1430 1434 1438 1442 1446 1450 1454 1458 1462 1466 1470 1474 1478 1482 1486 1490 1494 1498 1502 1506 1510 1514 1518 1522 1526 1530 1534 1538 1542 1546 1550 1554 1558 1562 1566 1570 1574 1578 1582 1586 1590 1594 1598 1602 1606 1610 1614 1618 1622 1626 1630 1634 1638 1642 1646 1650 1654 1658 1662 1666 1670 1674 1678 1682 1686 1690 1694 1698 1702 1706 1710 1714 1718 1722 1726 1730 1734 1738 1742 1746 1750 1754 1758 1762 1766 1770 1774 1778 1782 1786 1790 1794 1798 1802 1806 1810 1814 1818 1822 1826 1830 1834 1838 1842 1846 1850 1854 1858 1862 1866 1870 1874 1878 1882 1886 1890 1894 1898 1902 1906 1910 1914 1918 1922 1926 1930 1934 1938 1942 1946 1950 1954 1958 1962 1966 1970 1974 1978 1982 1986 1990 1994 1998 2002 2006 2010 2014 2018 2022 2026 2030 2034 2038 2042 2046 2050 2054 2058 2062 2066 2070 2074 2078 2082 2086 2090 2094 2098 2102 2106 2110 2114 2118 2122 2126 2130 2134 2138 2142 2146 2150 2154 2158 2162 2166 2170 2174 2178 2182 2186 2190 2194 2198 2202 2206 2210 2214 2218 2222 2226 2230 2234 2238 2242 2246 2250 2254 2258 2262 2266 2270 2274 2278 2282 2286 2290 2294 2298 2302 2306 2310 2314 2318 2322 2326 2330 2334 2338 2342 2346 2350 2354 2358 2362 2366 2370 2374 2378 2382 2386 2390 2394 2398 2402 2406 2410 2414 2418 2422 2426 2430 2434 2438 2442 2446 2450 2454 2458 2462 2466 2470 2474 2478 2482 2486 2490 2494 2498 2502 2506 2510 2514 2518 2522 2526 2530 2534 2538 2542 2546 2550 2554 2558 2562 2566 2570 2574 2578 2582 2586 2590 2594 2598 2602 2606 2610 2614 2618 2622 2626 2630 2634 2638 2642 2646 2650 2654 2658 2662 2666 2670 2674 2678 2682 2686 2690 2694 2698 2702 2706 2710 2714 2718 2722 2726 2730 2734 2738 2742 2746 2750 2754 2758 2762 2766 2770 2774 2778 2782 2786 2790 2794 2798 2802 2806 2810 2814 2818 2822 2826 2830 2834 2838 2842 2846 2850 2854 2858 2862 2866 2870 2874 2878 2882 2886 2890 2894 2898 2902 2906 2910 2914 2918 2922 2926 2930 2934 2938 2942 2946 2950 2954 2958 2962 2966 2970 2974 2978 2982 2986 2990 2994 2998 3002 3006 3010 3014 3018 3022 3026 3030 3034 3038 3042 3046 3050 3054 3058 3062 3066 3070 3074 3078 3082 3086 3090 3094 3098 3102 3106 3110 3114 3118 3122 3126 3130 3134 3138 3142 3146 3150 3154 3158 3162 3166 3170 3174 3178 3182 3186 3190 3194 3198 3202 3206 3210 3214 3218 3222 3226 3230 3234 3238 3242 3246 3250 3254 3258 3262 3266 3270 3274 3278 3282 3286 3290 3294 3298 3302 3306 3310 3314 3318 3322 3326 3330 3334 3338 3342 3346 3350 3354 3358 3362 3366 3370 3374 3378 3382 3386 3390 3394 3398 3402 3406 3410 3414 3418 3422 3426 3430 3434 3438 3442 3446 3450 3454 3458 3462 3466 3470 3474 3478 3482 3486 3490 3494 3498 3502 3506 3510 3514 3518 3522 3526 3530 3534 3538 3542 3546 3550 3554 3558 3562 3566 3570 3574 3578 3582 3586 3590 3594 3598 3602 3606 3610 3614 3618 3622 3626 3630 3634 3638 3642 3646 3650 3654 3658 3662 3666 3670 3674 3678 3682 3686 3690 3694 3698 3702 3706 3710 3714 3718 3722 3726 3730 3734 3738 3742 3746 3750 3754 3758 3762 3766 3770 3774 3778 3782 3786 3790 3794 3798 3802 3806 3810 3814 3818 3822 3826 3830 3834 3838 3842 3846 3850 3854 3858 3862 3866 3870 3874 3878 3882 3886 3890 3894 3898 3902 3906 3910 3914 3918 3922 3926 3930 3934 3938 3942 3946 3950 3954 3958 3962 3966 3970 3974 3978 3982 3986 3990 3994 3998 4002 4006 4010 4014 4018 4022 4026 4030 4034 4038 4042 4046 4050 4054 4058 4062 4066 4070 4074 4078 4082 4086 4090 4094 4098 4102 4106 4110 4114 4118 4122 4126 4130 4134 4138 4142 4146 4150 4154 4158 4162 4166 4170 4174 4178 4182 4186 4190 4194 4198 4202 4206 4210 4214 4218 4222 4226 4230 4234 4238 4242 4246 4250 4254 4258 4262 4266 4270 4274 4278 4282 4286 4290 4294 4298 4302 4306 4310 4314 4318 4322 4326 4330 4334 4338 4342 4346 4350 4354 4358 4362 4366 4370 4374 4378 4382 4386 4390 4394 4398 4402 4406 4410 4414 4418 4422 4426 4430 4434 4438 4442 4446 4450 4454 4458 4462 4466 4470 4474 4478 4482 4486 4490 4494 4498 4502 4506 4510 4514 4518 4522 4526 4530 4534 4538 4542 4546 4550 4554 4558 4562 4566 4570 4574 4578 4582 4586 4590 4594 4598 4602 4606 4610 4614 4618 4622 4626 4630 4634 4638 4642 4646 4650 4654 4658 4662 4666 4670 4674 4678 4682 4686 4690 4694 4698 4702 4706 4710 4714 4718 4722 4726 4730 4734 4738 4742 4746 4750 4754 4758 4762 4766 4770 4774 4778 4782 4786 4790 4794 4798 4802 4806 4810 4814 4818 4822 4826 4830 4834 4838 4842 4846 4850 4854 4858 4862 4866 4870 4874 4878 4882 4886 4890 4894 4898 4902 4906 4910 4914 4918 4922 4926 4930 4934 4938 4942 4946 4950 4954 4958 4962 4966 4970 4974 4978 4982 4986 4990 4994 4998 5002 5006 5010 5014 5018 5022 5026 5030 5034 5038 5042 5046 5050 5054 5058 5062 5066 5070 5074 5078 5082 5086 5090 5094 5098 5102 5106 5110 5114 5118 5122 5126 5130 5134 5138 5142 5146 5150 5154 5158 5162 5166 5170 5174 5178 5182 5186 5190 5194 5198 5202 5206 5210 5214 5218 5222 5226 5230 5234 5238 5242 5246 5250 5254 5258 5262 5266 5270 5274 5278 5282 5286 5290 5294 5298 5302 5306 5310 5314 5318 5322 5326 5330 5334 5338 5342 5346 5350 5354 5358 5362 5366 5370 5374 5378 5382 5386 5390 5394 5398 5402 5406 5410 5414 5418 5422 5426 5430 5434 5438 5442 5446 5450 5454 5458 5462 5466 5470 5474 5478 5482 5486 5490 5494 5498 5502 5506 5510 5514 5518 5522 5526 5530 5534 5538 5542 5546 5550 5554 5558 5562 5566 5570 5574 5578 5582 5586 5590 5594 5598 5602 5606 5610 5614 5618 5622 5626 5630 5634 5638 5642 5646 5650 5654 5658 5662 5666 5670 5674 5678 5682 5686 5690 5694 5698 5702 5706 5710 5714 5718 5722 5726 5730 5734 5738 5742 5746 5750 5754 5758 5762 5766 5770 5774 5778 5782 5786 5790 5794 5798 5802 5806 5810 5814 5818 5822 5826 5830 5834 5838 5842 5846 5850 5854 5858 5862 5866 5870 5874 5878 5882 5886 5890 5894 5898 5902 5906 5910 5914 5918 5922 5926 5930 5934 5938 5942 5946 5950 5954 5958 5962 5966 5970 5974 5978 5982 5986 5990 5994 5998 6002 6006 6010 6014 6018 6022 6026 6030 6034 6038 6042 6046 6050 6054 6058 6062 6066 6070 6074 6078 6082 6086 6090 6094 6098 6102 6106 6110 6114 6118 6122 6126 6130 6134 6138 6142 6146 6150 6154 6158 6162 6166 6170 6174 6178 6182 6186 6190 6194 6198 6202 6206 6210 6214 6218 6222 6226 6230 6234 6238 6242 6246 6250 6254 6258 6262 6266 6270 6274 6278 6282 6286 6290 6294 6298 6302 6306 6310 6314 6318 6322 6326 6330 6334 6338 6342 6346 6350 6354 6358 6362 6366 6370 6374 6378 6382 6386 6390 6394 6398 6402 6406 6410 6414 6418 6422 6426 6430 6434 6438 6442 6446 6450 6454 6458 6462 6466 6470 6474 6478 6482 6486 6490 6494 6498 6502 6506 6510 6514 6518 6522 6526 6530 6534 6538 6542 6546 6550 6554 6558 6562 6566 6570 6574 6578 6582 6586 6590 6594 6598 6602 6606 6610 6614 6618 6622 6626 6630 6634 6638 6642 6646 6650 6654 6658 6662 6666 6670 6674 6678 6682 6686 6690 6694 6698 6702 6706 6710 6714 6718 6722 6726 6730 6734 6738 6742 6746 6750 6754 6758 6762 6766 6770 6774 6778 6782 6786 6790 6794 6798 6802 6806 6810 6814 6818 6822 6826 6830 6834 6838 6842 6846 6850 6854 6858 6862 6866 6870 6874 6878 6882 6886 6890 6894 6898 6902 6906 6910 6914 6918 6922 6926 6930 6934 6938 6942 6946 6950 6954 6958 6962 6966 6970 6974 6978 6982 6986 6990 6994 6998 7002 7006 7010 7014 7018 7022 7026 7030 7034 7038 7042 7046 7050 7054 7058 7062 7066 7070 7074 7078 7082 7086 7090 7094 7098 7102 7106 7110 7114 7118 7122 7126 7130 7134 7138 7142 7146 7150 7154 7158 7162 7166 7170 7174 7178 7182 7186 7190 7194 7198 7202 7206 7210 7214 7218 7222 7226 7230 7234 7238 7242 7246 7250 7254 7258 7262 7266 7270 7274 7278 7282 7286 7290 7294 7298 7302 7306 7310 7314 7318 7322 7326 7330 7334 7338 7342 7346 7350 7354 7358 7362 7366 7370 7374 7378 7382 7386 7390 7394 7398 7402 7406 7410 7414 7418 7422 7426 7430 7434 7438 7442 7446 7450 7454 7458 7462 7466 7470 7474 7478 7482 7486 7490 7494 7498 7502 7506 7510 7514 7518 7522 7526 7530 7534 7538 7542 7546 7550 7554 7558 7562 7566 7570 7574 7578 7582

Refrigeration 494(1):16-171. Available at books.google.com/books?id=YZc7AQAAAMAA. Nuckolls, A.H. 1933. The comparative life, fire, and explosion hazards of common refrigerants. Miscellaneous Hazard 2375. Underwriters Laboratory, Northbrook, IL. Shelton, J.C., and A.M. Jacobi. 1997. A fundamental study of refrigerant line transients: Part 1—Description of the problem and survey of relevant literature. ASHRAE Transactions 103(1):65-87. This file is licensed to Osama Khayata (femail protected). Copyright ASHRAE 2018. 2.28 2018 ASHRAE Handbook—Refrigeration (SI) Strong, A.P. 1984. Hot gas defrost—A one-a-more-a-time. IAHR Technical Paper T-53. International Institute of Ammonia Refrigeration, Arlington, VA. Licensed for single user. © 2018 ASHRAE, Inc. Shelton, J.C., and A.M. Jacobi. 1997. A fundamental study of refrigerant line transients: Part 2—Pressure excursion estimates and initiation mechanisms. ASHRAE Transactions 103(2):32-41. Related Commercial Resources This file is licensed to Osama Khayata (femail protected). Copyright ASHRAE 2018. Related Commercial Resources CHAPTER 3 CARBON DIOXIDE REFRIGERATION SYSTEMS Applications..... System Design..... System Safety..... Piping..... Heat Exchangers and Vessels..... 3.2 3.3 3.7 3.7 3.8 Compressors for CO2 Refrigeration Systems..... 3.8 Lubricants..... 3.9 Evaporators..... 3.10 Defrost..... 3.10 Installation, Start-up, and Commissioning..... 3.11 ARBON Dioxide (R-744) is one of the naturally occurring compounds collectively known as “natural refrigerants.” It is nonflammable and nontoxic, with no known carcinogenic, mutagenic, or other toxic effects, and no dangerous products of combustion. Using carbon dioxide in refrigerating systems can be considered a form of carbon capture, with a potential beneficial effect on climate change. It has no adverse local environmental effects. Carbon dioxide exists in a gaseous state at normal temperatures and pressures within the Earth’s atmosphere. Currently, the use of carbon dioxide as a refrigerant is limited. Widespread availability made CO2 an attractive refrigerant. The use of CO2 refrigeration systems became established in the 1890s and CO2 became the refrigerant of choice for freezing and transporting perishable food products around the world. Meat and other food products from Argentina, New Zealand and Australia were shipped via refrigerated vessels to Europe for distribution and consumption. Despite having traveled a several-week voyage spanning half the globe, the receiving consumer considered the condition of the frozen meat to be comparable to the fresh product. By 1900, over 300 refrigerated ships were delivering meat products from many distant shores. In the same year, Great Britain imported 360,000 tons of refrigerated beef and lamb from Argentina, New Zealand, and Australia. The following year, refrigerated banana ships arrived from Jamaica, and tropical fruit became a lucrative cargo for vessel owners. CO2 gained dominance as a refrigerant in marine applications ranging from coolers and freezers for crew provisions to systems designed to preserve an entire cargo of frozen products. Safety was the fundamental reason for CO2’s development and growth. Marine CO2-refrigerated shipping rapidly gained popularity for its reliability in the distribution of a wide variety of fresh food products to many countries around the world. The CO2 marine refrigeration industry saw phenomenal growth, and by 1910 some 1800 systems were in operation on ships transporting refrigerated food products. By 1935, food producers shipped millions of tons of food products including meats, dairy products, and fruits to Great Britain annually. North America also was served by CO2 marine refrigeration in both exporting and receiving food products. The popularity of land-based refrigeration systems. This included a wide variety of domestic and commercial CFC uses. The development of the hermetic and semihermetic compressors accelerated the development of systems containing CFCs. For the next 35 years, a number of CFC refrigerants gained popularity, replacing practically all other refrigerants except ammonia, which maintained its dominant position in industrial refrigeration systems. In the 1970s, the atmospheric effects of CFC emissions were highlighted. This led to a concerted effort from governments, scientists, and industrialists to limit these effects. Initially, this took the form of quotas on production, but soon moved to a total phaseout, first of CFCs and then of hydrochlorofluorocarbons (HCFCs). The ozone depleting potential (ODP) rating of CFCs and HCFCs prompted the development of hydrofluorocarbon (HFC) refrigerants. Subsequent environmental research shifted the focus from ozone depletion to climate change, producing a second rating known as the global warming potential (GWP). Table 1 presents GWPs for several common refrigerants. Table 2 compares performance of current refrigerants used in refrigeration systems. In recent years, CO2 has once again become a refrigerant of great interest. However, high-pressure CO2 systems (e.g., 3.4 MPa at a saturation temperature of -1°C, or 6.7 MPa at 26.7°C) present some challenges for containment and safety. Advances in materials science since the 1950s enable the design of cost-effective and efficient high-pressure carbon dioxide systems. The attraction of using CO2 in modern systems is based on its licensed for single user. © 2018 ASHRAE, Inc. C The preparation of this chapter is assigned to TC 10.3, Refrigerant Piping, Controls and Accessories. Table 1 Refrigerant Refrigerant Number Group Refrigerant Data Chemical Formula Temperature at GWP at 101.3 kPa, Safety 100 °C Group Years R-22 HCFC R-134a HFC R-410A HFC blend CHClF2 CF3CH2F R-32 (50%) HFC-125 (50%) R-507A HFC blend HFC-125 (50%) HFC-143a (50%) R-717 Ammonia NH3 R-744 CO2 R-408 R-409 R-503 R-507 R-508 R-509 R-510 R-511 R-512 R-513 R-514 R-515 R-516 R-517 R-518 R-519 R-520 R-521 R-522 R-523 R-524 R-525 R-526 R-527 R-528 R-529 R-530 R-531 R-532 R-533 R-534 R-535 R-536 R-537 R-538 R-539 R-540 R-541 R-542 R-543 R-544 R-545 R-546 R-547 R-548 R-549 R-550 R-551 R-552 R-553 R-554 R-555 R-556 R-557 R-558 R-559 R-560 R-561 R-562 R-563 R-564 R-565 R-566 R-567 R-568 R-569 R-570 R-571 R-572 R-573 R-574 R-575 R-576 R-577 R-578 R-579 R-580 R-581 R-582 R-583 R-584 R-585 R-586 R-587 R-588 R-589 R-590 R-591 R-592 R-593 R-594 R-595 R-596 R-597 R-598 R-599 R-600 R-601 R-602 R-603 R-604 R-605 R-606 R-607 R-608 R-609 R-610 R-611 R-612 R-613 R-614 R-615 R-616 R-617 R-618 R-619 R-620 R-621 R-622 R-623 R-624 R-625 R-626 R-627 R-628 R-629 R-630 R-631 R-632 R-633 R-634 R-635 R-636 R-637 R-638 R-639 R-640 R-641 R-642 R-643 R-644 R-645 R-646 R-647 R-648 R-649 R-650 R-651 R-652 R-653 R-654 R-655 R-656 R-657 R-658 R-659 R-660 R-661 R-662 R-663 R-664 R-665 R-666 R-667 R-668 R-669 R-670 R-671 R-672 R-673 R-674 R-675 R-676 R-677 R-678 R-679 R-680 R-681 R-682 R-683 R-684 R-685 R-686 R-687 R-688 R-689 R-690 R-691 R-692 R-693 R-694 R-695 R-696 R-697 R-698 R-699 R-700 R-701 R-702 R-703 R-704 R-705 R-706 R-707 R-708 R-709 R-710 R-711 R-712 R-713 R-714 R-715 R-716 R-717 R-718 R-719 R-720 R-721 R-722 R-723 R-724 R-725 R-726 R-727 R-728 R-729 R-730 R-731 R-732 R-733 R-734 R-735 R-736 R-737 R-738 R-739 R-740 R-741 R-742 R-743 R-744 R-745 R-746 R-747 R-748 R-749 R-750 R-751 R-752 R-753 R-754 R-755 R-756 R-757 R-758 R-759 R-760 R-761 R-762 R-763 R-764 R-765 R-766 R-767 R-768 R-769 R-770 R-771 R-772 R-773 R-774 R-775 R-776 R-777 R-778 R-779 R-780 R-781 R-782 R-783 R-784 R-785 R-786 R-787 R-788 R-789 R-790 R-791 R-792 R-793 R-794 R-795 R-796 R-797 R-798 R-799 R-800 R-801 R-802 R-803 R-804 R-805 R-806 R-807 R-808 R-809 R-810 R-811 R-812 R-813 R-814 R-815 R-816 R-817 R-818 R-819 R-820 R-821 R-822 R-823 R-824 R-825 R-826 R-827 R-828 R-829 R-830 R-831 R-832 R-833 R-834 R-835 R-836 R-837 R-838 R-839 R-840 R-841 R-842 R-843 R-844 R-845 R-846 R-847 R-848 R-849 R-850 R-851 R-852 R-853 R-854 R-855 R-856 R-857 R-858 R-859 R-860 R-861 R-862 R-863 R-864 R-865 R-866 R-867 R-868 R-869 R-870 R-871 R-872 R-873 R-874 R-875 R-876 R-877 R-878 R-879 R-880 R-881 R-882 R-883 R-884 R-885 R-886 R-887 R-888 R-889 R-890 R-891 R-892 R-893 R-894 R-895 R-896 R-897 R-898 R-899 R-900 R-901 R-902 R-903 R-904 R-905 R-906 R-907 R-908 R-909 R-910 R-911 R-912 R-913 R-914 R-915 R-916 R-917 R-918 R-919 R-920 R-921 R-922 R-923 R-924 R-925 R-926 R-927 R-928 R-929 R-930 R-931 R-932 R-933 R-934 R-935 R-936 R-937 R-938 R-939 R-940 R-941 R-942 R-943 R-944 R-945 R-946 R-947 R-948 R-949 R-950 R-951 R-952 R-953 R-954 R-955 R-956 R-957 R-958 R-959 R-960 R-961 R-962 R-963 R-964 R-965 R-966 R-967 R-968 R-969 R-970 R-971 R-972 R-973 R-974 R-975 R-976 R-977 R-978 R-979 R-980 R-981 R-982 R-983 R-984 R-985 R-986 R-987 R-988 R-989 R-990 R-991 R-992 R-993 R-994 R-995 R-996 R-997 R-998 R-999 R-1000 R-1001 R-1002 R-1003 R-1004 R-1005 R-1006 R-1007 R-1008 R-1009 R-1010 R-1011 R-1012 R-1013 R-1014 R-1015 R-1016 R-1017 R-1018 R-1019 R-1020 R-1021 R-1022 R-1023 R-1024 R-1025 R-1026 R-1027 R-1028 R-1029 R-1030 R-1031 R-1032 R-1033 R-1034 R-1035 R-1036 R-1037 R-1038 R-1039 R-1040 R-1041 R-1042 R-1043 R-1044 R-1045 R-1046 R-1047 R-1048 R-1049 R-1050 R-1051 R-1052 R-1053 R-1054 R-1055 R-1056 R-1057 R-1058 R-1059 R-1060 R-1061 R-1062 R-1063 R-1064 R-1065 R-1066 R-1067 R-1068 R-1069 R-1070 R-1071 R-1072 R-1073 R-1074 R-1075 R-1076 R-1077 R-1078 R-1079 R-1080 R-1081 R-1082 R-1083 R-1084 R-1085 R-1086 R-1087 R-1088 R-1089 R-1090 R-1091 R-1092 R-1093 R-1094 R-1095 R-1096 R-1097 R-1098 R-1099 R-1100 R-1101 R-1102 R-1103 R-1104 R-1105 R-1106 R-1107 R-1108 R-1109 R-1110 R-1111 R-1112 R-1113 R-1114 R-1115 R-1116 R-1117 R-1118 R-1119 R-1120 R-1121 R-1122 R-1123 R-1124 R-1125 R-1126 R-1127 R-1128 R-1129 R-1130 R-1131 R-1132 R-1133 R-1134 R-1135 R-1136 R-1137 R-1138 R-1139 R-1140 R-1141 R-1142 R-1143 R-1144 R-1145 R-1146 R-1147 R-1148 R-1149 R-1150 R-1151 R-1152 R-1153 R-1154 R-1155 R-1156 R-1157 R-1158 R-1159 R-1160 R-1161 R-1162 R-1163 R-1164 R-1165 R-1166 R-1167 R-1168 R-1169 R-1170 R-1171 R-1172 R-1173 R-1174 R-1175 R-1176 R-1177 R-1178 R-1179 R-1180 R-1181 R-1182 R-1183 R-1184 R-1185 R-1186 R-1187 R-1188 R-1189 R-1190 R-1191 R-1192 R-1193 R-1194 R-1195 R-1196 R-1197 R-1198 R-1199 R-1200 R-1201 R-1202 R-1203 R-1204 R-1205 R-1206 R-1207 R-1208 R-1209 R-1210 R-1211 R-1212 R-1213 R-1214 R-1215 R-1216 R-1217 R-1218 R-1219 R-1220 R-1221 R-1222 R-1223 R-1224 R-1225 R-1226 R-1227 R-1228 R-1229 R-1230 R-1231 R-1232 R-1233 R-1234 R-1235 R-1236 R-1237 R-1238 R-1239 R-1240 R-1241 R-1242 R-1243 R-1244 R-1245 R-1246 R-1247 R-1248 R-1249 R-1250 R-1251 R-1252 R-1253 R-1254 R-1255 R-1256 R-1257 R-1258 R-1259 R-1260 R-1261 R-1262 R-1263 R-1264 R-1265 R-1266 R-1267 R-1268 R-1269 R-1270 R-1271 R-1272 R-1273 R-1274 R-1275 R-1276 R-1277 R-1278 R-1279 R-1280 R-1281 R-1282 R-1283 R-1284 R-1285 R-1286 R-1287 R-1288 R-1289 R-1290 R-1291 R-1292 R-1293 R-1294 R-1295 R-1296 R-1297 R-1298 R-1299 R-1300 R-1301 R-1302 R-1303 R-1304 R-1305 R-1306 R-1307 R-1308 R-1309 R-1310 R-1311 R-1312 R-1313 R-1314 R-1315 R-1316 R-1317 R-1318 R-1319 R-1320 R-1321 R-1322 R-1323 R-1324 R-1325 R-1326 R-1327 R-1328 R-1329 R-1330 R-1331 R-1332 R-1333 R-1334 R-1335 R-1336 R-1337 R-1338 R-1339 R-1340 R-1341 R-1342 R-1343 R-1344 R-1345 R-1346 R-1347 R-1348 R-1349 R-1350 R-1351 R-1352 R-1353 R-1354 R-1355 R-1356 R-1357 R-1358 R-1359 R-1360 R-1361 R-1362 R-1363 R-1364 R-1365 R-1366 R-1367 R-1368 R-1369 R-1370 R-1371 R-1372 R-1373 R-1374 R-1375 R-1376 R-1377 R-1378 R-1379 R-1380 R-1381 R-1382 R-1383 R-1384 R-1385 R-1386 R-1387 R-1388 R-1389 R-1390 R-1391 R-1392 R-1393 R-1394 R-1395 R-1396 R-1397 R-1398 R-1399 R-1400 R-1401 R-1402 R-1403 R-1404 R-1405 R-1406 R-1407 R-1408 R-1409 R-1410 R-1411 R-1412 R-1413 R-1414 R-1415 R-1416 R-1417 R-1418 R-1419 R-1420 R-1421 R-1422 R-1423 R-1424 R-1425 R-1426 R-1427 R-1428 R-1429 R-1430 R-1431 R-1432 R-1433 R-1434 R-1435 R-1436 R-1437 R-1438 R-1439 R-1440 R-1441 R-1442 R-1443 R-1444 R-1445 R-1446 R-1447 R-1448 R-1449 R-1450 R-1451 R-1452 R-1453 R-1454 R-1455 R-1456 R-1457 R-1458 R-1459 R-1460 R-1461 R-1462 R-1463 R-1464 R-1465 R-1466 R-1467 R-1468 R-1469 R-1470 R-1471 R-1472 R-1473 R-1474 R-1475 R-1476 R-1477 R-1478 R-1479 R-1480 R-1481 R-1482 R-1483 R-1484 R-1485 R-1486 R-1487 R-1488 R-1489 R-1490 R-1491 R-1492 R-1493 R-1494 R-1495 R-1496 R-1497 R-1498 R-1499 R-1500 R-1501 R-1502 R-1503 R-1504 R-1505 R-1506 R-1507 R-1508 R-1509 R-1510 R-1511 R-1512 R-1513 R-1514 R-1515 R-1516 R-1517 R-1518 R-1519 R-1520 R-1521 R-1522 R-1523 R-1524 R-1525 R-1526 R-1527 R-1528 R-1529 R-1530 R-1531 R-1532 R-1533 R-1534 R-1535 R-1536 R-1537 R-1538 R-1539 R-1540 R-1541 R-1542 R-1543 R-1544 R-1545 R-1546 R-1547 R-1548 R-1549 R-1550 R-1551 R-1552 R-1553 R-1554 R-1555 R-1556 R-1557 R-1558 R-1559 R-1560 R-1561 R-1562 R-1563 R-1564 R-1565 R-1566 R-1567 R-1568 R-1569 R-1570 R-1571 R-1572 R-1573 R-1574 R-1575 R-1576 R-1577 R-1578 R-1579 R-1580 R-1581 R-1582 R-1583 R-1584 R-1585 R-1586 R-1587 R-1588 R-1589 R-1590 R-1591 R-1592 R-1593 R-1594 R-1595 R-1596 R-1597 R-1598 R-1599 R-1600 R-1601 R-1602 R-1603 R-1604 R-1605 R-1606 R-1607 R-1608 R-1609 R-1610 R-1611 R-1612 R-1613 R-1614 R-1615 R-1616 R-1617 R-1618 R-1619 R-1620 R-1621 R-1622 R-1623 R-1624 R-1625 R-1626 R-1627 R-1628 R-1629 R-1630 R-1631 R-1632 R-1633 R-1634 R-1635 R-1636 R-1637 R-1638 R-1639 R-1640 R-1641 R-1642 R-1643 R-1644 R-1645 R-1646 R-1647 R-1648 R-1649 R-1650 R-1651 R-1652 R-1653 R-1654 R-1655 R-1656 R-1657 R-1658 R-1659 R-1660 R-1661 R-1662 R-1663 R-1664 R-1665 R-1666 R-1667 R-1668 R-1669 R-1670 R-1671 R-1672 R-1673 R-1674 R-1675 R-1676 R-1677 R-1678 R-1679 R-1680 R-1681 R-1682 R-1683 R-1684 R-1685 R-1686 R-1687 R-1688 R-1689 R-1690 R-1691 R-1692 R-1693 R-1694 R-1695 R-1696 R-1697 R-1698 R-1699 R-1700 R-1701 R-1702 R-1703 R-1704 R-1705 R-1706 R-1707 R-1708 R-1709 R-1710 R-1711 R-1712 R-1713 R-1714 R-1715 R-1716 R-1717 R-1718 R-1719 R-1720 R-1721 R-1722 R-1723 R-1724 R-1725 R-1726 R-1727 R-1728 R-1729 R-1730 R-1731 R-1732 R-1733 R-1734 R-1735 R-1736 R-1737 R-1738 R-1739 R-1740 R-1741 R-1742 R-1743 R-1744 R-1745 R-1746 R-1747 R-1748 R-1749 R-1750 R-1751 R-1752 R-1753 R-1754 R-1755 R-1756 R-1757 R-1758 R-1759 R-1760 R-1761 R-1762 R-1763 R-1764 R-1765 R-1766 R-1767 R-1768 R-1769 R-1770 R-1771 R-1772 R-1773 R-1774 R-1775 R-1776 R-1777 R-1778 R-1779 R-1780 R-1781 R-1782 R-1783 R-1784 R-1785 R-1786 R-1787 R-1788 R-1789 R-1790 R-1791 R-1792 R-1793 R-1794 R-1795 R-1796 R-1797 R-1798 R-1799 R-1800 R-1801 R-1802 R-1803 R-1804 R-1805 R-1806 R-1807 R-1808 R-1809 R-1810 R-1811 R-1812 R-1813 R-1814 R-1815 R-1816 R-1817 R-1818 R-1819 R-1820 R-1821 R-1822 R-1823 R-1824 R-1825 R-1826 R-1827 R-1828 R-1829 R-1830 R-1831 R-1832 R-1833 R-1834 R-1835 R-1836 R-1837 R-1838 R-1839 R-1840 R-1841 R-1842 R-1843 R-1844 R-1845 R-1846 R-1847 R-1848 R-1849 R-1850 R-1851 R-1852 R-1853 R-1854 R-1855 R-1856 R-1857 R-1858 R-1859 R-1860 R-1861 R-1862 R-1863 R-1864 R-1865 R-1866 R-1867 R-1868 R-1869 R-1870 R-1871 R-1872 R-1873 R-1874 R-1875 R-1876 R-1877 R-1878 R-1879 R-1880 R-1881 R-1882 R-1883 R-1884 R-1885 R-1886 R-1887 R-1888 R-1889 R-1890 R-1891 R-1892 R-1893 R-1894 R-1895 R-1896 R-1897 R-1898 R-1899 R-1900 R-1901 R-1902 R-1903 R-1904 R-1905 R-1906 R-1907 R-1908 R-1909 R-1910 R-1911 R-1912 R-1913 R-1914 R-1915 R-1916 R-1917 R-1918 R-1919 R-1920 R-1921 R-1922 R-1923 R-1924 R-1925 R-1926 R-1927 R-1928 R-1929 R-1930 R-1931 R-1932 R-1933 R-1934 R-1935 R-1936 R-1937 R-1938 R-1939 R-1940 R-1941 R-1942 R-1943 R-1944 R-1945 R-1946 R-1947 R-1948 R-1949 R-1950 R-1951 R-1952 R-1953 R-1954 R-1955 R-1956 R-1957 R-1958 R-1959 R-1960 R-1961 R-1962 R-1963 R-1964 R-1965 R-1966 R-1967 R-1968 R-1969 R-1970 R-1971 R-1972 R-1973 R-1974 R-1975 R-1976 R-1977 R-1978 R-1979 R-1980 R-1981 R-1982 R-1983 R-1984 R-1985 R-1986 R-1987 R-1988 R-1989 R-1990 R-1991 R-1992 R-1993 R-1994 R-1995 R-1996 R-1997 R-1998 R-1999 R-2000 R-2001 R-2002 R-2003 R-2004 R-2005 R-2006 R-2007 R-2008 R-2009 R-2010 R-2011 R-2012 R-2013 R-2014 R-2015 R-2016 R-2017 R-2018 R-2019 R-2020 R-2021 R-2022 R-2023 R-2024 R-2025 R-2026 R-2027 R-2028 R-2029 R-2030 R-2031 R-2032 R-2033 R-2034 R-2035 R-2036 R-2037 R-2038 R-2039 R-2040 R-2041 R-2042 R-2043 R-2044 R-2045 R-2046 R-2047 R-2048 R-2049 R-2050 R-2051 R-2052 R-2053 R-2054 R-2055 R-2056 R-2057 R-2058 R-2059 R-2060 R-2061 R-2062 R-2063 R-2064 R-2065 R-2066 R-2067 R-2068 R-2069 R-2070 R-2071 R-2072 R-2073 R-2074 R-2075 R-2076 R-2077 R-2078 R-2079 R-2080 R-2081 R-2082 R-2083 R-2084 R-2085 R-2086 R-2087 R-2088 R-2089 R-2090 R-2091 R-2092 R-2093 R-2094 R-2095 R-2096 R-2097 R-2098 R-2099 R-2100 R-2101 R-2102 R-2103 R-2104 R-2105 R-2106 R-2107 R-2108 R-2109 R-2110 R-2111 R-2112 R-2113 R-2114 R-2115 R-2116 R-2117 R-2118 R-2119 R-2120 R-2121 R-2122 R-2123 R-2124 R-2125 R-2126 R-2127 R-2128 R-2129 R-2130 R-2131 R-2132 R-2133 R-2134 R-2135 R-2136 R-2137 R-2138 R-2139 R-2140 R-2141 R-2142 R-2143 R-2144 R-2145 R-2146 R-2147 R-2148 R-2149 R-2150 R-2151 R-2152 R-2153 R-2154 R-2155 R-2156 R-2157 R-2158 R-2159 R-2160 R-2161 R-2162 R-2163 R-2164 R-2165 R-2166 R-2167 R-2168 R-2169 R-2170 R-2171 R-2172 R-2173 R-2174 R-2175 R-2176 R-2177 R-2178 R-2179 R-2180 R-2181 R-2182 R-2183 R-2184 R-2185 R-2186 R-2187 R-2188 R-2189 R-2190 R-2191 R-2192 R-2193 R-2194 R-2195 R-2196 R-2197 R-2198 R-2199 R-2200 R-2201 R-2202 R-2203 R-2204 R-2205 R-2206 R-2207 R-2208 R-2209 R-2210 R-2211 R-2212 R-2213 R-2214 R-2215 R-2216 R-2217 R-2218 R-2219 R-2220 R-2221 R-2222 R-2223 R-2224 R-2225 R-2226 R-2227 R-2228 R-2229 R-2230 R-2231 R-2232 R-2233 R-2234 R-2235 R-2236 R-2237 R-2238 R-2239 R-2240 R-2241 R-2242 R-2243 R-2244 R-2245 R-2246 R-2247 R-2248 R-2249 R-2250 R-2251 R-2252 R-2253 R-2254 R-2255 R-2256 R-2257 R-2258 R-2259 R-2260 R-2261 R-2262 R-2263 R-2264 R-2265 R-2266 R-2267 R-2268 R-2269 R-2270 R-2271 R-2272 R-2273 R-2274 R-2275 R-2276 R-2277 R-2278 R-2279 R-2280 R-2281 R-2282 R-2283 R-2284 R-2285 R-2286 R-2287 R-2288 R-2289 R-2290 R-2291 R-2292 R-2293 R-2294 R-2295 R-2296 R-2297 R-2298 R-2299 R-2300 R-2301 R-2302 R-2303 R-2304 R-2305 R-2306 R-2307 R-2308 R-2309 R-2310 R-2311 R-2312 R-2313 R-2314 R-2315 R-2316 R-2317 R-2318 R-2319 R-2320 R-2321 R-2322 R-2323 R-2324 R-2325 R-2326 R-2327 R-2328 R-2329 R-2330 R-2331 R-2332 R-2333 R-2334 R-2335 R-2336 R-2337 R-2338 R-2339 R-2340 R-2341 R-2342 R-2343 R-2344 R-2345 R-2346 R-2347 R-2348 R-2349 R-2350 R-2351 R-2352 R-2353 R-2354 R-2355 R-2356 R-2357 R-2358 R-2359 R-2360 R-2361 R-2362 R-2363 R-2364 R-2365 R-2366 R-2367 R-2368 R-2369 R-2370 R-2371 R-2372 R-2373 R-2374 R-2375 R-2376 R-2377 R-2378 R-2379 R-2380 R-2381 R-2382 R-2383 R-2384 R-2385 R-2386 R-2387 R-2388 R-2389 R-2390 R-2391 R-2392 R-2393 R-2394 R-2395 R-2396 R-2397 R-2398 R-2399 R-2400 R-2401 R-2402 R-2403 R

For cooling air at the evaporator(s) and for condenser heat rejection to ambient air or evaporative condensers, use the same procedures. Performance of coils and expansion devices such as thermostatic expansion valves may also be graphed, once the basic This file is licensed to Osama Khayat (email protected). Copyright ASHRAE 2018. 5.3

Licensed for single user. © 2018 ASHRAE, Inc. Component Balancing in Refrigeration Systems Fig. 1 Brine Chiller Balance Curve concept of heat and mechanical energy input equivalent combinations is recognized.

Chapter 2 of the 2017 ASHRAE Handbook—Fundamentals has further information. This method finds the natural balance points of compressors operating at their maximum capacities. For multiple-stage loads at several specific operating temperatures, the usual way of controlling compressor capacities is with a suction pressure control and compressor capacity control device. This control accommodates any mismatch in pumping capabilities of multistage compressors, instead of allowing each compressor to find its natural balance point.

The analysis could be developed to determine points of complex systems. However, because applications, components and piping arrangements are so diverse, many designers use available capacity performance data from vendors and plot balance points for chosen components. Individual computer programs may be available for specific components, which speeds the process. 4. ENERGY AND MASS BALANCES A systematic, point-to-point flow analysis of the system (including piping) is essential in accounting for pressure drops and heat gains, particularly in long suction lines. Air-cooled condensers, in particular, can have large pressure drops, which must be included in the analysis to estimate a realistic balance. Making a flow diagram of the system with designated pressures and temperatures, loads, enthalpies, flow rates, and energy requirements helps identify all important factors and components. An overall energy and mass balance for the system is also essential to avoid mistakes. The overall system represented by the complete flow diagram should be enclosed by a dotted-line envelope. Any energy inputs to or outputs from the system that directly affect the heat content of the refrigerant itself should cross the dotted line and must enter the energy balance equations. Accurate estimates of ambient heat gains through insulation and heat losses from discharge This file is licensed to Osama Khayat (email protected). Copyright ASHRAE 2018. 5.4

2018 ASHRAE Handbook—Refrigeration (SI) lines (where they are significant) improve the comprehensiveness of the energy balance and accuracy of equipment selections. Cascade condenser loads and subcooler or desuperheating loads carried by a refrigerant are internal to the system and thus do not enter into the overall energy balance. The total energy entering the system equals the total energy leaving the system. If calculations do not show an energy balance within reasonable tolerances for the accuracy of data used, then an omission occurred or a mistake was made and should be corrected. The analysis can be applied to other types of systems, such as those involving water flows, chilled water, steam, and hot water. In some cases, the flow equations for the system may be solved by hand. In most cases, however, the use of a computer program is required. When the needed data are available, nor are conditions proper at a given job site to allow calculation of a comprehensive, accurate energy balance for an operating system. Water-cooled condensers and oil coolers for heat rejection and the use of electric motor drives, where motor efficiency and power factor curves are available, offer the best hope for estimating the actual performance of the individual components in a system. Evaporator heat loads can be derived from measured heat rejection and derived mechanical or measured electrical energy inputs. A comprehensive flow diagram assists in a field survey. Various coolant flow detection devices are available for direct measurement inside a pipe and for measurement from outside the pipe with variable degrees of accuracy.

Sometimes flow rates may be estimated by simply weighing or measuring an accumulation of coolant over a brief time interval. Temperature and pressure measurement devices should be calibrated and be of sufficient accuracy. Calibrated digital scanning devices for comprehensive simultaneous readings are best. Electrical power meters are not always available, so voltage and current at each leg of a motor power connection must be measured. Voltage drops for long power leads must be calculated when the voltage measurement points are far removed from the motor. Motor load versus efficiency and power factor curves must be used to determine motor output to the system. Gears and belt drives can multiply torque and speed, but will cause additional losses. In this case, performance curves may be helpful. To estimate the energy input to the system, the drive motor's nameplate data are useful. Calculating steam turbine performance requires measurements of turbine speed, steam pressures and temperatures, and condensate mass flow coupled with confidence that the vendor's performance curves truly represent the current mechanical condition. Plant personnel normally have difficulty in obtaining operating data at specified performance values.

chemistry deals with any chemical reactions that could take place in an HVAC/R system between refrigerants, lubricants, and construction materials of various system components (e.g., compressor, heat transfer coils, connecting tubing, expansion device). Higher temperatures or contaminants such as air, moisture, or residual process chemicals (e.g., metal cutting fluids, cleaning agents) complicate chemical interactions between components. Phase changes occur in the refrigeration cycle; in particular, the temperature extremes from the highest discharge line temperature to the lowest evaporating temperature are of importance to the end user. This chapter covers the chemical aspects of refrigerants and lubricants, and their compatibility with each other as well as with system materials. Two distinct chemical evaluations are generally undertaken when considering new refrigerant or lubricant candidates: (1) chemical compatibility testing to assess the stability of refrigerant and lubricant with each other and with system components, and (2) material compatibility testing to assess the stability of system component materials with refrigerant and/or lubricant. Lubricants are extensively covered in Chapter 12, and contaminant control is discussed in Chapter 7. Detailed information on various refrigerants is provided in Chapters 1 and 2 of this volume, and in Chapters 29 and 30 of the *ASHRAE Handbook—HVAC Systems and Equipment*. The primary reason for choosing a refrigerant purity specification is to ensure that the refrigerant is suitable for the intended application. The ASHRAE Handbook—HVAC Systems and Equipment provides information on applications and the standards for refrigerant purity. Refrigerant flammability is important to consider in many refrigerant system applications, including domestic refrigeration, air conditioning. Flammability standards have been established and are being developed worldwide for many refrigerant and lubricant system applications. For details on refrigerant flammability and combustibility, see the latest revision of ASHRAE Standard 34. 2. LUBRICANTS Lubricants in use and under consideration for the new refrigerants are mineral oils, alkyl benzenes, polyol esters, polyalkylene glycols, modified polyalkylene glycols, and polyvinyl ethers. Gunderson and Hart (1962) and Rudnik (1936) give excellent introductions to synthetic lubricants, including polyglycols and esters. Rudnik (2013) also includes a specific chapter on refrigeration lubricants. A detailed discussion of the various types of lubricants, their properties, and areas of application is in Chapter 12. The following sections specifically address the stability and/or reactivity of lubricants in the presence of refrigerants, contaminants, and materials of construction. Mineral Oils REFRIGERANTS Refrigerants have been used in specially designed equipment to provide cooling for people and cooling or refrigeration for food, materials, and specific processes since the 1800s. Today's refrigerants are chosen to provide the most efficient thermodynamic performance affordably, safely, and with minimal effect on the environment. Halocarbons have dominated air-conditioning and refrigeration applications since the 1950s, largely because of their superior safety performance. Industrial and commercial applications have traditionally used ammonia, hydrocarbons, and carbon dioxide refrigerants. This continues today, with the addition of halocarbons in the form of hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs). The use of hydrocarbons as refrigerants is limited to small systems, such as domestic refrigeration, and is referred to as low global warming potential (LGP) refrigerants. Hydrocarbons are also used as refrigerants in heat pump applications (HFOs). New HFO candidates such as R-1234yf, R-1234ze(E), R-1233zd(E), R-1336mzz(E), R-1224yd(Z), and HFO blends are of particular interest because of their low global warming potential (GWP). For details on environmental concerns, thermodynamic properties, and refrigerant acceptability, see Chapter 29 of the 2017 ASHRAE Handbook—Fundamentals. Refrigerant Standards With the introduction of many new pure refrigerants and refrigerant blends, demand for refrigerant specification has necessarily. The preparation of this chapter is assigned to Task 3.2, Refrigerant System Chemistry. Mineral oils were the lubricant of choice for the vast majority of refrigeration applications for many decades when chlorofluorocarbons (CFCs) such as R-12 were the dominant refrigerant technology. They are still used today in many applications using hydrochlorofluorocarbons (HCFCs) such as R-22 or hydrocarbon refrigerants such as isobutane (R-600a).

[illegible]

either lubricant. 3. SYSTEM REACTIONS/Thermal Stability Halocarbons. All common halocarbon refrigerants have excellent thermal stability, as shown in Table 1. Clear-cut differences in lubrication, although wear on steel was more significant with POE and wear on aluminum was more significant with PVE. No carboxylic compounds were observed with POE. The results of the tests are summarized in Table 2. Bier et al. (1990) studied R-12, R-134a, and R-152a. For R-134a in contact with metals, traces of hydrogen fluoride (HF) were detected after 10 days at 200°C. This decomposition did not increase much with time. R-152a showed traces of HF at 180°C after five days in a steel container. Bier et al. suggested that vinyl fluoride forms during thermal decomposition of R-152a, and can then react with water to form acetaldehyde. Hansen and Finsen (1992) conducted lifetime tests on small hermetic compressors with a ternary mixture of R-22/152a/124 and an alkyl benzene lubricant. In agreement with Bier et al., they found that vinyl fluoride and acetaldehyde formed in the compressor. Aluminum, copper, and brass and solder joints lower the temperature at which decomposition begins. Decomposition also increases with time. Under extreme conditions, such as above red heat or with molten metal, extreme temperatures may occur in devices such as centrifugal compressors if the impeller runs against the housing when the system malfunctions. Using R-12 as the test refrigerant, Eiseman (1963) found that aluminum was most reactive, followed by iron and stainless steel. Copper is relatively unreactive. Using aluminum as the reactive metal, Eiseman reported that R-14 causes the most vigorous reaction, followed by R-22, R-12, R-114, R-11, and R-113. Dekleva et al. (1993) studied the reaction of various CFCs, HCFCs, and HFCs in vapor tubes at very high temperatures in the presence of various catalysts and measured the onset temperature of decomposition. These data also showed HFCs to be more thermally stable than CFCs and HCFCs, and that, when molten aluminum is in contact with R-134a, a layer of unreactive aluminum fluoride forms and inhibits further reaction. Research indicates that commonly used refrigerant system desiccants catalyze the decomposition of some refrigerants at 150°C, producing HCl and/or HF gas (Field and Lewis, 1990; Rohatgi, 1990). Because desiccants are normally applied to refrigerant systems in areas of low operating temperatures, this increased reactivity is not an issue, but nonetheless it is important for system engineers to be aware of this phenomenon.

Rate behavior too complex to allow extrapolation to 1% per year. eConcisions Average strengths of carbon/chlorine, carbon/hydrogen, and carbon/fluorine bonds are 328, 412, and 441 kJ/mol, respectively (Pauling 1960). The relative stabilities of refrigerants that contain chlorine, hydrogen, and fluorine bonded to carbon can be understood by considering these bond strengths.

There have been a number of reactions that depend largely on the presence of the C-Cl bond. Spauschuk and Doderer (1961) concluded that R-112 can react with a hydrocarbon oil by exchanging a chlorine for a hydrogen. In this reaction (characteristic of chlorine-containing refrigerants), R-12 forms the reduction product R-22. R-22 forms R-32. (Spauschuk and Doderer 1961) and R-115 forms R-125 (Parmelee 1965). For R-123, Carrier (1989) demonstrated that the reduction product R-133a is formed at high temperatures. Factor and Miranda (1991) studied the reaction between R-12, steel, and oil sludge. They concluded that it can proceed by a predominantly Friedel-Crafts mechanism in which Fe+3 compounds are key catalysts. They also concluded that oil sludge can be formed by a pathway that does not generate R-22. They suggest that, except for the initial formation of Fe+3 salts, the free-radical mechanism plays only a minor role. Further work is needed to clarify this mechanism. Huttenlocher (1992) tested 23 refrigerant/lubricant combinations for stability in sealed glass tubes. HFC refrigerants were shown to be very stable even at temperatures much higher than normal operating temperatures. HCFC-124 and HCFC-142b were slightly more reactive than the HFCs, but less reactive than CFC-12. HCFC-123 was less reactive than CFC-11 by a factor of approximately 10. Fluoroethers were studied as alternative refrigerants.

Copyright ASHRAE 2014. Licensed for single user. © 2018 ASHRAE, Inc. Refrigerant system Chemistry figures 7 and 8 show sealed-tube test data for reaction rates of R-22 and R-12 with oil in the presence of copper and mild steel. Formation of chlorine gas was taken as a measure of decomposition. These figures show the extent to which refrigerant decomposition is accelerated by the presence of less reactive metals in the refrigerant system. Chemists and chemists in the field have long known that the presence of copper in the refrigerant system is a major catalyst for the effect of chlorinated residues in the system. Komatsu et al. (1991) showed that R-12 and R-113 degrade PAG lubricants. Powers and Rosen (1992) performed sealed-tube tests and concluded that the threshold for reactivity for R-12 in R-134a and PAG lubricant is between 1 and 3%. In some very poorly reported instances, the use of counterfeited refrigerant caused violent reactions and unexpected explosions. Counterfeit R-134a containing very reactive R-40 (methyl chloride or chloromethane) has been found in mobile and stationary air conditioning and in transport refrigeration systems. This practice has resulted in fatalities in the mobile refrigeration industry. Other systems containing R-22, R-404A, and R-410A have also been contaminated (AHRH 2013; UNEP 2013).

R-40 contaminated refrigerant in an HVAC-R system may react with ammonia components to produce strong acids and other highly reactive compounds, which can lead to reactivity with air and/or moisture when systems are opened for service, resulting in a possible explosion. ASHRAE Research Project RP-665 (Hamilton 2014) examined the potential for R-40 reacting with ammonia components. The results showed that R-40 reacts with ammonia components to form ammonium salts. Ammonia salts are formed from degradation of R-134a followed by chlorination. There was no evidence of trimethyl aluminum (TMA), which was unexpected because the reactions appeared to be pyrophoric. Aluminum metal reactivity with R-40 depends on catalysts to accelerate the reaction. Generally, Al380 is more reactive than Al100. Elevated levels of water can suppress the reaction of R-40. POE degrades in the presence of R-40 reaction products. AHRI Standard 700 would have allowed up to 0.5% of R-40 under other volatile impurities, but Hamilton's findings suggest this is not acceptable. A limit for R-40 was subsequently added to AHRI Standard 700, set to 300 mg/kg. Tests for detecting such contaminants can be conducted in the field or in the laboratory. Compounds resulting from reaction of R-40 must be neutralized and rendered safe before decommissioning or servicing any suspected contaminated systems. Recovering and disposal must be conducted by personnel trained in handling hazardous materials that may be pyrophoric. Ammonia reactions involving ammonia, oxygen, oil degradation acids, and moisture are common factors in the formation of ammonia compressor deposits. Sedgwick (1966) suggested that ammonia or ammonium hydroxide reacts with organic acids produced by oxidation of the compressor oil to form ammonium salts (soaps), which can decompose further to form amides (sludge) and water. The reaction is as follows in Equation (2): NH₃ + RCOOH → RCONH₂ + H₂O Fig.

Lubricants and Refrigerants at High Temperature. Higher system temperatures may occur when refrigerants such as CO₂ or R-32 are used. Rohatgi (2011) studied the stability of lubricants This file is licensed to Osama Khayatya (email protected). Copyright ASHRAE 2018. Licensed for single user. © 2018 ASHRAE, Inc. 6.6 2018 ASHRAE Handbook —Refrigeration (SI) with CO₂ under a number of conditions at high temperature, with the following conclusions:

- Mineral oils and alkylbenzene lubricants were most stable in CO₂. Polyalkylene glycols (PAG) were less stable, followed by polyol esters (POE).
- At 225°C, naphthenic mineral oil showed higher total acid number (TAN) than paraffinic mineral oil and alkylbenzene.
- Aged uncapped PAG showed lower TAN than aged dicapped PAG, except when both the moisture level and the aging temperature were high.
- For POE lubricants, aged linear acid POE showed the highest TAN values in all conditions of moisture and temperature, followed by mixed acid POEs; branched acid POEs showed the lowest TANS.

The concentration of diacid linear POE was higher than that of the branched POE.

Aging temperature had a greater effect than moisture on the presence of iron in the aged POE lubricants. Rohatgi (2012) studied the stability of the low-global-warming-potential hydrofluoroetheral (HFO) refrigerant R-1234yf ($\text{CF}_3\text{CH}_2\text{F}$) against various types of lubricants. The results show that HFO has good compatibility with many different types of lubricants. Similar results were observed in the concentrated brine solution tests. The authors concluded that the HFO can be used with many different types of lubricants without need for special design considerations. Further studies will continue to investigate the long-term performance of HFO systems. The authors also noted that the HFO systems have excellent energy efficiency and low global warming potential compared to other refrigerants.

150°C. Prolonged exposure to these thermal excursions can damage motor insulation, depending on thermal stability of the insulation materials, reactivity with the refrigerant and lubricant, and temperature levels encountered. Another potential for high temperatures is in the bearings. Oilfilm temperatures in hydrodynamically lubricated journal bearings are usually not much higher than the bulk oil temperature; however, in elastohydrodynamic films in bearings with a high slide/roll ratio, the temperature can be hundreds of degrees above the bulk oil temperature (Keping and Shizhu 1991). Local hot spots in boundary lubrication can reach very high temperatures, but fortunately the amount of material exposed to these temperatures is usually very small. The appearance of methane or other small hydrocarbon molecules in the refrigerant indicates lubricant cracking by high bearing temperatures. Thermal decomposition of organic insulation materials and some types of lubricants produces noncondensable gases such as carbon dioxide which may increase system pressure. Lower operating pressures result in lower condensing temperatures, which increases the risk of compressor liquid slugging during start-up. Dissolved and suspended decomposition products circulate throughout the refrigeration system, where they clog oil passages; interfere with operation of expansion, suction, and discharge valves; or plug capillary tubes or other fixed passages. Appropriate control mechanisms in the refrigeration system minimize exposure to high temperatures. Identifying potential reactions, performing adequate laboratory tests to qualify materials before field use, and finding means to remove contaminants generated by high-temperature excursions are equally important (see Chapter 7). Hydrolysis of Halogenated Refrigerants and Polyol Ester Lubricants

Halogenated refrigerants are susceptible to reaction with water (hydrolysis), but the rates of reaction are so slow that they are Table 3 Rate of Hydrolysis in Water (Grams per Litre of Water per Year) 101.3 kPa at 30°C Refrigerant Formula 113 11 12 21 114 22 CCl₂FCClF₂ CCl₃FC CCl₂CF₂ CHCl₂FC CCl₂FC-CFIF CHCl₂F Water Alone