

Energy Savings Potential and RD&D Opportunities for Non- Vapor-Compression HVAC Technologies

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Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies

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Executive Summary

While vapor-compression technologies have served heating, ventilation, and air-conditioning (HVAC) needs very effectively, and have been the dominant HVAC technology for close to 100 years, the conventional refrigerants used in vapor-compression equipment contribute to global climate change when released to the atmosphere. Leaders from the United States and other countries have responded with proposals to phase-down hydrofluorocarbon refrigerants (HFCs) for HVAC equipment over the next 20 years. The anticipated commitment to reduce HFC consumption has stimulated interest in alternative refrigerants with low-GWP. Researchers have identified low-GWP HFCs, hydrocarbons, ammonia, carbon dioxide, and hydrofluoroolefins (HFOs) as possible alternatives to the HFCs used today. Nevertheless, many of these alternative refrigerants potentially trade a GWP advantage for disadvantages related to toxicity, flammability, lower efficiency, and/or increased equipment cost.

The U.S. Department of Energy (DOE) Building Technologies Office (BTO) engaged Navigant Consulting, Inc. (Navigant) to characterize and evaluate alternatives to vapor-compression technology options to serve future residential and commercial HVAC applications. The objectives of this study were to:

- Identify alternatives to vapor-compression technology in residential and commercial HVAC applications
- Characterize these technologies based on their technical energy savings potential, development status, non-energy benefits, and other factors affecting end-user acceptance and their ability to compete with conventional vapor-compression systems
- Make specific research, development, and deployment (RD&D) recommendations to support further development of these technologies, should DOE choose to support non-vapor-compression technology further.

While this study focused on space-conditioning applications, many of the technologies investigated are potentially applicable to refrigeration applications as well.

Table ES-1-1 presents the technology options that we evaluated. We evaluated all technologies as stand-alone space-conditioning systems—not as components of space-conditioning systems, as some of these technologies are currently used. We screened out two technology options because available literature suggests that they are not suitable for space-conditioning applications. Additionally, we found a paucity of publicly available information for three technology options that are still in the early stages of research and development (R&D). Consequently, we could not quantitatively compare them to other options and thus only performed limited analysis on these options.

Table ES-1-1: Technologies Considered in This Analysis

| Screened-Out Technology Options | Early-Stage Technology Options | Remaining Viable Technology Options |
|---|--|--|
| Total: 2 | Total: 3 | Total: 17 |
| Pulse-Tube Refrigeration Vortex-Tube Cooling | Bernoulli Heat Pump Critical-Flow Refrigeration Cycle Electrocaloric | Absorption Heat Pump Adsorption Heat Pump Brayton Heat Pump Duplex-Stirling Cycle Ejector Heat Pump Evaporative Cooling Evaporative Liquid Desiccant A/C Ground-Coupled Solid Desiccant A/C Magnetocaloric Membrane Heat Pump Standalone Liquid Desiccant A/C Standalone Solid Desiccant A/C Thermoacoustic Thermoelastic Thermoelectric Thermotunneling Vuilleumier Heat Pump |

Note: we evaluated the desiccant and evaporative technologies as standalone air-conditioning systems, not as supplements to vapor compression or other technologies.

We then analyzed each of the 17 remaining viable technology options and characterized their current development status and performance to better understand their technical energy savings potential over vapor-compression technology for U.S. residential and commercial HVAC systems. Based on these analyses, we developed estimates for unit energy savings over baseline vapor-compression systems and identified relevant markets for each technology option (e.g., end use, building type, climate region, etc.). We calculated the technical energy savings potential for each technology option using BTO’s Prioritization Tool and our unit energy savings estimates. Figure ES-1-1 presents the technical energy savings potential for each of the non-vapor compression technology options.

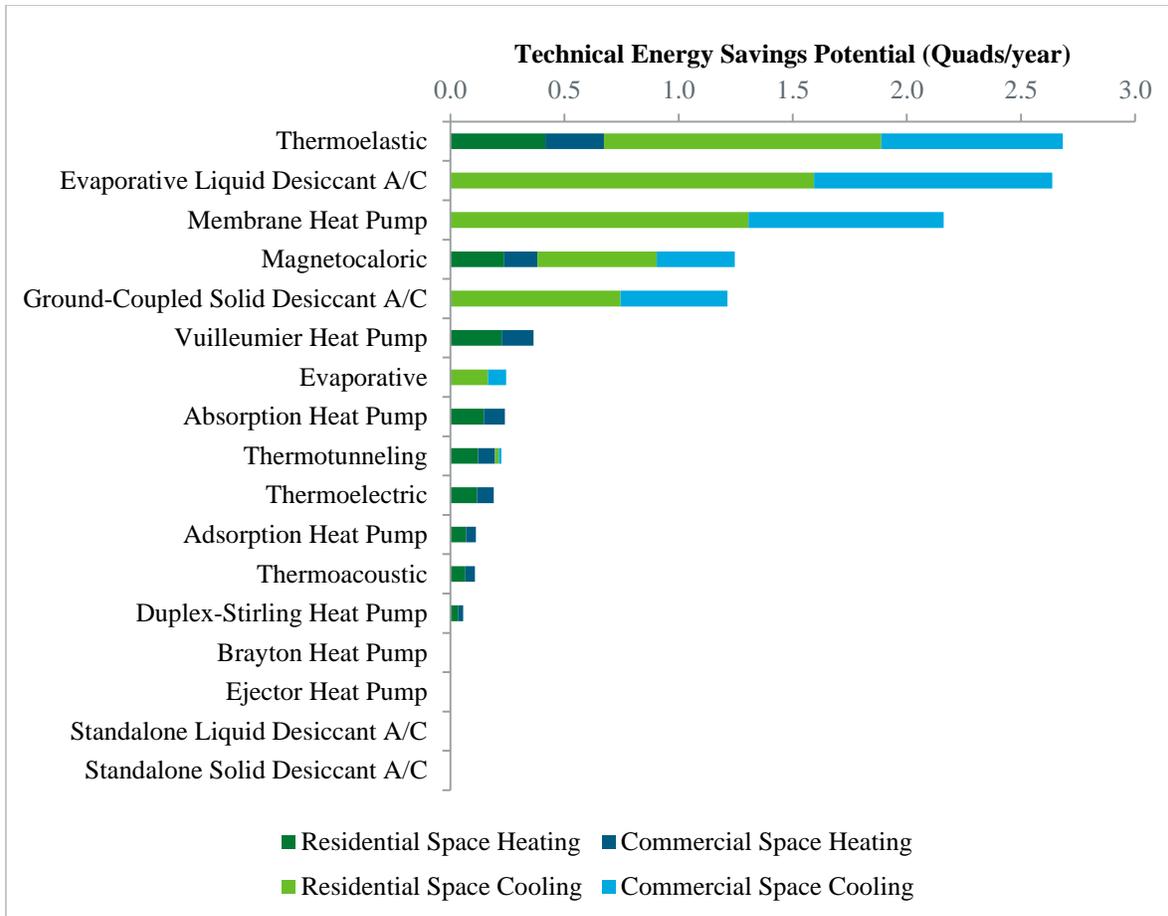


Figure ES-1-1: Comparison of technical energy savings potential (Quads/year)

To identify the most promising areas for potential further RD&D, we performed a scorecard analysis to evaluate each technology option based on the following criteria: technical energy savings potential, fit with BTO mission, non-energy benefits, and cost/complexity. We assigned each criterion a weighting factor to reflect its overall importance, and ranked the list of technology options by their final scores. Figure ES-1-2 presents their overall final scores. These scores reflect our current understanding of the technology options based on available information and judgment. In general, technology options scoring near the top of the list offer higher potential energy savings and higher probability of success if supported through BTO initiatives. However, lower-ranking technology options are still relevant for BTO’s consideration because although their savings may be modest today, additional R&D could advance their efficiency and performance beyond current limitations.

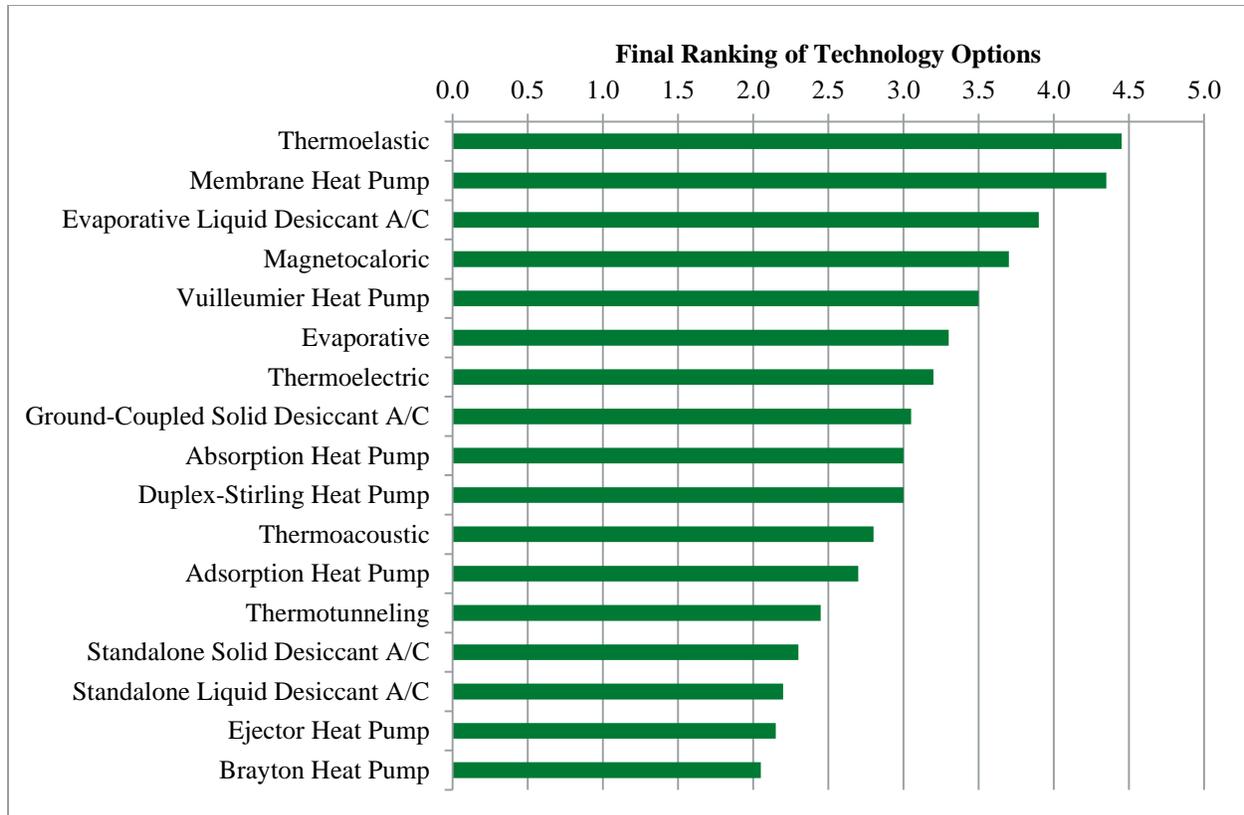


Figure ES-1-2: Final ranking of technology options

Based on these rankings, we have classified these 17 technology options into four categories: Most Promising, Very Promising, Moderately Promising, and Least Promising, as outlined in Table ES-1-2. We identified the two technology options with overall scores over 4.0 as the “Most Promising” alternatives to vapor compression because they exhibit substantial potential for energy savings, offer significant non-energy benefits, are not projected to be significantly more expensive or complex, and/or fit very well with the BTO mission. We identified four technology options with overall scores of 3.5 or greater as “Very Promising” alternatives because they exhibit moderate-to-high energy savings potential, offer significant non-energy benefits, and/or fit well with the BTO mission. The seven technology options that we classified as “Moderately Promising” offer low-to-moderate energy savings potential or other benefits compared to vapor compression; however, these scores reflect the current status of these technology options, and may become more attractive as further development improves their performance. Finally, we identified four technology options as “Least Promising” alternatives to vapor compression because they offer zero energy savings compared to vapor compression. These technology options may offer cost savings in certain instances, but are not projected to provide source energy savings.

Table ES-1-2: Categorization of Technology Options

| Most Promising | Very Promising | Moderately Promising | Least Promising |
|---|---|---|---|
| <ul style="list-style-type: none"> • Membrane Heat Pump • Thermoelastic | <ul style="list-style-type: none"> • Evaporative Liquid Desiccant A/C • Magnetocaloric • Vuilleumier Heat Pump | <ul style="list-style-type: none"> • Evaporative Cooling • Thermoelectric • Ground-Coupled Solid Desiccant A/C • Absorption Heat Pump • Duplex-Stirling Heat Pump • Thermoacoustic • Adsorption Heat Pump • Thermotunneling | <ul style="list-style-type: none"> • Standalone Solid Desiccant A/C • Standalone Liquid Desiccant A/C • Ejector Heat Pump • Brayton Heat Pump |
| <p>Note: we evaluated the desiccant and evaporative technologies as standalone air-conditioning systems, not as supplements to vapor compression or other technologies.</p> | | | |

Based on our review of the technology options selected for this study, if DOE decides to support further development of non-vapor compression technologies, we recommend that DOE consider the RD&D initiatives summarized in Table ES-1-3 through Table ES-1-6.

Table ES-1-3: Highest-Priority RD&D Initiatives

| Recommended Initiatives | Applicable Technology Options |
|--|---|
| Develop and test prototypes of membrane heat pumps and thermoelastic systems | <ul style="list-style-type: none"> • Membrane Heat Pump • Thermoelastic |

Table ES-1-4: Moderate-to-High-Priority RD&D Initiatives

| Recommended Initiatives | Applicable Technology Options |
|---|---|
| Develop pre-production designs and evaluate manufacturing cost of evaporative liquid desiccant A/C | <ul style="list-style-type: none"> • Evaporative Liquid Desiccant A/C |
| Develop and test demonstration prototype of Vuilleumier heat pump | <ul style="list-style-type: none"> • Vuilleumier Heat Pump |
| Develop cost-effective gas-fired heat pumps for heating-only or reversible operation, including integrating space-conditioning and water-heating capabilities | <ul style="list-style-type: none"> • Absorption Heat Pump • Adsorption Heat Pump • Thermoacoustic • Vuilleumier Heat Pump |
| Develop high-efficiency regenerating components for liquid desiccant air conditioners | <ul style="list-style-type: none"> • Evaporative Liquid Desiccant A/C • Standalone Liquid Desiccant A/C |
| Develop cost-effective, compact heat exchangers to transfer heat to and from solid-state modules without requiring large temperature differences | <ul style="list-style-type: none"> • Magnetocaloric • Thermoelectric • Thermotunneling • Electrocaloric |

Table ES-1-5: Moderate-Priority RD&D Initiatives

| Recommended Initiatives | Applicable Technology Options |
|---|--|
| Support field testing and modeling to prove the performance of advanced evaporative cooling technologies | <ul style="list-style-type: none"> • Evaporative Cooling |
| Construct laboratory prototypes of ground-coupled solid desiccant air conditioners at modest capacities and evaluate performance at a variety of test conditions | <ul style="list-style-type: none"> • Ground-Coupled Solid Desiccant A/C |
| Develop prototypes using selected technology options and test in space-heating mode to assess their applicability to and efficiency in space-heating applications | <ul style="list-style-type: none"> • Magnetocaloric • Thermoacoustic • Thermoelastic • Thermoelectric • Thermotunneling |
| Support development of alternative component designs that improve the size, weight, and/or cost of absorption heat pumps | <ul style="list-style-type: none"> • Absorption Heat Pump |
| Support development of alternative adsorption heat-pump designs | <ul style="list-style-type: none"> • Adsorption Heat Pump |

Table ES-1-6: Long-Term and Low-Effort RD&D Initiatives

| Recommended Initiatives | Applicable Technology Options |
|--|---|
| Monitor the development of advanced materials for solid-state heat-pump cycles | <ul style="list-style-type: none"> • Magnetocaloric • Thermoelectric • Thermotunneling |

For the three early-stage technology options (including the Bernoulli heat pump, critical-flow refrigeration cycle, and electrocaloric technology), recent laboratory experimentation and theoretical analyses suggest the potential for high efficiency in space-conditioning applications, but each requires further demonstration before consideration as a viable alternative to vapor-compression technology. We recommend monitoring their development and, if results are promising for HVAC applications, support further investigation into characterizing the fundamental fluid and material interactions behind these novel cycles. The goals of these research efforts would be to increase the understanding of their operation, develop analytical models, and then conduct a parametric study with the model to identify promising areas of further development.

Additionally, we identified some technology options that can enhance the performance of conventional vapor-compression systems during the course of this study. Although evaluating applications as subsystems to vapor-compression equipment was beyond the scope of this assignment, we summarized these opportunities for future reference. We recommend evaluating the potential for these component technologies through analytical modeling and laboratory investigation. If initial findings are promising, these components could be integrated into demonstration prototypes for further testing in vapor-compression systems.

Table of Contents

| | |
|--|-------|
| Executive Summary | iv |
| Table of Contents | xi |
| List of Figures | xiv |
| List of Tables | xvi |
| List of Acronyms | xviii |
| 1 Introduction | 1 |
| 1.1 Background: Vapor-Compression Technology..... | 1 |
| 1.2 Breakdown of HVAC Energy Consumption..... | 5 |
| 2 Approach | 8 |
| 2.1 Initial List of Technology Options | 9 |
| 2.2 Initial Screening | 9 |
| 2.3 Identification of Early-Stage Technology Options | 9 |
| 2.4 In-Depth Research and Analysis | 10 |
| 2.5 Estimating Unit Energy Savings | 12 |
| 2.6 Estimating Technical Energy Savings Potential | 12 |
| 2.7 Development of Scoring Criteria | 13 |
| 2.8 Scoring Technology Options and Making Recommendations..... | 14 |
| 3 Summary of 17 Non-Vapor-Compression Technology Options..... | 15 |
| 3.1 Solid-State Technology Options | 17 |
| 3.2 Electro-Mechanical Technology Options..... | 18 |
| 3.3 Thermally Driven Technology Options | 19 |
| 4 Observations | 21 |
| 4.1 Technical Energy Savings Potential..... | 21 |
| 4.2 Supplementary Components for Vapor-Compression Systems | 22 |
| 4.3 Development Status..... | 22 |
| 4.4 Cost, Size, and Complexity | 23 |
| 4.5 Non-Energy Benefits..... | 24 |
| 4.6 Potential Disadvantages | 26 |
| 5 Summary of Results | 27 |
| 5.1 Final Ranking of Technology Options..... | 27 |

| | | |
|------------|--|-----|
| 5.2 | Early-Stage Technology Options | 29 |
| 5.3 | Summary of Observations | 29 |
| 6 | Recommendations | 31 |
| 6.1 | Highest-Priority RD&D Initiatives | 31 |
| 6.2 | Moderate-to-High-Priority RD&D Initiatives..... | 31 |
| 6.3 | Moderate-Priority RD&D Initiatives | 33 |
| 6.4 | Long-Term and Low-Effort RD&D Initiatives..... | 34 |
| 6.5 | Initiatives for Early-Stage Technology Options..... | 35 |
| 6.6 | Initiatives to Supplement Vapor-Compression Systems..... | 35 |
| | References..... | 36 |
| Appendix A | Abridged Analyses for Screened Technology Options | 38 |
| A.1 | Pulse-Tube Refrigeration | 39 |
| A.2 | Vortex-Tube Cooling | 42 |
| Appendix B | Abridged Analyses for Early-Stage Technology Options..... | 45 |
| B.1 | Bernoulli Heat Pump..... | 46 |
| B.2 | Critical-Flow Refrigerant Cycle..... | 51 |
| B.3 | Electrocaloric..... | 55 |
| Appendix C | In-Depth Analyses of the 17 Viable Non-Vapor-Compression Technology Options | 60 |
| C.1 | Solid-State Technology Options | 62 |
| C.1.1 | Magnetocaloric | 63 |
| C.1.2 | Thermoelectric..... | 70 |
| C.1.3 | Thermotunneling | 78 |
| C.2 | Electro-Mechanical Technology Options..... | 83 |
| C.2.1 | Brayton Heat Pump | 84 |
| C.2.2 | Evaporative Cooling..... | 89 |
| C.2.3 | Membrane Heat Pump..... | 94 |
| C.2.4 | Thermoacoustic | 99 |
| C.2.5 | Thermoelastic | 107 |
| C.3 | Thermally Driven Technology Options | 113 |
| C.3.1 | Absorption Heat Pump | 115 |
| C.3.2 | Adsorption Heat Pump | 125 |

| | | |
|------------|---|-----|
| C.3.3 | Duplex-Stirling Heat Pump | 132 |
| C.3.4 | Ejector Heat Pump..... | 136 |
| C.3.5 | Evaporative Liquid Desiccant Air Conditioner..... | 142 |
| C.3.6 | Ground-Coupled Solid Desiccant Air Conditioner | 147 |
| C.3.7 | Standalone Liquid Desiccant Air Conditioner | 152 |
| C.3.8 | Standalone Solid Desiccant Air Conditioner..... | 160 |
| C.3.9 | Vuilleumier Heat Pump..... | 165 |
| Appendix D | Methodology to Estimate Technical Energy Savings Potential | 169 |
| Appendix E | Comparison of U.S. Census Regions and Building America Climate Zones | 174 |
| Appendix F | Technical Energy Savings Potential of the 17 Viable Non-Vapor-Compression Technology Options..... | 176 |
| Appendix G | Supplementary Technologies for Vapor-Compression Systems..... | 177 |

List of Figures

| | |
|--|-----|
| Figure ES-1-1: Comparison of technical energy savings potential (Quads/year)..... | vi |
| Figure ES-1-2: Final ranking of technology options | vii |
| Figure 1-1: Refrigerant safety groupings in ANSI/ASHRAE Standard 34–2010 | 2 |
| Figure 1-2: Current state of HFC/HCFC refrigerants and viable next-generation refrigerant options..... | 3 |
| Figure 1-3: 2013 U.S. residential building sector primary energy consumption (Quads/year)..... | 5 |
| Figure 1-4: 2013 U.S. commercial building sector primary energy consumption (Quads/year).... | 6 |
| Figure 1-5: U.S. building sector HVAC primary annual energy consumption, by technology..... | 7 |
| Figure 1-6: Climate zone breakdown of space-cooling energy consumption..... | 7 |
| Figure 2-1: Technology selection, screening, and assessment process | 8 |
| Figure 4-1: Comparison of technical energy savings potential (Quads/year)..... | 21 |
| Figure 5-1: Final ranking of technology options | 27 |

Appendix A

| | |
|--|----|
| Figure A-1: Schematic of a pulse-tube refrigerator | 40 |
| Figure A-2: Schematic of a vortex-tube cooler..... | 43 |
| Figure A-3: Personal air conditioning vests..... | 43 |

Appendix B

| | |
|---|----|
| Figure B-1: Schematic of a Bernoulli cooling principle..... | 47 |
| Figure B-2: Diagram of current Bernoulli heat pump system | 48 |
| Figure B-3: Schematic of a critical-flow refrigeration cycle | 52 |
| Figure B-4: Electrocaloric cycle | 56 |
| Figure B-5: Experimental setup for characterizing the electrocaloric cooling cycle..... | 57 |

Appendix C

| | |
|--|-----|
| Figure C-1: Magnetic cooling cycle | 64 |
| Figure C-2: The active magnetic regenerator cycle | 65 |
| Figure C-3: Thermoelectric cooling module..... | 72 |
| Figure C-4: ZT for various thermoelectric materials | 73 |
| Figure C-5: Schematic of thermotunneling system | 79 |
| Figure C-6: Schematic of Brayton cycle..... | 85 |
| Figure C-7: Advanced membrane cooling process | 96 |
| Figure C-8: Standing-wave heat pump and heat engine | 101 |
| Figure C-9: Traveling-wave heat pump..... | 102 |
| Figure C-10: Temperature and stress curves of NiTi..... | 108 |
| Figure C-11: Circulating implementation of thermoelastic cooling system..... | 109 |
| Figure C-12: Schematic of a single-effect LiBr absorption chiller..... | 117 |
| Figure C-13: Schematic of an ammonia-water absorption system with generator-absorber heat exchange (GAX) | 118 |
| Figure C-14: Schematic of adsorption chiller..... | 127 |
| Figure C-15: Typical duplex-Stirling heat pump..... | 133 |
| Figure C-16: Basic diagram of an ejector | 137 |
| Figure C-17: Typical ejector heat pump | 138 |

Figure C-18: Synairco air conditioner schematic 149
Figure C-19: Design configuration for a liquid desiccant air conditioner 154
Figure C-20: Solid desiccant wheel 162
Figure C-21: Schematic of kinematic Vuilleumier heat pump 166

Appendix E

Figure E-1: U.S. census regions..... 174
Figure E-2: Building America climate zones..... 175

List of Tables

| | |
|---|------|
| Table ES-1-1: Technologies Considered in This Analysis | v |
| Table ES-1-2: Categorization of Technology Options | viii |
| Table ES-1-3: Highest-Priority RD&D Initiatives | viii |
| Table ES-1-4: Moderate-to-High-Priority RD&D Initiatives..... | ix |
| Table ES-1-5: Moderate-Priority RD&D Initiatives..... | ix |
| Table ES-1-6: Long-Term and Low-Effort RD&D Initiatives | x |
| Table 2-1: Technologies Considered in This Analysis | 10 |
| Table 2-2: Summary of Key Technology Characteristics..... | 11 |
| Table 2-3: Baseline Equipment and Efficiencies..... | 12 |
| Table 2-4: Technology Option Scoring Matrix | 14 |
| Table 3-1: Non-Vapor-Compression Technology Options by Category | 16 |
| Table 3-2: Summary of Solid-State Technology Options | 17 |
| Table 3-3: Summary of Electro-Mechanical Technology Options..... | 18 |
| Table 3-4: Summary of Thermally Driven Technology Options..... | 19 |
| Table 4-1: Technology Option Development Status | 23 |
| Table 4-2: Estimated Cost and Complexity for Technology Options beyond Early-Stage R&D | 24 |
| Table 4-3: Non-Energy Benefits of Technology Options (Compared to Vapor Compression) | 25 |
| Table 4-4: Potential Disadvantages of Technology Options (Compared to Vapor Compression) | 26 |
| Table 5-1: Scoring Results for Technology Options | 28 |
| Table 5-2: Categorization of Technology Options | 29 |

Appendix B

| | |
|---|----|
| Table B-1: Recommended Next Steps for the Development of Bernoulli Heat Pumps..... | 49 |
| Table B-2: Recommended Next Steps for the Development of Critical-Flow Refrigeration Cycle | 53 |
| Table B-3: Next Steps for the Development of Electrocaloric Technology..... | 58 |

Appendix C

| | |
|--|-----|
| Table C-1: Non-Vapor-Compression Technology Options by Category | 60 |
| Table C-2: Summary of Solid-State Technology Options..... | 62 |
| Table C-3: Next Steps for the Development of Magnetocaloric Technology | 68 |
| Table C-4: Next Steps for the Development of Thermoelectric Technology..... | 76 |
| Table C-5: Next Steps for the Development of Thermotunneling Technology..... | 81 |
| Table C-6: Summary of Electro-Mechanical Technology Options | 83 |
| Table C-7: Next Steps for the Development of Advanced Evaporative Cooling | 92 |
| Table C-8: Next Steps for the Development of Advanced Membrane Heat Pumps | 98 |
| Table C-9: Next Steps for the Development of Thermoacoustic Technology..... | 105 |
| Table C-10: Next Steps for the Development of Thermoelastic Cooling..... | 111 |
| Table C-11: Summary of Thermally Driven Technology Options..... | 113 |
| Table C-12: Summary of Cost Estimates for Conventional Electric Chillers and Absorption Chillers..... | 121 |

Table C-13: Next Steps for the Development of Absorption Heat Pumps 121

Table C-14: Representative COPs for Adsorption Heat Pumps 128

Table C-15: Next Steps for the Development of Adsorption Heat Pumps 129

Table C-16: Next Steps for the Development of Duplex-Stirling Heat Pumps 135

Table C-17: Next Steps for the Development of Ejector Heat Pumps 140

Table C-18: Next Steps for the Development of Evaporative Liquid Desiccant Air
Conditioners 145

Table C-19: Next Steps for the Development of Ground-Coupled Solid Desiccant Air
Conditioners 151

Table C-20: Next Steps for the Development of Standalone Liquid Desiccant Air
Conditioners 158

Table C-21: Next Steps for the Development of Standalone Solid Desiccant Air
Conditioners 164

Table C-22: Next Steps for the Development of Vuilleumier Heat Pumps 168

Appendix D

Table D-1: Baseline Equipment Efficiency Information (Site Energy) 170

Table D-2: Baseline Equipment Site and Source Energy COPs 171

Table D-3: Reported Parasitic Electric Consumption for Available Absorption Heat Pumps ... 172

List of Acronyms

| | |
|--------|---|
| A/C | Air Conditioning |
| °C | Degrees Celsius |
| °F | Degrees Fahrenheit |
| °K | Degrees Kelvin |
| ACEEE | American Council for an Energy-Efficient Economy |
| AEC | Annual Energy Consumption |
| AEO | U.S. Energy Information Administration's Annual Energy Outlook |
| AHRI | Air-Conditioning, Heating, and Refrigeration Institute |
| ANSI | American National Standards Institute |
| ARPA-e | Advanced Research Projects Agency - Energy |
| ARTI | Air-Conditioning, Heating, and Refrigeration Technology Institute |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| ASME | American Society of Mechanical Engineers |
| BTO | Building Technologies Office |
| Btu | British Thermal Unit |
| CEO | Chief Executive Officer |
| CFC | Chlorofluorocarbon |
| CFD | Computational Fluid Dynamics |
| COP | Coefficient of Performance |
| DC | Direct Current |
| DOE | U.S. Department of Energy |
| EER | Energy Efficiency Ratio |
| EIA | U.S. Energy Information Administration |
| ERV | Energy Recovery Ventilator |
| ESTCP | Environmental Security Technology Certification Program |
| GAX | Generator-Absorber Heat Exchanger |
| GHG | Greenhouse Gas |
| GRI | Gas Research Institute |
| GTI | Gas Technology Institute |
| GWP | Global-Warming Potential |
| HCFC | Hydrochlorofluorocarbon |
| HFC | Hydrofluorocarbons |
| HFO | Hydrofluoroolefins |
| HHV | Higher Heating Value |
| HSPF | Heating Seasonal Performance Factor |
| HVAC | Heating, Ventilation, Air Conditioning, and Refrigeration |
| HVAC&R | Heating, Ventilation, and Air Conditioning |

| | |
|---------|--|
| Hz | Hertz |
| IDEC | Indirect-Direct Evaporative Cooler |
| IEA | International Energy Agency |
| IIR | International Institute of Refrigeration |
| LHV | Lower Heating Value |
| MOF | Metal-Organic Framework |
| NEDO | Japanese New Energy and Industrial Technology Development Organization |
| NIST | National Institute of Standards and Technology |
| NREL | National Renewable Energy Laboratory |
| NYSERDA | New York State Energy Research and Development Authority |
| ODP | Ozone-Depletion Potential |
| ORNL | Oak Ridge National Laboratory |
| P-Tool | BTO Prioritization Tool |
| PNNL | Pacific Northwest National Laboratory |
| Quad | Quadrillion Btu |
| R&D | Research and Development |
| RD&D | Research, Development, and Demonstration |
| RPM | Revolutions Per Minute |
| RTU | Packaged Rooftop HVAC Unit |
| SBIR | Small Business Innovation Research Program |
| SEER | Seasonal Energy Efficiency Ratio |
| SMA | Shape-Memory Alloy |
| SWEEP | Southwest Energy Efficiency Project |
| T | Tesla |
| TESP | Technical Energy Savings Potential |
| ton | Ton of Refrigeration (12,000 Btu/hour) |
| TSD | Technical Support Document |
| U.S. | United States |
| UEC | Unit Energy Consumption |
| UES | Unit Energy Savings |
| UMD | University of Maryland |
| W | Watt |
| WCEC | Western Cooling Efficiency Center |
| ZT | Dimensionless Figure of Merit for Thermoelectric Materials |

1 Introduction

The U.S. Department of Energy (DOE) Building Technologies Office (BTO) commissioned this characterization and technology assessment of alternatives to vapor-compression technology for residential and commercial heating, ventilation, and air-conditioning (HVAC) applications. The main objectives of this study were to:

- Identify a list of alternatives to vapor-compression technology for residential and commercial HVAC applications
- Characterize these technology options based on their technical energy savings potential, development status, non-energy benefits, and other factors affecting end-user acceptance and their ability to compete with conventional vapor-compression systems
- Make specific recommendations to DOE regarding the best approach in supporting the development and deployment of these technologies, should DOE chose to support non-vapor-compression technology further.

1.1 Background: Vapor-Compression Technology

Vapor-compression systems have effectively and efficiently served HVAC needs for residential and commercial buildings for close to 100 years. Having replaced absorption and other cooling systems, vapor compression has become the dominant HVAC technology due to its scalability, relatively compact size, high reliability, and other attributes. Vapor-compression systems move heat through a closed-loop cycle by compressing, condensing, expanding, and evaporating a refrigerant fluid. Depending on the configuration and operating mode, vapor-compression systems can supply space cooling and/or space heating to maintain a comfortable environment within buildings. While a long list of working fluids can serve as the vapor-compression refrigerant, most systems utilize one of several synthetic refrigerants designed specifically for the temperatures and operating conditions of HVAC applications. However, these conventional refrigerants have detrimental effects on the global environment when released into the atmosphere.¹

Before the 1990s, HVAC equipment predominantly operated with a working fluid from the refrigerant classes known as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). However, when scientists discovered that CFCs and HCFCs contributed significantly to the depletion of the ozone layer, the HVAC industry adopted an alternative class of synthetic refrigerants known as hydrofluorocarbons (HFCs), which are still widely used today.

HFCs have effectively contributed to the phase-out of CFCs and HCFCs, but they pose another environmental issue. Although HFCs have zero ozone-depletion potential (ODP), this refrigerant class has a disproportionate contribution to global greenhouse gas (GHG) emissions when released to the atmosphere. For example, the common HFC refrigerants HFC-134a and HFC-

¹ Although steps can be taken to reduce the loss of refrigerant from vapor-compression systems, refrigerant commonly escapes from most HVAC systems to the atmosphere slowly over time through leaky joints, fittings, and couplings in the refrigerant line; during equipment installation, servicing, repair, or removal; and through equipment damage.

410A have global warming potentials (GWP) of 1,370 and 2,100 times that of carbon dioxide (CO₂), respectively (UNEP 2011). To curb anthropogenic climate change, the United States, Canada, and Mexico announced a proposal in April 2013 to phase down HFC consumption by 85% during the period 2016–2033 (UNEP 2013). Recent proposed U.S. energy legislation also included this phase-down schedule.² Additionally, several institutions within the European Union endorsed an agreement to phase down HFC consumption by roughly 80% in 2030 (European Commission 2013).

The anticipated commitment to reduce HFC consumption has stimulated interest in alternative refrigerants with low GWP. Researchers have identified low-GWP HFCs, hydrocarbons, ammonia, carbon dioxide, and hydrofluoroolefins (HFOs) as possible alternatives to the HFCs used today. As was the case with the transition from CFC and HCFC to HFC refrigerants, many of these alternative refrigerants suffer from other undesirable characteristics, including toxicity, flammability, and/or lower efficiency. Because HVAC systems operate near or within areas inhabited by people and sometimes experience refrigerant leaks, the HVAC industry and other stakeholders are especially concerned about toxic or flammable working fluids. To provide guidance for the industry, ASHRAE Standard 34–2010 defines refrigerant safety group classifications based on toxicity and flammability, as shown in Figure 1-1. Refrigerants with higher flammability or toxicity levels are more hazardous than those with lower flammability or toxicity levels. As a result, building codes and other safety standards often restrict or discourage the use of non-A1 refrigerants (ARTI 2010).

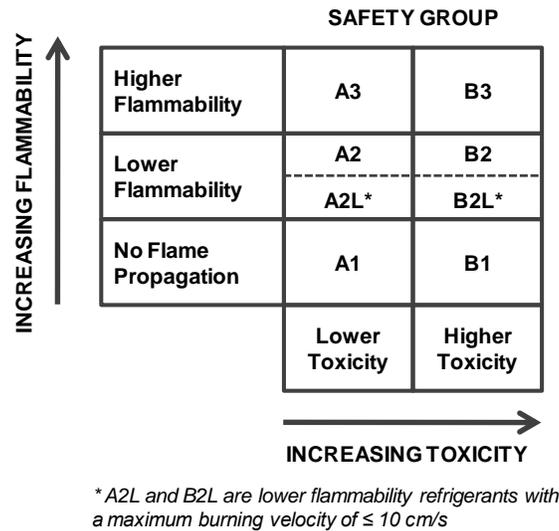


Figure 1-1: Refrigerant safety groupings in ANSI/ASHRAE Standard 34–2010
Source: ASHRAE (2010)

The viable alternatives for each existing refrigerant have varying degrees of flammability, toxicity, and GWP, as illustrated in Figure 1-2. This diagram provides an overview of the next-

² The Climate Security Act of 2007 (i.e., the Lieberman-Warner bill) and the Clean Energy Jobs and American Power Act of 2010 (i.e., the Kerry-Lieberman bill), neither of which has become law.

generation refrigerant options currently available to replace existing HFC and HCFC refrigerants, categorized by safety group.

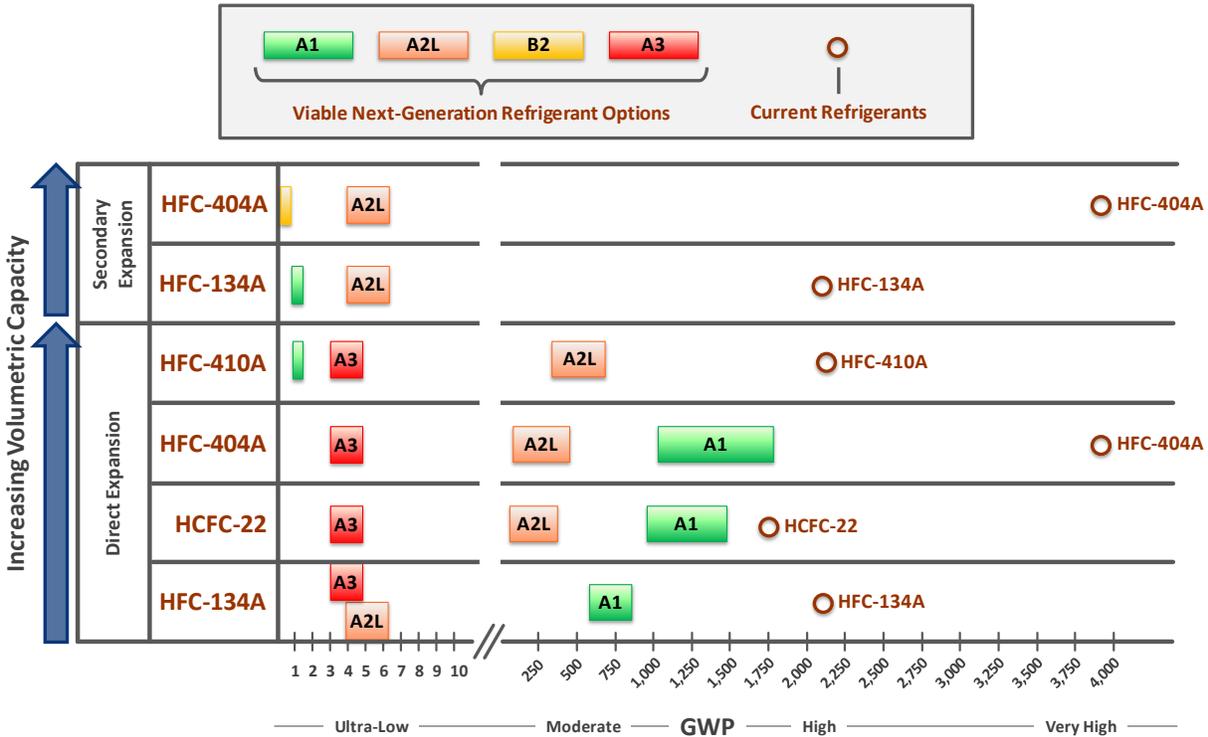


Figure 1-2: Current state of HFC/HCFC refrigerants and viable next-generation refrigerant options

Source: Goetzler et al. (2011b)

Selecting a replacement refrigerant involves a tradeoff between safety, efficiency, cost, and GWP. As evidenced by Figure 1-2, decreasing GWP generally corresponds to increasing flammability, which poses a significant issue under current safety standards. Moreover, alternatives for HFC-134a and HFC-410A may have lower volumetric capacities. Refrigerants with lower volumetric capacity may require higher mass flow rates and subsequently larger compressors, heat exchangers, piping, etc. to achieve the required heating and/or cooling capacities (Leck et al. 2011). As a drop-in replacement, this alternative refrigerant may have a lower efficiency, but manufacturers can redesign systems and components to mitigate these issues for new equipment. Although these redesigns can reach the efficiency of current products, the cost of baseline vapor-compression systems of the future may increase, because low-GWP systems may need to use higher cost components and designs to make up for the intrinsic efficiency reduction.

The phase-out of HFCs will impose constraints on standard vapor-compression equipment including increased cost, reduced efficiency, and potential trade-offs of safety. Because many HFC alternatives reduce the attractiveness of vapor-compression HVAC technologies, the HVAC industry would benefit from alternative technologies that provide space conditioning for residential and commercial buildings without the use of vapor-compression equipment. This

report provides a summary characterization of non-vapor-compression technology options, evaluates their energy savings potential over current HVAC systems, and recommends activities for BTO to advance their development and market success, should they choose to further support non-vapor-compression technologies.

Beyond HVAC applications, the proposed HFC phase-out also affects vapor-compression systems in residential and commercial refrigeration. While many of the alternative refrigerants for space-cooling applications pose similar issues for refrigeration (e.g., performance, safety, cost, etc.), non-vapor-compression technologies may present a different value proposition for refrigeration applications. Although some of technology options profiled in this report can be applicable to refrigeration, the scope of this report focuses on space-heating and space-cooling applications for non-vapor-compression technologies.

1.2 Breakdown of HVAC Energy Consumption

According to data used in the BTO’s Prioritization Tool³ or “P-Tool,” the U.S. residential building sector consumed 21.36 quadrillion Btu (quad) of primary energy in 2013.⁴ Energy consumption associated with HVAC equipment (i.e., space heating, and space cooling) accounts for over 35% of the total residential energy consumption at 7.79 quads (see Figure 1-3).

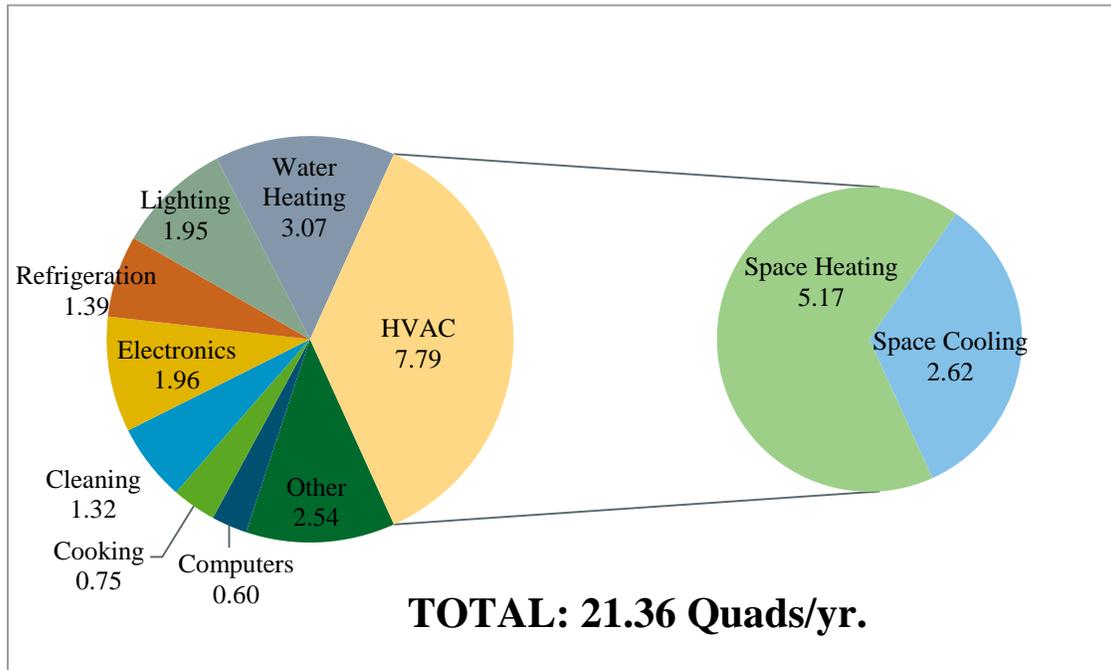


Figure 1-3: 2013 U.S. residential building sector primary energy consumption (Quads/year)
Source: Prioritization Tool (2013)

Moreover, the U.S. commercial building sector consumed 13.72 quads of primary energy in 2013. The energy consumption associated with HVAC equipment (i.e., space heating, space cooling, and ventilation) accounts for over 40% of the total commercial energy consumption at 5.67 quads (Figure 1-4).

³ The Prioritization Tool or P-Tool is a Microsoft Excel model that assesses and compares building-related energy-efficient technologies and activities, and projects their potential energy savings and economics. BTO uses the P-Tool to support its programmatic decision-making. The P-Tool draws on data from the Energy Information Administration’s (EIA) Annual Energy Outlook (AEO) 2010 to forecast baseline energy consumption in the buildings sector, segregated by geographic location, end use, and fuel type. Tool users input information, including unit energy savings, end use, and applicable market, about efficiency measures of interest. The tool applies these inputs to its baseline energy forecasts to develop estimates of technical energy savings potential, market potential, and the costs of efficiency initiatives, among other outputs. The P-Tool also has the capability of “staging” various efficiency measures, which accounts for the potential interactions among multiple measures. The P-Tool is currently under development at the time of this writing. For additional information on the Prioritization Tool’s capabilities, outputs, caveats, and functions, refer to Abdelaziz et al. (2013) and Farese et al. (2012).

⁴ Primary energy accounts for the losses in generation, transmission, and distribution. We only account for these losses for electricity, as the transmission and distribution losses for natural gas and other fossil fuels tend to be small. Primary energy does not account for the losses associated with extraction.

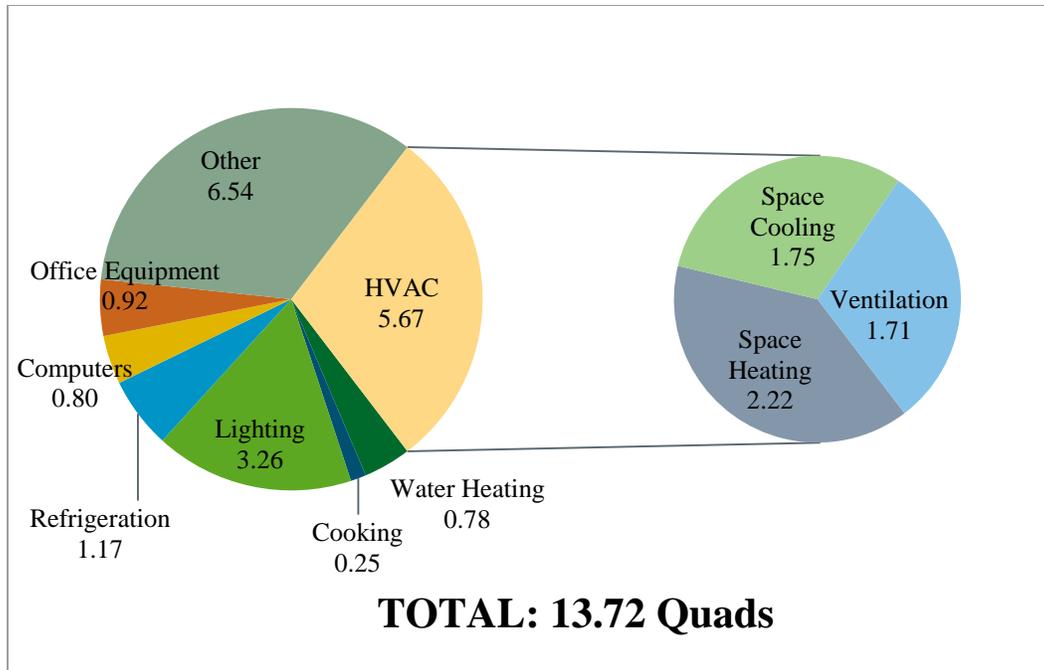


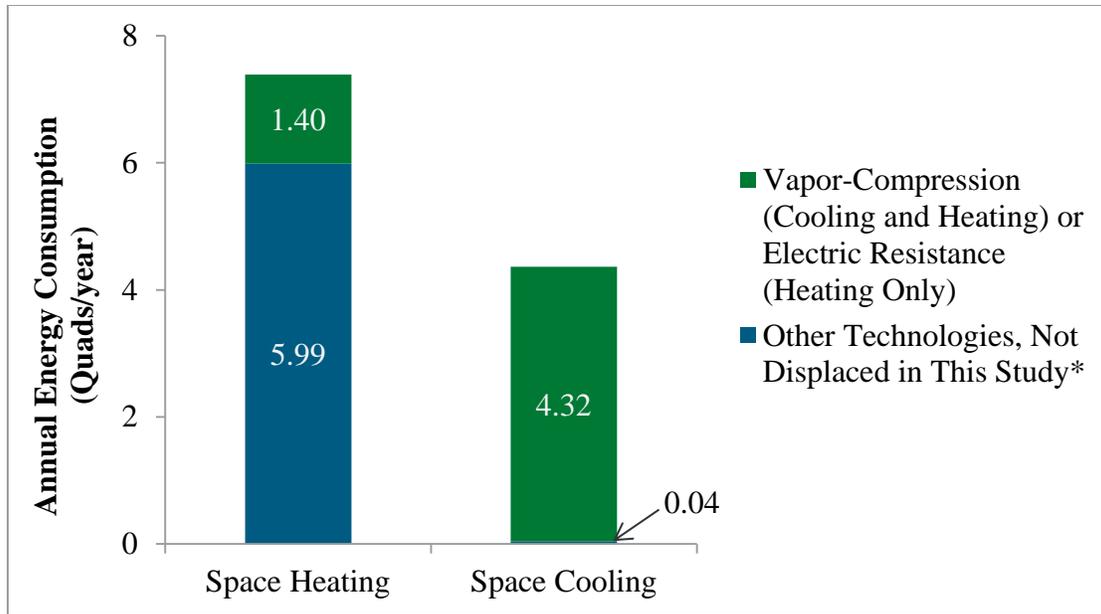
Figure 1-4: 2013 U.S. commercial building sector primary energy consumption (Quads/year)

Source: Prioritization Tool (2013)

This study focuses on energy consumption associated with HVAC equipment, which represents 38% of total primary energy consumption in the U.S. buildings sector (13.46 of 35.08 quads annually). Because the purpose of this report is to investigate alternatives to vapor compression in HVAC applications, we focused specifically on the energy consumption associated with HVAC equipment that currently utilizes vapor-compression technology and would thus be displaced by alternatives. Consequently, we broke down the total HVAC energy consumption by equipment type to estimate the technical energy savings potential⁵ of candidate technology options. For cooling applications, this equipment subset includes all technologies except for gas-fired chillers. For heating applications, it includes all vapor-compression heat pumps as well as electric resistance heaters, which have COPs of 1.0 and could therefore be displaced by high-efficiency alternatives to vapor compression. As described further in Section 2.6, we used the P-Tool to determine the energy consumption of these baseline technologies.

Figure 1-5 provides energy consumption for heating and cooling, respectively, by applicable equipment type. We based all estimates of technical energy savings potential on these annual energy consumption estimates.

⁵ Technical energy savings potential is the theoretical national primary energy savings that could be achieved if all technically suitable installations are replaced with a particular energy-saving technology.



*These technologies include gas-fired chillers (for cooling) and all fuel-fired heating technologies except for gas-fired heat pumps.

Figure 1-5: U.S. building sector HVAC primary annual energy consumption, by technology
Source: Prioritization Tool (2013)

Certain cooling-only technologies that we analyzed are only applicable in either hot-dry or hot-humid climate regions. Therefore, we segmented the 4.32 quads of vapor-compression space-cooling energy consumption illustrated in Figure 1-6 by climate zone based on P-Tool data. As Figure 1-6 shows, the hot-humid climate zone accounts for 65% of total vapor-compression space-cooling energy consumption, while the hot-dry climate zone accounts for only 7%.

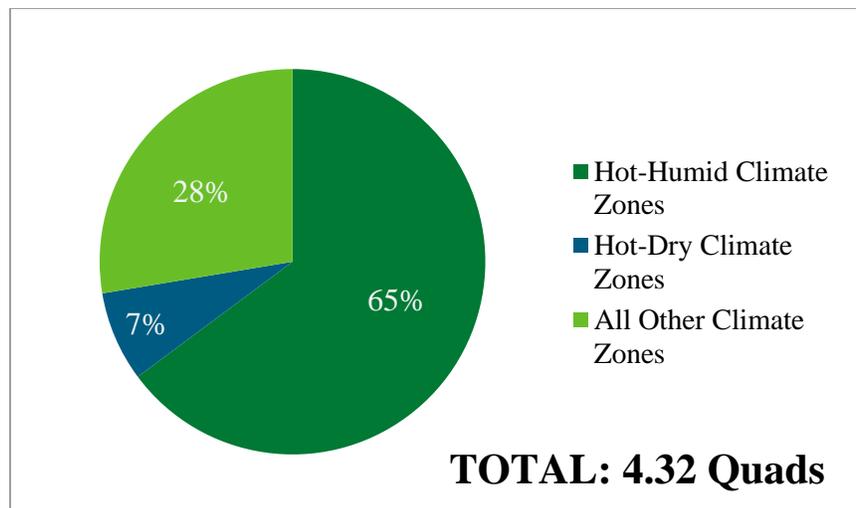


Figure 1-6: Climate zone breakdown of space-cooling energy consumption
Source: Prioritization Tool (2013)

2 Approach

We examined a broad portfolio of technology options (22 options in total) that could replace vapor compression in HVAC equipment. We initially screened out two technology options because available literature suggests that they are not suitable for HVAC applications, leaving 20 technology options for further, more thorough evaluation. We then filtered out three technology options that may have promise as a vapor-compression alternative in HVAC applications, but for which we could not find adequate documentation to evaluate—we refer to these as early-stage technology options. Finally, we performed more in-depth analysis, including estimation of the technical energy savings potential and evaluation of the state of technology development, on the remaining 17 technology options. Figure 2-1 presents the overall flow of the technology selection, screening, and assessment processes.

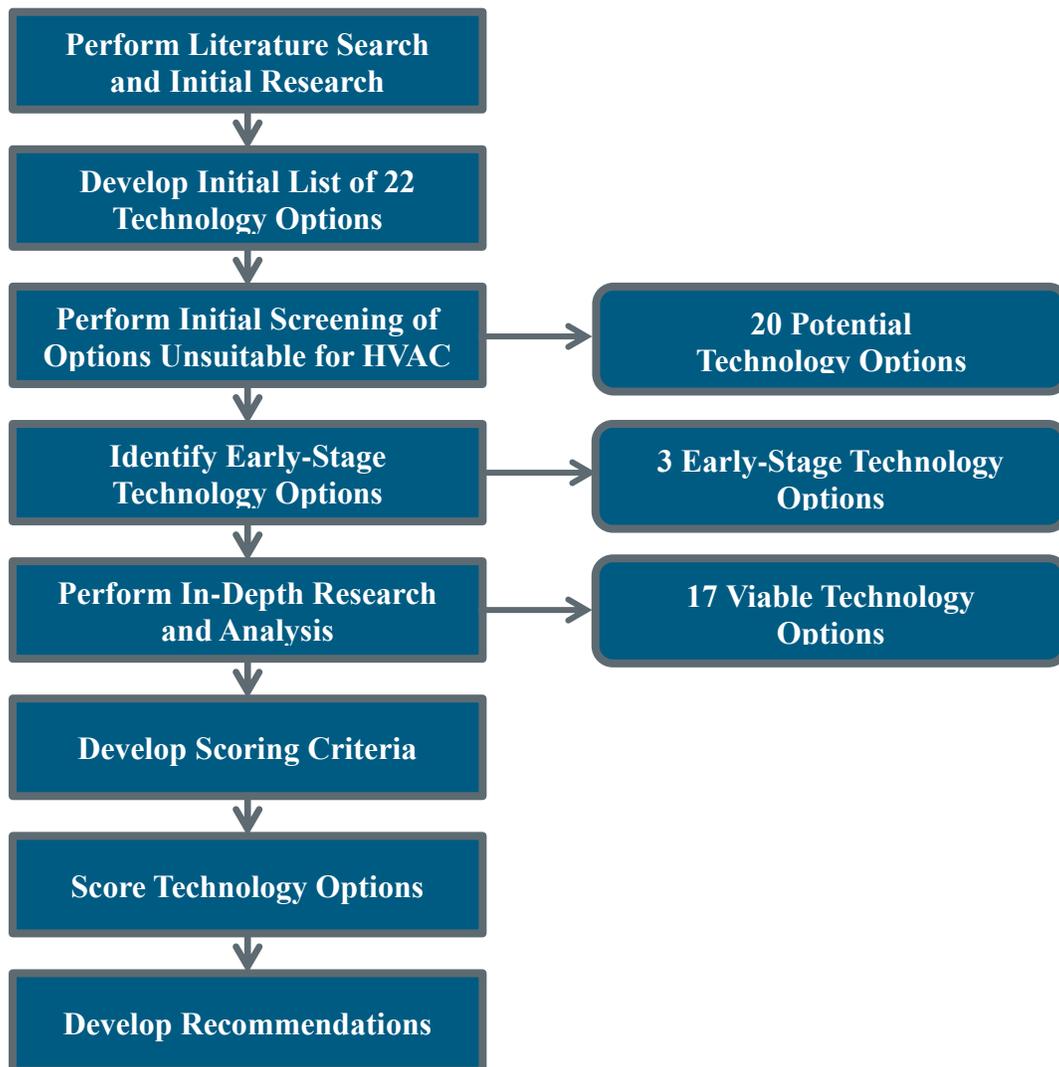


Figure 2-1: Technology selection, screening, and assessment process

2.1 Initial List of Technology Options

We first generated the initial, comprehensive list of technology options that could potentially serve as alternatives to vapor compression in residential and commercial space-heating and space-cooling applications. We compiled this list without considering the economics, technical maturity, or level of expected energy savings (if any). We identified the technology options included in the initial list through a variety of sources, including:

- Prior Navigant reports on alternative HVAC technologies (e.g., Goetzler et al. 2011a, Goetzler et al. 2012)
- HVAC industry organizations, publications, and websites (e.g., ASHRAE)
- U.S. and international governmental organizations and national laboratories (e.g., Oak Ridge National Laboratory, ARPA-e, NYSERDA)
- University research (e.g., University of Maryland, Pennsylvania State University)
- Internal Navigant sources and HVAC experts.

After compiling the initial, comprehensive list of technology options, we conducted a literature review for each option to develop technical descriptions and energy savings projections. Where technology options also showed potential to augment conventional vapor-compression systems, we noted this opportunity for each application, but did not include these in our analysis, as they are not direct alternatives to vapor compression. Section 4.2 provides additional observations for these specific applications.

2.2 Initial Screening

We screened out two technology options, the vortex-tube and pulse-tube cycles, because available literature suggests that they are not suitable for space-conditioning applications:

- **Pulse-Tube Refrigeration:** The low efficiencies of pulse-tube refrigerators (estimated cooling COP of 0.39 for HVAC applications) are impractical outside of cryogenic refrigeration.
- **Vortex-Tube Cooling:** The low efficiency (maximum COP of 0.10) and need for a compressed air source limit the applicability of the vortex-tube cooling to industrial process cooling and personal cooling vests.

Appendix A contains brief summaries of the two technology options screened from further consideration.

2.3 Identification of Early-Stage Technology Options

Publicly available information is scarce for three technology options that are still in the early stages of R&D. Because we were unable to find energy and cost savings estimates for these options, we could not quantitatively compare them to other options. Thus, we removed them from the scoring and screening process and recommend monitoring their development. These technologies are:

- **Bernoulli Heat Pump:** Bernoulli heat pumps accelerate a gaseous working fluid through a converging-diverging nozzle to produce cooling across the nozzle throat.

- **Critical-Flow Refrigeration Cycle:** The critical-flow refrigeration cycle utilizes a supersonic nozzle to expand a liquid refrigerant and absorb heat from a secondary fluid to provide space cooling.
- **Electrocaloric:** The electrocaloric effect is a phenomenon in which a dielectric material exhibits reversible temperature change when exposed to a changing electric field.

Although the energy savings associated with these technologies have not yet been well-characterized, each appears to be technically applicable to all space-heating and -cooling applications in residential and commercial buildings. Appendix B summarizes these three technology options with their abridged analyses.

2.4 In-Depth Research and Analysis

Table 2-1 lists the screened-out technology options, the early-stage technology options, and the remaining technology options.

Table 2-1: Technologies Considered in This Analysis

| Screened-Out Technology Options | Early-Stage Technology Options | Remaining Viable Technology Options |
|---|--|--|
| Total: 2 | Total: 3 | Total: 17 |
| Pulse-Tube Refrigeration Vortex-Tube Cooling | Bernoulli Heat Pump Critical-Flow Refrigeration Cycle Electrocaloric | Absorption Heat Pump Adsorption Heat Pump Brayton Heat Pump Duplex-Stirling Cycle Ejector Heat Pump Evaporative Cooling Evaporative Liquid Desiccant A/C Ground-Coupled Solid Desiccant A/C Magnetocaloric Membrane Heat Pump Standalone Liquid Desiccant A/C Standalone Solid Desiccant A/C Thermoacoustic Thermoelastic Thermoelectric Thermotunneling Vuilleumier Heat Pump |

For each of the 17 remaining viable technology options, we estimated unit energy savings and compiled projections of their installed costs.

Table 2-2 lists the key technology characteristics that we investigated. Further, we identified barriers to market adoption and potential next steps toward greater market adoption. Appendix C contains the summary analysis reports for these 17 technology options.

Table 2-2: Summary of Key Technology Characteristics

| Characteristic | Description |
|---|--|
| Unit Energy Savings | See Section 2.5 below. |
| Fuel Type(s) | Fuel(s) required to power the technology and indicates whether, if the technology is entirely electric, it can run on DC current. |
| Working Fluid(s) | Working fluids used by the technology’s thermodynamic cycle (if applicable). |
| Complexity/Size | Projection for system complexity and size compared to current vapor-compression systems, expressed as Low, Moderate, or High. Includes an assessment for the number of components, the necessity of a secondary heat transfer loop for unitary applications, etc. |
| Projected Cost | Projection for representative installed cost of each technology option as cited in the literature and by expert sources. Expressed as Low, Moderate, and High relative to vapor-compression systems and focuses on intrinsic cost barriers. |
| Threshold Attributes | Assessment of non-energy characteristics for which the technology would likely need to meet or exceed those of vapor-compression systems to achieve market penetration. Expressed as Low, Moderate, and High relative to vapor compression, such characteristics include safety, reliability, maintainability, and lifetime. |
| Excitement Attributes | Assessment of non-energy characteristics that would make the technology an exciting option compared to vapor compression. Expressed as Low, Moderate, High, such characteristics include very low noise, improved comfort, novel packaging opportunities, and increased peak demand reduction potential. |
| Ability to Utilize Low-Temperature Thermal Sources | Ability of the technology to use low-grade, waste, or solar heat to provide space conditioning. |
| Technical Maturity | Assessment of the technical readiness of the core technology for HVAC applications, as evidenced by the development status of prototypes or commercialization efforts. Expressed in levels of Low, Moderate, and High technical maturity. |
| Market Maturity | Assessment of the economic readiness and acceptability of the technology option, as evidenced by its commercialization in various applications, market penetration, and adoption by major manufacturers. Expressed in levels of Low, Moderate, and High market maturity. |
| Level of Stakeholder Support | Expected level of interest that key stakeholders (e.g., utilities, environmental advocates, contractors, manufacturers, or consumer organizations) will likely express support or oppose widespread adoption of the technology once it is fully developed. Expressed as Low, Moderate, and High, the reasons for their support or opposition may include peak-demand savings, safety, reliability, changes in sales, installation, service infrastructure, and fuel switching, among others. |
| Fit with BTO Mission | <p>Evaluation for how the technology option fits with BTO’s mission based on the following criteria:</p> <ul style="list-style-type: none"> • Likelihood of success, or achieving success much faster, with BTO support • Technical risk of developing a commercialized product with significant energy savings • Likelihood of the technology, once fully developed, to be embraced by major industry stakeholders. |

2.5 Estimating Unit Energy Savings

We estimated the unit energy savings for each technology option over current vapor-compression systems. Unless noted otherwise, we compared each viable technology to a baseline technology that meets current codes and standards (or current typical practice for new equipment installations) for U.S. residential and commercial buildings. It is important to note that the unit energy savings estimate excludes the potential savings obtained by raising the efficiency of the currently installed base to today’s codes, standards, and typical practice; however, this estimate serves the purposes of this report. Table 2-3 provides a summary of the baseline equipment types for this analysis and their respective efficiencies.

Table 2-3: Baseline Equipment and Efficiencies

| Equipment Type (Capacity) | Baseline Equipment | | | | Source |
|------------------------------------|--|-------------|---------------------------|------------|------------------|
| | Cooling | | Heating | | |
| | Type | Efficiency | Type | Efficiency | |
| Residential (3–5 tons) | Split-System Air Conditioner | 13 SEER | Split-System Heat Pump | 8.2 HSPF | DOE (2004) |
| Light Commercial (11.5–20 tons) | Rooftop Air Conditioner | 10.8 EER | Rooftop Heat Pump | 3.2 COP | DOE (2012) |
| Large Commercial (>300 tons) | Chiller (water-cooled, positive displacement) | 0.62 kW/ton | - | - | ASHRAE (2013) |

For non-electric technology options, such as gas-fired heat pumps, we converted conventional and non-vapor-compression technology options to a source energy COP and adjusted these values to account for the electricity consumption associated with parasitic loads, i.e., the fans, pumps, controls, etc. required to generate and distribute the heating and/or cooling to building occupants. We made similar adjustments for solid-state electric technology options whose published COPs did not include parasitic energy consumption. Finally, for technologies that are capable of both heating and cooling, but whose heating performance is unknown or undocumented, we used the first law of thermodynamics to estimate their space-heating energy consumption. Appendix D provides additional information on these estimates.

2.6 Estimating Technical Energy Savings Potential

Next, we estimated the technical energy savings potential for each viable technology option by comparing available performance information to the efficiencies of baseline technologies in each major market segment. Technical energy savings potential is the theoretical national primary energy savings that could be achieved if all technically suitable installations are immediately replaced with a particular energy-saving technology. We estimated technical energy savings potential using a methodology consistent with that of the BTO Prioritization Tool³ (P-Tool), and the following assumptions:

1. Each technology option is implemented in all technically feasible applications unless noted otherwise. In some cases, we excluded certain DOE climate zones where the technology option would be a poor technical fit.
2. Each technology option is implemented properly so that it will achieve the expected energy performance.
3. Technology options requiring further R&D will achieve the energy performance currently predicted.

To estimate technical energy savings potential, the P-Tool applies the percentage of unit energy savings to the baseline energy consumption of its applicable market. We utilized the same methodology, using the P-Tool's source data to obtain baseline energy consumption projections for 2013, to which we applied our unit energy savings.⁶ We selected markets for each technology option based on the relevant applications of that technology option, and considered the following three different potential markets in our analysis:

1. **Market #1:** All residential and commercial space-cooling applications (excluding gas-fired chillers, as explained in Section 1.2) and all residential and commercial space-heating applications that use electricity as their main input.
2. **Market #2:** All residential and commercial space-cooling applications in U.S. census regions 5, 6, and 7.⁷ This is the target market for cooling-only technologies that are most applicable in hot-humid climates.
3. **Market #3:** All residential and commercial space-cooling applications in census region 8. This is the target market for cooling-only technologies that are most applicable in hot-dry climates.

Appendix F presents the technical energy savings potential for the viable technology options (listed in Table 2-1). As mentioned in Section 2.5, this percent unit energy savings is relative to the energy consumption of equipment meeting current codes and standards. Unit energy savings, and the resulting technical energy savings potential, would be higher had we estimated savings relative to the energy consumption of currently installed equipment.

2.7 Development of Scoring Criteria

After analyzing the 17 viable technology options, we evaluated them based on the four criteria shown in Table 2-4. We assigned each criterion a weighting factor to reflect its overall importance. We scored each technology option (using a five-point scale) against each criterion, and calculated an overall score by multiplying the initial score by the weighting factor. Section 5.1 contains the scoring results for each technology option.

⁶ Where appropriate, we converted efficiency improvements into energy savings by relating the system efficiency to original energy use. For example, if efficiency improves 10%, energy use is divided by 110% ($= 1.1$), resulting in energy savings of 9.1%. ($= 1 - \frac{1}{1.1}$).

⁷ The P-Tool uses census regions rather than climate zones to distinguish geographic areas of the United States. Maps indicating how U.S. census regions compare to climate zones can be found in Appendix E.

Table 2-4: Technology Option Scoring Matrix

| Scoring Criteria | Wt. Factor | Score | | | | |
|---|------------|------------------------------|--|---|--|--|
| | | 1 | 2 | 3 | 4 | 5 |
| Technical Energy Savings Potential | 35% | No savings | < 0.25 Quads/yr. | 0.25 – 1 Quads/yr. | 1 – 2 Quads/yr. | > 2 Quads/yr. |
| Fit with BTO Mission | 30% | Very weak fit | Moderately weak fit | Neither strong nor weak fit | Moderately strong fit | Very strong fit |
| Other Non-Energy Benefits | 20% | Provides few or no benefits | Likely to provide some modest benefits | Potential for significant benefits, but not well understood | Provides 1 or 2 quantified, well-documented benefits | Provides extensive, quantifiable, well-documented benefits |
| Cost/ Complexity | 15% | Much higher cost/ complexity | Moderately higher cost/ complexity | Slightly higher cost/complexity | Potential for similar cost/ complexity | Potential for lower cost/ complexity |

2.8 Scoring Technology Options and Making Recommendations

After establishing the scoring criteria and removing early-stage technology options from consideration, we scored each of the viable 17 technology options based on our research and the input of Navigant HVAC experts. Based on these scores, we recommended potential RD&D initiatives that could support the development and propagation of these technology options. These recommendations are found in Section 6.

3 Summary of 17 Non-Vapor-Compression Technology Options

This section summarizes the 17 non-vapor-compression technology options evaluated. Appendix C provides detailed summaries for each of the 17 priority technology options. We categorize the technology options as:

- **Solid-State Technology Options** produce useful temperature differences based on the intrinsic material properties of their core solid-state substance when activated through electrical input.
- **Electro-Mechanical Technology Options** are activated through electrical input and alter the phase or other properties of a working fluid to pump heat.
- **Thermally Driven Technology Options** use thermal energy as the primary input to drive a heat pump (for cooling, heating, or both cooling/heating).

Table 3-1 maps each category to its corresponding technology options and their respective technical energy savings potentials.

Table 3-1: Non-Vapor-Compression Technology Options by Category

| Technology Category | Technology Option | Applicable Market Number* | Heating Technical Energy Savings Potential (Quads/yr.) | Cooling Technical Energy Savings Potential (Quads/yr.) | Total Technical Energy Savings Potential (Quads/yr.) |
|---------------------------------------|------------------------------------|---------------------------|--|--|--|
| Solid-State Technology Options | Magnetocaloric | 1 | 0.38 | 0.86 | 1.25 |
| | Thermoelectric | 1 | 0.19 | 0.00 | 0.19 |
| | Thermotunneling | 1 | 0.20 | 0.02 | 0.22 |
| Electro-Mechanical Technology Options | Brayton Heat Pump | 1 | 0.00 | 0.00 | 0.00 |
| | Evaporative Cooling | 3 | 0.00 | 0.25 | 0.25 |
| | Membrane Heat Pump | 1 | 0.00 | 2.16 | 2.16 |
| | Thermoacoustic | 1 | 0.11 | 0.00 | 0.11 |
| | Thermoelastic | 1 | 0.67 | 2.01 | 2.68 |
| Thermally Driven Technology Options | Absorption Heat Pump | 1 | 0.24 | 0.00 | 0.24 |
| | Adsorption Heat Pump | 1 | 0.11 | 0.00 | 0.11 |
| | Duplex-Stirling Heat Pump | 1 | 0.06 | 0.00 | 0.06 |
| | Ejector Heat Pump | 1 | 0.00 | 0.00 | 0.00 |
| | Evaporative Liquid Desiccant A/C | 1 | 0.00 | 2.64 | 2.64 |
| | Ground-Coupled Solid Desiccant A/C | 2 | 0.00 | 1.21 | 1.21 |
| | Standalone Liquid Desiccant A/C | 2 | 0.00 | 0.00 | 0.00 |
| | Standalone Solid Desiccant A/C | 2 | 0.00 | 0.00 | 0.00 |
| | Vuilleumier Heat Pump | 1 | 0.36 | 0.00 | 0.36 |

* Market #1: All residential and commercial space-cooling applications (excluding gas-fired chillers, as explained in Section 1.2) and all residential and commercial space-heating applications that use electricity as their main input.

Market #2: All residential and commercial space-cooling applications in U.S. census regions 5, 6, and 7.⁸ This is the target market for cooling-only technologies that are most applicable in hot-humid climates.

Market #3: All residential and commercial space-cooling applications in census region 8. This is the target market for cooling-only technologies that are most applicable in hot-dry climates.

⁸ The P-Tool uses census regions rather than climate zones to distinguish geographic areas of the United States. Maps indicating how U.S. census regions compare to climate zones can be found in Appendix E.

3.1 Solid-State Technology Options

Table 3-2 provides a brief description and final ranking for the technology options selected for in-depth analysis within the Solid-State Technology Options category. Appendix C.1 provides detailed summaries for each of the priority technology options in this category.

Table 3-2: Summary of Solid-State Technology Options

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|------------------------|---|-----------------|---|---------------|
| Magnetocaloric | Magnetocaloric technology operates on the magnetocaloric effect, a phenomenon in which a paramagnetic material exhibits reversible temperature change when exposed to a changing magnetic field. | High | Emerging | 3.70 |
| Thermoelectric | Under an applied voltage, thermoelectric materials generate a temperature difference that can provide space conditioning. | Moderate | Available in low-load applications, but in R&D stage for HVAC | 3.20 |
| Thermotunneling | Thermotunneling technology is an advanced form of thermoelectric technology in which electrons are transmitted across a nanometer-scale vacuum via quantum tunneling to produce cooling or heating. | Moderate | R&D | 2.45 |

3.2 Electro-Mechanical Technology Options

Table 3-3 provides a brief description and final ranking for the technology options selected for in-depth analysis within the Electro-Mechanical Technology Options category. Appendix C.2 provides detailed summaries for each of the priority technology options in this category.

Table 3-3: Summary of Electro-Mechanical Technology Options

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|--------------------------------|---|-----------------|--------------------|---------------|
| Brayton-Cycle Heat Pump | Brayton-cycle heat pumps generate usable heating and cooling by compressing and then expanding a gaseous working fluid, which is usually air. | Moderate | R&D | 2.05 |
| Evaporative Cooling | Evaporative cooling systems use water to absorb sensible heat from airstreams, evaporating the water and thus cooling the air. | Low | Available | 3.30 |
| Membrane Heat Pump | Driven by a vacuum pump, advanced-membrane heat pumps provide cooling and dehumidification and/or heating and humidification by transferring moisture across a number of membranes. | Moderate | Emerging | 4.35 |
| Thermoacoustic | Thermoacoustic technology uses high-amplitude sound waves in a noble gas to pump heat. | Moderate | R&D | 2.80 |
| Thermoelastic | Using the unique properties of shape-memory alloys (SMA), thermoelastic cooling systems stress and release a SMA core that absorbs heat from, or rejects heat to, its surroundings. | Moderate | R&D | 4.45 |

3.3 Thermally Driven Technology Options

Table 3-4 provides a brief description and final ranking for the technology options selected for in-depth analysis within the Thermally Driven Technology Options category. Appendix C.3 provides detailed summaries for each of the priority technology options in this category.

Table 3-4: Summary of Thermally Driven Technology Options

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|---|---|-----------------|--------------------|---------------|
| Absorption Heat Pump | Absorption systems use a refrigerant-absorbent working-fluid pair and thermal energy source to drive a heating and/or cooling cycle. | High | Available | 3.00 |
| Adsorption Heat Pump | Refrigerant vapor adheres to the surface (or within the structure) of specialized adsorbent materials. These materials release the vapor when heated to a high pressure and temperature, replacing a compressor in a heat-pump cycle. | Moderate | Available | 2.70 |
| Duplex-Stirling Heat Pump | Duplex-Stirling heat pumps compress and expand a gaseous refrigerant to produce space conditioning by oscillating the working fluid between two chambers. The work for the Stirling heat-pump cycle is provided by a piston shared with a Stirling engine. | N/A | R&D | 3.00 |
| Ejector Heat Pump | Ejectors accelerate and compress refrigerant using a secondary fluid pressurized by the additional of thermal energy. | Low | Emerging | 2.15 |
| Evaporative Liquid Desiccant A/C | Evaporative liquid desiccant air conditioners consist of a primary channel that dries and cools incoming air using a liquid desiccant stream and a secondary channel that evaporatively cools a water layer using a portion of the dried air, thereby further cooling the supply air. | Moderate | R&D | 3.90 |
| Ground-Coupled Solid Desiccant A/C | Ground-coupled solid desiccant A/C technology combines two technologies: ground-coupled fluid systems and solid desiccants. The primary stage first dries the supply air using a solid desiccant wheel and the secondary stage sensibly cools the air using a ground-coupled fluid loop. | High | R&D | 3.05 |
| Standalone Liquid Desiccant A/C | Desiccants are materials that have a high affinity for water, and can remove water from moist air when exposed to an airstream. In HVAC systems, liquid desiccant air conditioners (LDACs) absorb moisture from air to both dry and reduce the latent heat content of the incoming air, thereby cooling it. | Moderate | Emerging | 2.40 |

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|---------------------------------------|--|-----------------|--------------------|---------------|
| Standalone Solid Desiccant A/C | Standalone solid desiccant air conditioners dry incoming air with solid desiccant materials, thereby facilitating a secondary sensible cooling step accomplished with a different cooling technology. | Moderate | Available | 2.30 |
| Vuilleumier Heat Pump | Similar to Stirling heat pumps, the Vuilleumier heat pump cyclically compresses and expands a gaseous working fluid between different volumes to produce a hot and cold side. With a high-temperature heat source, such as a gas burner, the system can generate space heating and cooling as well as water heating. | Moderate | Emerging | 3.50 |

4 Observations

We identified a wide range of technology options having the potential to serve as alternatives to vapor-compression technologies in residential and commercial HVAC applications. This section:

- Compares the potential energy savings of each technology option
- Discusses general observations regarding the current state of development, cost/complexity, non-energy benefits, and disadvantages of each technology option.

4.1 Technical Energy Savings Potential

Figure 4-1 illustrates the technical energy savings potential, segmented by end use, of each of our 17 viable technology options. Appendix D describes the methodology that we used to calculate technical energy savings potentials, and Appendix F lists the specific assumptions made for each technology option.

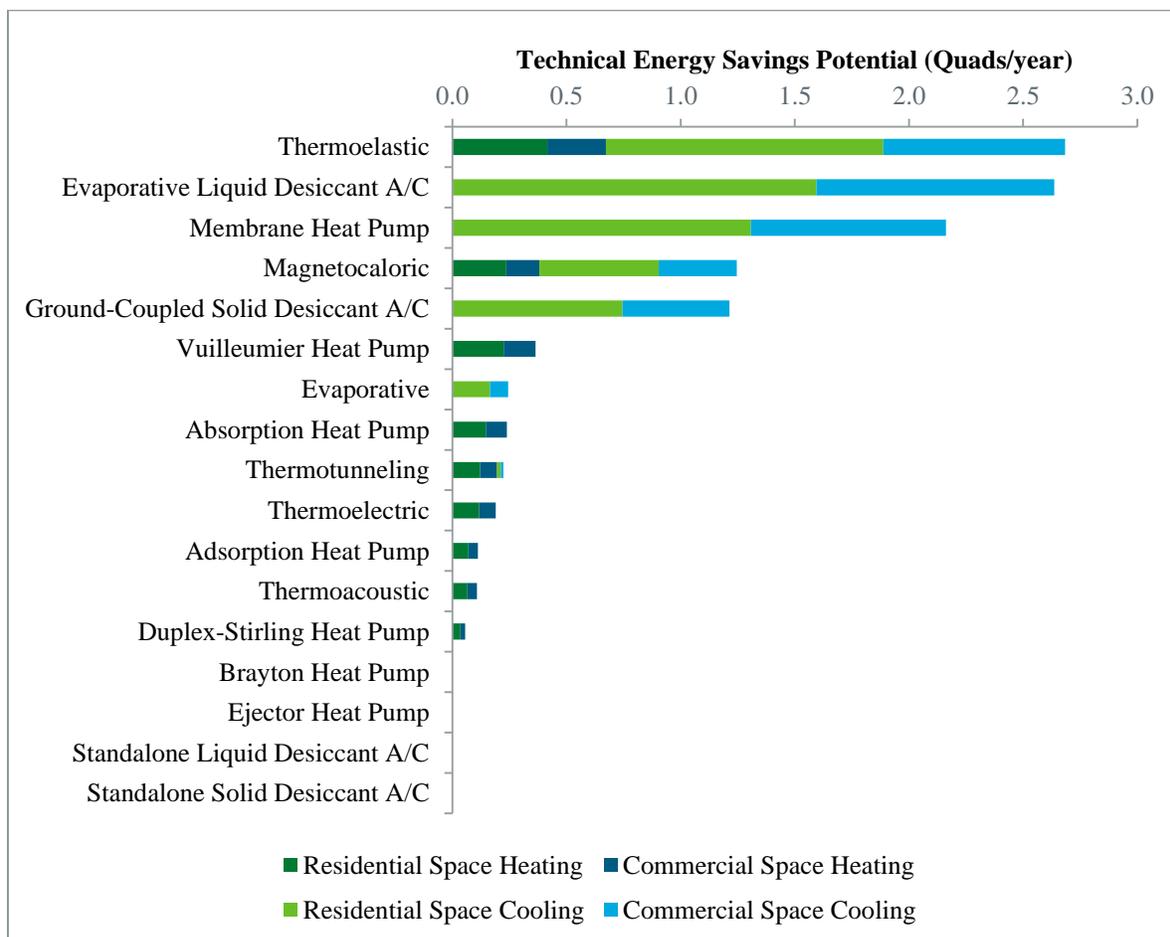


Figure 4-1: Comparison of technical energy savings potential (Quads/year)

Although many of these technology options can provide both space heating and space cooling, some options do not offer savings opportunities in one of these two operating modes. In many of these cases, the efficiency of the one operating mode may be sufficient to make up for the lack of savings in the other operating mode. However, as described in Appendix C, much of the research

done on the selected technology options has focused on space-cooling applications; therefore, space-heating performance is less certain. Consequently, as described in Section 2.5 and Appendix D, we estimated space-heating energy consumption for the thermoelectric, thermoacoustic, thermotunneling, and magnetocaloric technologies. Further investigation is needed to quantify their energy savings opportunities in space-heating applications.

Moreover, some of these technology options offer only marginal energy savings, if any, compared to current vapor-compression equipment. Future codes and standards are not expected to decrease their stringency in response to the scheduled HFC phase-down, so to meet standards, vapor-compression equipment will most likely compensate with higher efficiency components and designs. Because vapor-compression systems may experience cost increases due to these advanced components and designs, these non-vapor compression technologies may offer a cost advantage, but are not expected to gain an efficiency advantage due to the refrigerant regulations.

4.2 Supplementary Components for Vapor-Compression Systems

In addition to energy savings as a direct replacement to vapor compression, several of the non-vapor-compression technology options could offer potential savings if used as a subsystem in conventional vapor-compression systems. For example, some technology options can improve system efficiency by serving as an expansion device, auxiliary compressor, mechanical generator, or as a secondary cooling stage. Evaluating applications as subsystems to vapor-compression equipment was beyond the scope of this assignment. Appendix G contains additional information for these supplementary applications for future reference.

4.3 Development Status

Table 4-1 summarizes the development status of our 17 viable technologies, which are fairly evenly split among the R&D, emerging, and commercialized stages.

Table 4-1: Technology Option Development Status

| Development Status | Technology Options |
|--|---|
| R&D | Brayton-Cycle Heat Pump* Duplex-Stirling Heat Pump Evaporative Liquid Desiccant A/C Ground-Coupled Solid Desiccant A/C* Thermoacoustic Thermoelastic Thermoelectric* Thermotunneling |
| Emerging Technology | Ejector Heat Pump Magnetocaloric Membrane Heat Pump Standalone Liquid Desiccant A/C Vuilleumier Heat Pump |
| Commercially Available | Absorption Heat Pump Adsorption Heat Pump Evaporative Cooling Standalone Solid Desiccant A/C |
| * These technologies are commercially available either as supplements to vapor-compression technology or as the core technology in non-HVAC applications; however, their application as complete HVAC systems is still in the R&D stage. | |

4.4 Cost, Size, and Complexity

For technology options not yet widely available, estimating the initial cost, size, and complexity poses some challenges:

- Technology developers often do not substantiate their cost (and performance) claims, and there are often few publicly available, independent, detailed examinations.
- Uncertainties in cost associated with the current development status of the technology.

In most cases, we evaluated cost and complexity qualitatively, considering the incremental first cost and the added complexity associated with installation, operation, and maintenance for the technology option compared to conventional technology.

Developers of technology options in R&D stages often project costs based on large economies of scale and mature manufacturing techniques. However, because such technology options still require significant materials-science improvements and performance breakthroughs, these cost projections may be highly uncertain. Nevertheless, some of these immature technology options may have lower equipment complexity compared to vapor compression because they have fewer moving parts, potentially lowering cost, reducing maintenance requirements, and providing higher reliability.

Table 4-2 categorizes estimated cost and complexity for the technology options that are beyond early-stage R&D. For most of the technology options, potential energy savings impacts (and even upfront costs) vary widely depending on the specific building type, size, location, existing HVAC systems, etc. Even with this uncertainty, these technology options can likely provide significant energy savings with relatively favorable economics for a variety of applications, especially where HVAC loads are high.

Table 4-2: Estimated Cost and Complexity for Technology Options beyond Early-Stage R&D

| Category* | Technology Options |
|--|---|
| Low Cost/Complexity | Ejector Heat Pump Evaporative Cooling |
| Moderate Cost/Complexity | Adsorption Heat Pump Brayton Heat Pump Evaporative Liquid Desiccant A/C Membrane Heat Pump Standalone Liquid Desiccant A/C Standalone Solid Desiccant A/C Thermoacoustic Thermoelastic Thermoelectric Thermotunneling Vuilleumier Heat Pump |
| High Cost/Complexity | Absorption Heat Pump Duplex-Stirling Heat Pump Magnetocaloric Ground-Coupled Solid Desiccant A/C |
| * These cost categories represent our projection for the representative installed cost and system complexity of each technology option as cited in the literature and by expert sources. They are expressed as Low, Moderate, and High relative to vapor-compression systems. Cost assessment focuses on intrinsic cost barriers, while complexity assessment considers the number of components, the necessity of a secondary heat transfer loop for unitary applications, etc. | |

4.5 Non-Energy Benefits

In addition to reducing energy consumption, many of the analyzed technology options feature other non-energy benefits. Table 4-3 summarizes the non-energy benefits of these technology options. These additional benefits provide both qualitative and quantitative value to building owners and occupants. In some instances, the additional benefits offered by these technology options (e.g., improved occupant comfort, extended equipment life) may be as important as, or more important than, HVAC energy savings to end users. Two of the benefits considered in Table 4-3 are related to energy consumption (peak-demand reduction and ability to utilize low-temperature thermal sources), but are not necessarily linked directly to the energy savings offered by a technology. A technology may have potential for peak-demand reduction even if it does not provide source energy savings. For example, a gas-fired technology option that is less

efficient than vapor compression will still reduce electricity demand, even though it does not reduce overall source energy consumption. Similarly, a technology that exhibits a lower thermal COP than a vapor-compression system could result in lower source energy consumption and/or operating costs by utilizing available low-grade heating sources, such as waste or solar heat.

Table 4-3: Non-Energy Benefits of Technology Options (Compared to Vapor Compression)

| Technology Option | Non-Energy Benefits | | | | | | | |
|------------------------------------|---------------------------------|--|--------------------------------------|-----------------|-------------------------------------|--------------------------------------|---|-------------------------|
| | Opportunity for Novel Packaging | Ability to Utilize Low-Temperature Thermal Sources | Improved Comfort/Indoor Air Quality* | Noise Reduction | Well-Suited to Proportional Control | Implementation in Novel Applications | Improved Reliability and/or Maintainability | Peak Demand Reduction** |
| Absorption Heat Pump | | ✓ | | | | | | ✓ |
| Adsorption Heat Pump | | ✓ | | | | | | ✓ |
| Brayton Heat Pump | | | | | | | ✓ | |
| Duplex-Stirling Heat Pump | | | | | | | ✓ | ✓ |
| Ejector Heat Pump | | ✓ | | | | | ✓ | ✓ |
| Evaporative Cooling | | | | | | | | ✓ |
| Evaporative Liquid Desiccant A/C | | ✓ | ✓ | | | | | ✓ |
| Ground-Coupled Solid Desiccant A/C | | ✓ | ✓ | | | | | ✓ |
| Magnetocaloric | | | | ✓ | | | | |
| Membrane Heat Pump | | | ✓ | | | | | ✓ |
| Standalone Liquid Desiccant A/C | | ✓ | ✓ | ✓ | | | | ✓ |
| Standalone Solid Desiccant A/C | | ✓ | ✓ | | | | | ✓ |
| Thermoacoustic | | | | | ✓ | | ✓ | |
| Thermoelastic | | | | | | | | |
| Thermoelectric | ✓ | | | ✓ | | ✓ | ✓ | |
| Thermotunneling | ✓ | | | ✓ | | | | |
| Vuilleumier Heat Pump | | | | | | | ✓ | ✓ |

Note: A check mark (✓) designates the technology option offers the specific non-energy benefit.

* Improved comfort and indoor air quality can also refer to the ability of a technology option to independently control temperature and humidity.

** Potential for peak-demand reduction refers to the ability of a technology option to substantially use less electricity during peak-demand hours beyond incremental efficiency improvements. The technologies that we identified as having peak demand reduction potential either use natural gas (or other fossil fuels) as their primary fuel source or provide electricity savings of over 50%.

4.6 Potential Disadvantages

Vapor-compression technology has achieved widespread adoption in HVAC applications because it is efficient, compact, reliable, well-understood, and safe. Although the alternative technology options examined in this report have the advantage of utilizing low-GWP working fluids (or no working fluids), some have other characteristics, such as increased noise or safety risks, that might negatively impact their acceptance by end users. Because some of these technology options have lower efficiencies than current vapor-compression equipment, these alternative technology options may still have a higher net impact on GHG emissions due to their indirect impacts (i.e., increased electricity consumption and the associated emissions from electricity generation, transmission, and distribution). The potential disadvantages of the analyzed technology options are summarized in Table 4-4.

Table 4-4: Potential Disadvantages of Technology Options (Compared to Vapor Compression)

| Technology Option | Disadvantages | | | | |
|------------------------------------|------------------------------|-------------------------------------|-----------------------------------|-----------------------|--|
| | Increased Energy Consumption | Increased On-Site Water Consumption | Reliability and Maintenance Risks | Low Manufacturability | Low Applicability to All Climate Zones |
| Absorption Heat Pump | | | ✓ | | |
| Adsorption Heat Pump | | | | | |
| Brayton Heat Pump | ✓ | | | | |
| Duplex-Stirling Heat Pump | | | | | |
| Ejector Heat Pump | ✓ | | | | |
| Evaporative Cooling | | ✓ | ✓ | | ✓ |
| Evaporative Liquid Desiccant A/C | | ✓ | ✓ | | |
| Ground-Coupled Solid Desiccant A/C | | | | | ✓ |
| Magnetocaloric | | | | | |
| Membrane Heat Pump | | ✓ | | | |
| Standalone Liquid Desiccant A/C | ✓ | ✓ | ✓ | | ✓ |
| Standalone Solid Desiccant A/C | ✓ | | | | ✓ |
| Thermoacoustic | | | | | |
| Thermoelastic | | | ✓ | | |
| Thermoelectric | | | | | |
| Thermotunneling | | | | ✓ | |
| Vuilleumier Heat Pump | | | | | |

5 Summary of Results

5.1 Final Ranking of Technology Options

Based in part on the characteristics described in the above sections, we scored and ranked the 17 technology options using the scoring criteria introduced in Section 2.7. Figure 5-1 presents the overall final score for each technology, while Table 5-1 contains the detailed scoring results. These scores reflect our current understanding of the technology options based on available information and judgment. Because of the high degree of uncertainty in technologies under development, these scores are not a precise and absolute determination for any technology option. Instead, this scoring and ranking process generally indicates which non-vapor-compression technology options appear to provide the greatest potential for space-heating and space-cooling applications. In general, technology options scoring near the top of the list offer higher potential energy savings and higher probability of success if supported through R&D initiatives. However, lower-ranking technology options are still relevant for consideration because although their savings may be modest today, additional R&D could advance their efficiency and performance beyond current limitations.

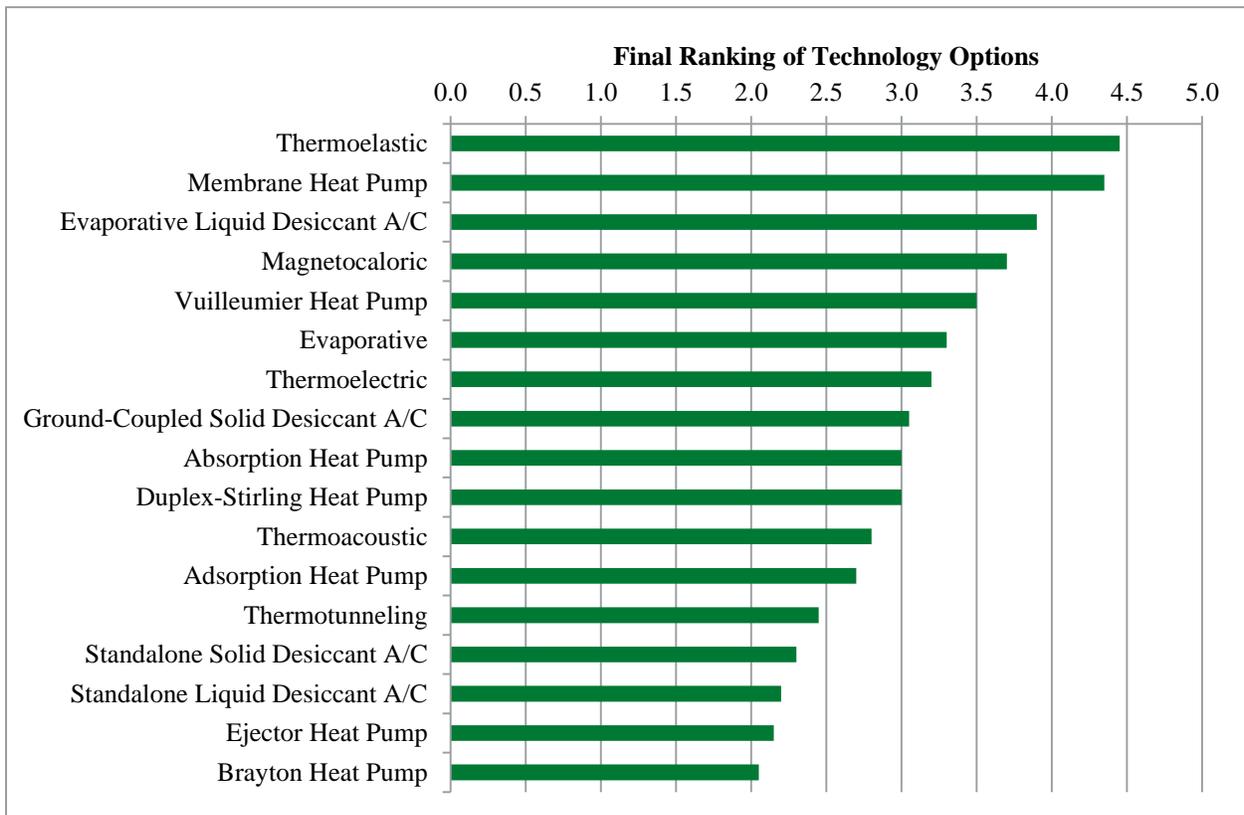


Figure 5-1: Final ranking of technology options

Table 5-1: Scoring Results for Technology Options

| Technology Name | Technical Energy Savings Potential (35%) | Fit with BTO Mission (30%) | Other Non-Energy Benefits (20%) | Cost/Complexity (15%) | Overall Score |
|------------------------------------|--|----------------------------|---------------------------------|-----------------------|---------------|
| Thermoelastic | 5 | 5 | 3 | 4 | 4.45 |
| Membrane Heat Pump | 5 | 4 | 4 | 4 | 4.35 |
| Evaporative Liquid Desiccant A/C | 5 | 4 | 4 | 1 | 3.90 |
| Magnetocaloric | 4 | 4 | 4 | 2 | 3.70 |
| Vuilleumier Heat Pump | 3 | 4 | 4 | 3 | 3.50 |
| Evaporative Cooling | 2 | 4 | 4 | 4 | 3.30 |
| Thermoelectric | 2 | 3 | 5 | 4 | 3.20 |
| Ground-Coupled Solid Desiccant A/C | 4 | 3 | 3 | 1 | 3.05 |
| Absorption Heat Pump | 2 | 4 | 4 | 2 | 3.00 |
| Duplex-Stirling Heat Pump | 2 | 4 | 4 | 2 | 3.00 |
| Thermoacoustic | 2 | 3 | 3 | 4 | 2.80 |
| Adsorption Heat Pump | 2 | 3 | 4 | 2 | 2.70 |
| Thermotunneling | 2 | 1 | 5 | 3 | 2.45 |
| Standalone Solid Desiccant A/C | 1 | 3 | 3 | 3 | 2.30 |
| Standalone Liquid Desiccant A/C | 1 | 3 | 4 | 1 | 2.20 |
| Ejector Heat Pump | 1 | 3 | 3 | 2 | 2.15 |
| Brayton Heat Pump | 1 | 2 | 4 | 2 | 2.05 |

Note: we evaluated the desiccant and evaporative technologies as standalone air conditioning systems, not as supplements to vapor compression or other technologies.

Based on these rankings, we have classified these 17 technology options into four categories: Most Promising, Very Promising, Moderately Promising, and Least Promising, as outlined in Table 5-2. We identified the two technology options with overall scores over 4 as the “Most Promising” alternatives to vapor compression because they may exhibit substantial potential for energy savings, offer significant non-energy benefits, are not projected to be significantly more expensive or complex, and/or fit very well with the BTO mission. We identified four technology options with overall scores of 3.5 or greater as “Very Promising” alternatives because they exhibit moderate-to-high energy savings, offer significant non-energy benefits, and/or fit will with the BTO mission. The seven technology options that we classified as “Moderately

Promising” offer low-to-moderate energy savings potential or other benefits compared to vapor compression; however, these scores reflect the current status of these technology options, and may become more attractive as further development improves their performance. Finally, we identified four technology options as “Least Promising” alternatives because they offer zero energy savings compared to vapor compression. These technology options may offer cost savings in certain instances, but are not projected to provide source energy savings.

Table 5-2: Categorization of Technology Options

| Most Promising | Very Promising | Moderately Promising | Least Promising |
|---|---|---|---|
| <ul style="list-style-type: none"> • Membrane Heat Pump • Thermoelastic | <ul style="list-style-type: none"> • Evaporative Liquid Desiccant A/C¹ • Magnetocaloric • Vuilleumier Heat Pump | <ul style="list-style-type: none"> • Evaporative Cooling¹ • Thermoelectric • Ground-Coupled Solid Desiccant A/C¹ • Absorption Heat Pump • Duplex-Stirling Heat Pump • Thermoacoustic • Adsorption Heat Pump • Thermotunneling | <ul style="list-style-type: none"> • Standalone Solid Desiccant A/C¹ • Standalone Liquid Desiccant A/C¹ • Ejector Heat Pump • Brayton Heat Pump |

¹ We evaluated the desiccant and evaporative technologies as standalone air-conditioning systems, not as supplements to vapor compression or other technologies.

5.2 Early-Stage Technology Options

As mentioned in Section 2.3, we also identified three early-stage technology options: the Bernoulli heat pump, critical-flow refrigeration cycle, and the electrocaloric heat pump. We did not fully analyze these technology options due to the limited publicly available information on their cost and performance characteristics. However, it is possible that these technologies may exhibit opportunities for energy savings and other benefits as they are developed further.

5.3 Summary of Observations

The key findings from these analyses are:

- We identified 20 technologies that are potential alternatives to vapor compression in space-heating and space-cooling applications.
- Of these 20 technology options, three are in very early stages of development, with very little information publicly available, so we could not evaluate them. The remaining 17 technology options are in various stages of development, ranging from early prototype development to those that have been commercialized for decades.
- Most of these technologies offer at least some potential for source energy savings compared to current vapor-compression equipment. Many of them also offer other attractive benefits compared to vapor compression, including reduced cost or complexity, increased reliability, improved indoor air quality, ability to utilize low-temperature thermal sources, and potential for peak-demand reduction, among others.

- Many of the technology options also have several disadvantages compared to current vapor-compression equipment, including higher cost and/or complexity, increased reliability and maintenance risks, limited applicability for certain climate zones, and others. Some of these attributes can be resolved through additional development, while others are intrinsic issues for the technology.

6 Recommendations

Based on our review of the technology options identified in this study, we recommend the RD&D initiatives outlined in this section if non-vapor-compression technology is deemed to merit further support when balanced against other potential RD&D priorities. We classified each initiative into a priority segment based on the final technology categorizations in Table 5-2 and the initiative's alignment with the BTO's research mission. Because several of the "Very Promising" and "Moderately Promising" technology options outlined in Section 5 require additional material advances to establish their potential for energy savings in space-conditioning applications, we classify these activities as long-term initiatives. We also include recommended initiatives, where applicable, for the technology options that we have classified as "Least Promising" because it is possible that further development of these technologies will reveal greater potential for energy savings.

6.1 Highest-Priority RD&D Initiatives

1. *Develop and test prototypes of membrane heat pumps and thermoelastic systems.*

These technology options have demonstrated potentially large source energy savings in limited testing, but require additional investigation at system capacities and operating conditions more relevant to HVAC applications. We recommend the development of larger (approx. 1–3 tons for thermoelastic and 5 tons for membrane heat pumps) and more complete prototypes, complete with auxiliary components, and performance test prototypes under conditions more representative of HVAC products. In addition, we recommend accelerated life testing to establish the longevity of the core membrane and thermoelastic materials. If results are favorable, develop and test larger, more production-ready prototypes in a variety of conditions to ascertain their applicability in various climate regions and capture the interest of potential manufacturing partners.

6.2 Moderate-to-High-Priority RD&D Initiatives

1. *Develop pre-production designs and evaluate manufacturing cost of evaporative liquid desiccant A/C.*

Computer simulations and testing of breadboard components have revealed that evaporative liquid desiccant A/C offers significant potential for energy savings. However, researchers have not yet developed design concepts that are suitable for large-scale manufacturing, which are needed to understand better the likely manufacturing costs, reliability, and maintenance requirements. We therefore recommend the development of production-oriented design concepts for evaporative liquid desiccant A/C technologies. If results are favorable, continue development with larger, more production-ready designs that would interest potential manufacturing partners.

2. *Develop and test demonstration prototype of Vuilleumier heat pump.*

For residential and light-commercial markets, Vuilleumier heat pumps could offer the potential of a gas-fired, reversible heat pump without the toxicity and flammability issues of current ammonia-based absorption systems. Although current analytical research and modeling suggest high COPs, additional investigation is required to understand the operation, performance, and

efficiency of Vuilleumier heat pumps in space-heating, space-cooling, and water-heating modes. We recommend developing and testing a residential-sized prototype (3–5 tons) with a complete set of auxiliary components, to:

- Measure efficiency and overall performance in the various operating modes; and
 - Improve packaging of the core heat pump and auxiliary components.
3. ***Develop cost-effective gas-fired heat pumps for heating-only or reversible operation, including integrating space-conditioning and water-heating capabilities.***
Applicable Technology Options: Absorption Heat Pump, Adsorption Heat Pump, Thermoacoustic, Vuilleumier Heat Pump

For residential and light-commercial applications, several gas-fired heat-pump technologies could offer significant efficiency improvements and large peak-demand reductions in heating-mode, but have not gained wider acceptance due to their high first cost relative to vapor-compression systems. Especially for northern U.S. regions, gas-fired heat pumps designed primarily for heating mode could greatly reduce source energy consumption compared to vapor-compression and other gas-fired heating technologies. For reversible heat pumps, increased consumption in the cooling mode could be offset by heating-mode savings, in addition to any cost savings from operating with natural gas. We recommend the development of cost-effective and reliable gas-fired heat pumps primarily designed for residential and light-commercial applications. Additionally, we recommend developing gas-fired heat pumps that can satisfy water-heating loads in addition to space-heating and/or space-cooling loads to provide additional energy savings and further improve system economics.

4. ***Develop high-efficiency regenerating components for liquid desiccant air conditioners.***
Applicable Technology Options: Evaporative Liquid Desiccant A/C, Standalone Liquid Desiccant A/C

The low efficiency of current standalone liquid desiccant air conditioners (LDACs) is in large part attributable to the low COPs of the single-effect regenerators that have been used in LDAC prototypes developed thus far. Because regenerators are also used in evaporative LDACs, advancements in this component technology could benefit multiple technology options at once. We recommend the development of multiple-effect regenerators and reevaluation of the potential of LDAC once cost and performance of high-COP regenerators is better understood.

5. ***Develop cost-effective, compact heat exchangers to transfer heat to and from solid-state modules without requiring large temperature differences.***
Applicable Technology Options: Electrocaloric, Magnetocaloric, Thermoelectric, Thermotunneling

The limited heat-transfer surfaces available in many solid-state technology options present a barrier to efficient operation in space-conditioning applications. Efficient and cost-effective space conditioning requires close temperature approaches with solid-state heat sinks and sources. Achieving low temperature approaches, however, tends to require significant parasitic energy

consumption (e.g., by fans or blowers), which reduce efficiency gains. We recommend the development of innovative heat-exchanger designs that will reduce the cost, size, and parasitic energy consumption of magnetocaloric, thermoelectric, thermotunneling, and electrocaloric space-conditioning technologies.

6.3 Moderate-Priority RD&D Initiatives

1. *Support field testing and modeling to prove the performance of advanced evaporative cooling technologies.*

Advanced evaporative cooling technologies have been commercialized for many years, and offer substantial potential for energy savings in hot-dry climate zones. However, they are often not capable of meeting relative-humidity requirements during certain periods, even in hot-dry climates. Their inability to dehumidify is an inherent characteristic of the technology and therefore cannot be resolved through further RD&D. However, they can be supplemented with dehumidification technologies (as is the case with evaporative liquid desiccant air conditioners) or used by consumers in hot-dry regions who are willing to endure humid indoor conditions for a few weeks of the year. In either case, evaporative cooling technologies face significant market barriers, including the poor reputation of their direct evaporative predecessors (associated with performance, comfort, and maintenance issues) and a limited understanding on the part of consumers of the energy performance, water consumption, and water-quality requirements associated with evaporative cooling. We recommend conducting field tests and simulations for a wide range of operating conditions that will reveal the energy benefits of evaporative coolers to raise awareness about these technologies, and help to counteract their poor perception by the public. Field tests will also help to quantify water consumption water-quality requirements, and maintenance requirements.

2. *Construct laboratory prototypes of ground-coupled solid desiccant air conditioners at modest capacities and evaluate performance at a variety of test conditions.*

Although researchers have achieved promising results for ground-coupled solid desiccant air conditioners through small-scale testing, they have been unable to maintain high efficiency as test conditions vary. We recommend developing and testing modified prototypes and evaluating their ability to maintain consistent energy performance while providing acceptable space cooling across a variety of conditions. These steps will a) help to identify whether ground-coupled solid desiccant air conditioning can reliably offer energy savings compared to vapor compression, and b) signal where to redirect resources to resolve key issues. We recommend the development of 1–5 ton prototypes for ground-coupled solid desiccant air conditioners to quantify the efficiency of the cycles, recognize additional developmental requirements, and better assess their future potential. If results are favorable, further work may be warranted to develop and test larger, more production-ready designs that would interest potential manufacturing partners.

3. *Develop prototypes using selected technology options and test in space-heating mode to assess their applicability to and efficiency in space-heating applications.*

Applicable Technology Options: Magnetocaloric, Thermoacoustic, Thermoelastic, Thermoelectric, Thermotunneling

Although the magnetocaloric, thermoacoustic, thermoelastic, thermoelectric, and thermotunneling technology options are theoretically applicable to space heating as well as space cooling, there is a paucity of information about their performance in space-heating applications. We recommend developing and testing prototypes in space-heating applications to evaluate whether these technology options offer opportunities for overall space-conditioning energy savings, even if they do not offer savings for space cooling alone. We recommend that this include measuring efficiencies and identifying additional developmental requirements to better assess their potential.

4. *Support development of alternative component designs that improve the size, weight, and/or cost of absorption heat pumps.*

Absorption heat pumps are a well-understood technology option with low-GWP working fluids (water/ammonia, LiBr/water), but they have not been widely commercialized in the residential and light-commercial sectors due to both working fluid issues (e.g., toxicity, flammability, etc.) and physical, non-energy characteristics (e.g., size, weight, cost, and complexity). Improving the design of the absorber, generator, condenser, and other components could lead to smaller and potentially less expensive absorption systems. Even without additional advances in cooling COPs, reversible or heat-only absorption systems could achieve greater market success and national energy savings in heating-mode by lowering their upfront cost. We recommend development efforts that enhance fluid and heat transfer throughout absorption systems as a means of reducing size, weight, cost, and complexity.

5. *Support development of alternative adsorption heat-pump designs.*

Despite using non-toxic and low-GWP working fluids, adsorption heat pumps have garnered limited manufacturer and consumer interest due to the high incremental cost and lack of energy savings compared to vapor compression. Operating two or more adsorption beds in a cyclical process (per current practice) inherently increases the complexity, size, and weight of an adsorption heat pump compared to a continuous-flow process. Operating in a more continuous process with more rapid adsorption bed cycles, or using adsorbent materials with higher thermal densities, could potentially lower the size, weight, and/or cost of an adsorption system. We recommend the development of adsorption heat pumps utilizing advanced methods for heat and mass transfer (for more rapid bed cycling), adsorbent materials with high thermal density, compact adsorption beds, and other concepts.

6.4 Long-Term and Low-Effort RD&D Initiatives

1. *Monitor the development of advanced materials for solid-state heat-pump cycles.*
Applicable Technology Options: Magnetocaloric, Thermoelectric, Thermotunneling

The low efficiency of current solid-state cooling/heat-pump devices, especially at temperature differences relevant to space conditioning, has limited the adoption of existing solid-state cooling systems (i.e., thermoelectric systems) to non-HVAC cooling applications such as spot cooling/heating and low-load refrigeration. We recommend monitoring current R&D efforts for these technology options that are improving thermal performance through advances in basic material science, nano-scale engineering, and control mechanisms. Because some solid-state

technologies are of substantial interest for heat-to-power applications, we also recommend monitoring efforts in these applications. If researchers identify new materials that offer significant efficiency improvements at large temperature differences, we recommend reevaluating these technology options for HVAC applications.

6.5 Initiatives for Early-Stage Technology Options

In recent years, researchers have demonstrated several alternative cooling cycles (including the Bernoulli heat pump, critical-flow refrigeration cycle, and electrocaloric technology, which are summarized in Appendix B) through laboratory experimentation, but at capacities, and achieving efficiencies, much lower than needed for space-conditioning applications. These initial results demonstrate the technology option's capability to generate below-ambient temperatures, and, along with supporting theoretical analyses, suggest the potential for high efficiency in space-conditioning applications. We recommend monitoring their development and, if results are promising for HVAC applications, support further investigation into characterizing the fundamental fluid and material interactions behind these novel cycles. The goals of these research efforts would be to increase the understanding of their operation, develop analytical models, and then conduct a parametric study with the model to identify promising areas of further development.

6.6 Initiatives to Supplement Vapor-Compression Systems

During the course of this study, we identified some technology options that can enhance the performance of conventional vapor-compression systems. Although evaluating applications as subsystems to vapor-compression equipment was beyond the scope of this assignment, we summarized these opportunities in Appendix G for future reference. We recommend evaluating the potential for these component technologies through analytical modeling and laboratory investigation. If initial findings are promising, these components could be integrated into demonstration prototypes for further testing in vapor-compression systems.

References

Abdelaziz et al. 2013. “Technology Prioritization: Transforming the U.S. Building Stock to Embrace Energy Efficiency.” Cleantech Conference & Showcase 2013. TechConnect World. U.S. Department of Energy. May 2013.

ARTI. 2010. “Review of Regulations and Standards for the Use of Refrigerants with GWP Values Less than 20 in HVAC&R Applications.” Air Conditioning and Refrigeration Technology Institute. ARTI Report No. 09001–01. April 2010.

ASHRAE. 2010. “Designation and Safety Classifications of Refrigerants.” ANSI/ASHRAE Standard 34–2010.

ASHRAE. 2013. “Energy Standard for Buildings Except Low-Rise Residential Buildings.” ANSI/ASHRAE/IES Standard 90.1–2013.

DOE. 2004. “Energy Conservation Program for Consumer Products; Central Air Conditioners and Heat Pumps Energy Conservation Standards.” U.S. Department of Energy. 69 FR 50997. August 17, 2004.

DOE. 2012. “Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment.” U.S. Department of Energy. 77 FR 71340. May 16, 2012.

European Commission. 2013. “European Commissioner Connie Hedegaard Welcomes Major Step Forward to Reduce Some of the Most Dangerous Greenhouse Gases.” Memo. December 18, 2013.

Farese et al. 2012. “A Tool to Prioritize Energy Efficiency Investments.” National Renewable Energy Laboratory. August 2012.

Goetzler et al. 2011a. “Energy Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems.” Prepared for U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program. September 2011.

Goetzler et al. 2011b. “Research and Development Roadmap for Next-Generation Low-GWP Refrigerants.” Prepared for UT-Battelle, LLC – Oak Ridge National Laboratory, Subcontract Number 4000093134. June 13, 2011.

Goetzler et al., 2012. “Energy Savings Potential and RD&D Opportunities for Residential Building HVAC Systems.” Prepared for U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office. September 2012.

Leck et al. 2011. “Performance of Novel Low GWP Refrigerants for AC and Heating.” International Conference on Air-Conditioning & Refrigeration. July 2011.

Prioritization Tool. 2013. Currently under development by U.S. Department of Energy, Building Technologies Office. Accessed December 2013.

UNEP. 2011. "2010 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee." United Nations Environment Programme. Montreal Protocol on Substances that Deplete the Ozone Layer. February 2011.

UNEP. 2013. "Proposed Amendment to the Montreal Protocol Submitted by Canada, Mexico and the United States of America." April 18, 2013. Open Ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. Thirty-Third Meeting. June 2013.

Appendix A Abridged Analyses for Screened Technology Options

As discussed in Section 2.2, we screened two technology options from further analysis because they presented issues of practicality, scope, or feasibility that we deemed insurmountable barriers to potential investigation by DOE. This appendix consists of abridged analyses for the vortex tube cooling cycle, and pulse tube refrigeration cycle, and includes a description of each technology, its development status, and its potential applications.

A.1 Pulse-Tube Refrigeration

| | |
|--------------------------|---|
| Brief Description | Pulse-tube refrigerators compress and expand a working fluid in a linear tube to provide cooling, particularly at low temperatures. |
|--------------------------|---|

| Technology Characteristics | Value | Comments |
|---|-------------|---|
| Unit Energy Savings | 0% | <ul style="list-style-type: none"> No information available for HVAC applications For cryocooling applications, COPs ranging from 0.01 (Wang 2007) to 0.10 (Unger and Wood 2000). |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | Helium | |
| Complexity/Size | Moderate | <ul style="list-style-type: none"> Similar to other cryocoolers e.g., Stirling Requires secondary loop to deliver cooling |
| Projected Cost | Moderate | Similar to other cryocoolers e.g., Stirling |
| Threshold Attributes | Moderate | No moving parts in cold section resulting in high reliability, and low vibration |
| Excitement Attributes | Moderate | Reaches very low temperatures (4–100 K) |
| Ability to Utilize Low-Temperature Thermal Sources | N/A | |
| Technical Maturity | Moderate | <ul style="list-style-type: none"> Technology currently used for cryocooling applications Not developed for space conditioning |
| Market Maturity | Low | Not developed for space conditioning applications due to low cooling efficiency |
| Level of Stakeholder Support | Low | Stakeholders unlikely to support this technology based on its low applicability for building conditioning |
| Fit with BTO Mission | Low | Not a viable alternative for vapor-compression cooling systems. |

Background

Technology Description

Similar to the Stirling cycle, pulse-tube refrigerators cyclically compress and expand a gas, typically helium, within several enclosed chambers to produce a usable temperature gradient. A piston compresses the gas through the tube, raising its pressure, and directs it through an orifice and into a buffer reservoir, where it rejects heat to ambient. The piston then expands the gas back through the tube, lowering its temperature, and accepting heat from a heat exchanger to provide cooling. A secondary fluid then distributes this cooling to the application. A regenerator, made of a porous metal mesh, stores a portion of the thermal energy to pre-heat or pre-cool the gas throughout the cycle for improved efficiency. Systems can use multiple stages of pulse-tubes to

achieve lower temperatures. Figure A-1 provides a diagram of a simple pulse-tube refrigeration system.



Figure A-1: Schematic of a pulse-tube refrigerator

Source: Hooijkaas (2000)

Whereas a Stirling cooler utilizes a moving displacer, the pulse tube itself contains no moving parts, offering inherently high reliability and low vibration, which is attractive for cryocooling applications. Pulse-tube refrigerators can achieve very low temperatures (4–100 K) for cryocooling applications such as gas liquefaction, and the cooling of sensors, superconductors, medical specimens, etc. Nevertheless, pulse-tube refrigerators are not considered a viable alternative for space conditioning applications due to their low efficiencies. Limited performance information exists for temperatures relevant for HVAC applications, but Fischer and Labinov (2000) estimated system COPs of 0.39 for cooling and 0.88 for heating. For low-temperature and cryocooling applications, most systems range from 0.5–100W with a cooling COP ranging from 0.01 (Wang 2007) to 0.10 (Unger and Wood 2000).

Technical Maturity and Current Developmental Status

Pulse-tube refrigerators are currently available for cryocooling applications from several vendors including: Sumitomo, Thales Cryogenics, Cryomech, and others.

Barriers to Market Adoption

The low efficiencies of pulse-tube refrigerators are impractical for space conditioning applications.

Energy Savings Potential

Potential Market and Replacement Applications

Pulse-tube refrigerators are not replacements for current space conditioning systems.

Energy Savings

Pulse-tube refrigerators offer no energy savings compared to current vapor-compression systems, and there is little research into its potential for space conditioning applications.

Cost, Size, and Complexity

Pulse-tube refrigerators operate similarly to other cryocoolers, but are simpler and more reliable as they do not have moving parts within the cooler itself.

Peak-Demand Reduction and Other Non-Energy Benefits

Simple design with no moving parts in the core system, ability to maintain low temperatures.

References

Cao et al. 2009. "Theoretical and Experimental Study on a Pulse Tube Cryocooler Driven with a Linear Compressor." International Cryocooler Conference. 2009.

Cryomech. 2012. "Cryorefrigerator Specification Sheet – PT90 with CP950." Cryomech, Inc. October 10, 2012.

Fischer and Labinov. 2000. "Not-in-Kind Technologies for Residential and Commercial Unitary Equipment." Oak Ridge National Laboratory. February 2000.

Hooikaas, H. 2000. "Miniature Stirling-Type Pulse-Tube Refrigerators." Eindhoven University of Technology. June 13, 2000.

Hu et al. 2007. "A Thermoacoustically Driven Two-Stage Pulse Tube Cryocooler." International Cryocooler Conference. 2007.

Rawat, V. 2009. "Theoretical and Experimental Studies on Pulse Tube Refrigeration." National Institute of Technology Rourkela. May 2009.

SHI Cryogenics. 2008. "SRP-062B Pulse Tube 0.5W at 4.2K." Sumitomo Cryogenics of America, Inc. March 2008.

Unger and Wood. 2000. "Performance Comparison of M77 Stirling Cryocooler and Proposed Pulse Tube Cryocooler." Sunpower, Inc. Advances in Cryogenic Engineering, Volume 45. 2000.

Wang, C. 2007. "A Novel Three-Stage 4 K Pulse Tube Cryocooler." Cryomech, Inc. International Cryocooler Conference. 2007.

Wilson and Gredeon. 2004. "Status of Pulse Tube Cryocooler Development at Sunpower, Inc." International Cryocooler Conference. 2004.

A.2 Vortex-Tube Cooling

| | |
|--------------------------|---|
| Brief Description | Vortex tubes separate compressed air into hot and cold airstreams for process cooling applications. |
|--------------------------|---|

| Technology Characteristics | Value | Comments |
|--|----------------|---|
| Unit Energy Savings | 0% | Cooling COP approx. 0.1 and less (Gao 2005) |
| Fuel Type(s) | N/A | Utilizes a compressed air source |
| Working Fluid(s) | Compressed air | |
| Complexity/Size | Low | |
| Projected Cost | Low | One to several hundred dollars for personal air conditioning vest and vortex tube |
| Threshold Attributes | Moderate | Compact, lightweight, adjustable |
| Excitement Attributes | Low | Personal cooling if compressed air available |
| Ability to Utilize Low-Temperature Thermal Sources | N/A | |
| Technical Maturity | High | Widely utilized throughout industrial processes and settings |
| Market Maturity | Moderate | If compressed air is available, inexpensive and convenient way to provide spot cooling to machines, electronics, and people |
| Level of Stakeholder Support | Low | Stakeholders unlikely to support this technology based on its low applicability for building conditioning |
| Fit with BTO Mission | Low | Not a viable alternative for vapor-compression cooling systems. |

Background

Technology Description

Vortex tube cooling cycle utilizes compressed air and several geometric features to generate separate hot and cold air streams that can provide usable heating and cooling. Originally characterized in the early 20th century, compressed air enters the vortex tube through a tangential nozzle and rotates down the tube at high RPM to produce a hot air stream at the tube walls and a cold air stream in the center. A nozzle at one end of the tube directs the hot outer airstream out of one side of the tube and directs the cool gas to the other end of the tube. The temperature difference between the incoming air and existing air streams can be +/-60°F or greater at 100 psig, and adjustable with inlet pressure and nozzle position. Figure A-2 provides a diagram of a vortex-tube cooler.

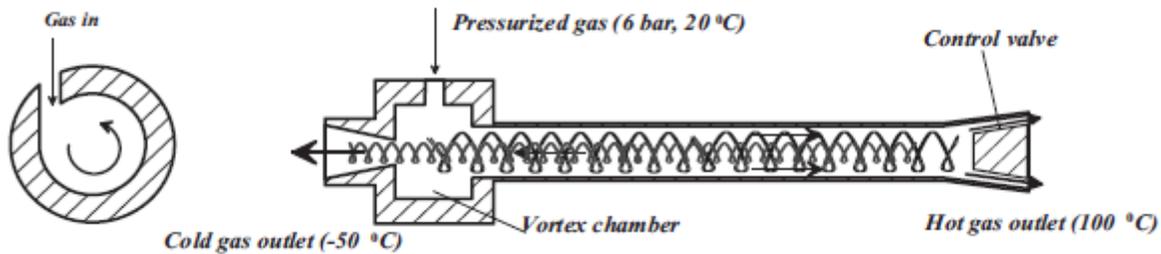


Figure A-2: Schematic of a vortex-tube cooler

Source: Gao (2005)

Due to their low efficiency, vortex tubes have limited application for space conditioning, except for specialized instances. Vortex tube COPs are typically below 0.1, which limit their application only for instances where conventional vapor-compression systems are impractical (Nellis and Klein 2002). For many industrial settings where compressed air is available, vortex tubes supply cold air on demand for spot cooling of machinery or electronics and personal cooling suits for workers in hazardous conditions, shown in Figure A-3. Additionally, vortex tube diameters must remain relatively small to function, so cooling capacity is restricted to fractional ton sizes.



Figure A-3: Personal air conditioning vests

Source: Vortec (2012)

Technical Maturity and Current Developmental Status

Vortex tubes are available for process applications from Vortec, Nex Flow, Exair and others. No products are available for building heating or cooling other than personal cooling vests that require a compressed air source.

Barriers to Market Adoption

Low efficiency and the need for a compressed air source limit the applicability for space-conditioning applications. Most buildings lack the infrastructure of a compressed air system, and a personal air compressor is too energy intensive to be portable for long periods.

Energy Efficiency Advantages

No advantages expected.

*Energy Savings Potential**Potential Market and Replacement Applications*

As mentioned previously, vortex-tube cooling is only relevant for building conditioning as a personal cooling mechanism where other methods are unavailable or impractical.

Energy Savings

As a primary cooling system, vortex tubes would provide no energy savings with COPs on the order of 0.1 and less (Gao 2005).

Some research has investigated the benefit of vortex tubes to recover a portion of throttling losses in R-744 vapor-compression cycles, similar to ejectors (Li et al. 2000). Findings in this area have been inconclusive thus far (Nellis and Klein 2002).

Cost and Complexity

Containing no moving parts (other than the compressed air source), vortex tubes are inherently simple, lightweight, and compact. The price for the vortex tubes and personal cooling vests range from one to several hundred dollars depending on capacity and air pressure.

Peak-Demand Reduction and Other Non-Energy Benefits

Convenient and simple way to provide personal cooling where compressed air is available.

References

Baker and Rothkamp. 1954. "Investigations of the Ranque-Hilsch (Vortex) Tube." Oak Ridge National Laboratory. September 16, 1954.

Exair. 2013. Exair Corporation. <http://www.exair.com/>

Gao, Chengming. 2005. "Experimental Study of the Ranque-Hilsch Vortex Tube." Eindhoven University of Technology. November 2005.

Li et al. 2000. "Thermodynamic Analysis of Vortex Tube and Work Output Devices for the Transcritical Carbon Dioxide Cycle." Preliminary Proceedings of the 4th IIR-Gustav Lorentzen Conference on Natural Working Fluids. 2000.

Nellis and Klein. 2002. "The Application of Vortex Tubes to Refrigeration Cycles." International Refrigeration and Air Conditioning Conference. July 2002.

Nex Flow. 2013. Nex Flow Air Products Corp. <http://www.nex-flow.com>

Sanu et al. 2012. "Performance Analysis of a Vortex Tube by Using Compressed Air." International Journal of Scientific & Engineering Research. Volume 3, Issue 9, September 2012.

Vortec. 2012. ITW Vortec. <http://www.vortec.com/default.aspx>

Appendix B Abridged Analyses for Early-Stage Technology Options

As discussed in Section 2.3, we performed an abridged analysis of 3 early-stage technology options for which there was a paucity of publicly available information. This appendix consists of abridged analyses for those 3 technology options at an early stage of its development, including:

- Bernoulli Heat Pump
- Critical-Flow Refrigeration Cycle
- Electrocaloric Heat Pump.

Each abridged analysis provides a description of each technology, its development status, and its potential applications.

B.1 Bernoulli Heat Pump

| | |
|--------------------------|---|
| Brief Description | Bernoulli heat pumps accelerate a working fluid through a converging-diverging nozzle to produce cooling across the nozzle throat. The technology utilizes a helium-based working fluid with no GWP or ODP. |
|--------------------------|---|

| Technology Characteristics | Value | Comments |
|--|-------------------------------------|--|
| Unit Energy Savings | N/A | Current proof-of-concept prototype has very low COP, but expected to improve in future iterations. |
| Fuel Type(s) | Electricity | Blower or motor to drive gaseous working fluid |
| Working Fluid(s) | Helium-based mixture of noble gases | |
| Complexity/Size | Moderate | Relatively simple design with potential for compact size |
| Projected Cost | Moderate | Component trade-offs exist that may result in lower equipment costs. |
| Threshold Attributes | Moderate | Noise, size, and weight should decrease by eliminating the need for a compressor. |
| Excitement Attributes | High | <ul style="list-style-type: none"> Utilizes natural working fluid Quieter operation |
| Ability to Utilize Low-Temperature Thermal Sources | N/A | |
| Technical Maturity | Low | Core technology has been demonstrated, but is far from a production-ready prototype. |
| Market Maturity | Low | Still in early-stage development with several years away from a production-ready prototype. |
| Level of Stakeholder Support | Moderate | We have not identified any reason that stakeholders would actively support or oppose the technology once fully developed |
| Fit with BTO Mission | Moderate-to-High | Demonstrated cooling cycle, but with additional development needed to compare with vapor-compression systems. |

Background

Technology Description

Bernoulli heat pumps accelerate a gaseous working fluid through a venturi nozzle to cause variations in temperature. Figure B-1 provides a simplified schematic of the principle. When entering the nozzle, the cross-sectional area of the working fluid decreases, and its velocity increases, while maintaining mass flow rate. The acceleration of the working fluid drives the energy conversion from random molecular motion (i.e., temperature and pressure) to directed flow (i.e., velocity) reduces the temperature and pressure of the working fluid, creating a usable

temperature gradient at the nozzle throat or apex. A secondary working fluid, such as an air or water, then rejects heat to the nozzle throat, before returning to the heat load.

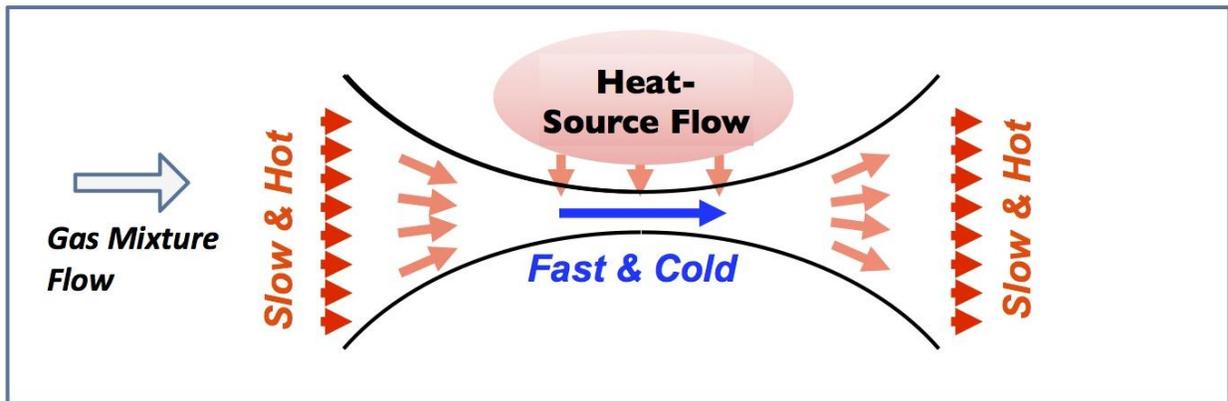


Figure B-1: Schematic of a Bernoulli cooling principle

Source: Machflow Energy Inc. (2013)

Bernoulli heat pumps use a working fluid comprised of several noble gases (e.g., helium with neon, krypton, xenon, etc.) as the mixtures product lower Prandtl numbers than an individual gas. Fluids with low Prandtl numbers transfer heat quickly relative to their velocity such that they exhibit greater capability for conduction rather than convection. Combining this attribute with a throat section made of conductive material (e.g., copper) results in rapid heat transfer across the nozzle throat, even as the working fluid reaches velocities approaching Mach 1.

Bernoulli heat pumps generate cooling as the working fluid accelerates through the venturi-shaped duct. Depending on the configuration, the system requires a blower to move the working fluid and/or a motor to rotate a number of nozzles. Capacity can be varied by modulating the flow rate of the working fluid, and can provide an additional capacity boost, at the expense of efficiency, by running at higher speeds. In addition to the venturi heat exchanger, a gas cooler rejects the excess heat of the working fluid to ambient before the gas returns to the venturi section. Figure B-2 illustrates the current design of a Bernoulli heat pump from Machflow Energy.

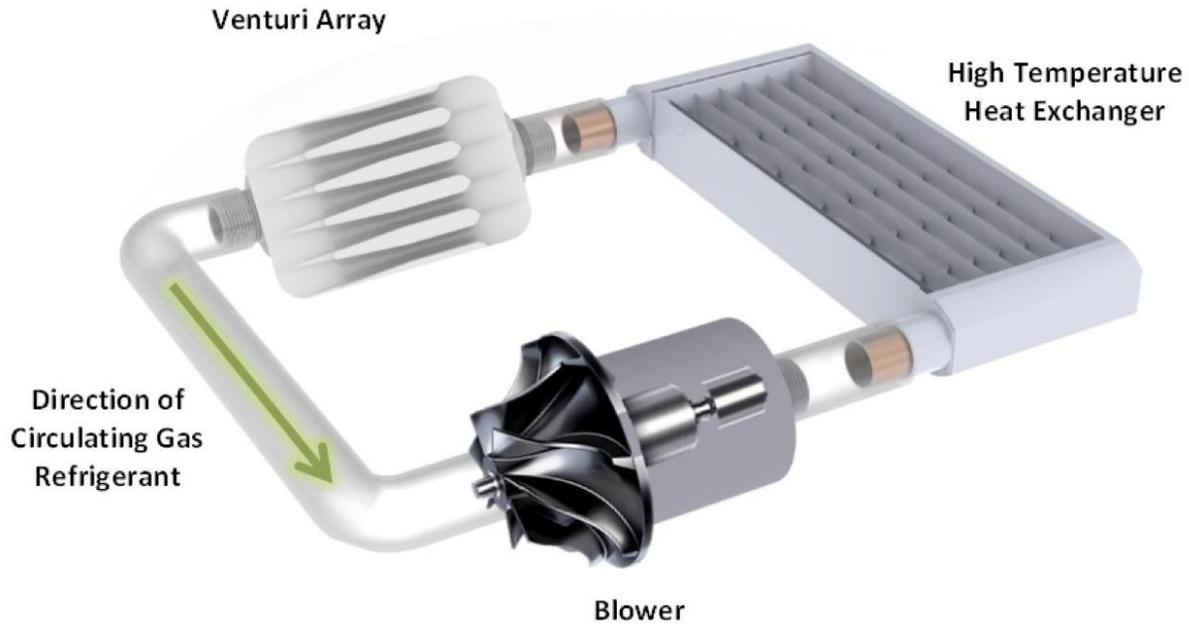


Figure B-2: Diagram of current Bernoulli heat pump system

Source: Machflow Energy Inc. (2013)

Technical Maturity and Current Developmental Status

Machflow Energy Inc., a small business associated with Clark University, produced a proof-of-concept prototype in 2011. The prototype successfully demonstrated the Bernoulli cooling cycle, producing approx. 5 W of cooling capacity, and identified numerous areas for future optimization. The next area of development will be to improve the micro-scale heat transfer between the working fluid and the nozzle section. The company has also filed several patents regarding this technology, and has received a Department of Energy grant to continue research in the area (Clark News Hub 2010).

Barriers to Market Adoption

The Bernoulli heat pump is an early-stage technology whose prospects for building cooling cannot be assessed without further product development. Scaling the technology to the capacities required for residential and commercial building applications is the largest challenge. At this scale, dozens of venturi nozzles would be required, and evenly distributing the working fluid through each will be challenging. Because of this scaling issue, the technology may first be deployed for electronics or battery cooling.

Energy Efficiency Advantages

The Bernoulli heat pump could achieve comparable cooling efficiency, in theory, without the use of HCFC or HFC refrigerants.

Energy Savings Potential

Potential Market and Replacement Applications

Because of the relatively simple design, the Bernoulli heat pump would be applicable for most vapor-compression cooling applications. The first applications would be expected to use air as a

secondary working fluid and more easily replace split- and packaged-system designs, rather than chillers.

Energy Savings

Prototypes to date have produced COPs on the order of 0.1, but the research team believes optimized designs could achieve COPs in the range of 2–3 in the near term, and higher efficiencies in the long term (Agosta 2013).

Compared to standard-efficiency A/C equipment, we estimate that Bernoulli heat pumps could achieve comparable performance and efficiency utilizing more benign working fluids. Actual achievable efficiency will depend on additional technology development and prototype design that includes parasitic loads to deliver the cooling to building occupants.

Cost and Complexity

The Bernoulli heat pump is expected to have comparable or favorable cost compared to vapor-compression systems, but additional product development is needed to make credible projections (Agosta, 2013). While the initial prototype used a Plexiglas venturi section, accurately manufacturing an array of venturis out of improved materials may be costly. The blower or motor would cost less than the compressor and expansion valve used in a VC system.

Peak-Demand Reduction and Other Non-Energy Benefits

Unless COP exceeds those of conventional systems, peak demand will not be affected. By utilizing benign refrigerants, direct GHG emissions would decrease as a result of refrigerant leakage. Equipment noise and weight should decrease due to the elimination of the compressor.

Next Steps for Technology Development

Continued research on Bernoulli heat pumps is needed to improve the micro-scale heat transfer in the nozzle section and develop a field-ready prototype with the capacity, performance, and efficiency on par with conventional systems.

Table B-1 presents the potential next steps to advance Bernoulli heat pumps.

Table B-1: Recommended Next Steps for the Development of Bernoulli Heat Pumps

| Initiatives |
|---|
| Perform basic research to improve heat transfer in the nozzle section |
| Develop methods to evenly distribute working fluid across an array of nozzles |
| Investigate methods to manufacture arrays of nozzles for higher capacities |
| Design a next-generation prototype with optimized components |

References

Agosta, Charles. 2013. CEO of Machflow Energy. Personal Communication with Jim Young of Navigant. October 25, 2013.

Clark News Hub. 2010. "Clark Physicist's Green Cooling Tech Startup Gets \$1M Stimulus Grant." Clark University. September 1, 2010. Retrieved from <http://news.clarku.edu/news/2010/09/01/clark-physicist%E2%80%99s-green-cooling-tech-startup-gets-1m-stimulus-grant/>.

Eckelbecker, Lisa. 2010. "Clark Business Gets \$1M Stimulus – Clark Business Researches Air Conditioning." Worcester Telegram & Gazette. August 31, 2010. Retrieved from <http://www.telegram.com/article/20100831/NEWS/8310335/1116>.

Machflow Energy, Inc. 2013. <http://www.machflow.com/>. Accessed November 4, 2013.

Magill, Bobby. 2012. "Why is there a Helium Shortage?" Popular Mechanics. June 25, 2012. Retrieved from <http://www.popularmechanics.com/science/health/med-tech/why-is-there-a-helium-shortage-10031229>.

Roberge, Amanda. 2012. "CEO One on One: Charles C. Agosta." Worcester Telegram & Gazette. October 7, 2012. Retrieved from <http://www.telegram.com/article/20121007/NEWS/110079921/1002/RSS01&source=rss#.UH1-XrRbuSO>

Viscarolasaga, Efrain. 2008. "Clark U. Startup Goes with \$2M Flow." Mass High Tech Website. May 30, 2008. Retrieved from <http://www.masshightech.com/stories/2008/05/26/weekly10-Clark-U-startup-goes-with-2M-flow.html>.

Williams and Agosta. 2011. "Centrifugal Bernoulli Heat Pump." U.S. Patent No.: US 7,918,094 B2. April 5, 2011.

Williams and Agosta. 2013. "Cylindrical Bernoulli Heat Pump." U.S. Patent No.: US 8,402,784 B2. March 26, 2013.

B.2 Critical-Flow Refrigerant Cycle

| | |
|--------------------------|---|
| Brief Description | The critical-flow refrigeration cycle utilizes a supersonic nozzle to expand a liquid refrigerant and absorb heat from a secondary fluid to then provide space cooling. |
|--------------------------|---|

| Technology Characteristics | Value | Comments |
|--|-------------|--|
| Unit Energy Savings | N/A | Core technology suggests COPs of up to 10, but prototype development is several years away. |
| Fuel Type(s) | Electricity | Refrigerant cycle driven by a pump |
| Working Fluid(s) | Varies | Refrigerant selection and nozzle design can be customized for the specific application. |
| Complexity/Size | Moderate | Compact design expected after additional development |
| Projected Cost | N/A | |
| Threshold Attributes | Moderate | Benign refrigerants |
| Excitement Attributes | N/A | |
| Ability to Utilize Low-Temperature Thermal Sources | N/A | |
| Technical Maturity | Low | Core technology still in early-stage research |
| Market Maturity | Low | Initial prototype is several years away |
| Level of Stakeholder Support | Moderate | We have not identified any reason that stakeholders would actively support or oppose the technology once fully developed |
| Fit with BTO Mission | High | Novel cooling cycle utilizing low-GWP and low-ODP refrigerants but unproven |

Background

Technology Description

Expansion of a high-pressure liquid refrigerant through the use of a thermostatic expansion valve or other device is commonplace in vapor-compression cycles to regulate the quality and flow rate of the refrigerant entering the evaporator. In vapor-compression systems, as the condensed refrigerant undergoes this expansion, its pressure and temperature drops, and part of the liquid evaporates. Researchers at Kansas State University are developing a cooling cycle that instead pumps a high-pressure refrigerant through a supersonic converging-diverging nozzle. As the liquid refrigerant passes through the nozzle, its velocity reaches supersonic (or critical-flow) conditions, substantially decreasing the refrigerant's pressure. This sharp pressure change vaporizes some of the refrigerant and absorbs heat from the surrounding conditions during this

phase change. Due to the design of the nozzle, a shockwave trips the supersonic two-phase refrigerant back to the starting conditions, condensing the remaining vapor. Figure B-3 below provides an overview of the critical-flow refrigeration cycle.

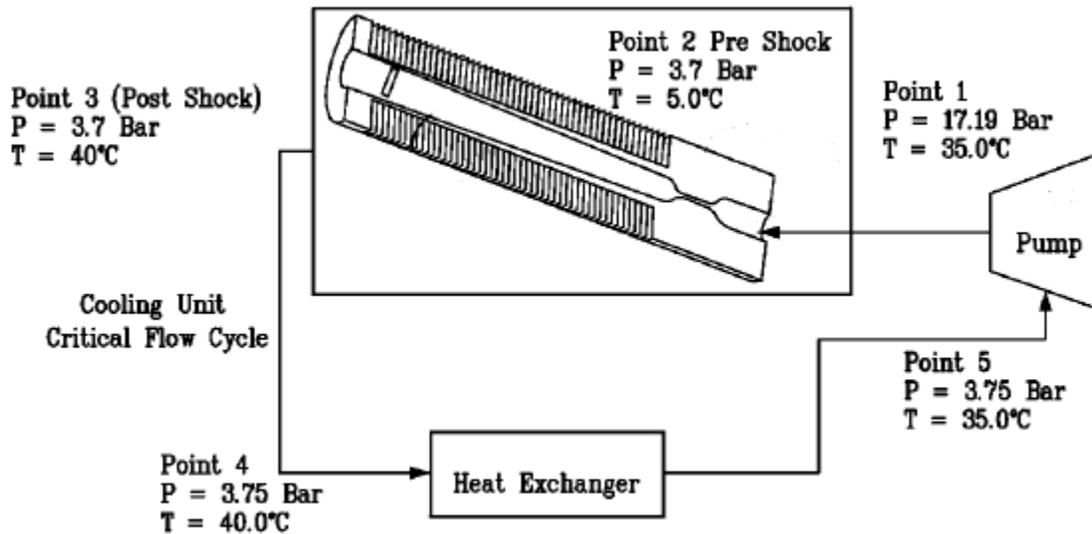


Figure B-3: Schematic of a critical-flow refrigeration cycle

Source: Debus et al. (2012)

The critical-flow refrigeration cycle would provide space cooling similar to a chiller by running a secondary fluid such as water or glycol over one or more nozzles. Rather than utilizing a compressor to raise the pressure of the refrigerant as in a vapor-cycle system, the critical-flow cycle utilizes a high-pressure pump to drive refrigerant liquid through the cooling cycle. Additionally, the design of the nozzle can be tailored for a given refrigerant, such that environmentally benign substances can act as the working fluid.

Technical Maturity and Current Developmental Status

This refrigeration cycle is still in early-stage development with prototype development several years away. The complex multi-phase flow at supersonic conditions presents numerous challenges to fully understanding and modeling the cycle. With the support of DOE and venture-capital investors, initial research was conducted at PAX Streamline and later Caitin (Giolda 2011). Researchers at Kansas State University have continued development of the cycle and have gained a better understanding for the fundamental physics of the nozzle design and operation. Through this research, they are identifying optimal working fluid and operating conditions to eventually demonstrate the core technology for space cooling or other applications (Hosni 2013).

Barriers to Market Adoption

The critical-flow refrigeration cycle is an early-stage technology whose prospects for building HVAC, electronics cooling, and other applications should be assessed after further product development. Multiple nozzles will likely be required to reach the capacities needed for residential and commercial HVAC applications, and uniform distribution of the refrigerant will be a technical challenge (Hosni 2013).

Energy Savings Potential

Potential Market and Replacement Applications

The critical-flow refrigeration cycle itself is a closed-loop system but requires a secondary fluid to transfer cooling to the building and reject heat from the hot liquid to ambient through a heat exchanger. While the cycle may be suitable for most cooling applications, a chiller utilizing water as the secondary fluid may be the first application.

Energy Savings

Researchers suspect the critical-flow refrigeration cycle could achieve efficiencies greater than current vapor-compression systems, potentially nearing a COP of 10, but additional development is required to develop a full prototype (Hosni 2013).

Cost and Complexity

Although the costs to build prototypes are high, the cost to manufacture the nozzle at high production volumes is not expected to be a significant challenge. Other system components are commonly found in current cooling systems, including fluid coolers, secondary water loops, pumps, etc., and are not expected to be a major technical risk.

Peak-Demand Reduction and Other Non-Energy Benefits

Systems could operate using alternative refrigerants that offer lower GWP and ODP than current refrigerants.

Next Steps for Technology Development

Table B-2 presents the potential next steps to advance critical-flow refrigeration cycle.

Table B-2: Recommended Next Steps for the Development of Critical-Flow Refrigeration Cycle

| Initiatives |
|--|
| Continue development of supersonic test chambers to better understand multi-phase heat transfer in nozzle. |
| Construct bench prototype to demonstrate the cooling cycle, its operating parameters, and performance. |

References

Debus et al. 2012. “Supersonic Cooling Nozzle Inlet.” WIPO Patent No.: WO 2012/018627 A1. February 9, 2012.

Gielda et al. 2012. “Heating and Cooling Systems and Methods.” U.S. Patent No.: US 2012/0312379 A1. December 13, 2012.

Gielda, Thomas. 2011. “Impact of High-Performance Computing on New Product Design: A Case Study for a Novel Cooling System.” Caitin Inc. July 20, 2011. Retrieved from [http://www.mcs.anl.gov/uploads/cels/papers/scidac11/final/GIELDA_SCIDDAC_JULY%20\(fin al\).pdf](http://www.mcs.anl.gov/uploads/cels/papers/scidac11/final/GIELDA_SCIDDAC_JULY%20(fin al).pdf).

Hosni, Mohammad. 2013. Lead Project Researcher. Kansas State University. Personal Communication with Jim Young of Navigant. November 14th, 2013.

B.3 Electrocaloric

| | |
|--------------------------|--|
| Brief Description | The electrocaloric effect is a phenomenon in which a dielectric material exhibits reversible temperature change when exposed to a changing electric field. |
|--------------------------|--|

| Technology Characteristics | Value | Comments |
|--|-------------|---|
| Unit Energy Savings | N/A | We have not identified any quantified estimates or measurements of electrocaloric efficiency. |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | None | |
| Complexity/Size | N/A | We have not identified any estimates or measurements of electrocaloric system complexity or size. |
| Projected Cost | N/A | We have not identified any estimates of electrocaloric system costs. |
| Threshold Attributes | N/A | We have not identified any projections of electrocaloric safety, maintainability, reliability, or lifetime. |
| Excitement Attributes | N/A | We have not identified any projections of any exciting attributes of electrocaloric technology. |
| Ability to Utilize Low-Temperature Heat Sources | Low | Electrocaloric technology cannot take advantage of thermal energy. |
| Technical Maturity | Low | Electrocaloric technology is in the very early R&D stage; we have only identified documentation of two proof-of-concept breadboard prototypes. DOE funded development of one prototype at UCLA through ARPA-e (ARPA-e 2013, Gu et al. 2013). |
| Market Maturity | Low | <ul style="list-style-type: none"> • We are not aware of any applications, HVAC or otherwise, that currently employ electrocaloric technology. • We are not aware of any private companies that are currently developing electrocaloric technology, nor is it clear whether electrocaloric research is presently ongoing. |
| Level of Stakeholder Support | Moderate | We are not aware of any reasons that stakeholders would actively promote or oppose the technology once it is fully developed. |
| Fit with BTO Mission | Moderate | Technical risk is high due to the inability of current prototypes to reach capacities relevant for HVAC applications. |

Background*Technology Description*

Electrocaloric cooling is based on the electrocaloric effect, a phenomenon in which a dielectric material exhibits reversible temperature change when exposed to a changing electric field. An electrocaloric system applies an electric field to a dielectric material while it is thermally isolated from the heat load. This aligns randomly oriented electron spins in the dielectric material ($A \rightarrow B$ in Figure B-4), which is an exothermic process that raises the material's temperature. The material is then connected to a heat sink, to which it rejects heat ($B \rightarrow C$). Once the material is isolated from the heat sink, upon removal of the electric field, the electron spins return to their randomized state, which is an endothermic process that cools the material ($C \rightarrow D$). The material is then connected to the heat load and absorbs heat from it ($D \rightarrow A$). During this step, the dielectric material returns to its original state, restarting the cycle (Dieckmann 2011).

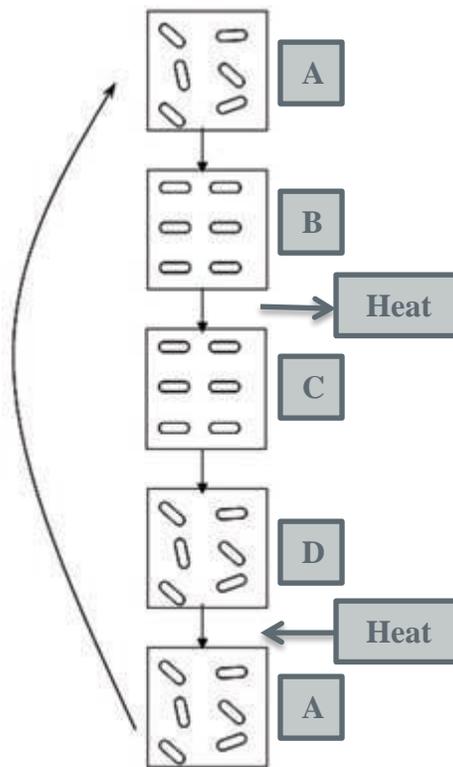


Figure B-4: Electrocaloric cycle

Source: Dieckmann (2011)

A practical implementation of this cycle could look like the depiction in Figure B-5, which represents a small electrocaloric “refrigerator” developed by researchers at the University of California Los Angeles (UCLA). In this setup, the electrocaloric material is attached to a motor that moves it up and down, alternating contact with a heater and a heat sink, using glycerol to promote thermal contact with the EC element. UCLA researchers altered the element’s electric field at the same frequency as its up-and-down motion, thus coordinating the motion with its ability to absorb and reject heat. This proof-of-concept prototype produced a maximum temperature difference of 0.9°F (Jia and Ju 2012).

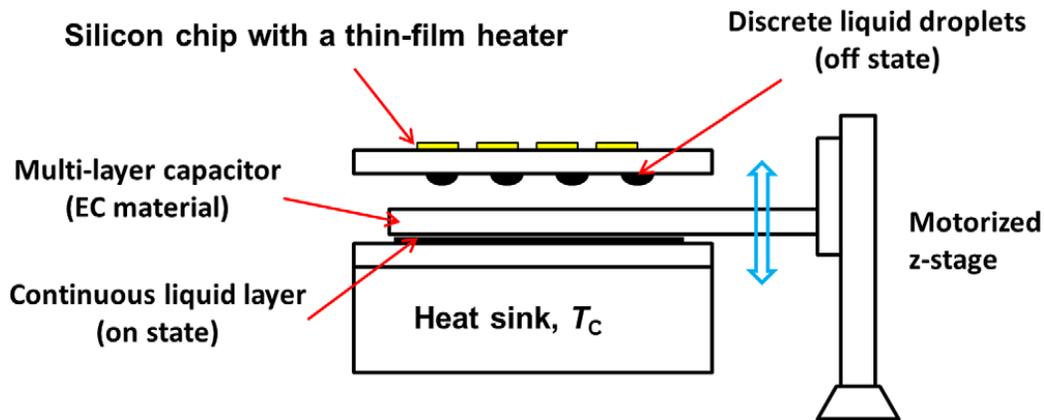


Figure B-5: Experimental setup for characterizing the electrocaloric cooling cycle
Source: Jia and Ju (2012)

Ceramics are the most common materials exhibiting an electrocaloric effect. However, researchers have recently discovered polymers that exhibit this effect (Dieckmann 2011). Researchers at Pennsylvania State University (PSU) have simulated a polymer electrocaloric refrigerator and project that such a device could achieve a temperature difference as large as 36°F (Gu et al. 2012).

In theory, the electrocaloric effect is very similar to the magnetocaloric effect. In practice, however, researchers find it much easier to produce an electrocaloric effect than to produce a magnetocaloric effect. The magnetic fields required for the latter are substantial and require impractically large magnets, whereas the electric fields required for the former are relatively simple to generate (Mischenko et al. 2006).

Technical Maturity and Current Developmental Status

Through 2012, DOE funded an electrocaloric cooling project co-researched by UCLA and Teledyne Scientific and Imaging, UCLA's industry partner, through the ARPA-e program (ARPA-e 2013). Lead researchers developed the breadboard, small-scale electrocaloric cooling system described in the above section. We were unable to contact researchers to determine whether work on this project is ongoing today.

A team of researchers at Pennsylvania State University (PSU) has also developed a breadboard, small-scale electrocaloric cooling device (Gu et al. 2013).

Energy Savings Potential

Potential Market and Replacement Applications

If successfully developed, electrocaloric technology would likely be technically applicable to all heating and cooling applications for residential and commercial buildings. It would also likely be technically applicable to all climate regions and building types.

Energy Savings

The team of researchers at PSU has projected a range of COPs for a breadboard system based on their polymer electrocaloric material. For a temperature lift of 36°F (source temperature of 99°F

and sink temperature of 63°F), the team projected COPs ranging from 3.7 to 4.9, depending on the frequency of oscillation (Gu et al. 2012). These projected COPs are 16–53% higher than the overall system COP of baseline air conditioners at AHRI test conditions (source temperature of 105°F and sink temperature of 55°F, Brown et al. 2010); however, they do not take system losses into account and were projected for very small capacities under slightly different temperature conditions. Simulation models have projected COPs of 8.7 for electrocaloric cooling systems with temperature lifts of 9°F and COPs as high as 30 at temperature lifts of 27°F (Guo et al. 2013, Ozbolt et al. 2013); however researchers have yet to observe this performance in experimental results. We have not identified any estimates or measurements of the efficiency of a full-scale electrocaloric prototype.

Cost, Size, and Complexity

We have not identified any estimates of the cost, size, or complexity of complete electrocaloric systems.

Next Steps for Technology Development

Mischenko et al. (2006) note that the macroscopic theory of electrocaloric theory is underdeveloped and plagued by disagreement. They also recommend augmenting electrocaloric cooling power by increasing electrocaloric film thickness in future prototypes.

Table B-3 presents the potential next steps to advance electrocaloric technology.

Table B-3: Next Steps for the Development of Electrocaloric Technology

| Initiatives |
|--|
| Develop electrocaloric devices with augmented cooling power |
| Support basic scientific research to improve general understanding of electrocaloric theory |
| Develop full-scale prototypes that prove the ability of electrocaloric technology to handle larger loads |
| Test existing electrocaloric devices to support understanding of their efficiency |
| Develop partnerships with industry to accelerate development of electrocaloric technology |

References

Advanced Research Projects Agency – Energy (ARPA-e), date unknown.⁹ “University of California Los Angeles (UCLA): Compact MEMS Electrocaloric Cooling Module.” Building Energy Efficiency through Innovative Thermodevices (BEETIT) Project Description. Retrieved November 13, 2013 from <http://arpa-e.energy.gov/?q=arpa-e-projects/compact-solid-state-cooling-systems>.

⁹ No publication date is listed on the ARPA-e website.

Brown et al. 2010. “The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications.” PNNL-19259. PNNL. March 2010. Prepared for the U.S. DOE under contract DE-AC05-76RL01830.

Dieckmann, John et al. 2011. “Solid-State Cooling, Part 2.” Emerging Technologies – ASHRAE Journal. March 2011. ASHRAE.

Gu, Haiming et al. 2012. “Compact Cooling Devices Based on Giant Electrocaloric Effect Dielectrics.” ASME 2012 Summer Heat Transfer Conference. July 2012. American Society of Mechanical Engineers.

Gu, Haiming et al. 2013. “A Chip Scale Electrocaloric Effect Based Cooling Device.” Applied Physics Letters 102. March 2013. American Institute of Physics.

Guo, Dongzhi et al. 2013. “Design of a Fluid-Based Micro-Scale Electrocaloric Refrigeration System.” ASME 2013 Heat Transfer Summer Conference. July 2013. American Society of Mechanical Engineers.

Jia, Yanbing and Y. Sungtaek Ju. 2012. “A Solid-State Refrigerator Based on the Electrocaloric Effect.” Applied Physics Letters 100. June 2012. American Institute of Physics.

Mischenko, A. et al. 2006. “Giant Electrocaloric Effect in Thin Film $\text{PbZr}_{0.95}\text{Ti}_{0.05}\text{O}_3$.” Science Magazine. March 2006.

Ozbolt, M. et al. 2013. “Electrocaloric vs. Magnetocaloric Energy Conversion.” International Journal of Refrigeration 37. July 2013.

Appendix C In-Depth Analyses of the 17 Viable Non-Vapor-Compression Technology Options

As discussed in Section 2.4, we performed an in-depth analysis for each of the 17 technology options we selected after the second round of screening. This appendix consists of the in-depth analyses for the 17 viable technology options, organized by category¹⁰ as presented in Table C-1.

Table C-1: Non-Vapor-Compression Technology Options by Category

| Technology Category | Technology Option | Technical Energy Savings Potential (Quads/yr.) |
|---------------------------------------|------------------------------------|--|
| Solid-State Technology Options | Magnetocaloric | 1.25 |
| | Thermoelectric | 0.19 |
| | Thermotunneling | 0.22 |
| Electro-Mechanical Technology Options | Brayton Heat Pump | 0.00 |
| | Evaporative Cooling | 0.25 |
| | Membrane Heat Pump | 2.16 |
| | Thermoacoustic | 0.11 |
| | Thermoelastic | 2.68 |
| Thermally Driven Technology Options | Absorption Heat Pump | 0.24 |
| | Adsorption Heat Pump | 0.11 |
| | Duplex-Stirling Heat Pump | 0.06 |
| | Ejector Heat Pump | 0.00 |
| | Evaporative Liquid Desiccant A/C | 2.64 |
| | Ground-Coupled Solid Desiccant A/C | 1.21 |
| | Standalone Liquid Desiccant A/C | 0.00 |
| | Standalone Solid Desiccant A/C | 0.00 |
| | Vuilleumier Heat Pump | 0.36 |

Each analysis contains the following subsections:

- Overview table:** Brief tabular description of the technology option, the estimated technical energy savings potential and three-step ratings (High, Moderate, Low) of the technology’s market readiness and its estimated cost/complexity.

¹⁰ Category descriptions are found in Section 3.

- **Background:** How the technology works, its practical uses, its technical maturity/current developmental status, its barriers to market adoption, and why the technology offers an efficiency improvement over conventional technologies.
- **Energy Savings Potential:** The technology's estimated energy savings based on technically reasonable level of penetration.
- **Cost, Size, and Complexity:** The estimated installed cost of the technology and factors that may increase or decrease the size of the HVAC system and the complexity of system operation and maintenance.
- **Peak-Demand Reduction and Other Non-Energy Benefits:** The technology's estimated ability to reduce electrical demand during peak hours and provide benefits beyond HVAC energy savings.
- **Next Steps for Technology Development:** What needs to be done to commercialize the technology further?
- **References:** References consulted during our investigation.

C.1 Solid-State Technology Options

Solid-state technology options produce useful temperature differences based on the intrinsic material properties of their core solid-state substance when activated through electrical input. Table C-2 provides a brief description and final ranking for the technology options selected for in-depth analysis within the Solid-State Technology Options category.

Table C-2: Summary of Solid-State Technology Options

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|------------------------|---|-----------------|---|---------------|
| Magnetocaloric | Magnetocaloric technology operates on the magnetocaloric effect, a phenomenon in which a paramagnetic material exhibits reversible temperature change when exposed to a changing magnetic field. | High | Emerging | 3.70 |
| Thermoelectric | Under an applied voltage, thermoelectric materials generate a temperature difference that can provide space conditioning. | Moderate | Available in low-load applications, but in R&D stage for HVAC | 3.20 |
| Thermotunneling | Thermotunneling technology is an advanced form of thermoelectric technology in which electrons are transmitted across a nanometer-scale vacuum via quantum tunneling to produce cooling or heating. | Moderate | R&D | 2.45 |

C.1.1 Magnetocaloric

| | | |
|----------------------------|--|------------------------|
| Brief Description | Magnetocaloric technology operates on the magnetocaloric effect, a phenomenon in which a paramagnetic material exhibits reversible temperature change when exposed to a changing magnetic field. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 20% | Emerging | High |

| Technology Characteristics | Value | Comments |
|--|-------------|--|
| Unit Energy Savings | 20% | For space cooling; based on the projected performance of a window A/C unit currently under development (Russek 2013). |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | None | The system uses a low-pressure water-based working fluid (Russek 2013). |
| Complexity/Size | Moderate | Current prototypes are larger than vapor-compression systems of identical capacity; however, design work could optimize components and drive down size (Russek 2013). |
| Projected Cost | High | The demand for rare-earth magnets is very high compared to its world supply, which could significantly increase system costs (Witkin 2012). |
| Threshold Attributes | Moderate | Equivalent threshold attributes to vapor compression are projected. |
| Excitement Attributes | Moderate | The water pump and electric motor used by the current A/C prototype are significantly quieter than a compressor (Russek 2013). |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Magnetocaloric systems cannot take advantage of waste heat. |
| Technical Maturity | Moderate | <ul style="list-style-type: none"> Technology is in mid-R&D stage, with some stakeholders attempting to commercialize in refrigeration applications within the next few years (Gaved 2013). Many prototypes of various capacities and for various applications, including HVAC, have been developed over the years. A/C prototype development is supported by DOE through ARPA-e funding (ARPA-e 2013). |
| Market Maturity | Low | We are not aware of any commercialized applications, HVAC or otherwise, that currently employ magnetocaloric technology. |
| Level of Stakeholder Support | High | Electric utilities will likely promote the technology because of its potential for peak-demand reduction. |
| Fit with BTO Mission | High | High technical risk based on the need to achieve higher efficiency for HVAC applications; unclear market potential due to concern about high magnet costs. |

Background

Technology Description

Magnetic cooling operates on the magnetocaloric effect, a phenomenon in which a paramagnetic material exhibits reversible temperature change when exposed to a changing magnetic field. A magnetic cooling system applies a magnetic field to a paramagnetic material. This aligns randomly oriented electron spins in the paramagnetic material (A→B in Figure C-1), an exothermic process that raises the material’s temperature and causes it to reject heat to its surroundings (B→C). Upon removal of the magnetic field, the magnetic spins return to their randomized state, an endothermic process that cools the material (C→D). The material then absorbs heat from the space to be cooled (D→A). During this step, the paramagnetic material returns to its original state and the cycle starts again.

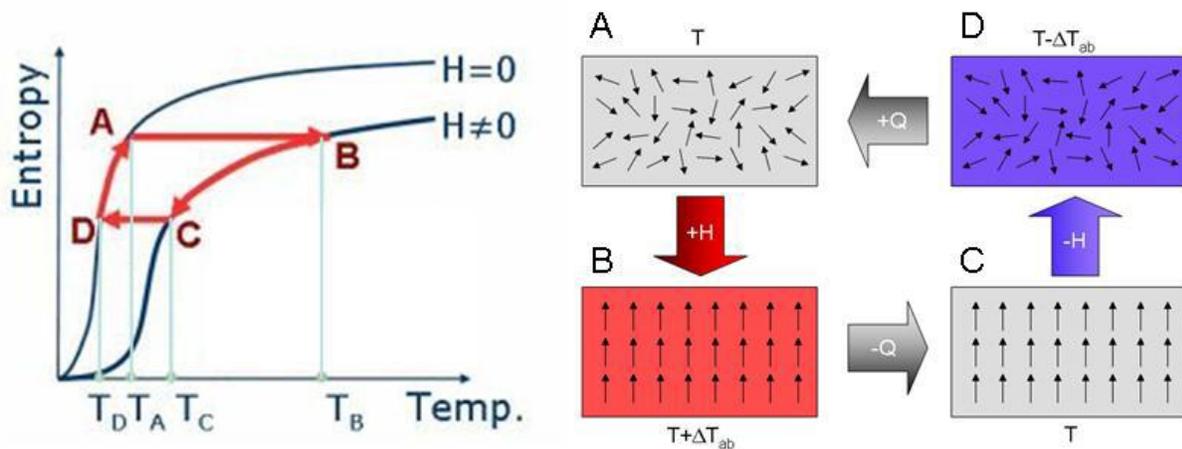


Figure C-1: Magnetic cooling cycle

Source: Goetzler et al. (2009)

The temperature gradient and subsequent capacity of magnetic cooling systems varies with the strength of the applied magnetic field. Dieckmann et al. (2007) report that existing permanent magnets suitable for air-conditioning applications can only produce a magnetic-field strength of up to 2 tesla (T), yielding a maximum temperature change of only 9°F. Although stronger magnetic fields could induce greater temperature changes (e.g., 10 T could produce a temperature change of 45°F), obtaining such strong magnetic fields would require superconducting electromagnets that draw significant power. This parasitic energy consumption could negate some or all of the efficiency gains associated with magnetic cooling.

Therefore, some type of regenerative cycle is necessary for magnetic cooling cycle to be viable for space cooling. One approach to accomplish this is the active magnetic regenerator cycle prototyped by Astronautics Corporation of America. This cycle uses a bed of magnetocaloric materials layered with materials having progressively higher Curie temperatures.¹¹ By successively applying a magnetic field to the bed (and thus shifting the temperature gradient

¹¹ The temperature above which a material’s permanent magnetism changes to induced magnetism

across the bed) and coordinating the flow of coolant, the temperature difference between the high and low sides is spanned regeneratively, and heat can be absorbed from the cold source (the cooling load) and rejected to the higher temperature sink (Boeder et al. 2006). Figure C-2 presents the concept of the active magnetic regenerator cycle.

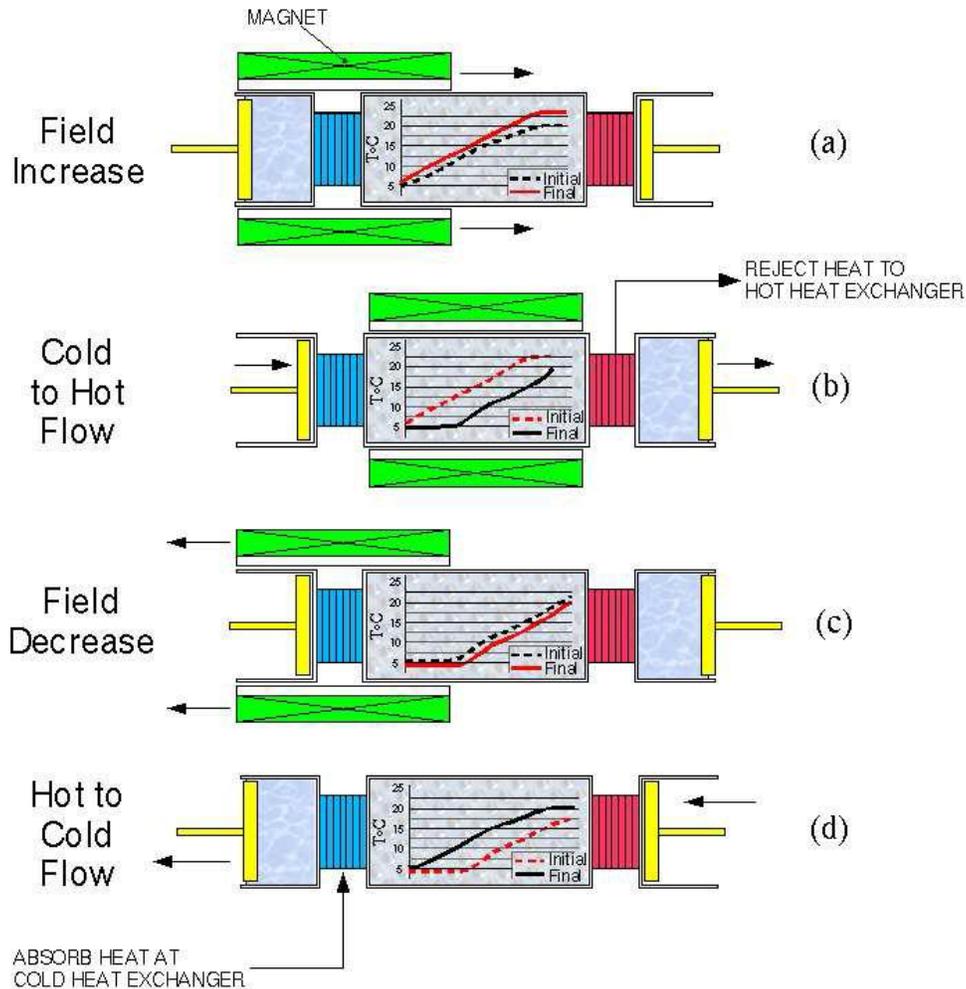


Figure C-2: The active magnetic regenerator cycle

Source: Boeder et al. (2006)

Technical Maturity and Current Developmental Status

Although many institutions have been working on the magnetocaloric effect for the past 40 years, equipment using the magnetic cooling cycle is not yet commercially available. According to research publications, including Dieckmann et al. (2007), Liu et al. (2009), and Gschneidner et al. (2008), current research efforts have focused on either: a) improving the cooling capacity of prototype systems using current magnetocaloric materials and permanent magnets; or b) identifying or developing new permanent magnets and magnetocaloric materials. Most of these efforts focus on near-room-temperature refrigeration applications.

A number of leading scientists and engineers from around the world have formed a working group on magnetic refrigeration in the IIR (International Institute for Refrigeration) to promote

magnetic cooling as a viable, energy-efficient and environmentally friendly cooling technology. Leading RD&D entities include the Center for Neutron Research (Liu et al. 2009) at the National Institute of Standards and Technology (NIST), University of Maryland and Iowa State University.

DOE is funding a magnetic cooling project co-researched by Astronautics and Ames National Laboratory through the ARPA-e program (ARPA-e 2013). Past prototypes constructed by Astronautics have had COPs of approximately 2.0; however, the goal of this project is to develop a 1-ton magnetic air conditioner with a COP of 4.0 that can also fit within the envelope of a window A/C unit. According to lead researcher Dr. Steven Russek, although Astronautics has not yet integrated all the components into a fully-functioning prototype system, their work is converging nicely toward this goal. Astronautics is eager to work with an industrial partner to help propel its technology to commercialization (Russek 2013).

Two companies claim to be in the process of commercializing magnetic systems for refrigerators. One, the French firm Cooltech, has announced that it plans to launch a magnetic refrigeration system for retail cold counters by the end of 2013, while the other, Camfridge, is working with Whirlpool to launch a domestic refrigerator within two years (Gaved 2013). However, neither of these companies has published any documentation of their prototypes' performance or shared their progress with other players in the magnetic cooling field (Russek 2013).

Barriers to Market Adoption

A potentially significant barrier to the market adoption of magnetic-cooling technology is the volatile nature of the global market for rare-earth magnets, as described further in the “Cost, Size, and Complexity” section below.

Energy Savings Potential

Potential Market and Replacement Applications

Magnetocaloric technology is technically applicable to all heating and cooling applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types. Because the electron spin alignment in paramagnetic materials is reversible, magnetocaloric technology can be used for heat pumps as well as air conditioning.

Energy Savings

According to Gschneidner et al. (2008), the magnetic refrigeration system has the potential to reduce energy consumption by 20% over a conventional vapor-compression system.

If the prototype being developed by Astronautics succeeds in achieving an overall COP of 4.0, magnetocaloric cooling could save approximately 20% of energy compared to baseline vapor-compression technology. Dr. Russek asserts that this will represent the highest COP and largest cooling power ever demonstrated by magnetic cooling and that its COP could only improve with the use of better components (e.g., pumps).

Cost, Size, and Complexity

A credible projection of costs for magnetocaloric technology in HVAC applications is not currently available given the early stage of development. However, Dieckmann et al. (2007) and other publications note that the permanent magnets used to induce the magnetocaloric effect account for a significant portion of the cost of the prototype systems developed so far. Political factors (e.g., trade restrictions by China, which accounts for 95% of the world's supply of rare-earth metals (Bell 2012)) are undeniably affecting market stability, but perhaps a more important factor is the increased demand for neodymium from other sectors. Witkin (2012) notes that increased demand of neodymium magnets for hybrid vehicles, electronics, and wind turbines is causing the shortage of neodymium worldwide, causing stakeholders to push for alternative materials. DOE's ARPA-e program is funding several such projects under its Rare Earth Alternatives in Critical Technologies (REACT) grant program. However, RD&D efforts to improve the magnetocaloric materials and heat exchangers of magnetocaloric systems should allow the required size of the magnet to shrink, thus reducing the need for rare-earth materials (Russek 2013). According to Russek, magnetocaloric materials themselves are extremely inexpensive.

Although the prototype being developed by Russek's team is supposed to fit within the envelope of a 1-ton unit, it is currently closer to the size of a 3-ton unit due to the size of the heat exchangers that were required to utilize a relatively small magnet. However, further development work could optimize these components and thus drive down the overall system size.

The magnetocaloric system requires several moving parts, including an electric motor to drive the active regenerator cycle and pumps to circulate the heat transfer fluid (Russek 2013).

Peak-Demand Reduction and Other Non-Energy Benefits

Because magnetocaloric systems are projected to operate at higher efficiencies than conventional systems, they could provide a commensurate reduction in peak demand.

Russek (2013) asserts that the pumps and motor utilized in his team's prototype are significantly quieter than the parts found in a vapor-compression system.

Next Steps for Technology Development

Researchers have investigated magnetic cooling for many years but are seeing recent improvements through technological breakthroughs in materials science and related fields. These advances can continue the development of the magnetic cooling cycle by reducing the cost of magnetic materials. Assuming researchers can address this central challenge, magnetocaloric technology will become a more attractive option for HVAC applications.

Moreover, although magnetocaloric technology can technically be used in space-heating applications, we were unable to locate any documentation of any space-heating prototypes or performance data. Testing will reveal the capabilities of magnetocaloric technology in space-heating applications.

Table C-3 presents the potential next steps to advance magnetocaloric technology.

Table C-3: Next Steps for the Development of Magnetocaloric Technology

| Initiatives |
|---|
| Develop paramagnetic materials that will produce a higher temperature lift in a lower magnetic field. |
| Engineer advanced regenerators and heat exchangers that will reduce the required magnet strength and thus reduce overall system size. |
| Conduct testing to investigate the performance of magnetocaloric technology in heating applications. |

References

Advanced Research Projects Agency – Energy (ARPA-e), date unknown.¹² “Astronautics Corporation of America: An Efficient, Green Compact Cooling System Using Magnetic Refrigeration.” Building Energy Efficiency through Innovative Thermodevices (BEETIT) Project Description. Retrieved October 28, 2013 from <http://arpa-e.energy.gov/?q=arpa-e-projects/air-conditioning-magnetic-refrigeration>.

Bell, Larry, 2012. “China’s Rare Earth Metals Monopoly Needn’t Put an Electronics Stranglehold on America.” Forbes. April 15, 2012.

Boeder, A., and Zimm, C., 2006. “Magnetic Refrigeration Technology for High Efficiency Air Conditioning.” Report prepared by Astronautics Corporation of America for the U.S. Department of Energy. December.

Dieckmann, J., Roth, K., and Brodrick, J., 2007. “Emerging Technologies – Magnetic Refrigeration.” ASHRAE Journal. pp. 74–76. August.

Gaved, Andrew, 2013. “Commercial & Domestic Magnetic Refrigeration Launches Imminent.” Refrigeration and Air Conditioning Magazine. June 27, 2013.

Goetzler et al. 2009. “Energy Savings Potential and RD&D Opportunities for Commercial Refrigeration.” Report prepared by Navigant Consulting, Inc. for the U.S. Department of Energy Building Technologies Program. September, 2009.

Gschneidner, K. A., and Pecharsky, V. K., 2008. “Thirty years of near room temperature magnetic cooling: Where we are today and future prospects.” International Journal of Refrigeration. Vol. 31, pp. 945–961. January 25, 2008.

Liu et al. 2009. “Origin and Tuning of the Magnetocaloric Effect for the Magnetic Refrigerant $Mn_{1.1}Fe_{0.9}(P_{0.80}Ge_{0.20})$.” January, 2009.

Russek, Steven. 2013. Director of Astronautics Technology Center, Astronautics Corporation of America. Personal Communication with Caitlin Johnson of Navigant. November 8, 2013.

¹² No publication date is listed on the ARPA-e website.

Witkin, Jim, 2012. “A Push to Make Motors With Fewer Rare Earths.” The New York Times.
April 20, 2013.

C.1.2 Thermoelectric

| | | |
|----------------------------|---|------------------------|
| Brief Description | Under an applied voltage, thermoelectric materials generate a temperature difference that can provide space conditioning. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 0% | R&D | Moderate |

| Technology Characteristics | Value | Comments |
|---|-----------------|---|
| Unit Energy Savings | 0% | <ul style="list-style-type: none"> Current thermoelectric technology is less efficient than vapor-compression technology (Brown 2010). However, it is likely that research will bring thermoelectrics to efficiency parity with vapor compression (Pokharna 2013). |
| Fuel Type(s) | Electricity | Must be powered by DC electricity. |
| Working Fluid(s) | None | Solid-state technology. |
| Complexity/Size | Low | Although fans and heat exchangers/sinks would be required, the overall system would be smaller, with fewer moving parts, than a vapor-compression system (Brown et al. 2010). |
| Projected Cost | Moderate | <ul style="list-style-type: none"> The cost per watt of current thermoelectric modules is too expensive for applications above 50 W (Dieckmann 2011). However, this cost will likely decrease as manufacturability increases (Bell 2009). |
| Threshold Attributes | High | High reliability, compact, no moving parts in the core system (Brown 2010). |
| Excitement Attributes | Moderate | <ul style="list-style-type: none"> Quiet operation (Brown 2010). Due to their small size, thermoelectric modules could be packaged and implemented to cool individual rooms or portions of rooms, rather than an entire building (Brown 2010). |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Thermoelectrics cannot take advantage of thermal energy in space-cooling applications, although thermoelectric generators, which are thermoelectric cooling modules run in reverse, can use waste heat to generate power. |
| Technical Maturity | Low-to-Moderate | <ul style="list-style-type: none"> Thermoelectrics are a mature technology, but higher-efficiency versions of this technology are in the early R&D stage. Through an ARPA-e grant, DOE is supporting the development of efficient non-equilibrium asymmetric thermoelectric devices, of which we have identified documentation of at least one prototype (ARPA-e 2013). |

| | | |
|-------------------------------------|----------|--|
| Market Maturity | Low | <ul style="list-style-type: none"> • Thermoelectric technology is widely commercially available in very low-load applications such as electronics cooling and small residential refrigeration. • However, it has not yet been commercialized to meet HVAC loads. • Many stakeholders are focused on thermoelectric generation; however, few are promoting the development of thermoelectrics for HVAC applications (Pokharna 2013). |
| Level of Stakeholder Support | Moderate | We have not identified any reasons that stakeholders would actively support or oppose the technology once it is fully developed. |
| Fit with BTO Mission | Moderate | Moderate technical risk due to low efficiencies to date, although several development efforts are currently underway for non-HVAC applications |

Background

Technology Description

Thermoelectric systems are solid-state systems that convert electrical energy into temperature gradients that drive thermal-energy flows. A thermoelectric element consists of two thermoelectric semiconductors: an n-type conductor (containing negative charge carriers) and a p-type conductor (containing positive charge carriers), connected electrically in series and thermally in parallel, mounted between two ceramic surfaces, shown in Figure C-3. The ceramic surfaces provide electrical insulation and thermal conduction from the elements to the heat sinks (Yang et al. 2008).

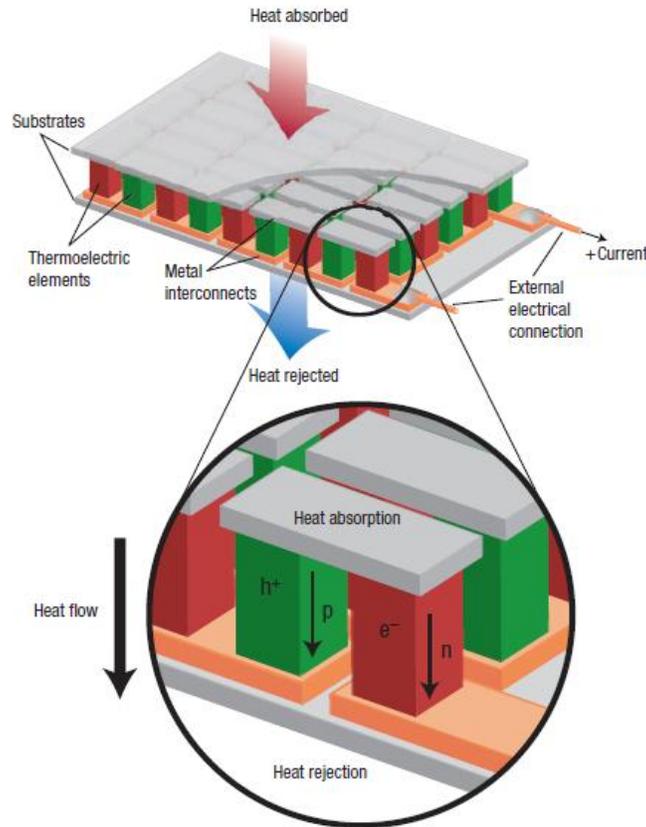


Figure C-3: Thermoelectric cooling module

Source: Synder and Toberer (2010)

The physical phenomenon that describes both the energy harvesting and thermal conditioning behavior of thermoelectric materials is the Seebeck effect. When placed within a thermal gradient, thermoelectric materials accumulate charge internally on both the hot and cold surfaces. If the temperature difference is great enough between the hot and cold surfaces, the buildup of charge on the opposite sides of the material creates a voltage difference resulting in a flow of current from the material. Conversely, when a voltage is placed across a thermoelectric material, the resulting current moves electrons from one surface to another. This phenomenon, which creates a thermal gradient, is known as the Peltier effect. Stacking multiple thermoelectric devices in series can increase the generated temperature difference.

Ideal thermoelectric modules have low thermal conductivity and high electrical conductivity properties, but most materials feature both high thermal conductivity and high electrical conductivity. Scientists rate thermoelectric materials using a dimensionless figure-of-merit based on their physical properties and thermal performance. Known as ZT , this figure compares a material's thermoelectric properties with its thermal conductivity and electrical resistivity in the following relationship:

$$ZT = \frac{\alpha^2 T}{\rho \lambda}$$

Where: α (occasionally presented as S) is the Seebeck coefficient, T is the absolute temperature, ρ is the electric resistivity, and λ (occasionally presented as k) is the thermal conductivity.

A thermoelectric material's ZT is one of the most important factors in determining its effectiveness and, therefore, the efficiency of the system into which it is placed. Figure C-4 demonstrates some of the measured ZT s for recently developed materials (as a function of temperature).

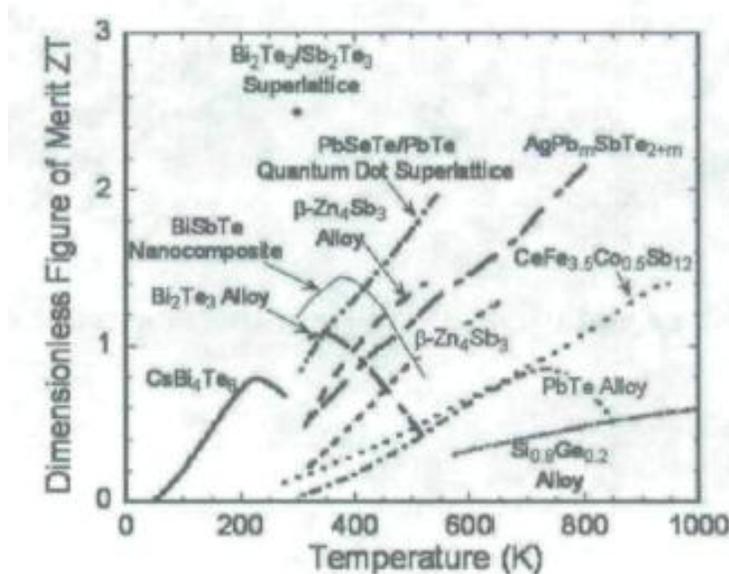


Figure C-4: ZT for various thermoelectric materials

Source Yang et al. (2008)

Technical Maturity and Current Developmental Status

Multiple manufacturers have commercialized small, low-efficiency thermoelectric cooling systems in seat conditioning for cars, portable refrigerators, wine cabinets, and spot cooling for electronics. Additionally, researchers have constructed a mechanical subcooler using thermoelectric modules to improve efficiency for vapor-compression systems (see Appendix G). Thermoelectric generators have also received much attention for their ability to convert waste heat to electricity for automotive and power-plant applications.

Sheetak, Inc. has developed a higher-efficiency “Green Cooler” thermoelectric technology (described further in the “Energy Savings” section below) that it has introduced in India for small refrigeration applications such as water coolers, compact refrigerators, and portable coolers (Sheetak 2013). They manufacture their products for Godrej, a large multinational corporation based India (Pokharna 2013).

Sheetak has also received funding through DOE’s ARPA-e program to develop non-equilibrium asymmetric thermoelectric (NEAT) devices (ARPA-e 2013). These thin-film thermoelectric devices, which have not yet been commercialized, are constructed using the same process technology used to create semiconductors. According to a leader at Sheetak, this process

eliminates some of the limitations associated with the composition of thermoelectric materials by changing their nanostructure, thus reducing their thermal conductivity (Pokharna 2013).

Sheetak indicates that the vast majority of thermoelectric research (and, thus, the vast majority of funding) is currently directed towards thermoelectric generation, rather than space conditioning (Pokharna 2013). However, advancements in thermoelectric generation would also benefit thermoelectric space conditioning because the Seebeck and Peltier effects are directly related.

Barriers to Market Adoption

Assuming that thermoelectric technology can ultimately achieve efficiency parity with vapor-compression technology, we are unable to identify any barriers to market adoption.

Energy Savings Potential

Potential Market and Replacement Applications

Thermoelectric technology is technically applicable to all space-heating and cooling applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types.

Energy Savings

Some of the most important factors contributing to the efficiency of thermoelectric technology are the ZT of the thermoelectric device, heat transfer to and from the modules, and backwards heat conduction through the modules. Current thermoelectric systems use materials with ZTs around 1.0. However, for most space-cooling applications, thermoelectric devices must achieve a ZT of 3.0 or greater to be competitive with vapor-compression technology (Dieckmann 2011).

Brown et al. (2010) states that an HVAC system using currently available thermoelectric materials would have a COP of 1.0–1.5, representing 10–15% of Carnot efficiency. Therefore, current thermoelectric devices have negative savings (increased energy use) compared to vapor-compression systems, which typically operate at 40–45% of Carnot efficiency at the same source and sink temperatures.

Typical existing thermoelectric refrigerators keep their modules on continuously to prevent backwards heat conduction through the module during off-periods. However, Sheetak has developed a switching method that, in experiments, doubled the COP of thermoelectric refrigerators during cooling transients and provided a fivefold reduction in steady-state energy consumption. Their proprietary “Green Cooler” technology utilizes thermal diodes and thermal capacitors to reduce this heat flow, enabling the module to be intermittently turned on and off. Sheetak claims that, even without increasing ZT, the Green Cooler yields up to eightfold energy savings compared to conventional thermoelectric refrigerators (Ghoshal 2009).

Sheetak’s (as yet un-commercialized) high-efficiency NEAT thermoelectric module currently has a ZT of 1.5. Sheetak is optimistic that they will develop a module with a ZT of 3.0, representing parity with vapor-compression efficiency, within a few years, although they provide no concrete justification for this projection (Pokharna 2013).

Cost and Complexity

According to Dieckmann et al. (2011), thermoelectric systems currently only have an economic advantage over vapor-compression systems for applications requiring less than 50 W of cooling, regardless of efficiency.

Mass production of larger thermoelectric systems that integrate many smaller thermoelectric units presents challenges relating to the difficulty of maintaining reliable thermal connections and thus adds significantly to the cost of these systems. However, thanks to advances in solid-state manufacturing techniques, thermoelectric cooling systems will likely become easier to integrate into HVAC systems (Bell 2009). Therefore, costs are likely to decrease as manufacturability improves.

Thermoelectric modules are very small, only a few millimeters thick, and would require fans and large heat sinks to distribute thermal energy. The parasitic energy consumption required to achieve low temperature approaches with these limited heat-transfer surfaces is significant.

Peak-Demand Reduction and Other Non-Energy Benefits

Unless thermoelectric cooling systems become more efficient than vapor-compression systems, they are unlikely to lower peak demand compared to vapor-compression systems.

Thermoelectric cooling systems also have the potential for greater reliability, more compact size, quieter operation, and more modular implementation. For example, small-capacity units could be used to cool individual rooms, thereby reducing ducting losses and facilitating zone control (Brown et al. 2010).

Next Steps for Technology Development

The viability of thermoelectric systems as an alternative to vapor-compression systems is highly dependent on increasing the ZTs of thermoelectric materials. Bell (2008) is optimistic that the nanomaterials research used to develop semiconductors and photovoltaics can provide a pathway for thermoelectric researchers to transform laboratory achievements of high-ZT materials into commercialized thermoelectric products.

Bell (2009) also notes that, although ZTs of up to 3.0 have been reported by researchers in the past, their claims are typically spurious and irreproducible due to the following problems:

- Measuring the properties needed to calculate ZT is difficult, and many research findings are based on extrapolation of these properties rather than performance of integrated prototypes. This leads to highly uncertain test results because of the variation among samples.
- Small variations in material preparation or fabrication can result in major differences in properties and performance.

Bell notes that entities that could otherwise speed thermoelectric commercialization have instead hesitated to do so because of the above problems; consequently, reproducible test results are needed to garner confidence in ZT measurements and support for research in this area.

Finally, as noted above, achieving low temperature approaches with thermoelectric systems requires parasitic energy consumption that reduces efficiency gains. Therefore, there is a need for compact, cost-effective innovative heat-exchanger designs that will reduce parasitic consumption.

Table C-4 presents the potential next steps to advance thermoelectric technology.

Table C-4: Next Steps for the Development of Thermoelectric Technology

| Initiatives |
|---|
| Continue research on high-ZT thermoelectric materials, focusing on materials optimized for cooling applications. |
| Validate the repeatability and reproducibility of new ZT test methodologies. |
| Develop robust, optimized fabrication methods to create practical thermoelectric systems. |
| Develop cost-effective, compact heat exchangers to transfer heat without requiring large temperature differences. |

References

Advanced Research Projects Agency – Energy (ARPA-e), date unknown. “Sheetak, Inc.: Non-Equilibrium Asymmetric Thermoelectric (NEAT) Devices.” Building Energy Efficiency through Innovative Thermodevices (BEETIT) Project Description. Retrieved October 31, 2013 from <http://arpa-e.energy.gov/?q=arpa-e-projects/high-efficiency-solid-state-cooling-technologies>.

Bell, Lon. 2009. “Accelerating the Commercialization of Promising New Thermoelectric Materials.” BSST LLC, Irwindale, California USA. ASM International.

Bell, Lon. 2008. “Addressing the Challenges of Commercializing New Thermoelectric Materials.” BSST LLC. International Conference on Thermoelectrics. August, 2008.

Brown, DR. et al. 2010. “The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications.” PNNL-19259. PNNL. March 2010. Prepared for the U.S. DOE under contract DE-AC05-76RL01830.

Dieckmann, John et al. 2011. “Solid-State Cooling, Part 1.” Emerging Technologies – ASHRAE Journal. March 2011. ASHRAE.

Ghoshal, U. and Guha, A. 2009. “Efficient Switched Thermoelectric Refrigerators for Cold Storage Applications.” Journal of Electric Materials. March 4, 2009.

Goetzler, W. et al. 2009. “Energy Savings Potential and R&D Opportunities for Commercial Refrigeration.” Final Report. Navigant Consulting, Inc. September 23, 2009.

Pokharna, Himanshu. 2013. Vice President for Business Development of Sheetak, Inc. Personal Communication with Caitlin Johnson of Navigant. November 1, 2013.

Sheetak. 2013. "Cooling Engines for a Greener Tomorrow." Retrieved from <http://www.sheetak.com/>.

Snyder, G.J., and Toberer, E.S. 2008. "Complex Thermoelectric Materials", *Nature Materials*, 7, 105 (2008).

Yang et al. 2008. "Thermoelectric Technology Assessment: Application to Air Conditioning and Refrigeration." *HVAC&R Research*. September, 2008.

C.1.3 Thermotunneling

| | | |
|----------------------------|---|------------------------|
| Brief Description | Thermotunneling technology is an advanced form of thermoelectric technology in which electrons are transmitted across a nanometer-scale vacuum via quantum tunneling to produce cooling or heating. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 1% | R&D | Moderate |

| Technology Characteristics | Value | Comments |
|---|-------------|---|
| Unit Energy Savings | 1% | Predicted efficiency is 55% of Carnot, compared to 40–45% of Carnot for typical vapor-compression systems in HVAC applications (Cool Chips 2011). We adjusted this efficiency to account for parasitic energy consumption (see Appendix D). |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | None | |
| Complexity/Size | Low | <ul style="list-style-type: none"> Thermotunneling modules would be of similar size to thermoelectric modules, which are very compact. Although fans and heat exchangers/sinks would be required, the overall system would be smaller than a vapor-compression system of the same capacity (Cool Chips 2011). |
| Projected Cost | Moderate | <ul style="list-style-type: none"> Projected to be on par with the cost of thermoelectric systems, which is significantly more expensive than vapor compression above 50 W of cooling (Dieckmann 2011). However, as for thermoelectrics, this cost may decrease as manufacturability increases (Bell 2009). |
| Threshold Attributes | Moderate | <ul style="list-style-type: none"> Benefits: No moving parts in the core system. Drawbacks: Tight tolerances required for manufacturing (Brown 2010). |
| Excitement Attributes | Moderate | <ul style="list-style-type: none"> Quiet (Brown 2010). As with thermoelectric technology, novel packaging concepts (e.g. localized cooling) could be possible. |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Thermotunneling cannot take advantage of waste heat streams. |
| Technical Maturity | Low | Technology is in very early R&D stage; we have not identified any prototypes demonstrations or test results. |
| Market Maturity | Low | <ul style="list-style-type: none"> We are not aware of any applications, HVAC or otherwise, that currently employ thermotunneling. Thermotunneling technology under the licensed name of “Cool Chips” is being developed by Borealis Exploration Limited, a publicly traded company. |

| | | |
|-------------------------------------|----------|---|
| Level of Stakeholder Support | Moderate | We have not identified any reasons that stakeholders would actively support or oppose this technology once fully developed. |
| Fit with BTO Mission | Low | The major technology developer is not interested in receiving government aid to support its R&D (Cox 2013). |

Background

Technology Description

Like thermoelectric technology, thermotunneling (a.k.a. thermionic cooling) is a solid-state cooling technology enabled by the Peltier effect that may be suitable for HVAC applications once fully developed. Thermotunneling is based on the scientific principle that the energy needed to transfer electrons between two surfaces is reduced when the two surfaces are only nanometers apart and operating in a vacuum. This phenomenon is due to a quantum process called quantum tunneling, or field emission.

Thermotunneling cooling systems consist of three main elements, as shown in Figure C-5:

- Under an applied voltage, an electron-emitter plate emits high-energy electrons, cools down as a result, and provides a low-temperature surface.
- An electron-collector plate absorbs high-energy electrons, heats up as a result, and provides a high-temperature surface.
- The proximity of the plates reduces electron migration and determines the overall effectiveness of the thermotunneling process.
- A thin vacuum layer or evacuated gap lies between the plates and reduces backwards heat transfer, thereby raising system efficiency.

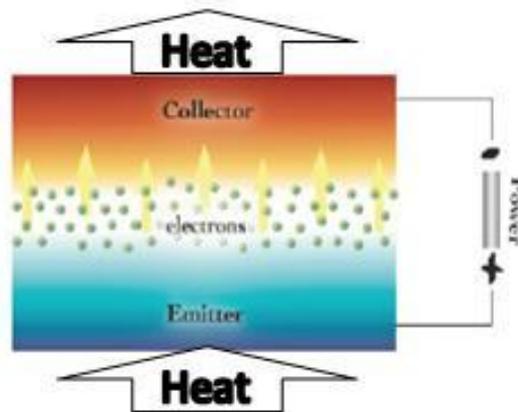


Figure C-5: Schematic of thermotunneling system

Source: CoolChips PLC (2011)

To obtain the advantages of thermotunneling, the plate surfaces of the system must use low-work function materials, which have a low energy threshold for electron emission. Nano-engineering of the material surfaces can further enhance their material properties.

Technical Maturity and Current Developmental Status

This technology is not commercially available and presents significant development challenges that will require long-term R&D efforts to resolve.

Over the course of a 3-year DOE-funded research project, GE investigated various low-work-function materials and identified a number of designs for thermotunneling cooling systems, but did not produce a prototype with sufficient cooling capacity (Weaver et al. 2007).

Borealis Exploration Limited is a private company that is also investigating applications for thermotunneling technology. Brown et al. noted that, despite having many patents, Borealis has not developed a prototype (Brown et al. 2010). However, Borealis reports that they have lab-scale prototypes and are looking to make commercial prototypes under the licensed name of “Cool Chips” (Cool Chips 2011). Moreover, the CEO of Borealis has expressed a preference for supporting its work through private funds rather than receiving assistance from the federal government (Cox 2013).

Barriers to Market Adoption

The limited understanding of the quantum-mechanical effects involved and the nano-scale surface interactions of the materials, as well as challenges in limiting the losses from thermal radiation, are key development challenges for these systems. Moreover, the plates of a thermotunneling device must be normal to each other, separated by only nanometers in a vacuum, to ensure good performance. Maintaining these tight tolerances during manufacturing and throughout the lifetime of the product will therefore be another significant design challenge.

Energy Savings Potential

Potential Market and Replacement Applications

Thermotunneling technology is technically applicable to all heating and cooling applications for residential and commercial buildings. This technology is technically applicable to all climate regions and building types.

Energy Savings

Weaver et al. (2007) reports that, based on theoretical modeling, thermotunneling cooling systems have the potential to reach a Carnot efficiency of 80%, compared to vapor-compression systems that typically operate at 40–45% of Carnot efficiency in HVAC applications (Brown et al. 2010). Accounting for ancillary losses in a complete thermotunneling system, they estimate space-cooling efficiency gains of about 35% over conventional vapor-compression technology.

Borealis (Cool Chips 2011) predicts that thermotunneling cooling modules could achieve 50–55% of Carnot efficiency. However, this estimation does not take into account the system losses associated with fans and other balance-of-plant components in an HVAC application.

Cost, Size, and Complexity

A credible projection of costs for thermotunneling in HVAC applications is not currently available given its early stage of development. However, because their technologies are similar, it is likely that the cost of high-capacity thermotunneling cooling systems would be on par with those of thermoelectric cooling systems, which are significantly more expensive than vapor-

compression systems at cooling capacities greater than 50 W (Dieckmann et al. 2011). However, thanks to advances in solid-state manufacturing techniques, thermoelectric cooling systems will likely become easier to integrate into HVAC systems (Bell 2009). Therefore, costs are likely to decrease as manufacturability improves.

Once fully developed, this solid-state technology would require moving parts (e.g., fans) to distribute thermal energy. The compact size of existing thermoelectric modules suggests that thermotunneling modules could be equally small and simple. Borealis notes that thermotunneling cooling chips will only be a few millimeters thick (Cool Chips 2011).

Peak-Demand Reduction and Other Non-Energy Benefits

Because thermotunneling cooling systems are projected to operate at higher efficiencies than conventional systems, they could provide a commensurate reduction in peak demand.

Like most other solid-state technologies, thermotunneling modules are quieter than vapor-compression systems and can be placed virtually anywhere.

Next Steps for Technology Development

Brown et al. (2010) reports some of the advances that must occur for thermotunneling cooling to be viable, including:

- Research and development of designs that establish and maintain nanometer-scale gaps over larger areas, and keeping electrode materials clean during fabrication and assembly
- Development of low-work-function materials for thermotunneling designs
- Development of semiconductor materials for designs using nano-structured superlattices with improved thermal properties
- Development of more precise control of the energy levels of emitted electrons.

Table C-5 presents the potential next steps to advance thermotunneling technology.

Table C-5: Next Steps for the Development of Thermotunneling Technology

| Initiatives |
|---|
| Identify and investigate various low-work-function materials that could show potential for thermotunneling. |
| Develop the fabrication techniques needed to maintain the precise orientation and conditions. |
| Develop a prototype device showing a verified cooling effect and investigate its performance over time. |

References

Bell, Lon. 2009. “Accelerating the Commercialization of Promising New Thermoelectric Materials.” BSST LLC, Irwindale, California USA. ASM International.

Brown, et al. 2010 “The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications.” PNNL-19259. PNNL. March 2010. Prepared for the U.S. DOE under contract DE-AC05-76RL01830.

Cool Chips PLC. 2011. “Cool Chips – Technical Overview.” Borealis Exploration Limited. Retrieved from <http://www.coolchips.gi/technology/Coolchipstech3Jan06.pdf>.

Cox, Rodney. 2013. CEO of Borealis Exploration Limited. Personal Communication with Caitlin Johnson of Navigant. October 29, 2013.

Dieckmann, John et al. 2011. “Solid-State Cooling, Part 1.” Emerging Technologies – ASHRAE Journal. March 2011. ASHRAE.

Sachs, et al. 2004. “Emerging Energy-Saving Technologies and Practices for the Building Sector as of 2004.” American Council for Energy-Efficient Economy. Report Number A042. October 2004.

Weaver, et al. 2007. “Thermotunneling Based Cooling Systems for High Efficiency Buildings.” Final Technical Report. GE Global Research. DE-FC26-04NT42324.

C.2 Electro-Mechanical Technology Options

Electro-mechanical technology options are activated through electrical input and alter the phase or other properties of a working fluid to pump heat. Table C-6 provides a brief description and final ranking for the technology options selected for in-depth analysis within the Electro-Mechanical Technology Options category.

Table C-6: Summary of Electro-Mechanical Technology Options

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|----------------------------|---|-----------------|--------------------|---------------|
| Brayton Heat Pump | Brayton heat pumps generate usable heating and cooling by compressing and then expanding a gaseous working fluid, which is usually air. | Moderate | R&D | 2.05 |
| Evaporative Cooling | Evaporative cooling systems use water to absorb sensible heat from airstreams, evaporating the water and thus cooling the air. | Low | Available | 3.30 |
| Membrane Heat Pump | Driven by a vacuum pump, advanced-membrane heat pumps provide cooling and dehumidification and/or heating and humidification by transferring moisture across a number of membranes. | Moderate | Emerging | 4.35 |
| Thermoacoustic | Thermoacoustic technology uses high-amplitude sound waves in a noble gas to pump heat. | Moderate | R&D | 2.80 |
| Thermoelastic | Using the unique properties of shape-memory alloys (SMA), thermoelastic cooling systems stress and release a SMA core that absorbs heat from, or rejects heat to, its surroundings. | Moderate | R&D | 4.45 |

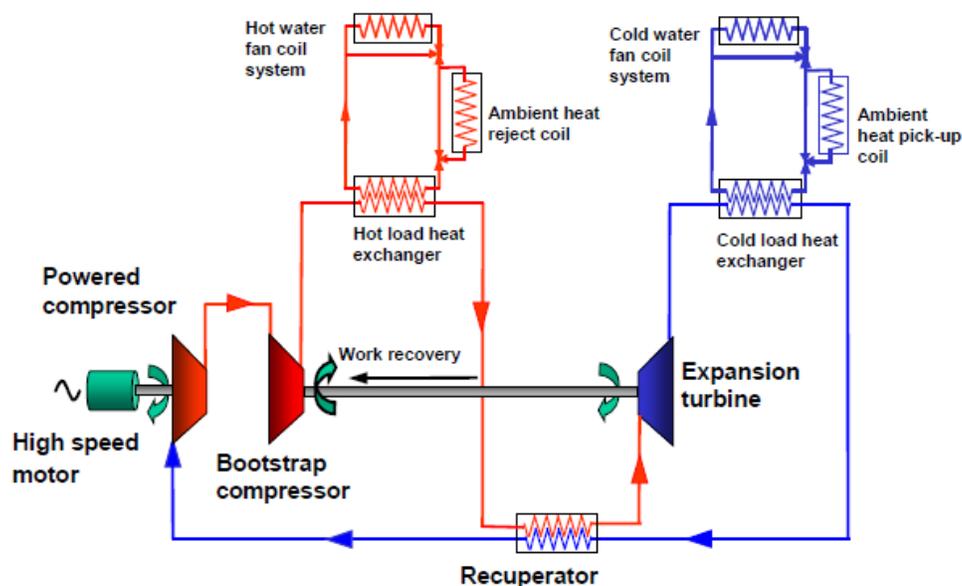
C.2.1 Brayton Heat Pump

| | | |
|----------------------------|---|------------------------|
| Brief Description | Brayton heat pumps generate usable heating and cooling by compressing and then expanding a gaseous working fluid, which is usually air. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 0% | Available for certain industries | Moderate |

| Technology Characteristics | Value | Comments |
|--|----------------------|--|
| Unit Energy Savings | 0% | Heating COPs approx. 1.3–1.6 and cooling COPs approx. 0.5–0.8 (Butler et. al. 2001) |
| Fuel Type(s) | Electricity | <ul style="list-style-type: none"> Electricity for building space conditioning For other applications, other fuels commonly drive the cycle. |
| Working Fluid(s) | Air, CO ₂ | <ul style="list-style-type: none"> Working fluid in gaseous state throughout the cycle Can operate in an open-cycle configuration with ambient air |
| Complexity/Size | Moderate | <ul style="list-style-type: none"> Current systems for aircraft conditioning are compact and lightweight Utilize turbo-machinery operating at high pressures and speeds. |
| Projected Cost | N/A | Cost estimates for HVAC applications are unavailable. |
| Threshold Attributes | High | <ul style="list-style-type: none"> Using air as a refrigerant is attractive for its low or no cost, toxicity, flammability, GWP, ODP, etc. Current systems for aircraft or train conditioning offer higher reliability and lower maintenance than vapor-compression systems. |
| Excitement Attributes | Low | |
| Ability to Utilize Low-Temperature Thermal Sources | N/A | |
| Technical Maturity | Low-to-Moderate | Commercialized for several applications for transportation conditioning, refrigeration, and process cooling. |
| Market Maturity | Low | No products available for building space conditioning |
| Level of Stakeholder Support | Low | Electric utilities unlikely to support this electrically driven technology due to low COPs compared to vapor-compression system. |
| Fit with BTO Mission | Low | Technology has been developed, but has little applicability for building space conditioning. |

Background*Technology Description*

The Brayton cooling cycle operates under the general principal that the temperature of a high-pressure gas will decrease as the gas expands to a lower pressure, and can then provide cooling. Conversely, the temperature of the gas rises when compressed, and can provide space heating. As shown in Figure C-6, the basic components of the cycle include a compressor, an expansion turbine, and high- and low-temperature heat exchangers. Often, the turbine and compressor share a common shaft in a “bootstrap” configuration, so that the expansion work can at least partially offset the required compressor work, improving system COP. Additionally, an internal heat exchanger, also known as a recuperator or regenerator, can pre-condition the gas before compression or expansion to achieve the required hot or cold temperatures more efficiently.

**Figure C-6: Schematic of Brayton cycle**

Source: Butler et al. (2001)

Unlike the vapor-compression cycle, the working fluid does not undergo a phase change, but operates in the gaseous state throughout the cycle. Without phase-change, the system pressures are not limited by the characteristics of the working fluid, but are selected for the desired temperature difference and pressure ratio between the high- and low-pressure sides of the cycle. This allows Brayton heat pumps to operate as an open cycle with ambient air as the working fluid, or as a closed cycle with a refrigerant such as R-744 (CO₂). When operating as an open cycle, desiccants or other drying methods are commonly used to avoid condensation in the expansion turbine. Depending on the application, the Brayton cycle can generate hot and cold temperatures ranging from -100°C (-148°F) to 200°C (392°F) (Lewis et al. 2007).

Technical Maturity and Current Developmental Status

The Brayton cycle has achieved market success in applications where vapor-compression systems pose significant issues. Because of its simple design, high-reliability, and ability to achieve very low temperatures, the Brayton cooling cycle has been used for decades throughout various industries, including:

- Transportation space conditioning (e.g., aircraft, train, ship)
- Commercial and industrial refrigeration (e.g., cold storage, blast freezing, cryocooling)
- Process Cooling (e.g., natural-gas liquefaction).

For these applications, cooling COPs generally range from 0.4 to 0.7 depending on the specific temperature requirements (Lewis et al. 2007).

The components, operations, and performance of the Brayton cycle are well known. Current systems utilize compact turbo-machinery capable of operating at the high speeds (approx. 10,000 RPM and higher) to achieve the required flow rates. The efficiency of the compressor and expander largely determine the COPs for a given application, and high-efficiency components are available for use in aerospace, automotive, and process industries. As a well understood and mature cycle, few have developed products as alternatives to vapor-compression for use in residential and commercial buildings, due to the relatively low heating and cooling COPs. Some of the efforts to date include:

- In the late 1970s, Foster-Miller Associates developed a prototype Brayton-cycle water heater as part of a DOE funded project. With a goal to achieve 1.7 COP, the prototype unit performed with a COP of 1.26 (Dieckmann et. al. 1979).
- At the University of Bristol, a team developed and tested a closed-cycle heat pump to provide heating and cooling to a conference room. The unit achieved a heating COP of 1.33 and cooling COP of 0.53 during testing, and expected heat-exchanger improvements would raise the heating and cooling COPs to 1.62 and 0.78, respectively (Butler et al. 2001).
- In 2009, researchers at California Polytechnic State University, San Luis Obispo designed and tested a Brayton-cycle cooler for automotive space conditioning. The unit achieved a peak COP of 0.73 during a laboratory test (Forster 2009).

Barriers to Market Adoption

For residential and commercial buildings, Brayton-cycle systems have achieved limited interest due to their low system efficiencies compared to vapor compression.

Energy Savings Potential

Potential Market and Replacement Applications

Because the cycle can match most operating temperatures by selecting different pressure ratios, a Brayton heat pump could serve as a replacement for most conventional HVAC systems.

Energy Savings

With heating and cooling COPs below that of conventional vapor-compression systems, Brayton heat pumps are not expected to provide energy savings.

Cost, Size, and Complexity

Brayton heat pumps are relatively simple, lightweight, and compact, especially when operating in an open-cycle configuration where one of the heat exchangers is eliminated. Cost is largely determined by the compressor and expander, with higher-efficiency turbo-machinery carrying a cost premium. Specific cost information is unavailable.

Peak-Demand Reduction and Other Non-Energy Benefits

Currently available products for other industries offer high reliability and minimal maintenance requirements. Brayton heat pumps commonly use air as the working fluid, which offers many benefits as a free, non-toxic, non-flammable, and environmentally benign refrigerant. As an electrically driven cycle, no peak-demand reduction is expected.

Next Steps for Technology Development

Brayton heat pumps offer limited potential for high COPs compared to other conventional and alternative systems, but are a well understood technology with successful adoption in certain applications, such as space conditioning for aircraft or trains. Technically, this technology could serve HVAC applications with limited additional development, but appears to offer little as an alternative to vapor-compression systems.

References

Butler et al. 2001. "Using Air for Cooling." Building Research Establishment Ltd. January 2, 2001.

Dieckmann et al. 1979. "Research and Development of an Air-Cycle Heat-Pump Water Heater." Foster-Miller Associates, Inc. October 1, 1979.

Engelking and Kruse. 1996. "Development of Air Cycle Technology for Transport Refrigeration." International Refrigeration and Air Conditioning Conference. July 1996.

Forster, Christopher. 2009. "Development of an Air-Cycle Environmental Control System for Automotive Applications." California Polytechnic State University - San Luis Obispo. December 2009.

Kikuchi et al. 2005. "Development of Air Cycle System for Refrigeration." Mitsubishi Heavy Industries, Ltd. Technical Review Vol. 42, No. 4. November 2005.

Kruse et al. 2006. "Performance of High Pressure Air Cycle in Comparison With Synthetic and Natural Vapor Compression Refrigeration Cycles." International Refrigeration and Air Conditioning Conference. July 2006.

Lewis et al. 2007. "Fostering the Development of Technologies and Practices to Reduce the Energy Inputs into the Refrigeration of Food – Reviews of Alternative Refrigerant Technologies." Centre for Energy and Built Environment Research. Brunel University. July 2007.

Machida and Boone. 2011. "Development of Air Refrigeration System – Pascal Air." Mayekawa Manufacturing Company, Ltd. International Congress of Refrigeration. August 2011.

McGovern and Duignan. 1994. "An Air Cycle Design Concept for Domestic or Small Commercial Refrigerators." International Refrigeration and Air Conditioning Conference. July 1994.

Nobrega and Sphaier. 2012. "Modeling and Simulation of a Desiccant Assisted Brayton Refrigeration Cycle." International Refrigeration and Air Conditioning Conference. July 2012.

Tassou et al. 2008. "Food Transport Refrigeration - Approaches to Reduce Energy Consumption and Environmental Impacts of Road Transport." Applied Thermal Engineering Vol. 29, Issues 8-9. June 2009.

C.2.2 Evaporative Cooling

| | | |
|----------------------------|--|------------------------|
| Brief Description | Evaporative cooling systems use water to absorb sensible heat from airstreams, evaporating the water and thus cooling the air. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 75% | High | Low |

| Technology Characteristics | Value | Comments |
|--|-------------|--|
| Unit Energy Savings | 75% | Average estimated energy savings over vapor-compression (Dieckmann et al. 2009). |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | Water | Water is evaporated in an open loop. |
| Complexity/Size | Low | Evaporative systems have fewer components than equivalently-sized vapor-compression systems and therefore could potentially be smaller in size. |
| Projected Cost | Low | Advanced evaporative cooling systems currently cost approximately as much as equivalent vapor-compression systems (Dieckmann et al. 2009), although their lower complexity means that they could ultimately be cheaper. |
| Threshold Attributes | Low | Consumes approximately 3 gallons of water per ton-hour of cooling (Dieckmann 2009), freezing danger in the winter, poor reputation due to low performance characteristics of old “swamp cooler” direct evaporative coolers. |
| Excitement Attributes | Moderate | Significant reduction in peak electricity demand. |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Evaporative cooling systems cannot take advantage of waste heat. |
| Technical Maturity | High | Indirect and IDEC technologies are well past the prototype stage and have been commercialized for a number of years. |
| Market Maturity | Moderate | <ul style="list-style-type: none"> Though advanced evaporative cooling technologies are commercially available, they have very low penetration in the hot-dry regions where they are applicable. Many manufacturers (both major and small) produce advanced evaporative systems. |
| Level of Stakeholder Support | High | <ul style="list-style-type: none"> Regional efficiency organizations will likely continue to push for increased use of evaporative technologies (SWEEP/WCEC 2007). Utilities will likely promote evaporative technology because of its potential for peak-demand reduction. |
| Fit with BTO Mission | High | Low technical risk and high potential for stakeholder support for indirect and indirect-direct evaporative coolers currently on the market today. |

Background

Technology Description

For decades, buildings in dry regions of the country have incorporated various evaporative cooling strategies to provide energy-efficient space cooling. Typical direct evaporative coolers, also known as “swamp coolers,” require consistently low wet-bulb temperatures to operate, thus limiting the capacity and geographic reach of the system to states in the Mountain and Southwest regions of the United States. New technologies such as indirect, indirect/direct (IDEC), and hybrid evaporative cooling systems improve the energy efficiency, lower the water consumption, and expand the applicability of evaporative cooling. These technologies are described in detail below.

- **Direct:** Direct evaporative coolers pass supply air through a wetted surface. The water on this surface evaporates into the air, thus simultaneously providing cooling and increasing the air’s humidity.
- **Indirect:** Unlike direct systems, indirect evaporative coolers pass supply air through a heat exchanger channel that is evaporatively cooled by a secondary airstream. Because the supply air never comes in contact with the water, it does not become more humid, leading to more comfortable space cooling and improved indoor air quality.
- **Indirect-Direct:** An indirect/direct evaporative cooler (IDEC) combines both an indirect stage to cool without moisture addition and a direct stage to provide additional cooling with minimal moisture gain. This system allows for independent capacity and humidity control.
- **Hybrid:** Hybrid systems combine an indirect evaporative cooling component with a conventional vapor-compression cooling coil, thus expanding the applicability of evaporative systems to additional climate zones (SWEEP/WCEC 2007). Hybrid systems are described further in Appendix G.
- **Evaporative Liquid Desiccant A/C:** When combined with liquid desiccants, evaporative cooling systems can provide both cooling and dehumidification to address a much broader range of climate conditions. This technology combination is described further in Section C.3.5.

Technical Maturity and Current Developmental Status

Indirect, IDEC, and hybrid evaporative coolers are commercially available from several manufacturers, including Coolerado, Munters, and Applied Air.

Barriers to Market Adoption

Though it has been commercialized for some time, evaporative cooling technology has only achieved limited market penetration, even in hot, dry climates. For example, in 2005, evaporative cooling systems represented only 7% of HVAC equipment installations in California, despite the fact that its hot-dry climate is well-suited to evaporative cooling (Brost 2005). This low adoption rate is indicative of several significant market barriers that evaporative cooling faces:

- **Low applicability:** Evaporative cooling cannot adequately address loads in climate zones with wet-bulb temperatures above 75°F (Kinney 2004). Moreover, even hot-dry climate zones can experience humid conditions for a few weeks per year, severely limiting

evaporative coolers' performance (Higgins 2007). Therefore, as standalone space-cooling equipment, evaporative coolers cannot meet moisture removal requirements at all times of the cooling season, even in hot-dry areas.

- **Water consumption:** Assuming a typical water-utilization efficiency of 50 percent, evaporative cooling technologies consume almost 3 gallons of water per ton-hour (Dieckmann 2009), presenting a potential obstacle in areas where water is very scarce.
- **Potential for freezing damage:** In northern climates, outdoor evaporative cooling systems must be thoroughly drained and dried before the winter months to prevent the possibility of freeze damage (SWEEP/WCEC 2007).
- **Poor reputation:** Because of the capacity, humidity, and maintenance (e.g., scaling or biofouling) problems associated with older direct evaporative coolers, many HVAC contractors and consumers have a distorted view of advanced evaporative technologies (SWEEP/DOE 2007).

Energy Savings Potential

Potential Market and Replacement Applications

Advanced evaporative cooling technology is technically applicable to all space-cooling applications for residential and commercial buildings. This technology is technically applicable to all building types, but only in hot-dry climate regions.

Energy Savings

SWEEP/WCEC (2007) suggests that indirect and IDEC systems can typically achieve 50% and 80% savings, respectively, over equivalent vapor-compression systems.

Dieckmann et al. (2009) estimate that, on average, advanced evaporative cooling technologies are 75% more efficient than equivalent vapor-compression systems.

Cost, Size, and Complexity

Dieckmann et al. (2009) state that advanced evaporative coolers cost approximately as much as equivalent vapor-compression cooling systems.

SWEEP (2004) estimates that advanced evaporative coolers in residential applications cost between \$1,600 and \$3,500 as installed; in comparison, equivalent packaged vapor-compression systems cost, on average, approximately \$2,800 (DOE 2011).

Peak-Demand Reduction and Other Non-Energy Benefits

Because advanced evaporative cooling systems can operate at much higher efficiencies than vapor-compression systems, they could provide a commensurate reduction in peak demand.

Next Steps for Technology Development

SWEEP/WCEC (2007) has identified a number of R&D initiatives that would help expand the market penetration and regional availability of evaporative cooling:

1. Additional field testing in a variety of climate conditions to demonstrate long-term performance and address real or perceived maintenance problems, such as scaling and biofouling.

2. Development of modeling tools for evaluating and comparing the performance of advanced evaporative cooling systems.
3. Further evaluation of the water consumption and water quality associated with evaporative cooling technologies.

SWEEP/WCEC (2007) also identified several non-R&D initiatives, including:

1. Development of a consistent standard and test procedure to compare the energy efficiency of evaporative coolers to that of vapor-compression cooling systems to help raise consumer awareness.
2. Establishment of a regional commitment to cooling efficiency, including AHRI certification of evaporative coolers, to remove regulatory barriers to their installation.

Table C-7 presents the potential next steps to advance evaporative cooling technologies.

Table C-7: Next Steps for the Development of Advanced Evaporative Cooling

| Initiatives |
|---|
| Field testing in a variety of conditions to demonstrate long-term performance, quantify water consumption, and identify potential maintenance problems. |
| Develop highly reliable methods for freeze protection. |
| Development of evaporative cooling modeling tools |

References

Brost, Matt. 2005. “2005 California Statewide Residential Lighting and Appliance Efficiency Saturation Study.” RLW Analytics. Final Report. August 23, 2005.

Coolerado. 2011. “How It Works: Coolerado Hybrid H80.” Coolerado Corporation. Retrieved from <http://www.coolerado.com/>.

Dieckmann et al. 2009. “Going ‘Back to the Future’ of Evaporative Cooling.” ASHRAE Journal. May, 2009.

DOE. 2011. Technical Support Document for Residential Central Air Conditioners, Heat Pumps, and Furnaces Rulemaking, Direct Final Rule. U.S. Department of Energy. June 2011.

Higgins, Cathy and Reichmuth, Howard. “Desert CoolAire Package Unit Technical Assessment – Field Performance of a Prototype Hybrid Indirect Evaporative Air-Conditioner.” New Buildings Institute. Final Report, July 2007.

Kinney, Larry. 2004. “Evaporative Cooling for a Growing Southwest: Technology, Markets, and Economics.” Southwest Energy Efficiency Project. August, 2004.

Shepherd-Gaw, David. 2011. "Technology Spotlight: Hybrid Evaporative/DX Compressor Air Conditioners." Western's Energy Services Bulletin. March 31, 2011. Retrieved from <http://www.e3tconnect.org/profiles/blogs/technology-spotlight-hybrid>.

SWEEP. 2004. "New Evaporative Cooling Systems: An Emerging Solution for Homes in Hot Dry Climates with Modest Cooling Loads." Prepared for the Building America Program, U.S. DOE; Southwest Energy Efficiency Project (SWEEP). April 2004.

SWEEP/DOE. 2007. "Evaporative Cooling Policy and Program Options: Promising Peak Shaving in a Growing Southwest." Southwest Energy Efficiency Project (SWEEP). U.S. Department of Energy. May 2004.
http://www.swenergy.org/publications/documents/Evaporative_Cooling_Policy_Options.pdf.

SWEEP/WCEC. 2007. "SWEEP/WCEC Workshop on Modern Evaporative Cooling Technologies Workshop Summary." Southwest Energy Efficiency Project (SWEEP) and UC Davis Western Cooling Efficiency Center (WCEC). September 14, 2007.

C.2.3 Membrane Heat Pump

| | | |
|----------------------------|---|------------------------|
| Brief Description | Driven by a vacuum pump, advanced-membrane heat pumps provide cooling/dehumidification and/or heating/humidification by transferring moisture across a number of membranes. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 50% | Emerging | Moderate |

| Technology Characteristics | Value | Comments |
|--|-------------|--|
| Unit Energy Savings | 50% | For space-cooling, researchers claim that EER is twice that of vapor-compression systems, resulting in energy savings of 50% (Baxter 2014, Ehrenberg 2011). |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | Water | |
| Complexity/Size | Moderate | <ul style="list-style-type: none"> Prototypes are approximately the same size as vapor-compression systems of equivalent capacity. Requires several moving parts, including two pumps. Includes a heat-transfer loop (EE&T 2011). |
| Projected Cost | Moderate | Requires commercially available HVAC parts (Dais Analytic 2012); likely to cost approximately the same as vapor compression. |
| Threshold Attributes | Moderate | <ul style="list-style-type: none"> Benefits: Uses components that are familiar in HVAC applications (e.g., pumps) and should thus be easy to install and maintain (Dais Analytic 2012). Drawbacks: Consumes approximately 1.5-3 gallons of water per ton-hour of cooling. |
| Excitement Attributes | High | Provides dehumidification, independent control of temperature and humidity (Baxter 2014, Dais Analytic 2012). |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Advanced-membrane heat pumps cannot take advantage of waste heat. |
| Technical Maturity | Moderate | <ul style="list-style-type: none"> Dais Analytic has developed a second-generation A/C prototype using a membrane successfully commercialized in other applications (Dais Analytic 2012). Dais Analytic is supported by the DOE through ARPA-e funding and by the Department of Defense through ESTCP funding (ARPA-e 2013, Dais Analytic 2012). |
| Market Maturity | Low | <ul style="list-style-type: none"> Membrane heat pumps have not yet been commercialized. Dais Analytic is the only company we have identified that is attempting to commercialize membrane heat-pump technology in HVAC. |

| | | |
|-------------------------------------|------|--|
| Level of Stakeholder Support | High | Electric utilities are likely to support membrane heat-pump technology due to its potential for peak-demand reduction. |
| Fit with BTO Mission | High | <ul style="list-style-type: none"> • Technology has potentially high COPs, but high technical risk (which fits well with BTO’s mission) • Requires additional investigation to scale up initial prototypes |

Background

Technology Description

Emerging research in material science and nanotechnology has led to the development of selectively permeable membranes that transport water molecules across their surface very efficiently while inhibiting the migration of air. Already commercialized for water purification and enthalpy heat-recovery units, the capabilities of the membranes could supply high-efficiency dehumidification and cooling. Figure C-7 provides a schematic of the cooling process for one configuration of an advanced-membrane heat pump (EE&T 2011):

- Warm, humid air passes across a dehumidifier (1) lined with a membrane that is permeable to water vapor, but not dry air. A vacuum pump (2) creates a partial vacuum across the dehumidifier membrane that removes moisture from the airstream.
- After leaving the dehumidifier, the warm, dry air passes over a heat exchanger (3) cooled by a chilled-water loop and enters the conditioned space.
- A chiller (4), consisting of a water channel lined with the membrane, cools a water loop by evaporating a portion of the water. The vacuum pump (2) creates a partial vacuum that evaporates a portion of the liquid water as it travels across the same type of membrane used in the first step.
- The vacuum pump (2) pumps the water vapor from the dehumidifier (1) and chiller (4), and expels it through an expirator, which is a pump that pushes water through a third set of selectively permeable membranes to the atmosphere (5).

Alternatively, water spray, groundwater coupling, or other non-vapor-compression cooling technologies may also be used to provide the sensible cooling step in lieu of the chiller concept discussed above (Baxter 2014).

When configured as a reversible heat pump, the system can also provide humidification and heating (EE&T 2011), although the coupled nature of these heating and humidification functions may limit its space-heating applicability.

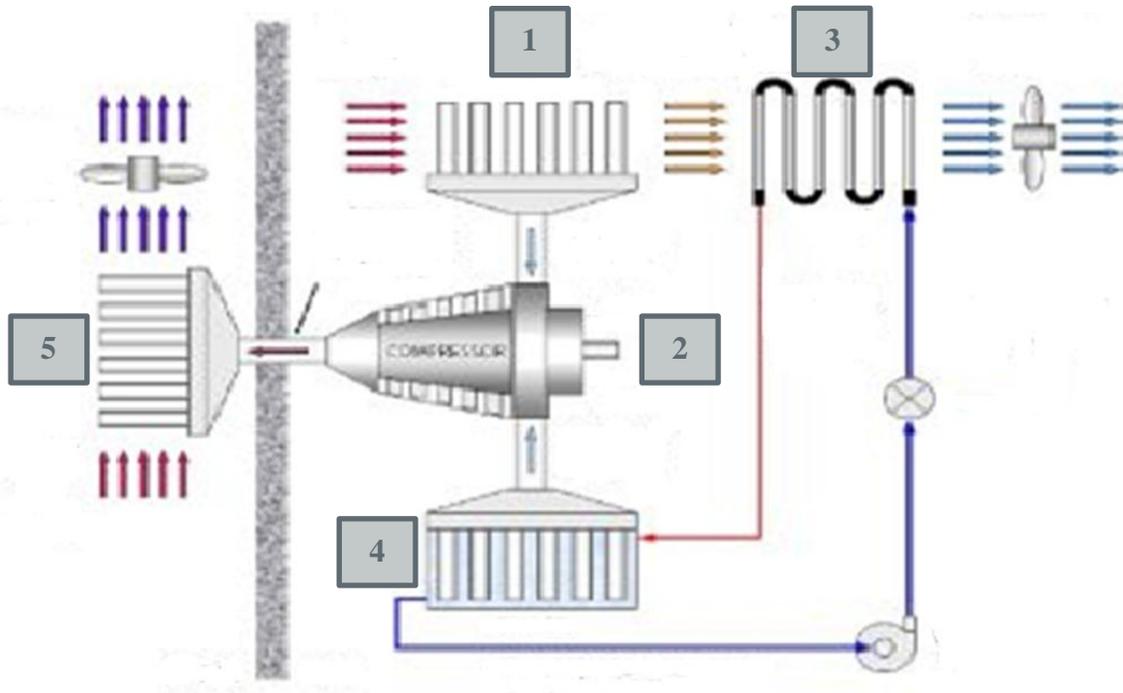


Figure C-7: Advanced membrane cooling process

Source: EE&T (2011)

Note: Red arrows indicate warm, humid air; yellow arrows indicate warm, dry air; and blue arrows indicate cool, dry air. Everything depicted to the right of the vertical partition is an indoor component.

Technical Maturity and Current Developmental Status

Researchers at Dais Analytic have received research grants through DOE’s ARPA-e program and the Department of Defense’s Environmental Security Technology Certification Program (ESTCP) to demonstrate the capabilities of their Aqualyte membrane for HVAC applications (ARPA-e 2013, Dais Analytic 2012). They have produced a 1-ton prototype air conditioner, branded as “NanoAir,” that is now in its second generation, and are currently planning to produce and field-test 5-ton prototype systems. The company ultimately hopes to partner with HVAC manufacturers to commercialize the components of the NanoAir system and license their processes for use in OEM product offerings. Dais Analytic has already commercialized their Aqualyte membranes as the core component in fixed-plate, energy-recovery ventilators (ERV) manufactured by MultiStack. Dais is currently using off-the-shelf vacuum pumps in their prototype and has identified further development of these components as a future focus (Baxter 2014). Additionally, because Dais’ current research focuses on the dehumidification components and not the chiller, additional development of this component will advance understanding of NanoAir’s sensible cooling capabilities.

Barriers to Market Adoption

The chiller used to provide sensible cooling to the airstream consumes water. Based on the cooling capacity of water, this chiller would consume at least 1.5 gallons of water per ton-hour of sensible cooling. However, if its water-utilization efficiency is as low as 50 percent (a typical

value for evaporative coolers), such a chiller would consume almost 3 gallons of water per ton-hour of cooling.

Energy Savings Potential

Potential Market and Replacement Applications

Membrane heat-pump technology is technically applicable to all heating and cooling applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types.

Energy Savings

Dais Analytic predicts that its NanoAir prototype will have a system EER of 26 (Dais Analytic 2012), which is more than double the EER of the most efficient vapor-compression air conditioners on the market today. Consequently, the increased EER of membrane heat pumps could result in energy savings of 50% (Ehrenberg 2011). Dais estimated these energy savings under SEER rating conditions using water spray, rather than their chiller design, to provide the sensible cooling step (Baxter 2014). Dais acknowledges that these savings projections are preliminary and that their evaluation of membrane heat pump performance should improve as they complete their next ARPA-e cycle (Baxter 2014).

We have not identified projections for the heating strategy of the NanoAir prototype when running in reverse. Because of this uncertainty, we only analyzed the energy savings of this technology in cooling mode.

Cost, Size, and Complexity

We have not identified any publicly available, credible projection of costs for membrane heat-pump technology in HVAC applications.

The membrane heat-pump system requires several moving parts, including pumps to create a vacuum, expel excess water, and circulate the water in the heat-transfer loop. It also requires a constant water supply. However, all of these components are familiar and available within the HVAC industry, and Dais Analytic has already commercialized the core membrane technology (Dais Analytic 2012). We therefore estimate that their NanoAir system should be roughly equivalent to vapor compression in its cost and complexity.

The current NanoAir prototype takes up approximately as much space as a vapor-compression air-conditioning system with the same capacity (EE&T 2011).

Peak-Demand Reduction and Other Non-Energy Benefits

Because membrane heat-pump systems are projected to operate at higher efficiencies than conventional systems, they could provide a commensurate reduction in peak demand.

According to Dais Analytic, NanoAir's membrane technology enables it to combine the benefits of a heat pump and humidifier in one system, which could be considered a benefit by end users who would otherwise install a separate humidifier. Additionally, developers suggest that NanoAir can independently control temperature and humidity, leading to improved indoor air conditions (Baxter 2014, Dais Analytic 2012).

Although researchers claim that NanoAir operates silently (EE&T 2011), many vacuum pumps on the market today are at least as loud as compressors. Therefore, it is unclear whether membrane heat pumps will be quieter than vapor compression.

Next Steps for Technology Development

Now that researchers have developed a second-generation prototype of a membrane heat-pump system and are in the process of developing larger, 5-ton prototypes, they will need to provide test results that confirm that this technology saves energy compared to vapor compression. Additionally, further investigation is needed to understand the humidification-heating capabilities of a reverse-driven system. Finally, further development of the vacuum pump and chiller could improve the performance of these components in a membrane heat pump application.

Table C-8 presents the potential next steps to advance membrane heat pump technology.

Table C-8: Next Steps for the Development of Advanced Membrane Heat Pumps

| Initiatives |
|--|
| Develop and field test larger-scale prototypes |
| Further investigation and testing of heating/humidification applications |
| Further specification and/or development of vacuum pump and chiller components |

References

Advanced Research Projects Agency – Energy (ARPA-e), date unknown. “Dais Analytic Corporation: Nanotechnology Membrane-Based Dehumidifier.” Building Energy Efficiency through Innovative Thermodevices (BEETIT) Project Description. Retrieved November 13, 2013 from <http://arpa-e.energy.gov/?q=arpa-e-projects/dehumidifying-air-cooling-refrigeration>.

Baxter, Stephen. 2014. Director of Engineering and Quality, Dais Analytic. Personal Communication with Caitlin Johnson of Navigant. March 3, 2014.

Dais Analytic. 2012. Retrieved from <http://www.daisanalytic.com/>.

EE&T. 2011. “DOE Takes a Look at Refrigerant-Free A/C.” Energy Efficiency & Technology. March 2, 2011.

Ehrenberg, Scott. 2011. Chief Technology Officer of Dais Analytic. Personal Communication with Jim Young. December 22, 2011.

C.2.4 Thermoacoustic

| | | |
|----------------------------|--|------------------------|
| Brief Description | Thermoacoustic technology uses high-amplitude sound waves in a noble gas to pump heat. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 0% | R&D | Moderate |

| Technology Characteristics | Value | Comments |
|---|-------------|---|
| Unit Energy Savings | 0% | <ul style="list-style-type: none"> Thermoacoustic efficiency in HVAC applications has not been publicly documented. However, models predict that, at typical space-cooling conditions, the maximum theoretical efficiency of thermoacoustic technology is lower than the maximum theoretical efficiency of vapor compression. However, this technology may save energy in refrigeration applications. The maximum efficiency achieved by current supermarket chiller prototype is 37% of Carnot efficiency, which is higher than the efficiency of equivalent vapor-compression refrigeration systems (27% of Carnot) (Garrett 2013). |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | None | |
| Complexity/Size | Moderate | Low complexity, though large heat exchangers are required, so size may be large (Brown et al. 2010). |
| Projected Cost | Moderate | Projected to be on par with the cost of vapor-compression systems from a high-production-volume perspective (Trevino 2013), although many necessary components are rare in the refrigeration industry and are, therefore, currently expensive (Garrett 2013). |
| Threshold Attributes | N/A | We have not identified any projections of the safety, reliability, maintainability, or lifetime of thermoacoustic technology. |
| Excitement Attributes | High | Well-suited to proportional control and capacity modulation (Garrett 2013). |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Thermoacoustic cooling systems cannot use waste heat, unless they are coupled with a thermoelectric engine run in reverse as generators (Garrett 2013). |
| Technical Maturity | Moderate | The thermoacoustic effect has been studied for over 200 years, and several institutions have developed patents and prototypes for a variety of refrigeration applications and some HVAC applications. |

| | | |
|-------------------------------------|----------|---|
| Market Maturity | Low | <ul style="list-style-type: none"> • Navigant is only aware of one commercialized application for thermoacoustic technology: a cryogenic commercial refrigeration product manufactured and sold by Chart Industries (Garrett 2013). • At least one public company is attempting to commercialize thermoacoustic technology in HVAC (Trevino 2013). • PSU has sub-licensed its technology to Heatcraft, a major HVAC manufacturer, to develop a supermarket chiller for commercialization (Garrett 2013). |
| Level of Stakeholder Support | Moderate | We have not identified any reasons that stakeholders would actively support or oppose the technology once fully developed. |
| Fit with BTO Mission | Moderate | <ul style="list-style-type: none"> • It is unclear whether or when the technology will be as efficient as vapor compression in HVAC applications, and it cannot be more efficient than vapor compression in HVAC applications because its maximum theoretical efficiency is lower. • However, the technology has potential for significant savings when commercialized in refrigeration applications. |

Background

Technology Description

Thermoacoustic technology utilizes the propagation of sound waves in a gas to pump heat. Sound waves are pressure oscillations that cause gas to compress and expand. When gas is compressed, it heats up, and it cools down when it expands. Gas will also flow from high- to low-pressure regions, thus enabling it to do work as a heat engine or to provide cooling as a heat pump. Although this effect occurs in all sound waves, the amplitudes of typical sound waves do not produce noticeable cooling: the decibel level of loud speech will only cause temperature fluctuations of approximately 0.00002°F. However, resonators can amplify the sound wave and consequently amplify its cooling effect.

There are two types of thermoacoustic devices: standing-wave and traveling-wave (or Stirling cooler) devices. Standing-wave thermoacoustic devices (as shown in Figure C-8) produce cooling by having a loudspeaker generate a standing wave in the resonator. Such a device has a hot and a cold heat exchanger separated by a “stack,” comprised of parallel plates or tubes made of a material with low thermal conductivity, such as glass or ceramic that slows heat transfer between the two heat exchangers. The gaseous working fluid (typically a noble gas) is located in between these plates, which are spaced to prevent adiabatic or isothermal expansion and contraction of the gas. Instead, the gas oscillates back and forth between the cold and hot heat exchangers.

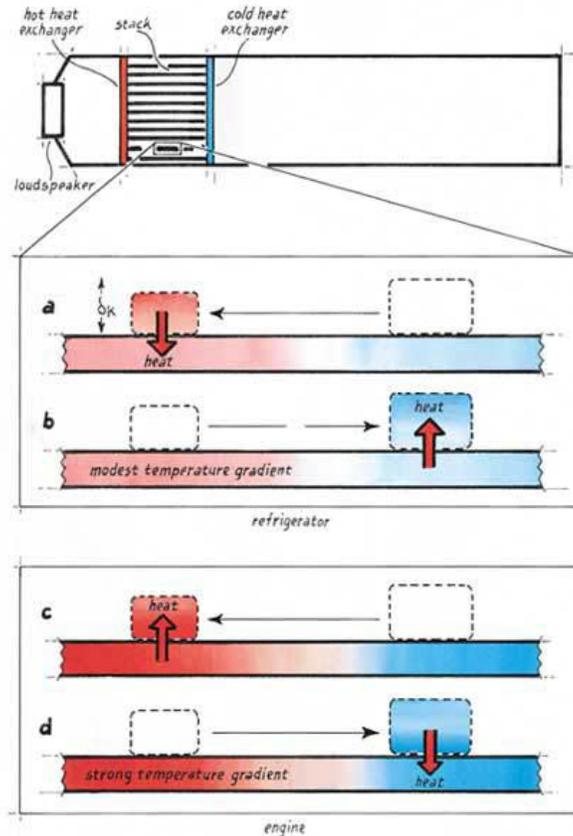


Figure C-8: Standing-wave heat pump and heat engine

Source: Brown (2011)

As shown in Figure C-8, once a standing wave is generated, a parcel of gas will move to the left, become compressed, and consequently heat up. Ultimately, the gas becomes hotter than the stack, so it rejects heat into the stack material and begins to move to the right, as shown in Figure C-9. The gas then expands and cools until it is cooler than the stack, at which point it absorbs heat and begins the cycle again. This repetitive action pumps heat from the cold heat exchanger to the hot heat exchanger.

Traveling-wave devices are similar to standing-wave devices except that they utilize a regenerator rather than a stack. The spaces in which gas oscillates within a regenerator are very small to promote good thermal contact with the gas.

A traveling-wave device is shown in Figure C-9. In such a device, a parcel of gas is compressed adiabatically by the sound wave in the space outside the regenerator, causing it to heat up. The parcel is displaced through the regenerator and rejects heat to it, expanding and cooling on the opposite side of the regenerator. The sound wave then causes the gas to move backwards through the regenerator, absorbing the same amount of heat from the cold end of the regenerator as it had rejected into the hot end (Brown 2010).

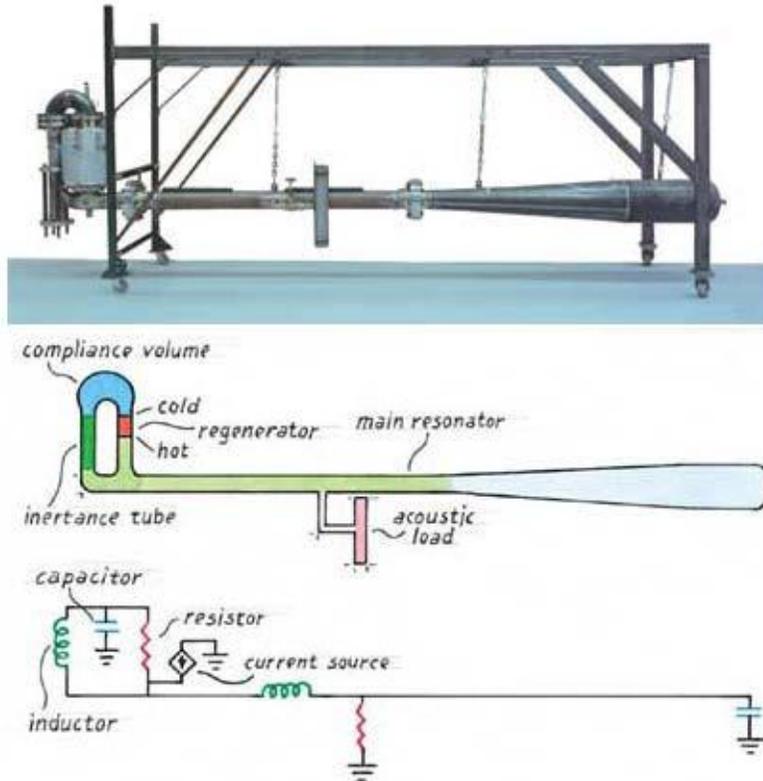


Figure C-9: Traveling-wave heat pump
Source: Brown (2010)

Both types of thermoacoustic cycles can technically be run in reverse, meaning that they can also provide space heating.

Technical Maturity and Current Developmental Status

Currently, one thermoacoustic product is commercially available: a cryogenic freezer manufactured by Chart Industries (Garrett 2013). Most research to date has focused on refrigeration applications, rather than HVAC applications.

DOE has funded thermoacoustics work for over thirty years, starting with research conducted at Los Alamos National Laboratory (Keolian and Poese 2013). DOE funded a thermoacoustic cooling project researched by Pennsylvania State University (PSU) through the ARPA-e program (ARPA-e 2013). Through their exclusive licensee, ThermoAcoustics Corporation, PSU's lead researchers have partnered with Heatcraft Worldwide Refrigeration, a business segment of Lennox International, to develop and eventually commercialize a supermarket chiller for refrigeration applications using thermoacoustic technology. This ARPA-e grant was initially focused on developing a thermoacoustic window air conditioner with a net COP of 4.0 that would remain within certain volumetric restrictions. At the time, PSU researchers were unable to reach these targets, so they refocused on supermarket refrigeration, which they found better suited to the technology's current strengths and the team's experience, as PSU has built several working prototypes of thermoacoustic refrigeration products in the past (Garrett 2013).

Despite their past failures in space cooling, the PSU team maintains that current thermoacoustic technology can be successful in niche air-conditioning applications (e.g., portable coolers for the military) and residential space heating, and that other space-cooling applications will become more attractive as heat-exchanger performance improves (Garrett 2013).

According to PSU, two Dutch companies (ECN and Aster Thermoacoustics) have developed several working prototypes for waste-heat recovery and a variety of other thermoacoustic applications; additionally, at least two companies, including Nirvana Energy Systems, are developing thermoacoustic electric generators (Garrett 2013, Nirvana 2013).

Cool Sound Industries (recently acquired by Global Digital Solutions Inc. [GDSI]) is a publicly traded company that is developing thermoacoustic technology for HVAC applications. They have had several offers of interest from companies outside the United States and are working to commercialize their technology. GDSI's current focus is on military (e.g., cooling for rocket launchers and nuclear subs) or remote applications (e.g., those that could be powered with a car battery or solar DC power), but they are looking towards expanding this focus to conventional residential and commercial HVAC applications. GDSI recently acquired a large engineering firm to increase their manufacturing capabilities (Trevino 2013).

All of the thermoacoustic prototypes described above utilize standing-wave technology.

Barriers to Market Adoption

As described further in the "Next Steps" section below, the heat exchangers are currently the least-understood component of thermoacoustic systems and must be optimized to increase overall system power density. Additionally, unlike vapor-compression equipment, which utilizes rotary motors, thermoacoustic technology requires linear motors. Although linear motors use the same materials as rotary motors and are easier to fabricate, they can currently only be purchased from two suppliers (Garrett 2013), thus inhibiting widespread adoption of thermoacoustic technology for HVAC applications.

Energy Savings Potential

Potential Market and Replacement Applications

Thermoacoustic technology is technically applicable to all space-heating and cooling applications for residential and commercial buildings. This technology is also technically applicable to all climate regions and building types.

Energy Savings

Researchers at Purdue University have developed a design optimization program that they used to determine the maximum possible Carnot efficiencies of standing-wave thermoacoustic coolers in their most common configurations. Their modeling results indicate that the Carnot efficiency of thermoacoustic coolers increases with temperature span, making it more suitable for general or low-temperature refrigeration applications than for space-cooling applications, for which they predicted maximum theoretical efficiencies lower than that of vapor compression (Paek et al. 2006). GDSI claims that it has achieved significant savings over vapor compression with its thermoacoustic cooling technology, but has not provided documentation of these savings (Trevino 2013).

Although current documentation of performance focuses on refrigeration and space-cooling applications, thermoacoustic technology can also be used in space-heating applications. For example, the PSU team envisions a heat-driven thermoacoustic heat pump to enhance a furnace or domestic water heater (Koelian and Poese 2013). However, we have not identified any performance information for thermoacoustic technology in space-heating applications.

Although it is not in the scope of this HVAC-centered report, PSU has reported energy savings information for their thermoacoustic technology as implemented in their 1-ton supermarket refrigeration prototype, called “Trillium.” According to Garrett (2013), Trillium currently has a COP that is 37% of Carnot efficiency at a source temperature of -20°F and a sink temperature of 95°F. This is higher than the efficiency of typical vapor-compression refrigeration systems (27% of Carnot) and could increase further with additional development of thermoacoustic components, although the theoretical limit of standing-wave applications is 40–50% of Carnot for refrigeration applications (Brown 2010).

Cost, Size, and Complexity

We have not identified any credible projection of costs for thermoacoustic technology in HVAC applications, although PSU indicates that Heatcraft will be developing preliminary cost estimates in early 2014. PSU also notes that, although high-efficiency, moving-magnet linear motors are easier to fabricate than rotary motors and contain roughly the same materials, they are currently special-order items available from only two manufacturers (Garrett 2013). However, they estimate that, in a world of equal demand volumes, their Trillium refrigeration prototype would cost the same as an equivalent vapor-compression system (Keolian and Poese 2013). GDSI estimates that thermoacoustic cooling technology will cost as much as, or less than, vapor-compression technology (Trevino 2013).

Once fully developed, this technology would require heat exchangers, fans, and a heat-transfer fluid loop to distribute thermal energy (Garrett 2013). Thermoacoustic cooling technology is not currently as power-dense as vapor-compression technology, so it requires more space for the same cooling capacity (Brown et al. 2010).

Peak-Demand Reduction and Other Non-Energy Benefits

The only moving part in the core thermoacoustic cooling system is the loudspeaker, which gives it an advantage over vapor compression in simplicity and maintainability. PSU and Brown et al. note that, because the linear motors used in thermoacoustic technology are controlled by modulating amplitude (as opposed to rotary motors, which are controlled by modulating frequency), they are easier to control and can maintain efficiency over a range of capacities. Therefore, this technology can easily adapt to meet a wide range of loads (Garrett 2013, Brown et al. 2010). This feature only represents a potential advantage over vapor-compression systems using single-speed compressors, which can only be operated at full capacity and therefore must be cycled on and off (Brown 2010). However, at this stage, it is unclear whether thermoacoustic technology provides any advantage over vapor-compression systems utilizing variable-speed compressors.

GDSI asserts that thermoacoustic technology is highly reliable and can last two to three times as long as vapor-compression (Trevino 2013). However, GDSI did not reference any documented test results to support these claims.

Next Steps for Technology Development

PSU reports the following advances that must occur for thermoacoustic cooling to become commercially available (Keolian and Poese 2013):

- **Improved heat exchangers:** To facilitate the isothermal steps in the thermoacoustic cycle, heat exchangers must have very textured surfaces to increase surface area while still allowing liquid to flow through them. Currently, the heat exchangers in PSU’s Trillium prototype account for half of the system’s efficiency losses and are the least-understood components. They also contribute to thermoacoustic systems’ low power density.
- **Increased understanding of the basic science behind thermoacoustics:** All funding for thermoacoustics work thus far has focused on applied engineering rather than the scientific fundamentals of this phenomenon. Improved understanding of the basic principles would facilitate future design work (Keolian and Poese 2013).
- **Increased production and availability of linear motors and other acoustic components,** although production of these components would increase as demand for thermoacoustic technology increases.

Table C-9 presents the potential next steps to advance thermoacoustic technology.

Table C-9: Next Steps for the Development of Thermoacoustic Technology

| Initiatives |
|---|
| Develop novel heat exchangers that will improve the efficiency and power density of thermoacoustic systems. |
| Test thermoacoustic devices run in reverse to assess their applicability to and efficiency in space-heating applications. |
| Support research into the basic physics behind thermoacoustic technology. |

References

Advanced Research Projects Agency – Energy (ARPA-e), date unknown. “Pennsylvania State University: Helium-Based Soundwave Chiller.” Building Energy Efficiency through Innovative Thermodevices (BEETIT) Project Description. Retrieved November 5, 2013 from <http://arpa-e.energy.gov/?q=arpa-e-projects/helium-based-soundwave-chiller>.

Brown, et al. 2010. “The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications.” PNNL-19259. PNNL. March 2010. Prepared for the U.S. DOE under contract DE-AC05-76RL01830.

Garrett, Steven. 2013. Professor of Acoustics at Pennsylvania State University. Personal Communication with Caitlin Johnson of Navigant. November 1, 2013.

Keolian, Robert and Poese, Matt. 2013. Associate Professor of Acoustics and Research Associate, respectively, at Pennsylvania State University. Personal Communication with Caitlin Johnson of Navigant. November 7, 2013.

Nirvana Energy Systems. 2013. Retrieved December 26, 2013 at <http://nirvanas.com/technology.html>.

Paek, Insu et al. 2006. "Evaluation of Thermoacoustic Cycles for Cooling Applications." International Refrigeration and Air Conditioning Conference. Paper 825.

Trevino, Ross. 2013. Director of Business Acquisitions, Global Digital Solutions, Inc. Personal Communication with Caitlin Johnson of Navigant. October 31, 2013 and November 5, 2013.

C.2.5 Thermoelastic

| | | |
|----------------------------|---|------------------------|
| Brief Description | Using the unique properties of shape-memory alloys (SMA), thermoelastic cooling systems stress and release a SMA core that absorbs heat from, or rejects heat to, its surroundings. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 47% | R&D | Moderate |

| Technology Characteristics | Value | Comments |
|---|-------------|---|
| Unit Energy Savings | 47% | COP of 6.0 projected in HVAC applications, compared to COP of 3.21 for baseline vapor-compression systems (Takeuchi 2013). |
| Fuel Type(s) | Electricity | |
| Working Fluid(s) | None | |
| Complexity/Size | Moderate | Cooling mechanism includes moving parts (rotating actuators). |
| Projected Cost | Moderate | Under mass production, system cost is projected to be roughly on par with that of vapor-compression systems (Takeuchi 2013). |
| Threshold Attributes | Low | Includes moving parts; very frequent loading cycles may induce fatigue and result in a short lifetime (Cui et al. 2012a). |
| Excitement Attributes | Low | None identified. |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Thermoelastic technology cannot take advantage of waste heat streams. |
| Technical Maturity | Low | Technology is in early R&D stage; we have identified documentation of only one proof-of-concept prototype, being developed by UMD and PNNL and supported by DOE through ARPA-e funding (ARPA-e 2013). |
| Market Maturity | Low | <ul style="list-style-type: none"> We are not aware of any applications, HVAC or otherwise, that currently employ thermoelastic technology. MEST, the startup associated with UMD, is supported by the NSF through SBIR funding (NSF SBIR 2013). MEST also has a small contract with a major HVAC manufacturer (Takeuchi 2013). |
| Level of Stakeholder Support | High | Electric utilities are likely to support the technology due to its potential for peak-demand reduction. |
| Fit with BTO Mission | High | <ul style="list-style-type: none"> Technology has potentially high COPs, but high technical risk (which fits well with BTO's mission) Requires additional development to prove performance in HVAC applications. |

Background

Technology Description

Through the deformation of a shape-memory alloy (SMA), thermoelastic (a.k.a. elastocaloric) cooling devices could replace conventional, compressor-driven air-conditioning and heat-pump systems because of the unique properties of the SMA materials. When mechanically stressed, SMA materials undergo a solid-to-solid martensitic phase transformation and reject heat¹³ to their surroundings. Because this phase transformation is reversible, SMA materials subsequently absorb heat as they return to their original shape.

Thus far, publicly documented experiments with thermoelastic cooling have focused on the use of nickel-titanium alloy (nitinol, or NiTi) wires (Takeuchi 2011). These wires were stressed (under either tension or compression) until reaching their strain limit, at which point their temperatures rose due to their phase transformation and subsequent release of heat. After reaching thermal equilibrium with the air, the wires were then unloaded, causing them to rapidly cool down. This phenomenon is illustrated in Figure C-10.

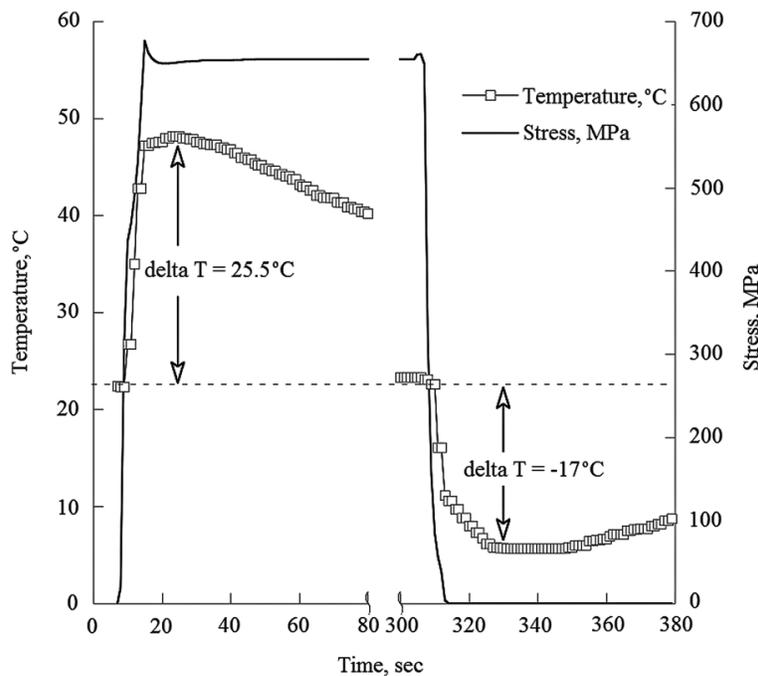


Figure C-10: Temperature and stress curves of NiTi

Source: Cui et al. (2012a)

A thermoelastic cooling system consisting of a SMA plate connected between two rotary actuators could produce usable space cooling by oscillating the SMA core.¹⁴ Such a system would likely operate at a frequency of 1 Hz, resulting in over 78 million stress-induced phase transformation over a ten-year lifetime, assuming operation of 6 months per year and 12 hours

¹³ In this application, researchers use the term “latent heat” to refer to the heat absorbed or released during any type of phase transition. However, to avoid confusion, we do not use this term in our report.

¹⁴ We were unable to obtain a clear description for how this oscillation is accomplished.

per day (Cui et al. 2012a). In an alternate configuration, a thermoelastic cooling system could consist of a circulating SMA belt that provides continuous space-conditioning as one side of the belt is stressed and the other is released, as illustrated in Figure C-11 (Cui et al. 2012b).

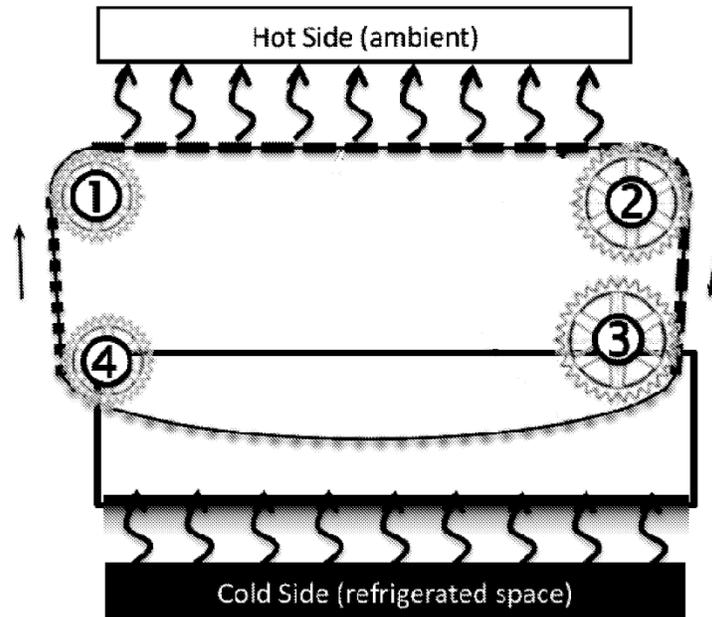


Figure C-11: Circulating implementation of thermoelastic cooling system

Source: Cui et al. (2012b)

Technical Maturity and Current Developmental Status

DOE is funding a thermoelastic cooling project co-researched by the University of Maryland (UMD), GE, and PNNL through the ARPA-e program (ARPA-e 2013). Lead researchers have developed an SMA material capable of thermoelastic cooling with the hopes of applying it to HVAC. The UMD team's proof-of-concept prototypes using thin NiTi wires as the thermoelastic material exhibit high COPs, as described in a later section. The UMD team is currently working with PNNL to design and test a 120 Btu/hr. prototype thermoelastic cooling system (Haas 2012), and they plan to develop a full-scale window air-conditioning unit within the next two years (Takeuchi 2013).

UMD has exclusively licensed its thermoelastic cooling technology to Maryland Energy and Sensor Technologies (MEST), a startup founded by Dr. Ichiro Takeuchi, leader of the UMD team. MEST received a Small Business Innovation Research (SBIR) Phase I grant from the U.S. government in 2012 to support its development of thermoelastic materials with long fatigue life (NSF SBIR 2013). Dr. Takeuchi claims that many major HVAC manufacturers have visited his lab facility and expressed interest in thermoelastic technology. MEST indicates that they have signed a small contract with one of these large manufacturers. In addition to supporting HVAC applications, MEST is exploring the possibility of using thermoelastic technology for refrigeration, passenger cooling in automobiles, and hand-crank instant cooling products. MEST

recently received a grant from the State of Maryland to support the development of a prototype for a car air-conditioning system (Takeuchi 2013).

Barriers to Market Adoption

Cui et al. (2012a) note that one potential disadvantage of SMA materials in HVAC applications is their low fatigue life. SMA materials used for thermoelastic cooling would undergo 78 million stress-induced phase transformations over the course of a ten-year lifespan and therefore must resist crack propagation or have no pre-existing cracks at or above the critical size of 14 microns. Developing materials that meet such stringent fatigue property requirements could prove difficult.

Energy Savings Potential

Potential Market and Replacement Applications

Thermoelastic technology is technically applicable to all heating and cooling applications for residential and commercial buildings. This technology would also be technically applicable to all climate regions and building types. Because the martensitic phase transformation of SMA materials is reversible, thermoelastic technology could be used for heat pumps as well as air conditioning.

Energy Savings

Cui et al. (2012a) have experimentally demonstrated SMA COPs of 2.7 for tension (source temperature of 5°C and sink temperature of 47.5°C) and 3.05 for compression (source temperature of 9°C and sink temperature of 29°C). However, if these SMA materials are incorporated into a cooling system that can utilize the SMAs' unloading work, their COPs can increase to 3.7 and 11.8, respectively, which correspond to 56.5% and 83.7%, respectively, of the tension and compression Carnot efficiencies, although these estimates do not take system losses into account. In comparison, typical vapor-compression cooling systems operate at 40–45% of Carnot efficiency at source temperatures of 7°C and sink temperatures of 40.5°C (Brown et al. 2010).

Haas (2012) states that, with a COP of approx. 12, thermoelastic cooling systems can be up to 175% more efficient than vapor-compression systems. However, the authors did not provide the assumptions used to develop this savings estimate.

Dr. Takeuchi estimates that a full-scale thermoelastic system will likely have a COP of around 6.0, which is approximately half of the material COP that his team has projected from their experimental results, assuming recovery of unloading energy (Takeuchi 2013). Another member of the UMD research team notes that current projections of system COP are uncertain due to the early developmental stage of thermoelastic technology. As a result, researchers' understanding of system performance changes frequently (Radermacher 2014). Although the UMD team has not yet published test results or thorough analyses justifying their COP claims, their participation in the ARPA-e program requires that they submit regular updates on prototype development and testing for independent review by DOE. As a result, because more detailed performance information could not be shared at this time, we took Dr. Takeuchi's projection at face value for the purposes of this report.

Cost, Size, and Complexity

A credible projection of costs for thermoelastic technology in HVAC applications is not currently available given its early stage of development.

Once fully developed, this technology would likely require several moving parts, including actuators to stress the SMA and fans to distribute thermal energy.

The MEST website claims that thermoelastic cooling technology does not require any expensive or rare materials, and that it will be easy to manufacture, although it does not provide any justification for these claims (MEST 2013). Dr. Takeuchi estimates that, when thermoelastic systems are mass-produced, the cost of SMA materials will drop to the point of putting total thermoelastic system cost on par with that of a vapor-compression system (Takeuchi 2013).

Peak-Demand Reduction and Other Non-Energy Benefits

Because thermoelastic cooling systems are projected to operate at higher efficiencies than conventional systems, they could provide a commensurate reduction in peak demand.

Next Steps for Technology Development

Further development of larger prototypes should reveal the potential of a thermoelastic cooling system for HVAC applications, because the benefits of the thermoelastic effect have only been proven on a small scale.

The key research need is to improve the reliability of SMA materials by developing materials that resist crack propagation under stress. Cui et al. (2012a) noted that the fatigue properties of SMA materials could theoretically be improved and that polymers that generate heat during their stretch transformation could potentially be used in lieu of SMA materials.

Table C-10 presents the potential next steps to advance thermoelastic cooling.

Table C-10: Next Steps for the Development of Thermoelastic Cooling

| Initiatives |
|--|
| Develop SMA materials with enhanced fatigue properties. |
| Identify, develop, and test polymers that could be used in lieu of SMA materials for thermoelastic cooling. |
| Develop a large-scale prototype that proves the ability of thermoelastic technology to handle residential- and commercial-level cooling loads. |

References

Advanced Research Projects Agency – Energy (ARPA-e), date unknown. “University of Maryland: Thermoelastic Cooling.” Building Energy Efficiency through Innovative Thermodevices (BEETIT) Project Description. Retrieved October 28, 2013 from <http://www.arpa-e.energy.gov/?q=arpa-e-projects/elastic-metal-alloy-refrigerants>.

Brown, DR. et al. 2010. "The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications." PNNL-19259. PNNL. March 2010. Prepared for the U.S. DOE under contract DE-AC05-76RL01830.

Cui, J. et al. 2012a. "Demonstration of High Efficiency Elastocaloric Cooling with Large Delta T Using NiTi Wires." Applied Physics Letters 101. August 2012.

Cui, J. et al. 2012b. "Thermoelastic Cooling." U.S. Patent No. US 20,120,273,158 A1. March 27, 2012.

Haas, Anne. 2012. "PNNL Shares Expertise at ARPA-e Summit." February 22, 2012. Retrieved from <http://www.pnnl.gov/news/release.aspx?id=914>.

Maryland Energy and Sensor Technologies, LLC (MEST), date unknown. "Our Technology." Retrieved October 28, 2013 from <http://www.energysensortech.com/ourtech.html>.

National Science Foundation Small Business Innovation Research (NSF SBIR), date unknown. "SBIR Phase I: Shape memory alloys with large latent heat low fatigue for solid-state refrigeration." Retrieved October 31, 2013 from <http://www.sbir.gov/sbirsearch/detail/391687>.

Radermacher, Reinhard. 2014. Professor of Mechanical Engineering at UMD, Director of the UMD Center for Environmental Energy Engineering. Personal Communication with Caitlin Johnson of Navigant. March 12, 2014.

Takeuchi, Ichiro. 2013. Professor of Materials Science and Engineering at UMD, co-founder of MEST. Personal Communication with Caitlin Johnson of Navigant. November 7, 2013.

C.3 Thermally Driven Technology Options

Thermally driven technology options use thermal energy as the primary input to drive a heat pump (for cooling, heating, or both cooling/heating). Table C-11 provides a brief description and final ranking for the technology options selected for in-depth analysis within the Thermally Driven Technology Options category.

Table C-11: Summary of Thermally Driven Technology Options

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|---|--|-----------------|--------------------|---------------|
| Absorption Heat Pump | Absorption systems use a refrigerant-absorbent working-fluid pair and thermal energy source to drive a heating and/or cooling cycle. | High | Available | 3.00 |
| Adsorption Heat Pump | Refrigerant vapor adheres to the surface (or within the structure) of specialized adsorbent materials. These materials release the vapor when heated to a high pressure and temperature, replacing a compressor in a heat-pump cycle. | Moderate | Available | 2.70 |
| Duplex-Stirling Heat Pump | Duplex-Stirling heat pumps compress and expand a gaseous refrigerant to produce space conditioning by oscillating the working fluid between two chambers. The work for the Stirling heat-pump cycle is provided by a piston shared with a Stirling engine. | N/A | R&D | 3.00 |
| Ejector Heat Pump | Ejectors accelerate and compress refrigerant using a secondary fluid pressurized by the additional of thermal energy. | Low | Emerging | 2.15 |
| Evaporative Liquid Desiccant A/C | Evaporative liquid desiccant air conditioners consist of a primary channel that dries and cools incoming air using a liquid desiccant stream and a secondary channel that evaporatively cools a water layer using a portion of the dried air, thereby further cooling the supply air. | Moderate | R&D | 3.90 |
| Ground-Coupled Solid Desiccant A/C | Ground-coupled solid desiccant A/C technology combines two technologies: ground-coupled fluid systems and solid desiccants. The primary stage first dries the supply air using a solid desiccant wheel and the secondary stage sensibly cools the air using a ground-coupled fluid loop. | High | R&D | 3.05 |

| Technology Option | Brief Description | Cost/Complexity | Technical Maturity | Final Ranking |
|--|--|-----------------|--------------------|---------------|
| Standalone Liquid Desiccant A/C | Desiccants are materials that have a high affinity for water, and can remove water from moist air when exposed to an airstream. In HVAC systems, liquid desiccant air conditioners (LDACs) absorb moisture from air to both dry and reduce the latent heat content of the incoming air, thereby cooling it. | Moderate | Emerging | 2.40 |
| Standalone Solid Desiccant A/C | Desiccants are materials that have a high affinity for water, and can remove water from moist air when exposed to an airstream. In HVAC systems, solid desiccant air conditioners absorb moisture from air to both dry and reduce the latent heat content of the incoming air, thereby cooling it. | Moderate | Available | 2.30 |
| Vuilleumier Heat Pump | Similar to Stirling heat pumps, the Vuilleumier heat pump cyclically compresses and expands a gaseous working fluid between different volumes to produce a hot and cold side. With a high-temperature heat source, such as a gas burner, the system can generate space heating and cooling as well as water heating. | Moderate | Emerging | 3.50 |

C.3.1 Absorption Heat Pump

| | | |
|-----------------------------|--|------------------------|
| Brief Description | Absorption systems use a refrigerant-absorbent working-fluid pair and thermal energy source to drive a heating and/or cooling cycle. Depending on the configuration, absorption heat pumps can operate in heating-only, cooling-only, or reversible modes. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| Heating: 17% Cooling: 0% | Available | High |

| Technology Characteristics | Value | Comments |
|------------------------------|---|---|
| Unit Energy Savings | Heating: 17 % Cooling: 0% (fossil-fuel-fired) | <ul style="list-style-type: none"> • Small-scale ammonia-water systems with heating COPs ranging from 1.4–1.7 (Robur 2009) and cooling COPs 0.5–0.7 (Ryan 2010). • Large water-LiBr chiller COPs ranging from 0.6–1.7 (Wang and Chua 2009) • For heating, estimated source energy savings of 17% estimating 1.4 COP and 0.023 kW-electric/kW-thermal for parasitic loads. • For cooling, no source energy savings are expected compared for residential and light-commercial air conditioners or large-commercial chillers. |
| Fuel Type(s) | Natural gas | Also other heat sources such as process steam, solar thermal, and waste heat streams |
| Working Fluid(s) | Ammonia-water, water-LiBr | Other working-fluid pairs under development (researchers have identified many possible working-fluid pairs) |
| Complexity/Size | High | <ul style="list-style-type: none"> • Larger size, weight due to less-efficient heat-pump cycle, and need to prevent corrosion and outside contaminants • LiBr chillers require measures to mitigate solution crystallization, which can cause unreparable system damage • Current LiBr chillers require a cooling tower, which is usually only acceptable in large commercial installations |
| Projected Cost | High | Upfront costs typically 25–300% more than conventional heating and cooling equipment |
| Threshold Attributes | Moderate | <ul style="list-style-type: none"> • Few moving parts in factory-sealed enclosure • Non-HFC refrigerants |
| Excitement Attributes | Moderate | <ul style="list-style-type: none"> • Significant reductions in peak electric demand • Thermally activated heat-pump cycle with potential to use solar thermal energy, but this adds significant cost and complexity. |

| | | |
|---|----------|---|
| Ability to Utilize Low-Temperature Thermal Sources | High | <ul style="list-style-type: none"> Available heating streams can drive absorption systems in place of a gas-fired burner. The required temperature of the heat stream ranges from 70°C to 230°C, depending on working fluid and number of generator effects.. |
| Technical Maturity | High | Absorption chillers (for space cooling) are a mature technology. Current development efforts are targeting product cost and complexity. |
| Market Maturity | Moderate | <ul style="list-style-type: none"> For large commercial buildings, LiBr absorption chillers are attractive economically due to peak-demand reduction and low fuel costs, but have lost market share in the United States over the last several decades. These products are more popular in foreign markets, especially Europe and Asia. Residential and light commercial ammonia-water heat-only or reversible products are available in Europe and emerging in the United States as an alternative to gas-fired heating. |
| Level of Stakeholder Support | Moderate | <ul style="list-style-type: none"> Gas utilities are likely to support this technology as a gas-fired technology for cooling, and improved heating efficiency Electric utilities will potentially oppose this technology because it requires a fuel switch from electricity to natural gas Potential issues from consumer for toxicity and safety of ammonia-based products |
| Fit with BTO Mission | High | High technical risk based on the need to develop cost-effective products for residential and light commercial markets. |

Background

Technology Description

Unlike a standard heat pump with an electric compressor, absorption heat pumps utilize thermal energy to drive a heat-pump cycle where a refrigerant is cyclically absorbed and desorbed from a secondary fluid. Absorption heat pumps can be designed as heating-only, cooling-only, or reversible (both heating and cooling) although cooling efficiencies are typically less than those for vapor-compression systems. Depending on the configuration of the heat pump, thermal energy that drives the absorption cycle can be supplied by a gas-fired burner, process steam, solar thermal collector, or waste-heat stream. Although not limited to hydronic systems, absorption heat pumps typically distribute heating and/or cooling through a water/brine loop and hydronic distribution system.

Absorption chillers are available for large chilled-water cooling applications with water as the refrigerant and lithium bromide (LiBr) salt solution as the absorbent. Despite their lower primary-energy efficiencies (double-effect COPs of 1.1–1.3), absorption chillers are attractive for reducing peak electrical demand and utilizing lower-cost natural gas or waste heat to provide cooling. Where higher temperature heating sources are available, absorption chillers can utilize multiple generator effects for improved efficiency, e.g., single-effect COPs of 0.6–0.7, double-effect COPs of 1.1–1.3 and triple-effect COPs of 1.6–1.7. Figure C-12 provides a schematic of

an absorption system in cooling mode. The key steps in the cycle for the cooling-mode operation for a LiBr chiller are:

- Liquid water refrigerant evaporates in the evaporator, accepting heat from the chilled water stream, and heads to the absorber
- In the absorber, a LiBr salt solution absorbs the water vapor, releasing heat to a cooling water stream, as the solution heads to the generator
- The generator provides a heating source, heating the water-LiBr solution, and releases the water vapor from the solution
- The water vapor enters the condenser, releasing heat to a cooling water stream, before traveling through an expansion device, where the vapor is cooled, to the evaporator.

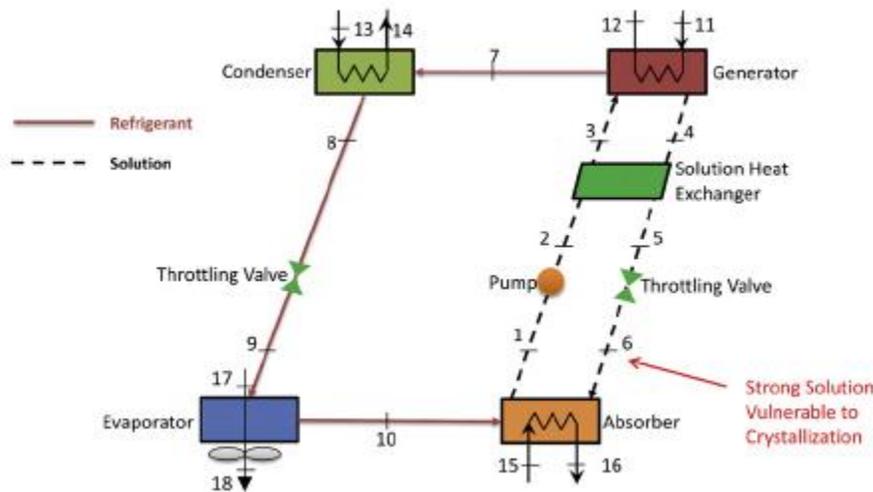


Figure C-12: Schematic of a single-effect LiBr absorption chiller

Source: Wang et al. (2011)

Heat-only and reversible absorption systems have been developed for residential and light commercial applications using ammonia as the refrigerant and water as the absorbent. In the heating mode, the absorption cycle transfers heat from both the environment (air, ground, or waste heat) and the combusted natural gas into space heating, therefore achieving higher heating efficiencies than other gas-fired systems, such as boilers or furnaces. An advanced system using a generator-absorber heat exchanger (GAX) harnesses the heat released as the water-ammonia solution absorbs the ammonia gas, increasing the efficiency of the absorption cycle. Figure C-13 provides a schematic of an ammonia-water GAX absorption system in heating mode. The key steps in the cycle for the ammonia-water absorption heat pumps in heating-mode operation are:

- Ammonia gas evaporates in the outdoor unit (or ground-loop), absorbing heat from the environment, and heads to the absorber
- In the absorber, a water-ammonia solution absorbs the ammonia gas, releasing heat to the space heating stream, as the solution heads to the generator

- The generator burns natural gas, heating the water-ammonia solution, and releases the ammonia gas from the solution
- The ammonia gas enters the condenser, releasing heat to the heating water stream, before traveling through an expansion device, where the gas is cooled, to the evaporator.

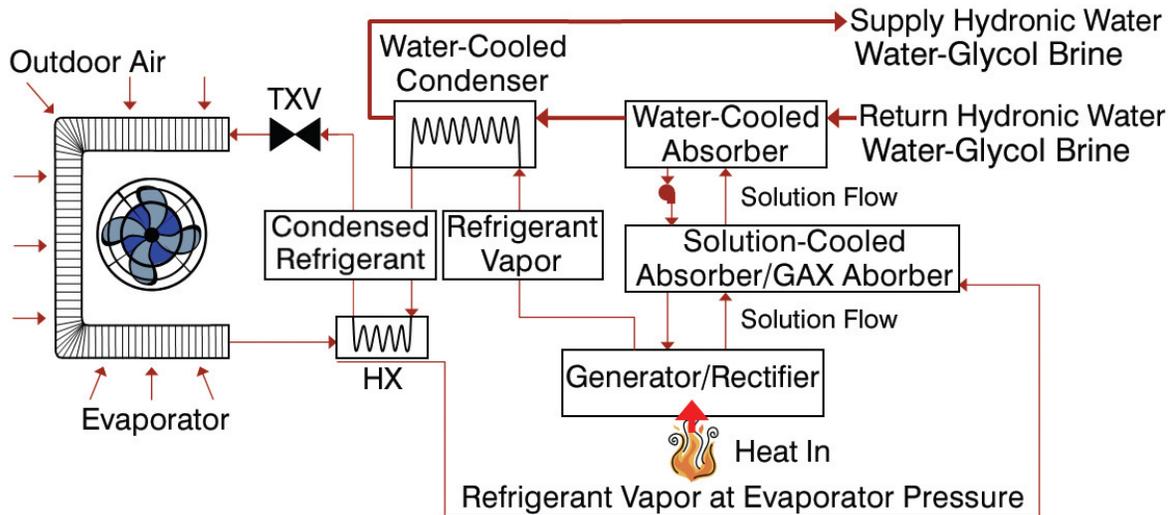


Figure C-13: Schematic of an ammonia-water absorption system with generator-absorber heat exchange (GAX)

Source: Dieckmann et al. (2005)

Technical Maturity and Current Developmental Status

For large commercial applications, several major U.S. manufacturers (e.g., Carrier, Trane, York) and numerous Asian manufacturers (e.g., Broad, Yazaki, Hitachi), offer LiBr absorption chillers ranging from several hundred to several thousand tons nominal cooling capacity. Most offerings are single- or double-effect systems, although some triple-effect systems are available after years of development by DOE, NEDO, and others (Foley et al. 2000). Kawasaki has partnered with the adsorption (see Section C.3.2 for discussion of adsorption heat pumps) manufacturer Power Partners, Inc. to sell their triple-effect absorption chiller in the U.S (Power Partners 2013).

Starting in the early 1980s, DOE, in coordination with ORNL and other industry partners, supported the development of absorption systems for residential and light commercial systems (DeVault et al. 2002). The manufacturers Robur, Buderus, Fulton, Ener-G, FireChill, Veismann, Vaillant, Vicot, SolarNext offer ammonia-water absorption heat pumps, with a number of other manufacturers currently developing products. ORNL researchers are also developing LiBr absorption technology for service water heating (i.e., a gas-fired heat-pump water heater) (Gluesenkamp et al. 2013).

In January 2012, numerous European manufacturers, gas utilities, and other stakeholders kicked off the three-year Heat4U Project to encourage wider adoption of absorption heat pumps¹⁵. Although these heat pumps are gaining popularity in Europe, acceptance in the United States has been slow with only Robur and Fulton having a U.S. market presence. Manufacturers have marketed these systems for high-end customers who would be able to afford the higher upfront cost of the systems with the understanding of significant life-time energy savings. Additionally, manufacturers commonly offer products in only one or two capacities for both residential and light-commercial markets. Although this practice reduces the number of models to manufacture, it limits the residential market to larger homes, and most commercial buildings require multiple units connected in series.

Barriers to Market Adoption

High first cost is the major barrier for this technology in both residential and commercial applications, but the economics become more favorable for larger buildings that can realize significant peak-demand savings. The size and weight of absorption systems are higher than vapor-compression systems due to the added material to prevent corrosion, maintain sealed vacuum conditions, and achieve the necessary heat and mass transfer. LiBr absorption chillers typically require cooling towers, which increases project complexity over air-cooled systems for large commercial applications, and are a major barrier to residential and light commercial buildings. Additionally, the working fluids of absorption heat pumps pose operating risks related to their toxicity (e.g., ammonia) and crystallization (e.g., LiBr). If the temperature of the LiBr solution deviates from a narrow range, the solution may crystallize and render the chiller inoperable.

Several efforts are underway to address these barriers and expand the usage of absorption heat pumps, including:

- Developing benign refrigerant pairs, such as refrigerant-ionic liquid solutions that pose minimal risk of crystallization or introducing a third working fluid that inhibits the crystallization process (Wang et al. 2011).
- Utilizing advanced designs for the absorber, generator, and condenser to reduce size, weight, and cost of absorption heat pumps. Some examples of innovative designs include using microchannel absorber with wicking materials for improved heat and mass transfer (TeGrotenhuis et al. 2012), designing compact and controllable absorbers and desorbers with a porous hydrophobic membrane (Isfahani and Moghaddam 2013, Isfahani et al. 2014), constructing the various chambers and channels of the absorption heat pump by building up thin metal sheets (Determan and Garimella 2010), or utilizing a cascade reverse-osmosis system to separate the refrigerant-absorbent pair in place of a thermal generator (Ricci 2013, Saunders 2012).

¹⁵ Funded by the European Commission's Seventh Framework Programme for Research. Details can be found at <http://www.heat4u.eu/en/>.

Energy Savings Potential

Potential Market and Replacement Applications

Absorption heat pumps are suitable for new or existing buildings with either a hydronic, forced-air or radiant heating system. For larger commercial buildings, absorption chillers operate similarly to electric vapor-compression chillers, but require a fuel supply (usually natural gas) and additional piping or exhaust venting for the heating source. Manufacturers currently offer self-contained residential systems, installed outside the building much like a condensing unit for an air conditioner, with two water/glycol pipes entering the home that in turn heat or cool the living space.

Energy Savings

Large commercial buildings sometimes use fossil-fuel-fired water-LiBr absorption chillers for cost savings even though they are less efficient than vapor-compression chillers, with cooling COPs ranging from 0.6–1.7 depending on the system design (Wang and Chua 2009):

- Single-effect: 0.6–0.7 COP with heating temperatures of 70–90°C
- Double-effect: 1.1–1.3 COP with heating temperatures of 140–160°C
- Triple-effect: 1.6–1.7 COP with heating temperatures of 200–230°C.

Manufacturers offer heating-only or reversible absorption heat pumps for light commercial and residential buildings, with heating COPs of 1.4–1.7 (Robur 2009) and cooling COPs of 0.5–0.7 (Ryan 2007). For northern climates, reversible heat pumps can provide some annual energy savings compared to electric heat pumps and other gas-fired technologies by offsetting increased consumption in the summer with energy savings in the winter.

On a source-energy basis, fossil-fuel-fired absorption heat pumps do not provide savings in the cooling mode over conventional vapor-compression systems. For heating, an absorption heat pump with a 1.4 COP provides approximately 17% source energy savings over a vapor-compression heat pump, accounting for parasitic electric consumption (estimated at 0.023 kW per kW of heating capacity).

Cost, Size, and Complexity

Absorption chillers carry a substantial first-cost penalty over vapor-compression equipment for large chilled-water systems. Table C-12 provides a summary of available cost estimates.

Table C-12: Summary of Cost Estimates for Conventional Electric Chillers and Absorption Chillers

| Chiller Type | Chiller Cost Estimates | | | | |
|---|------------------------|----------------------|------------------------|--------------|-----------------|
| | Bhatia (2010) | | | Trane (2010) | |
| | \$/ton (300 tons) | \$/ton (500 tons) | \$/ton (1,000 tons) | \$/ton | Range (tons) |
| Electric Centrifugal | \$340 | \$340 | \$350 | \$250–\$230 | 300–2,500 |
| Electric Rotary Screw (Water Cooled) | - | - | - | \$300–\$240 | 70–450 |
| Electric Rotary Screw (Air Cooled) | - | - | - | \$420 | 70–400 |
| Single-Effect Absorption | \$520 | \$430 | \$365 | \$350 | 90–1,600 |
| Double-Effect Absorption | \$625 | \$625 | \$625 | \$500 | 350–1,000 |

Peak-Demand Reduction and Other Non-Energy Benefits

As a thermally activated technology, absorption chillers offer substantial peak-demand savings. The working fluids of absorption cycles (e.g., ammonia-water, water-LiBr, etc.) operate with no ODP, and a low-GWP. When combined with a storage tank, absorption heat pumps can also provide efficient service water heating. When combined with solar thermal collectors, absorption heat pumps can operate with renewable energy.

Next Steps for Technology Development

Table C-13 presents the potential next steps to advance absorption heat pumps.

Table C-13: Next Steps for the Development of Absorption Heat Pumps

| Initiatives |
|---|
| Continue the development of improved designs for absorber, generator, condenser, and other components that allow higher efficiencies, more compact designs, and/or lower-cost absorption systems. |
| Continue research into alternative working pairs and additives that could reduce the risks of toxicity (in ammonia-water systems) and crystallization (in water-LiBr systems). |
| Promote European absorption heat-pump successes throughout the U.S HVAC industry to build up awareness. |

References

Abdelaziz, Omar. 2011. “Water-LiBr Enabling Technologies Using Chemical Additives.” Oak Ridge National Laboratory. March 2011.

- Annamalai and Pasupathy. 2012. "Effect Of Operational Parameters On Heat and Mass Transfer In Generator of R134a/DMF Absorption Refrigeration System." Indian Institute of Technology Madras. International Refrigeration and Air Conditioning Conference. July 2012.
- Babyak, Richard. 2003. "Technology Update: Air Conditioning & Refrigeration." Appliance Design. May 29, 2003.
- Bakker and Sijpheer. 2008. "Testing a Prototype Gas-Fired Residential Heat Pump." IEA Heat Pump Conference. May, 2008.
- Bhatia, A. 2010. "Overview of Vapor Absorption Cooling Systems." Continuing Education and Development Inc. May 24, 2010.
- Buderus. 2011. "GWPL 38 – Gas Absorption Heat Pump 38.3 kW." Buderus - Bosch Group. August, 2011.
- de Jong et al. 2000. "Field Experience with 65 Gas Fired Absorption Heat Pumps for Residential Use in the Netherlands." 2000.
- DeVault et al. 2002. "United States Department of Energy Absorption Heat Pump and Chiller Program." Oak Ridge National Laboratory. May 2002.
- Determan and Garimella. 2010. "A Microscale Monolithic Absorption Heat Pump." Georgia Institute of Technology. International Refrigeration and Air Conditioning Conference. July 2010.
- Dieckmann et al. 2005. "Heat-Only, Heat Activated Heat Pumps." ASHRAE Journal. January, 2005. p 40–41.
- FireChill. 2011. "Product Data-AHP40." FireChill Trading LLP. January, 2011.
- Foley et al. 2000. "The Future of Absorption Technology in America a Critical Look at the Impact of BHP and Innovation." Advanced Building Systems – 2000 Conference. June 2000.
- Fulton. 2011. "Invictus – Hydronic Heating and Cooling Systems with Gas Absorption Heat Pumps." Fulton Heating Solutions, Inc. 2011.
- Gauthier and Lajoie. 2008. "First North American Case Study: Geothermal Gas Fired Absorption Heat Pump." International Gas Union Research Conference. 2008.
- Gluesenkamp et al. 2013. "Gas-Fired Absorption Heat Pump Water Heater Development at ORNL." Oak Ridge National Laboratory. ACEEE Hot Water Forum. September 4th, 2013.
- Goffman, Ethan. 2010. "The Other Heat Pump." E Magazine Online. April 30, 2010. Retrieved from <http://www.emagazine.com/archive/5149>.

- Isfahani and Moghaddam. 2013. "Absorption Characteristics of Lithium Bromide (LiBr) Solution Constrained by Superhydrophobic Nanofibrous Structures." University of Florida. International Journal of Heat and Mass Transfer. April 23, 2013.
- Isfahani et al. 2014. "Physics of Lithium Bromide (LiBr) Solution Dewatering through Vapor Venting Membranes." University of Florida. International Journal of Multiphase Flow. Vol. 58. January 2014.
- Jokob, Uli. 2009. "Recent Development of Small-Scale Solar or Waste Heat Driven Cooling Kits for Air-Conditioning and Refrigeration." SolarNext AG. May 2009.
- Kim et al. 2012. "Thermodynamic Analysis of an Absorption Refrigeration System with Ionic-Liquid / Refrigerant Mixture as a Working Fluid." *Energy*. Volume 44, Issue 1. August 2012.
- Mori et al. 2003. "Development of Triple-Effect Absorption Chiller-Heater." Japan Gas Association. February 2003.
- Power Partners. 2013. "Under a Licensing Agreement, Power Partners is Selling Kawasaki Absorption Chillers in North America." Power Partners, Inc. May 1st, 2013.
<http://www.ppiway.com/brands-solutions/eco-max/about-us/news/under-a-licensing-agreement-power-partners-is-selling>
- Phillips, B.A. 1990. "Development of a High-Efficiency, Gas-fired, Absorption Heat Pump for Residential and Small-Commercial Applications." ORNL. September, 1990.
- Ricci, Stephen. 2013. Research Leader. Battelle Memorial Institute. Personal Communication with Jim Young of Navigant. October 2013.
- Robinet and Rota. 2013. "Successful Development of Gas Heat Pumps in Domestic and Commercial Heating Markets." European Gas Technology Conference. May 2013.
- Robur. 2009. "Gas Absorption Heat Pumps – A Great Step Forward Efficiency, Economy and Ecology." Workshop IEA-Roma. November 4, 2009.
- Rocky Research. 2011. "Aqua-Ammonia Absorption Solutions." Rocky Research Technologies. Retrieved from http://rockyresearch.com/technology/technology_hvacr_aquaammonia.php.
- Ryan, William. 2002. "New Developments in Gas Cooling." ASHRAE Journal. April, 2002.
- Ryan, Williams. 2007. "Assessment of Propane Fired Gas Air Conditioning, Heat Pumping and Dehumidification Technologies, Products, Markets and Economics." University of Illinois at Chicago. January 19, 2007.
- Saunders, Keri. 2012. "Battelle Memorial Institute – Cascade Reverse Osmosis Air Conditioning System." ARPA-e. February 2012.

Siegel, RP. 2013. "New Natural Gas Heat Pumps Provide Cool Savings." ThomasNet News. September 4th, 2013. Available at: <http://www.thomasnet.com/journals/fluid-gas-flow/new-natural-gas-heat-pumps-provide-cool-savings/>.

Smith, Vernon. 2003. "Final Report: Energy Efficient and Affordable Commercial and Residential Buildings." Architectural Energy Corporation. California Energy Commission. November, 2003. 500-03-096.

TeGrotenhuis et al. 2012. "Performance of a Compact Absorption Heat Pump Containing Microchannel Absorber Components." International Refrigeration and Air Conditioning Conference. July 2012.

Thonon, Bernard. 2008. "Promotion of Efficient Heat Pumps for Heating." ProHeatPump. August 2008.

TIAX. 2004. "Review of Thermally Activated Technologies." TIAX LLC. U.S. Department of Energy. Energy Efficiency and Renewable Energy. July, 2004.

Tischer, Luigi. 2011. "Thermally Activated Heat Pumps." Robur SpA. EHPA European Heat Pump Conference. June, 2011.

Trane. 2000. "Quick Reference for Efficient Chiller Design." American Standard Inc. May 2000.

Wang and Chua. 2009. "Absorption Cooling: A Review of Lithium Bromide-Water Chiller Technologies." University of Western Australia. *Recent Patents in Mechanical Engineering*. July 17, 2009.

Wang et al. 2011. "State-of-the-Art Review on Crystallization Control Technologies for Water / LiBr Absorption Heat Pumps." Oak Ridge National Laboratory. April 2011.

Yabase and Makita. 2012. "Steam Driven Triple Effect Absorption Solar Cooling System." Kawasaki Thermal Engineering. International Refrigeration and Air Conditioning. July 2012

C.3.2 Adsorption Heat Pump

| | | |
|----------------------------|--|------------------------|
| Brief Description | Refrigerant vapor adheres to the surface (or within the structure) of specialized adsorbent materials. When heated, these materials release the vapor at high pressure and temperature, then are cooled to accept refrigerant again. This process of adsorption and desorption can replace an electrically driven compressor in a heat-pump cycle. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| Heating: 8% Cooling: 0% | Available | Moderate |

| Technology Characteristics | Value | Comments |
|---|---|---|
| Unit Energy Savings | Heating: 8% Cooling: 0% (fossil-fuel-fired) | <ul style="list-style-type: none"> Space Cooling COP approx. 0.5–0.7 (RHC, 2012) Space Heating COP approx. 1.1–1.4 (Schossig, 2012) For space heating, estimated source energy savings of 8% estimating 1.25 COP and 0.023 kW-electric/kW-thermal for parasitic loads. |
| Fuel Type(s) | Natural gas | Can also utilize waste heat or solar thermal sources with temperatures 70–100°C (160-200°F) |
| Working Fluid(s) | Water | Most systems use water as the working fluid, but can also use ammonia, and other refrigerants |
| Complexity/Size | Moderate | <ul style="list-style-type: none"> Large size to achieve necessary capacities due to the inefficiency of the cycle Few moving parts Factory sealed (no field connection of refrigerant lines) Requires water connections for distribution |
| Projected Cost | High | Cost estimates are not available, but expected to be similar to or higher cost than absorption systems (Umamageswar and Livingston, 2011) |
| Threshold Attributes | High | Non-toxic, non-flammable working fluid in sealed package |
| Excitement Attributes | Moderate | Very compatible with low-temperature solar thermal systems |
| Ability to Utilize Low-Temperature Thermal Sources | High | Can utilize thermal streams 70–100°C / 160–200°F and higher |
| Technical Maturity | Moderate | Technology has been successfully demonstrated for residential and commercial heating and cooling systems. |
| Market Maturity | Moderate | Commercial-sized systems have been available for over a decade in foreign markets, residential-sizes systems just entering the market in Europe. |

| | | |
|-------------------------------------|------------------|--|
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> Gas utilities are likely to support this technology as a gas-fired technology for cooling, and improved heating efficiency Electric utilities will potentially oppose this technology because it requires a fuel switch from electricity to natural gas |
| Fit with BTO Mission | Moderate | <ul style="list-style-type: none"> Thermally activated technology that can utilize relatively low-temperature heating sources Moderate technical risk based on the need for system designs with improved heat and mass transfer |

Background

Technology Description

Adsorption heat pumps utilize porous materials that adsorb, or capture, a vapor refrigerant either on their surface or within their structure to drive a refrigeration cycle. Unlike the vapor-compression cycle, the adsorption cycle is not continuous, but relies on the cyclical adsorbing of vapor into the material or bed, and desorbing the vapor from the bed with a high-temperature heat source. During the desorbing process, the working fluid achieves high temperature and pressure and drives the refrigeration cycle in place of an electrically driven compressor. Once leaving the desorbing bed, the working fluid follows a process similar to vapor-compression systems by condensing in a heat exchanger (to reject heat to the environment), undergoing expansion and then evaporating into a vapor to then be adsorbed again. To provide continuous heating or cooling output, two or more adsorption beds oscillate between the adsorption and desorption state, such that, as one bed reaches saturation and must be regenerated, the other bed is fully regenerated and ready to accept vapor again. Figure C-14 provides an overview of an adsorption heat pump.

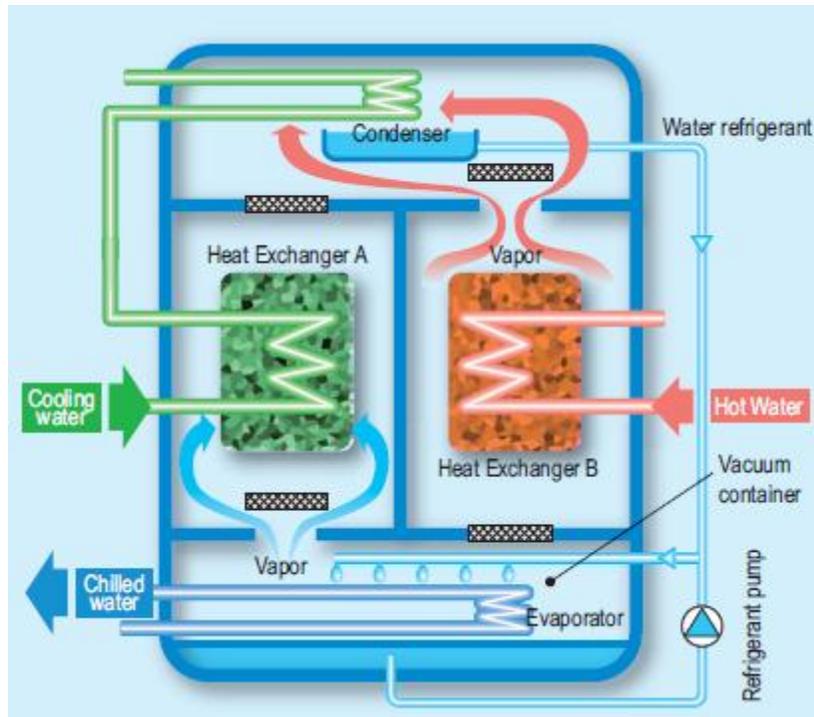


Figure C-14: Schematic of adsorption chiller

Source: Mayekawa (2009)

Similar to *absorption* systems, *adsorption* heat pumps require an external heat source to drive the adsorption-desorption process. Adsorption systems can utilize various adsorbents, including: activated carbon, zeolite, silica gel, metal organic frameworks (MOF), metal hydrides and other combinations. These adsorbents can operate with a variety of working fluids, including water, and can be optimized for an available heat source or to achieve a specific adsorption-desorption cycle rate. Depending on the configuration, the adsorption heat pump can utilize a high-temperature heating source, such as a gas burner, or available low-temperature (approx. 100°C) heating sources such as waste heat or solar heat. Unlike some absorption systems, adsorption working fluids pose little or no risk of crystallization if operating temperatures deviate from a narrow range.

Technical Maturity and Current Developmental Status

Several manufacturers currently offer fossil-fuel-fired adsorption chillers for space-cooling applications in conjunction with combined heat and power applications or using solar thermal systems, including: Mayekawa/Mycom, HIJC/Nishyodo, SorTech, InvenSor, SolarNext, Power Partners, Weatherite, and others. Several manufacturers offer adsorption-based heat pumps for space and water heating, including Viessmann and Vaillant.

Because of its attractiveness as a thermally activated heat pump, using water as a refrigerant, and moderate input temperatures, significant research in recent years has focused on improving performance and efficiency in adsorbent-bed design, working pairs, and novel applications (Yong 2007). Most systems currently use zeolite materials or silica gel as the adsorbent, but MOF materials could offer more compact adsorption beds, reducing the cost of adsorption heat pumps. Under an ARPA-e grant, researchers at PNNL, Power Partners, and Oregon State

University have successfully demonstrated an adsorption chiller using MOF materials (McGrail 2013).

Barriers to Market Adoption

Fuel-fired adsorption heat pumps have lower space-cooling COPs than vapor-compression systems and typically require large, heavy equipment that must maintain vacuum conditions.

Energy Savings Potential

Potential Market and Replacement Applications

Adsorption systems create hot and chilled water to provide space conditioning, similar to some vapor-compression systems. Manufacturers currently offer units for both residential and commercial markets.

Energy Savings

For cooling, adsorption systems are not expected to provide energy savings over conventional vapor-compression systems due to their low cooling COPs (0.5–0.7), except where waste or solar heat streams are available (RHC 2012). For heating, adsorption systems offer higher heating COPs than gas-fired furnaces and boilers (1.1–1.4), and could offer a potential source energy savings compared to vapor-compression systems, especially when coupled with solar thermal systems (Schossig 2012). Cooling COPs for adsorption heat pumps are similar to, or lower than, comparable absorption technology. Table C-14 provides a summary of cooling and heating COPs for commercially available adsorption systems.

Table C-14: Representative COPs for Adsorption Heat Pumps

| Vendor | Cooling COP ¹ (Heat Source °C) | Heating COP (Heat Source °C) | Source |
|----------|--|------------------------------------|-----------------|
| SorTech | 0.65 (55–95°C) | - | SorTech (2013) |
| Invensor | 0.60 (65–75°C) | - | InvenSor (2013) |
| Mayekawa | 0.52 (60–80°C) | - | Mayakawa (2010) |
| GBU | 0.45–0.65 (70–100°C) | - | GBU (1999) |
| Vaillant | - | 1.26–1.28 (90–100°C ²) | Tiemeier (2011) |
| Veissman | - | 1.25–1.35 (90–100°C ²) | Dawoud (2011) |

¹ Thermal COPs only, does not include parasitic. Actual COPs are highly dependent on system temperatures.

² Navigant estimate based on Dawoud et al. (2010).

On a source-energy basis, fossil-fuel-fired adsorption heat pumps do not provide savings for cooling mode over conventional vapor-compression systems. For heating, a fossil-fuel-fired adsorption heat pump with a 1.25 COP provides approximately 8% source energy savings over a

vapor-compression heat pump, accounting for parasitic electric consumption (estimated at 0.023 kW per kW of heating capacity).

Cost, Size, and Complexity

Adsorption systems generate chilled or hot water to be distributed throughout the building, and require additional systems to supply input thermal energy and reject excess heat. Most systems are large and heavy due to the use of multiple adsorption beds and to maintain internal vacuum conditions. Umamageswar and Livingston (2011) provide estimated costs for various chillers technologies, including: adsorption (\$1,300/ton), absorption (\$800/ton), mechanical (\$300/ton).

Peak-Demand Reduction and Other Non-Energy Benefits

By eliminating an electrically driven compressor, adsorption systems operate with very little electrical requirements, offering significant potential for peak-demand reduction. Additionally, because the adsorption bed retains the vapor until it is heated, systems can store thermal energy. This application is under development for passenger conditioning systems in electric vehicles (Ashley 2013).

Next Steps for Technology Development

Table C-15 presents the potential next steps to advance adsorption heat pumps.

Table C-15: Next Steps for the Development of Adsorption Heat Pumps

| Initiatives |
|--|
| Develop adsorbent materials with higher thermal densities to lower the size, weight, and cost of adsorption heat pumps. |
| Research novel designs for the adsorbent bed for reduced physical size, improved transition from absorption-desorption for multi-bed systems, reduced cycle time, and improved heat and mass transfer. |

References

Ashley, Steven. 2013. “Adsorption-based Thermal Batteries Could Help Boost EV Range by 40%.” SAE International. August 30, 2013.

Bakker et al. 2011. “Development of an Innovative 2.5 kW Silicagel-Water Adsorption Chiller.” Energy Research Centre of the Netherlands. IEA Heat Pump Conference. May 2011.

Dawoud, Belal. 2011. “Viessmann Gas Driven Sorption Heat Pumps.” Viessmann Werke Allendorf GmbH. December 2011.

Dawoud et al. 2010. “Experimental Investigation of the Effect of Zeolite Coating Thickness on the Performance of a Novel Zeolite-Water Adsorption Heat Pump Module.” Viessmann Werke Allendorf GmbH. Tenth International Conference Enhanced Building Operations. October 2010.

ECO-MAX. 2010. “ECO-MAX Adsorption Chillers...for Global Cooling.” Power Partners Inc. July 30, 2010.

- Emissionless PYT. 2006. "Hot Water Powered Adsorption Chiller." Emissionless PYT Ltd. www.emissionless.com
- GBU. 1999. "Technical Description – Adsorption Chiller NAK." GBU mbH. January 1999.
- InvenSor. 2013. "Adsorption Chiller InvenSor LTC 10 Plus." InvenSor GmbH. September 15, 2013.
- Jakob, Uli. 2009. "Green Chiller Association." International Conference Solar Air Conditioning. February 10, 2009.
- Li et al. 2011. "Review of Heat Pump Technologies and Applications." Sheffield University. January 2011.
- Mayakawa. 2010. "AdRef-Noa- Adsorption Chiller with Zeolite." Mayekawa Global. February 5, 2010.
- McGrail, Peter. 2013. Laboratory Fellow. Pacific Northwest National Laboratory. Personal Communication with Jim Young of Navigant. October 2013.
- RHC. 2012. "Strategic Research Priorities for Cross-cutting Technology European Technology Platform on Renewable Heating and Cooling." European Technology Platform – Renewable Heating and Cooling. April 2012.
- Schossig, Peter. 2012. "Fuel Driven Heat Pumps." Fraunhofer Institute for Solar Energy Systems. Chillventa 2012. October 8, 2012.
- SorTech. 2013. "Adsorption Refrigeration Unit Datasheet." SorTech AG. July 30 2013
- Te Grotenhuis et al. 2012. "Compact High Efficiency Adsorption Heat Pump." International Refrigeration and Air Conditioning Conference. July 2012.
- Tiemeier, Hendrik. 2011. "Vaillant Systems with zeoTHERM VAS 106/4." Vaillant Group. December 2011.
- Umamageswar and Livingston. 2011. "Trigeneration using Adsorption Chillers." U.S. Department of Energy. Gulf Coast Clean Energy Application Center. August 25, 2011.
- Wang et al. 2002. "Research on a Combined Adsorption Heating and Cooling System." Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University. Applied Thermal Engineering. Vol. 22, Issue 6. April 2002.
- Wang and Oliveira. 2005. "Adsorption Refrigeration – An Efficient Way to make Good Use of Waste Heat and Solar Energy." Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University. International Sorption Heat Pump Conference. June 2005.

Wang and Vineyard. 2001. "Adsorption Refrigeration." ASHRAE Journal. September 2011.

Weatherite. 2009. "Adsorption Chiller Technology." Weatherite Manufacturing Ltd. July 6, 2009.

White, John. 2012. "Literature Review on Adsorption Cooling Technology." University of Birmingham. August 7, 2012.

Yong and Wang. 2007. "Adsorption Refrigeration: A Survey of Novel Technologies." Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University. January 2007.

C.3.3 Duplex-Stirling Heat Pump

| | | |
|----------------------------|---|------------------------|
| Brief Description | Duplex-Stirling heat pumps compress and expand a gaseous refrigerant to produce space heating and cooling by oscillating the working fluid between two chambers. The work for the Stirling heat-pump cycle is provided by a piston shared with a Stirling engine. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| Heating: 4% Cooling: 0% | R&D | N/A |

| Technology Characteristics | Value | Comments |
|---|---|--|
| Unit Energy Savings | Heating: 4% Cooling: 0% (fossil-fuel-fired) | <ul style="list-style-type: none"> Estimated COPs for heating and cooling of 1.2–1.6 and 1.0 respectively (Bakker et al. 2010). Approx. 4% source energy savings for heating-mode. |
| Fuel Type(s) | Natural Gas | Potentially other high-temperature heat sources |
| Working Fluid(s) | Helium | Could use other gas refrigerants as well |
| Complexity/Size | Moderate | Potentially larger size, but installation and operation could be simpler |
| Projected Cost | N/A | |
| Threshold Attributes | Moderate | Sealed design with few moving parts could offer long lifetimes and low maintenance requirements. |
| Excitement Attributes | Moderate | Gas-fired heat pump with heating COP over unity that utilizes non-toxic working fluid. |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Requires high-temperature (approx. 500°C / 900°F) higher) heat source |
| Technical Maturity | Moderate | <ul style="list-style-type: none"> Minimal development to date of duplex-Stirling heat pump for space-conditioning applications Products have been developed for low-temperature refrigeration applications |
| Market Maturity | Moderate | <ul style="list-style-type: none"> No commercialized products for space conditioning Currently available for low-temperature and niche refrigeration as well as cryocooling applications |
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> Gas utilities are likely to support this technology as a gas-fired technology for cooling, and improved heating efficiency Electric utilities will potentially oppose this technology because it requires a fuel switch from electricity to natural gas |
| Fit with BTO Mission | Moderate | Potentially attractive as a gas-fired heat pump using a benign refrigerant. |

Background

Technology Description

Stirling-cycle machines cyclically compress and expand a gaseous working fluid between two volumes to either generate work (heat engine) or transfer heat (heat pump). In a duplex-Stirling heat pump, an external heat source drives a Stirling engine, creating the input work to drive a Stirling heat pump. The engine and heat-pump components share a common piston, commonly as a free-piston configuration without a crankshaft, as shown in Figure C-15. The working fluid, typically helium, resides in two sealed volumes separated by the piston.

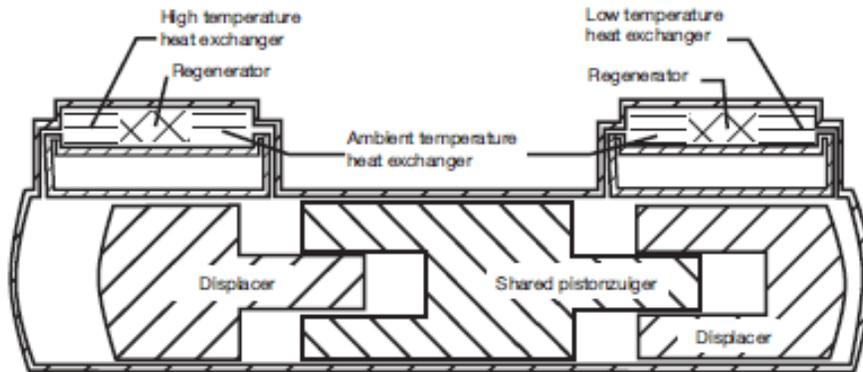


Figure C-15: Typical duplex-Stirling heat pump

Source: Lewis et al. (2007)

A gas burner (or other heat source) provides the high-temperature heating source (approx. 500°C / 900°F and greater), the working fluid in each volume compresses and expands to generate medium-temperature (50–70°C / 120–160°F) and low-temperature (10°C / 50°F and below) areas that can provide space heating and/or cooling. A secondary fluid, such as water, connects to these heat sources/sinks through a heat exchanger to then service the space-conditioning loads. While the heat-pump side could be driven by an electrically driven linear motor, the Stirling engine offers the potential for a gas fired-heat pump to replace electrically driven vapor-compression cycles.

Technical Maturity and Current Developmental Status

DOE, GRI/GTI, Sunpower Inc., and others investigated duplex-Stirling heat pumps for space-conditioning applications for several decades by, but system performance was lower than conventional and other thermally activated heat pumps (ADL 1996). More recently, some researchers investigated Rankine cycles driven by a Stirling engine operating as the compressor, with promising performance (Berchowitz et al. 2008). Infinia Corporation received an ARPA-e grant to develop a Stirling-cycle air conditioner, but the project was redirected to target towards supermarket freezers (Songgang 2013).

Stirling heat pumps operating with electric motors have been commercialized for process cooling, cryocooling, and commercial-refrigeration applications for several years. These systems currently achieve comparable or improved performance to vapor-compression systems, especially at lower temperatures (-20°C and below) (Lewis et al. 2007).

Barriers to Market Adoption

Currently no products on the market utilize duplex-Stirling heat pumps for space conditioning. Because cooling COPs are low, even compared to other gas-fired heat pumps, energy savings during the cooling season are not expected. For heating-dominated climates, the higher heating efficiency and cost savings may offset the low cooling efficiency.

Energy Savings Potential

Potential Market and Replacement Applications

Duplex-Stirling heat pumps would be suitable for most residential and commercial applications. The heat pump operates as a sealed system with water heat exchangers that could condition the space directly through a radiant system, or operate through an air-side heat exchanger for ducted systems. The gas burner would require an exhaust vent, similar to other gas-heating equipment.

Energy Savings

We found limited information on the efficiency of fossil-fuel-fired duplex-Stirling heat pumps for space-conditioning applications, especially when factoring in parasitic fan and pump consumption.

In an analysis for ORNL, Arthur D. Little, Inc. investigated the performance of several duplex-Stirling heat pumps and noted COPs ranging from 1.2–1.6 for heating and 0.5–0.79 for cooling. After accounting for parasitic loads, estimated COPs decreased to 0.9–1.1 for heating and 0.4–0.6 for cooling (ADL 1986).

Bakker et al. (2010) estimated COPs for duplex-Stirling heat pumps of 1.2–1.6 for heating and 1.0 for cooling.

While these estimates provide no savings in cooling mode, a fossil-fuel-fired duplex-Stirling heat pump with a COP of 1.2 could provide approximately 4% source energy savings for heating mode over a vapor-compression heat pump, accounting for parasitic electric consumption (estimated at 0.023 kW per kW of heating capacity).

Cost, Size, and Complexity

Cost for duplex-Stirling heat pumps is unknown at this stage. As a sealed system, installation and operation could be simpler than some vapor-compression systems by requiring only water connections to heat exchangers.

Peak-Demand Reduction and Other Non-Energy Benefits

Depending on the required electrical parasitic loads, duplex-Stirling heat pumps could provide significant peak-demand savings by offering gas-fired space cooling. Using helium as a working fluid is attractive because it is non-toxic and poses no ODP or GWP. With few moving parts operating in a sealed enclosure, systems could have long lifetimes and low maintenance requirements.

Next Steps for Technology Development

Table C-16 presents the potential next steps to advance duplex-Stirling heat pumps.

Table C-16: Next Steps for the Development of Duplex-Stirling Heat Pumps

| Initiatives |
|--|
| Investigate the potential for duplex-Stirling heat pumps for residential and commercial HVAC applications. |

References

ADL. 1986. “Status of Free Piston Stirling Engine Driven Heat Pumps – development, Issues, and Options.” Arthur D. Little, Inc. Prepared for Oak Ridge National Laboratory. ORNL/Sub/84-00205/1. April 1986.

Bakker et al. 2010. “Gas Heat Pumps.” GasTerra. December 2010.

Berchowitz, David. 1993. “Free-Piston Rankine Compression and Stirling Cycle Machines for Domestic Refrigeration.” Sunpower Inc. Greenpeace Ozone Safe Conference. October 1993.

Berchowitz et al. 2008. “CO₂ Stirling Heat Pump for Residential Use.” International Refrigeration and Air Conditioning Conference. July 2008.

Berchowitz et al. 2009. “CO₂ Based Free-Piston Stirling Heat Pump with Ground Source Heat Reservoir.” ISEC International Stirling Engine Committee. July 2009.

Haywood et al. 2002. “Stirling-Cycle Heat-Pumps and Refrigerators – a Realistic Alternative?” University of Canterbury. 2002.

Lewis et al. 2007. “Fostering the Development of Technologies and Practices to Reduce the Energy Inputs into the Refrigeration of Food – Reviews of Alternative Refrigerant Technologies.” Centre for Energy and Built Environment Research. Brunel University. July 2007.

Penswick and Urieli. 1984. “Duplex Stirling Machines.” Sunpower, Inc. 19th Annual Intersociety Energy Conversion Engineering Conference. August 1984.

Songgang, Qui. 2013. Infinia Corporation. Personal communication. October 16, 2013.

Streefkerk, Wouter. 2011. “Stirling Solar Cooling in Office Facades.” Delft University of Technology. April 14, 2011.

C.3.4 Ejector Heat Pump

| | | |
|----------------------------|---|------------------------|
| Brief Description | Ejectors accelerate and compress refrigerant using a secondary fluid pressurized by the additional of thermal energy. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 0% | Emerging | Low |

| Technology Characteristics | Value | Comments |
|---|---------------------------|--|
| Unit Energy Savings | 0% (fossil-fuel-fired) | Cooling COPs of 0.2–0.4 and heating COPs ranging from 1.1–1.3 (Rahamathullah et al. 2013) |
| Fuel Type(s) | Natural gas | Can utilize boiler, solar water heater, or waste heat stream |
| Working Fluid(s) | Varies | <ul style="list-style-type: none"> Refrigerant selection determined by ejector geometry and operating conditions Systems can use conventional or alternative refrigerants |
| Complexity/Size | Moderate | Generally a simple technology with few moving parts |
| Projected Cost | N/A | |
| Threshold Attributes | Moderate | <ul style="list-style-type: none"> Simple, proven design begets long lifetime and reliability Performance and efficiency drop significantly outside of specific design conditions |
| Excitement Attributes | Moderate | <ul style="list-style-type: none"> Ejectors can improve the efficiency of conventional systems Ability to utilize benign refrigerants |
| Ability to Utilize Low-Temperature Thermal Sources | Moderate | Can use a variety of low-quality heating sources, approx. 100°C / 200°F or greater |
| Technical Maturity | Moderate | Ejectors are mature technology, but their HVAC applications are under development |
| Market Maturity | Moderate | <ul style="list-style-type: none"> Not offered for space conditioning applications as the primary heat pump cycle Employed in mobile air conditioning and heat pump water heaters as an expansion device (DENSO 2004). |
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> Gas utilities are likely to support this technology as a gas-fired technology for cooling, and improved heating efficiency Electric utilities will potentially oppose this technology because it requires a fuel switch from electricity to natural gas, but ejector heat pumps are most applicable for cold-weather climates |

| | | |
|-----------------------------|----------|--|
| Fit with BTO Mission | Moderate | Potentially an attractive thermally activated heat-pump technology, but unclear at current efficiencies. |
|-----------------------------|----------|--|

Background

Technology Description

Employed for decades in industrial processes, ejectors are specialty mechanisms to raise the pressure of a fluid that have a wide variety of applications, including space conditioning. In general, ejectors utilize a high-pressure motive or driving fluid to accelerate and entrain a secondary fluid. In process applications, ejectors use high-pressure steam to raise the pressure of boiler inlet water, reclaim low-pressure steam, or create a partial vacuum within a chamber. When applied to a refrigeration cycle, ejectors can act as a compression or expansion device in place of standard components, and offer the ability to drive a heat pump cycle. Figure C-16 provides a diagram of a basic ejector nozzle.

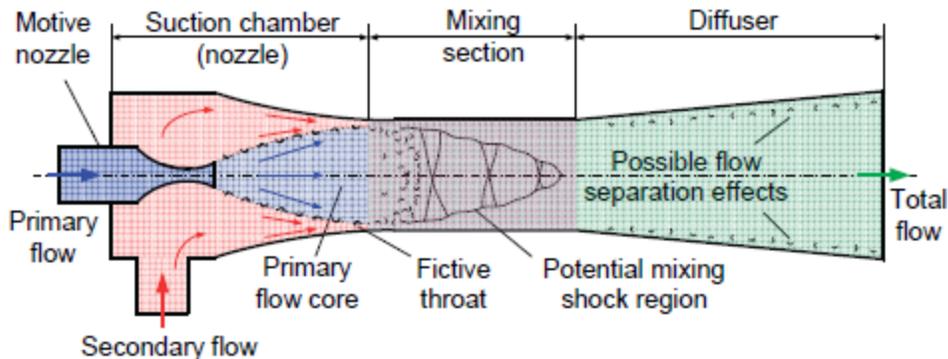


Figure C-16: Basic diagram of an ejector

Source: Elbel and Hrnjak (2008)

By raising the pressure of the secondary fluid, ejectors can drive a refrigerant-based cooling cycle. Ejector heat pumps raise the temperature and pressure of the motive fluid using a heating source (e.g., boiler), a liquid pump, and the ejector in place of an electrically driven compressor. Figure C-17 provides a schematic of an ejector heat pump. An ejector consists of a converging-diverging nozzle that converts the high internal energy (i.e., temperature and pressure) of the motive fluid into kinetic energy (i.e., velocity) through the Bernoulli principle. The high-velocity motive fluid creates a suction effect that accelerates the secondary fluid into the ejector’s mixing section, where the motive fluid entrains the secondary fluid. At this point, the fluid mixture decelerates through the diffuser section, which compresses the mixture.

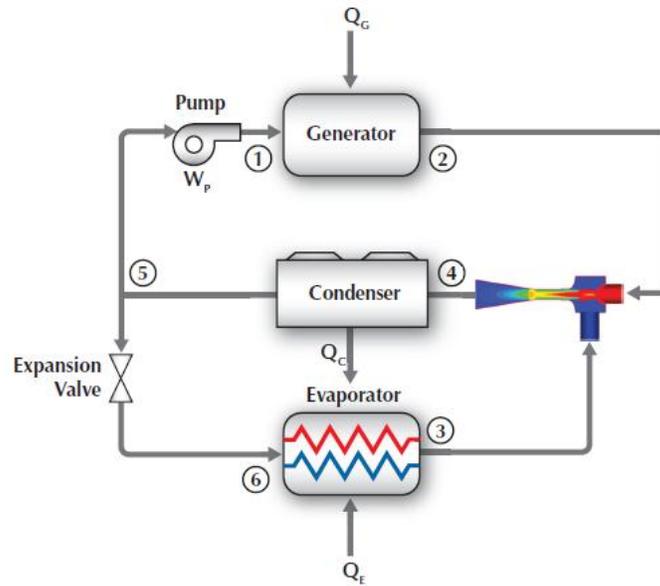


Figure C-17: Typical ejector heat pump

Source: Aidoun and Martel (2009)

For most applications, the ejector requires a heat source (approx. 100°C / 200°F or less) to generate high-pressure motive fluid, and can subsequently be served by a variety of waste heat streams or solar energy sources. Much of the research into ejector heat pumps targets this advantage over other thermally activated systems (e.g., absorption, adsorption) in addition to simple, reliable design (Buyadgie et al. 2010). Nevertheless, the COP of ejector heat pumps for both heating and cooling is generally less than other thermally activated or vapor-compression systems (Rahamathullah et al. 2013).

Additionally, ejectors can serve as secondary compressive devices that reduce the pressure lift of the electrically driven compressor, or as an expansion recovery device. The applications are discussed further in Appendix G.

Technical Maturity and Current Developmental Status

Ejectors themselves are a mature technology but have not achieved wide acceptance in the HVAC market. In recent years, researchers have shown increased interest in ejectors due to their potential to utilize low-quality heating sources and improve the operation of compressor-driven heat pumps. Currently, no commercially available residential or commercial cooling systems utilize an ejector, but there are several promising developments that show the potential for these systems in the future:

- CanmetENERGY, an office within the federal Natural Resources Canada program, highlighted ejector heat pumps as a strategic focus for their combined heat and power initiatives. Through these efforts, they hope to further the development of ejector-based systems through advanced modeling, CFD analysis, geometry and refrigerant optimization, and prototype construction (Aidoun and Martel 2009).
- While most ejector cycles use a single material for both the refrigerant and motive fluid, researchers are developing products using a binary fluid mixture to further improve the

cycle. By using two fluids with opposing characteristics, the designer can optimize the motive fluid for a low heat of vaporization in the generator, and the refrigerant for high heat of vaporization in the evaporator (Buyadgie et al. 2010). May-Ruben Technologies is developing an ejector heat pump for building heating and cooling using a binary fluid with a fractionating condenser to separate the fluids (Ruben, P. 2013). With support from the Gas Technology Institute and other partners, the company envisions a product that exceeds the heating efficiencies of packaged absorption systems available today (Ruben, C. 2013).

Barriers to Market Adoption

Low heating and cooling COPs compared to conventional vapor-compression and other thermally activated technologies are the primary barriers for ejector heat pumps. The performance and efficiency of ejector-based systems varies greatly with several key components, including: refrigerant selection, ejector geometries, operating pressures, heat input, condensing temperature, evaporating temperature, and others. Because of this, ejectors operate best when operating conditions are very consistent, with constant flow rate and minimal temperature variation, so that the refrigerant and geometry can be optimized. For most HVAC applications, equipment must perform over a wide range of conditions and capacities, which poses another barrier, even for ejector usage as a supplementary component to compressor-based systems. Several patents and research papers suggest promising development on adjustable ejectors for EcoCute water heaters, but it is unclear whether these efforts have resulted in product advancements (Chen et al. 2009).

Energy Efficiency Advantages

Fossil-fuel-fired ejector-based systems have significantly lower cooling and heating efficiencies (based on source energy) than conventional vapor-compression or other thermally activated technologies. Nevertheless, ejector heat pumps can utilize low-quality waste and solar heat to drive the heat pump, if readily available, to save energy.

Energy Savings Potential

Potential Market and Replacement Applications

Ejector heat pumps would be suitable for most residential and commercial space conditioning applications.

Energy Savings

Compared to compressor-driven cooling systems, fossil-fuel-fired ejector heat pumps are not expected to provide source energy savings, but potentially operating cost savings, especially for heating-dominated climates.

Rahamathullah et al. (2013) compiled available research on ejector heat pumps and showed cooling COPs generally ranging from 0.2–0.4 and heating COPs ranging from 1.1–1.3 for space conditioning applications.

Cost and Complexity

Ejector heat pumps operate without a vapor compressor and require a liquid pump to feed the boiler or heat source, and then distribution equipment such as a fan. The ejectors themselves are

common components in various industrial processes. Compared to electrically driven systems, ejector heat pumps could provide a cost advantage due to the lower cost of natural gas.

Peak-Demand Reduction and Other Non-Energy Benefits

As a thermally activated technology, ejector heat pumps significantly reduce the electrical energy required for space cooling. Ejector heat pumps can operate utilizing benign refrigerants such as water, carbon dioxide, etc., and utilize renewable heat sources such as solar thermal energy. Ejectors themselves have no moving parts and have high reliability, which provides benefit when integrated into a heat pump system. The design of the entire system will determine complexity and reliability of the complete ejector heat pump.

Next Steps for Technology Development

Table C-17 presents the potential next steps to advance ejector heat pumps.

Table C-17: Next Steps for the Development of Ejector Heat Pumps

| Initiatives |
|--|
| Investigate the potential for binary fluids to raise the cooling COP of ejector cycles closer to other thermally activated cycles. |
| Design prototype ejector heat pumps for heating-dominated markets. |

References

Aidoun and Martel. 2009. “Ejectors.” CanmetENERGY. Natural Resources Canada. July 2009. Retrieved from http://canmetenergy.nrcan.gc.ca/sites/canmetenergy.nrcan.gc.ca/files/files/2009-185_e.pdf

Bergander, Mark. 2006. “Refrigeration Cycle with Two-Phase Condensing Ejector.” International Refrigeration and Air Conditioning Conference. July 2006.

Buyadgie et al. 2010. “Solar Ejector Refrigerating and Air-Conditioning System (SERAS) Working on Zeotropic Mixtures.” International Refrigeration and Air Conditioning Conference. July 2010.

Chen et al. 2009. “Experimental Investigation of an Adjustable Ejector for CO₂ Heat Pump Water Heaters.” Journal of Zhejiang University. September 10, 2009.

DENSO. 2004. “Eco-Cute Blooms from Car Air Conditioner Technology.” DENSO Corporation. December 2004. Retrieved from <http://www.globaldenso.com/en/csr/report/2004/pdf/pdf/e07.pdf>.

Elbel and Hrnjak. 2008. "Ejector Refrigeration: An Overview of Historical and Present Developments with an Emphasis on Air-Conditioning Application." International Refrigeration and Air Conditioning Conference. July 2008.

Liu and Groll. 2008. "Recovery of Throttling Losses by a Two-Phase Ejector in a Vapor Compression Cycle." Prepared for Air-Conditioning and Refrigeration Technology Institute, Inc. ARTI Report No. 10110-01. May 2008.

Pottker et al. 2010. "Experimental Investigation of an R410A Vapor Compression System Working with an Ejector." International Refrigeration and Air Conditioning Conference. July 2010.

Rahamathullah et al. 2013. "A Review of Historical and Present Developments in Ejector Systems." International Journal of Engineering Research and Applications. Vol. 3, Issue 2, March-April 2013.

Ruben, Chelsea. 2013. May-Ruben Technologies. Personal Communication. November 4, 2013.

Ruben, Peter. 2013. "Transforming the Economics of Thermal Energy." May-Ruben Technologies. 2013. Retrieved from http://www.acamp.ca/alberta-micro-nano/images/cleantech/ruben-mayruben_bfe_heat_pump_acamp_cleantech_2013.pdf.

Weissler, Paul. 2009. "2010 Prius First with Ejector-Cycle Air Conditioning." SAE International. August 10, 2009. Retrieved from <http://articles.sae.org/6741/>.

C.3.5 Evaporative Liquid Desiccant Air Conditioner

| | | |
|----------------------------|--|------------------------|
| Brief Description | Evaporative liquid desiccant A/C technology combines two technologies: evaporative cooling and liquid desiccants. It consists of a primary stage that dries and cools incoming air using a liquid desiccant stream and a secondary stage that evaporatively cools a water film using a portion of the dried air, which, in turn, further cools the supply air. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 61% | Low | Moderate |

| Technology Characteristics | Value | Comments |
|---|------------------|---|
| Unit Energy Savings | 61% | National-average cooling energy savings estimate of DEVap, a desiccant-enhanced evaporative technology developed at NREL (Kozubal et al. 2011). |
| Fuel Type(s) | Natural Gas | Heat, used to regenerate desiccants, can be supplied via a boiler, waste heat, or solar heat. |
| Working Fluid(s) | Water, LiCl | Water is evaporated in an open loop; lithium chloride is typically used as the liquid desiccant. |
| Complexity/Size | Moderate-to-High | DEVap is projected to be approximately the same size as an equivalent vapor-compression system; however, this projection is uncertain because it has not yet been developed beyond the breadboard phase (Kozubal et al. 2012). |
| Projected Cost | Moderate-to-High | Potential to reach cost parity with vapor compression; however, current projections estimate that systems will cost 25% more than vapor-compression systems (Kozubal et al. 2012). |
| Threshold Attributes | Low | Increases on-site water consumption, potential freezing danger in the winter, poor reputation due to low performance characteristics of old “swamp cooler” direct evaporative coolers. |
| Excitement Attributes | Moderate | Potential for increased comfort, due to independent control of temperature and humidity (Kozubal et al. 2011), peak-demand-reduction potential. |
| Ability to Utilize Low-Temperature Thermal Sources | High | Can utilize low-temperature thermal sources to regenerate the liquid desiccant. |
| Technical Maturity | Low | Prototype evaporative liquid desiccant A/C systems have been developed, but not yet field tested or commercialized. |
| Market Maturity | Low | Evaporative liquid desiccant A/C technology is not commercially available. |
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> Expected support by gas utilities as a gas-fired technology for cooling Electric utilities will potentially oppose this technology because it requires a fuel switch from electricity to natural gas |

| | | |
|-----------------------------|------|--|
| Fit with BTO Mission | High | High technical risk as technology requires further prototype development and field testing to prove its performance characteristics. |
|-----------------------------|------|--|

Background

Technology Description

As described in Section C.2.2, researchers and manufacturers have developed advanced evaporative cooling technologies that are capable of providing energy-efficient space cooling for buildings in dry regions of the country. Moreover, as described in Section C.3.7, liquid desiccant cooling technologies can be used in humid regions to remove latent heat from the air, thus providing dehumidification. Desiccant-enhanced evaporative technologies combine these approaches to provide both sensible cooling and dehumidification in one package. The DEVap system developed at NREL is one example of this technology combination. DEVap consists of a primary stage that dries and cools incoming air using a liquid desiccant stream and a secondary stage that evaporatively cools a water layer using a portion of the dried air, thereby further cooling the supply air. This combination overcomes the limitations of both evaporative and liquid desiccant cooling systems because it can provide space conditioning in climate zones having either humid or dry air. Consequently, the DEVap system represents a complete cooling and dehumidifying system that can operate in both moist and dry climate conditions (Kozubal et al. 2011).

Technical Maturity and Current Developmental Status

Kozubal et al. (2011), at NREL, have conducted performance simulations for the DEVap A/C process, comparing it to high-efficiency vapor-compression systems in various U.S. cities. NREL has verified these models through lab testing of breadboard systems.

We have not identified any other attempts to develop or commercialize evaporative/liquid desiccant cooling technologies.

Barriers to Market Adoption

Though it has been commercialized for some time, evaporative cooling technologies (without desiccants) have only achieved limited market penetration, even in hot, dry climates. For example, in 2005, evaporative cooling systems represented only 7% of HVAC equipment installations in California, despite the fact that its hot-dry climate is well-suited to evaporative cooling (Brost 2005). This low adoption rate is indicative of several significant market barriers that evaporative cooling faces, as described further in Section C.2.2: low applicability to humid climate zones, increased on-site water consumption, potential for freezing damage, and the poor reputation of older direct evaporative coolers. Evaporative liquid desiccant A/C faces similar market barriers due to its water consumption (which is approximately equal to that of evaporative coolers) and potential for freeze damage; however, Kozubal et al. (2011) claim that it can be used in all climate regions, so its applicability is much greater than that of other evaporative cooling systems.

Evaporative liquid desiccant A/C also faces the market barrier associated with the corrosiveness of liquid desiccants (as described in Section C.3.7).

Energy Savings Potential

Potential Market and Replacement Applications

Evaporative/liquid desiccant cooling technology is technically applicable to all space-cooling applications for residential and commercial buildings. This technology is also technically applicable to all building types in all climate regions.

Energy Savings

In NREL simulations, the modeled DEVap system reduced source energy consumption by 39–84% (an average of 61% nationwide) compared to a traditional vapor-compression system supplemented with a dehumidifier, while providing the same cooling and humidity conditions (Kozubal et al. 2011).

Cost, Size, and Complexity

Although Kozubal et al. (2012) estimate that a 10-ton DEVap rooftop unit (RTU) would cost 25% more than an equivalent vapor-compression RTU, these cost estimates are based on breadboard design concepts that do not include complete bills of material. As a result, these cost projections are highly uncertain. DEVap systems do not require the use of any particularly expensive raw materials or components.

Kozubal et al. (2012) estimate that a DEVap RTU would be approximately the same size as a vapor-compression RTU; however, this size estimate is uncertain given that NREL has not developed DEVap beyond the breadboard phase.

Peak-Demand Reduction and Other Non-Energy Benefits

Because evaporative liquid desiccant A/C systems can use fossil fuels or waste heat to regenerate the desiccant, they can provide a reduction in electricity demand that is disproportionate to their efficiency improvement over vapor compression.

Conventional air-conditioning systems (particularly in residential buildings) recirculate air throughout the building and require supplementary ventilation for applications with high outdoor air requirements, consequently increasing energy consumption. In contrast, evaporative liquid desiccant A/C systems deliver 30 to 100 percent outdoor air, thus maintaining high indoor air quality while obviating the need for supplementary ventilation (SWEEP/DOE 2007, Kozubal et al. 2011).

These systems can achieve sensible heat ratios ranging from 0.0 to 1.0, thus providing improved air quality; moreover, they can provide some increase in comfort compared to vapor-compression systems due to their ability to independently control temperature and humidity (Kozubal et al. 2011).

Next Steps for Technology Development

Because evaporative liquid desiccant A/C technology is still in the breadboard development stage, continued conceptual design work is needed to address potential maintenance issues (e.g., freezing), refine packaging concepts, accommodate manufacturing, and develop a better understanding of system costs. Additionally, further modeling and field testing are needed to confirm this technology's performance in commercial applications for all climate regions,

because NREL has only modeled the performance of commercial DEVap in hot-humid and hot-dry climate zones.

Table C-18 presents the potential next steps to advance evaporative/liquid desiccant cooling.

Table C-18: Next Steps for the Development of Evaporative Liquid Desiccant Air Conditioners

| Initiatives |
|---|
| Simulations and field testing in a variety of conditions to confirm commercial energy savings for all climate zones. |
| Design work to address maintenance problems (e.g., freezing concerns), optimize for commercialization, and accommodate manufacturing. |
| Conducting cost analyses to develop a better understanding of overall system costs. |

References

Brost, Matt. 2005. “2005 California Statewide Residential Lighting and Appliance Efficiency Saturation Study.” RLW Analytics. Final Report. August 23, 2005.

Dieckmann et al. 2009. “Going ‘Back to the Future’ of Evaporative Cooling.” ASHRAE Journal. May 2009.

Higgins, Cathy and Reichmuth, Howard. “Desert CoolAire Package Unit Technical Assessment – Field Performance of a Prototype Hybrid Indirect Evaporative Air-Conditioner.” New Buildings Institute. July 2007.

Kinney, Larry. 2004. “Evaporative Cooling for a Growing Southwest: Technology, Markets, and Economics.” Southwest Energy Efficiency Project. August 2004.

Kozubal, et al. 2011. “Desiccant Enhanced Evaporative Air-Conditioning (DEVap): Evaluation of a New Concept in Ultra Efficient Air Conditioning.” NREL Report No. NREL/TP-5500-49722. January 2011.

Kozubal, et al. 2012. “Development and Analysis of Desiccant Enhanced Evaporative Air Conditioner Prototype.” NREL Report No. NREL/TP-5500-54755. April 2012.

SWEEP/DOE. 2007. “Evaporative Cooling Policy and Program Options: Promising Peak Shaving in a Growing Southwest.” Southwest Energy Efficiency Project (SWEEP). U.S. Department of Energy. May 2004. Available at: http://www.swenergy.org/publications/documents/Evaporative_Cooling_Policy_Options.pdf.

SWEEP/WCEC. 2007. "SWEEP/WCEC Workshop on Modern Evaporative Cooling Technologies Workshop Summary." Southwest Energy Efficiency Project (SWEEP) and UC Davis Western Cooling Efficiency Center (WCEC). September 2007.

C.3.6 Ground-Coupled Solid Desiccant Air Conditioner

| | | |
|----------------------------|--|------------------------|
| Brief Description | Ground-coupled solid desiccant A/C technology combines two technologies: ground-coupled fluid systems and solid desiccants. The primary stage first dries the supply air using a solid desiccant wheel and the secondary stage sensibly cools the air using a ground-coupled fluid loop. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 43% | R&D | High |

| Technology Characteristics | Value | Comments |
|---|-------------|--|
| Unit Energy Savings | 43% | Ground-coupled solid desiccant A/C prototype has a measured COP of 1.85 (Shopsis 2011). |
| Fuel Type(s) | Natural gas | Heat can be supplied via a gas burner, waste heat, or solar heat. |
| Working Fluid(s) | Water | System could utilize water or other heat transfer fluids. |
| Complexity/Size | High | Ground-coupled systems are difficult to install and maintain compared to air-source vapor-compression systems. |
| Projected Cost | High | Although we identified no cost projections for ground-coupled solid desiccant air conditioners, they are likely to be more expensive than conventional vapor-compression systems due to the expense of installing a ground-coupled fluid loop. |
| Threshold Attributes | Low | We did not identify any projections of the safety, reliability, maintainability, or lifetime of ground-coupled solid desiccant A/C systems. |
| Excitement Attributes | High | Projected improved indoor air quality, independent control of temperature and humidity (Shopsis 2011). |
| Ability to Utilize Low-Temperature Thermal Sources | High | Waste or solar heat can be used to heat the airstream that will regenerate the desiccant. |
| Technical Maturity | Moderate | <ul style="list-style-type: none"> Desiccant wheels and ground-coupled cooling loops are mature technologies that have been successfully utilized to supplement commercial HVAC applications for many years. However, current prototypes of ground-coupled solid desiccant air conditioners still face off-design-point performance issues that need to be resolved. |
| Market Maturity | High | Solid desiccant components have been commercialized for about two decades. However, we are not aware of any commercialized ground-coupled solid desiccant air conditioners. |

| | | |
|-------------------------------------|------------------|--|
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> • Expected support by gas utilities as a gas-fired technology for cooling, and improved heating efficiency • Electric utilities will potentially oppose solid desiccant A/C technology because it requires a fuel switch from electricity to natural gas. |
| Fit with BTO Mission | Moderate | Moderate potential as ground-coupled technology, more likely to achieve broad market success as a component for vapor-compression systems. |

Background

Technology Description

As described in Section C.3.8, solid desiccants have a high affinity for water and can remove latent heat (the energy required to condense or evaporate water) when exposed to an airstream. Because solid desiccants cannot remove the air’s sensible heat (temperature) without secondary systems, standalone solid desiccant systems mostly supplement vapor-compression air conditioners and chillers.

While several non-vapor-compression technologies can provide sensible cooling for a solid desiccant system, one potential variant developed by Synairco incorporates a ground-coupled fluid loop to lower the temperature of supply air once it is dried by the solid desiccant. This ground-coupled solid desiccant air conditioner provides both latent and sensible cooling without the use of vapor compression by incorporating a desiccant wheel and heat source with a ground-coupled fluid loop. By utilizing the relatively cool ground as a heat sink, water or another heat transfer fluid, can achieve temperatures of 60°F or lower. While this temperature is normally not sufficient to dehumidify supply air, the ground-coupled system can deliver adequate comfort by drying the air first with desiccants and then cooling the air with the fluid loop.

This ground-coupled solid desiccant air conditioner, which is depicted in Figure C-18, operates as follows:

- 1) The airstream to be cooled is split.
- 2) One of the airstreams (#1) is heated using a low-grade heat source (e.g., a gas burner, solar, or waste heat)
- 3) The two airstreams pass through the desiccant wheel. The non-heated airstream (#2) is dehumidified, while airstream #1 regenerates the desiccant and thus becomes more humid.
- 4) Both airstreams pass over coils filled with cooled, ground-coupled fluid (~60°F). Airstream #2, which is now dry, experiences sensible cooling. Because the dew-point temperature of airstream #1 has increased by being heated and humidified, airstream #1 experiences both latent and sensible cooling.
- 5) The streams are re-combined and circulated through the building.
- 6) The ground-coupled fluid, now heated by the supply air, then travels back underground to reject the excess heat (Shopsis 2012).

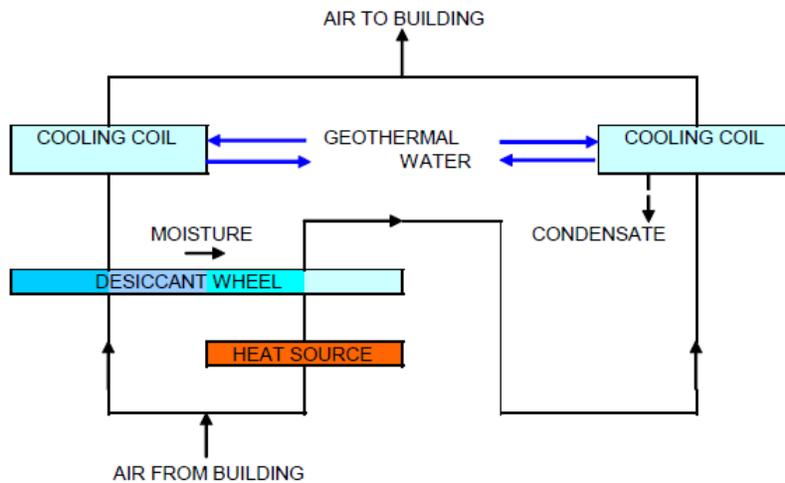


Figure C-18: Synairco air conditioner schematic

Source: Shopsis (2011)

Technical Maturity and Current Developmental Status

The core components of a ground-coupled solid desiccant air conditioner are widely available, but a complete system has not been commercialized to date. Solid desiccant wheels and ground-loop systems have been utilized for decades in both residential and commercial applications as energy recovery ventilators (ERVs) and geothermal heat pumps, respectively.

However, ground-coupled solid desiccant air conditioners have not yet been commercialized. Synairco has developed working prototypes of their design (one of which cools their corporate headquarters) and has worked on commercializing the product. The company received grants from the New York State Energy Research and Development Authority (NYSERDA), the Syracuse Center of Excellence, and Taitem Engineering to support its prototype development and demonstration projects (Shopsis 2011, Synairco 2011). However, the absolute efficiency of their current prototypes drops significantly as the building return air cools below AHRI rating conditions (80°F, with 50% relative humidity), thus limiting the applicability of the technology. Consequently, Synairco is considering selling the company to an entity with more manufacturing experience that may be able to overcome this roadblock and improve the technology's performance (Shopsis 2013).

Barriers to Market Adoption

As described in the “Cost, Size, and Complexity” section below, ground coupling significantly increases the complexity and installation cost of space-conditioning systems, due to the need for drilling equipment and potentially challenging piping systems to conduct the cooling fluid from the ground-coupled loop to the solid desiccant system (which may be located on a roof).

Energy Savings Potential

Potential Market and Replacement Applications

Ground-coupled solid desiccant air conditioners are technically applicable to space-cooling applications for residential and commercial buildings in hot-humid climate zones.

Energy Savings

Typical vapor-compression systems sometimes overcool the air to remove humidity and then reheat it to reach desired interior conditions. In contrast, a ground-coupled solid desiccant air conditioner provides greater independent control of latent and sensible loads, making it potentially more energy efficient to achieve desired indoor air conditions. Ground-coupled solid desiccant air conditioners offer significant energy savings only in hot-humid climates with large latent loads.

Synairco reports that its system achieved a source COP of 1.85 during lab tests at AHRI rating conditions (Shopsis 2011), which is higher than the source COP of baseline residential and commercial vapor-compression cooling equipment (1.05).

Cost, Size, and Complexity

We identified no credible cost projections for ground-coupled solid desiccant air conditioners. However, it is likely that such a system would be more expensive than an air-source vapor-compression air conditioner, because it is difficult and expensive to install systems that require ground coupling.

Ground-coupled solid desiccant air conditioners require a low-grade heat source. In certain applications, this heat could be obtained from the sun or from the waste-heat streams; in others, especially in areas where natural gas is inexpensive, this heat could come from a gas burner.

Peak-Demand Reduction and Other Non-Energy Benefits

As thermally driven systems, ground-coupled solid desiccant air conditioners obtain most of their energy from fossil fuels or sources of waste heat, and thus have significant potential for peak-demand reduction.

Ground-coupled solid desiccant air conditioners can achieve sensible heat ratios ranging from 0.0–1.0, and can provide improved indoor air quality and comfort compared to conventional vapor-compression systems (Shopsis 2011).

Next Steps for Technology Development

Researchers at Synairco have not yet developed a way to maintain relatively high efficiencies in their prototype ground-coupled solid desiccant air conditioner over a variety of conditions. Therefore, further testing and development work is needed to demonstrate the ability of this technology to maintain high efficiency while producing acceptable indoor air temperature and humidity over a wide variety of conditions.

Table C-19 presents the potential next steps to advance ground-coupled solid desiccant cooling technology.

Table C-19: Next Steps for the Development of Ground-Coupled Solid Desiccant Air Conditioners

| Initiatives |
|---|
| Further develop and test ground-coupled solid desiccant air conditioners to demonstrate their ability to maintain consistent energy performance while providing acceptable indoor air across a variety of conditions. |

References

Munters. 2012. “Desiccant Wheels.” Munters Corporation. 2012. Available at <http://www.munters.com/upload/DocumentLibrary/MuntersDesiccantWheels.pdf>.

Sachs et al. 2009. “Emerging Energy-Saving HVAC Technologies and Practices for the Buildings Sector (2009).” American Council for Energy-Efficient Economy. December 2009.

Shapiro and Shopsis. 2013. “Split-Air Flow Cooling and Dehumidification System.” U.S. Patent No. US20130186593 A1. July 25, 2013.

Shopsis, Crista. 2011. “Innovation in Ultra-Efficient Air-Conditioning.” Synairco, presentation given at Advanced Energy Conference. October 2011.

Shopsis, Crista. 2013. President of Synairco. Personal Communication. November 25, 2013.

Synairco. 2011. Retrieved from <http://www.synairco.com/> on November 15, 2013.

C.3.7 Standalone Liquid Desiccant Air Conditioner

| | | |
|----------------------------|---|------------------------|
| Brief Description | Desiccants are materials that have a high affinity for water, and can remove water from moist air when exposed to an airstream. In HVAC systems, liquid desiccant air conditioners (LDACs) use liquid desiccants to dry the incoming air. Unless coupled with other technologies, however, desiccants cannot provide sensible cooling and, therefore, do not provide a complete space-cooling function in most climates and applications. Use of a liquid desiccant (rather than solid desiccant) may facilitate coupling with a sensible cooling system. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 0% | Moderate | High |

| Technology Characteristics | Value | Comments |
|---|---------------------|---|
| Unit Energy Savings | 0% | Unless coupled with waste or solar heat, the thermal COP of LDACs is much lower than that of vapor-compression systems, although LDACs use much less electricity and therefore reduce demand (Dean et al. 2012). |
| Fuel Type(s) | Natural gas | Heat, used to regenerate desiccants, can be supplied via a boiler, waste heat, or solar heat. |
| Working Fluid(s) | LiCl/Water Solution | Other salt solutions can be used. LiCl/water is currently used. |
| Complexity/Size | High | LDACs are estimated to be more compact than equivalent vapor-compression systems (Lowenstein et al. 2006); however, current designs require a cooling tower (Dean et al 2012), which adds significant complexity. Moreover, LDACs need to be coupled with a secondary coil, cooled either by water (via ground coupling or a chiller) or by another space-cooling technology. |
| Projected Cost | Moderate-to-High | First-generation LDAC prototypes are estimated to cost 65% more than vapor-compression systems (Lowenstein 2006); however, costs are uncertain because researchers have not yet developed production-oriented designs. These cost projections do not include the cost of the ground coupling or the secondary cooling system required for sensible cooling. |
| Threshold Attributes | Low | Liquid desiccants are corrosive (Lowenstein et al. 2006); cooling towers increase site water consumption compared to vapor compression (Dean et al. 2012). |
| Excitement Attributes | High | Quiet, improved indoor air quality, independent control of temperature and humidity, peak demand reduction potential (Lowenstein 2006). |
| Ability to Utilize Low-Temperature Thermal Sources | High | Waste or solar heat can be used to regenerate the desiccant. |

| | | |
|-------------------------------------|------------------|---|
| Technical Maturity | Moderate | <ul style="list-style-type: none"> • Several institutions have developed successful patents and prototypes for high-efficiency LDACs; however, all existing LDAC prototypes are dehumidifiers supplemented with vapor-compression equipment for sensible cooling. • LDAC prototype development work is being supported by DOE through ARPA-e (ARPA-e 2013). |
| Market Maturity | Moderate | <ul style="list-style-type: none"> • All existing and emerging commercialized LDAC systems are dehumidifiers supplemented with vapor compression or water from an electric chiller. • We identified only one commercialized system: a low-efficiency LDAC manufactured by Advantix. • However, at least two mainstream manufacturers are in the process of commercializing products (e.g., Munters and UTC). |
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> • Electric utilities will potentially oppose this technology because it requires a fuel switch from electricity to natural gas • Expected support by gas utilities as a gas-fired technology for cooling |
| Fit with BTO Mission | Moderate | Moderate potential as standalone technology, more likely to achieve initial market success as a component for vapor-compression systems. |

Background

Technology Description

Air contains both sensible heat (temperature) and latent heat (the energy required to condense or evaporate water), both of which must be removed from either ventilation air or return air to provide suitable indoor conditions. A typical vapor-compression cooling system decreases the temperature of the heat exchanger surface below the dew point, condensing the water vapor and therefore removing latent heat from the air. Desiccants are materials that have a high affinity for water and can remove water from moist air when exposed to an airstream. A liquid desiccant air conditioner (LDAC) uses liquid desiccants to absorb moisture from air, thereby drying it. After capturing moisture, the desiccant is regenerated by a heat source, which releases the water vapor to the outdoor air. Once the desiccant is regenerated, it is cooled by either air or water and can then be used again in the cooling process. The water used to cool the desiccant then rejects heat to the atmosphere in a cooling tower.

Current LDAC prototypes and commercialized systems are only capable of meeting the latent load of incoming air and do not provide sensible cooling (AILR 2011). Consequently, rather than being standalone air conditioners, they are used as dehumidifiers to supplement downstream cooling provided by vapor-compression air conditioners or water from electric chillers.

However, just as solid desiccant air conditioners can use ground-coupled loops to sensibly cool air (as described in Section C.3.6), LDACs can also theoretically use chilled water from ground-coupled loops to meet sensible loads as standalone air-conditioning systems. Alternatively, they can be coupled with a secondary cooling technology to meet sensible cooling loads, including many of the non-vapor-compression technology options listed in this report. For example, liquid desiccant systems can be enhanced through the use of advanced evaporative cooling techniques. See further details in Section C.3.5.

LDACs commonly use glycols or halide salt solutions (such as lithium bromide or lithium chloride) as their desiccants. LDACs have two main components (Dieckmann 2008):

- A conditioner that exposes strong concentrations of liquid desiccant to the air, absorbs water vapor from the supply airstream, and feeds weakened concentrations of liquid desiccant to the regenerator.
- A regenerator that heats the desiccant, releasing water vapor to the exhaust airstream, and returns the liquid desiccant back to the conditioner at strong concentrations.

LDACs heat the liquid desiccant solution in the regenerator using natural gas or low-grade heating sources such as waste, process heat, or solar-heated water. Many systems also gain some “free” regeneration by exchanging heat between the desiccants streams entering and leaving the regenerator. Solar-assisted LDACs can use a vat of liquid desiccant to store heat for cooling during darkened periods (Lowenstein 2008).

Figure C-19 illustrates a complete LDAC dehumidification assembly with a conditioner, regenerator, and counterflow heat exchanger.

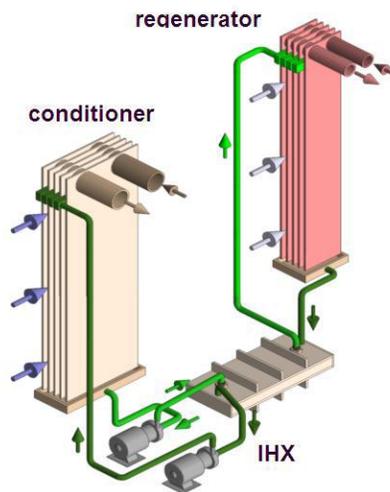


Figure C-19: Design configuration for a liquid desiccant air conditioner

Source: AIL Research (2011)

Regenerator efficiency is partially dependent upon the number of regeneration stages that it utilizes. For example, a “single-effect” regenerator has only one stage: a boiler in which it uses the heat of steam to regenerate the desiccant, whereas higher-effect regenerators use downstream byproducts (e.g., hot water that has condensed after the boiling operation) to provide additional heat.

LDACs can also be used to supplement existing vapor-compression systems, which can then provide additional sensible cooling downstream of the LDAC (Dieckmann 2008).

Technical Maturity and Current Developmental Status

Advantix offers a commercially available basic LDAC (using a single-effect regenerator), but their product sells in modest volumes, is less efficient than vapor-compression technology, and is meant to supplement a vapor-compression sensible-cooling system. A more advanced LDAC (one that uses higher-effect regenerators) is not yet commercially available, though several institutions are working on developing such a product. For example, AIL Research and NREL have jointly tested and optimized several large-scale prototypes (Lowenstein et al. 2006, Lowenstein and Miller 2008, Dean et al. 2012). AIL Research has recently sold its LDAC design to Munters Corporation, which plans to commercialize it and market it in regions where thermal energy costs are low compared to the cost of electricity (Dean et al. 2012). United Technologies Corporation (UTC), a multinational conglomerate that owns Carrier, is currently developing an LDAC with the support of an ARPA-e grant from DOE (ARPA-e 2013). NREL has licensed components of its DEVap design (described in Section C.3.5) to 7AC Technologies, which, with the support of 3M, is currently working on commercializing an liquid desiccant system to be implemented in commercial rooftop HVAC systems (7AC 2012). However, all of these designs and prototypes utilize LDAC technology as dehumidifiers to supplement a vapor-compression chiller or air conditioner and therefore do not represent standalone LDACs.

Barriers to Market Adoption

Lowenstein et al. note that the corrosiveness of many liquid desiccants poses a barrier to market adoption (Lowenstein 2006). In the past, liquid desiccant dehumidifiers used in industrial applications have encountered conditions that acidified the desiccant, causing it to foam or precipitate solid salts, although residential and commercial applications are typically much more controlled and thus should be less likely to experience unfavorable desiccant-air interactions (Lowenstein 2008).

If implemented as a ground-coupled system, standalone LDACs would face increased complexity and installation costs from the required drilling equipment and potentially challenging piping systems to conduct water from the ground loop to the LDAC (which may be located on a roof).

Energy Savings Potential

Potential Market and Replacement Applications

Liquid desiccant air-conditioning technology is technically applicable to all cooling applications for residential and commercial buildings, but only in hot-humid climate zones. While LDAC systems are theoretically capable of standalone operation through coupling with chilled water, most prototypes and commercialized products are used to supplement existing vapor-compression cooling systems.

Energy Savings

Typical vapor-compression systems must address latent loads by overcooling the air to remove humidity and then reheating it to reach optimum interior temperatures. In contrast, the LDAC significantly reduces the latent load experienced by a cooling system by directly removing humidity, making it easier to achieve ideal indoor air conditions. Consequently, LDACs offer significant energy savings only in hot-humid climates with large latent loads. ACEEE states that, in such climates, LDACs used as dehumidifiers could reduce HVAC costs by 30% (Sachs 2009).

Dieckmann et al. note that a high-efficiency LDAC (COP = 1.2) used as a dehumidifying component within a larger ventilation system for dedicated outdoor air systems (DOAS) could achieve primary unit energy savings of 15% over conventional systems. However, the most recent LDAC dehumidifying prototype developed by AILR has a thermal COP of 0.7 (Dean et al. 2012), which is lower than the COP of baseline vapor-compression equipment. Nonetheless, because their technology is mainly powered by fossil fuels, it could be desirable as a dehumidifier in areas where the cost of thermal energy is very low compared to the cost of electricity.

Using solar-heated water streams or waste-heat streams to regenerate the desiccant can increase the efficiency of an LDAC used as a dehumidifier, resulting in primary unit energy savings of 20–25% (Dieckmann 2008). A triple-effect fuel-fired regeneration system, if properly developed, could also achieve comparable savings.

We have not identified any energy use projections for standalone, ground-coupled LDACs.

Cost, Size, and Complexity

We identified no credible cost projections for high-efficiency LDAC dehumidification systems. Although AIL Research, Inc. estimates that a first-generation 23-ton advanced LDAC would cost 65% more than a comparable vapor-compression system (Lowenstein 2006, Dieckmann et al. 2008), this estimate is uncertain because this product has not yet been designed for production and commercialization.

Lowenstein et al. (2006) estimate that core LDACs would be more compact than equivalent vapor-compression systems. However, current designs utilize a cooling tower, which is an external component not required by unitary vapor-compression technologies (used in most residential and small commercial buildings) that adds significant maintenance and space requirements, increases potential liability (associated with the potential growth of *Legionella* in the tower sump), and increases site water consumption, compared to unitary vapor-compression technologies (Dean et al. 2012). Moreover, in order to provide sensible cooling as a standalone system, LDACs would theoretically require a ground-coupled water loop, which adds significant complexity and installation cost.

Desiccant systems also require a low-grade heat source for desiccant regeneration. In certain applications, this heat could be obtained from the sun or from the waste heat streams; in others, especially in areas where natural gas is inexpensive, this heat could come from a gas burner.

Peak-Demand Reduction and Other Non-Energy Benefits

As thermally driven systems with relatively small parasitic electric loads (Lowenstein 2008), LDACs obtain most of their energy from fossil fuels or sources of waste heat, and thus have significant potential for peak-demand reduction.

According to Lowenstein et al. (2006), liquid desiccant air conditioners can provide improved indoor air quality and comfort compared to conventional vapor-compression systems because they allow for independent control of sensible and latent loads.

LDAC core dehumidification systems consist of heat-and-mass exchangers whose only moving parts are the pumps required to circulate the desiccant; consequently, they should therefore be quieter than systems utilizing compressors.

Next Steps for Technology Development

Lowenstein (2008) notes the following research needs for LDAC used as a dehumidifier:

- Identification of a noncorrosive liquid desiccant: Lowenstein identifies weak organic acids (such as potassium or sodium formate and acetate) as potential less-corrosive alternatives, though their suitability for HVAC applications remains uncertain.
- Development of an air-cooled unit to replace units using cooling towers, thus lowering maintenance requirements, reducing liability, saving space, and reducing water consumption.
- Improved contact surfaces: incomplete surface wetting diminishes LDAC performance, and typical desiccants have higher surface tension than water, thus impeding wetting.
- Improvement of regenerator COPs by utilizing multiple-effect regenerators.
- Development of active management systems for managing desiccant quality and chemistry, thus preventing leaks and controlling its interaction with ambient air.

In addition, because LDACs are still in the prototype development stage, we were unable to identify any field tests or other data indicating how LDAC performs in a variety of climate zones and conditions. Further testing would provide more performance, reliability and safety data for these units and help demonstrate that they are ready for market introduction. Perhaps most importantly, we were unable to identify any reliable estimates of the cost of a fully commercialized LDAC unit; consequently, there is a need to develop production-oriented designs and cost projections. These steps will help prepare LDAC technology for successful commercialization as dehumidifying components in cooling systems.

Table C-20 presents the potential next steps advance liquid desiccant cooling technology.

Table C-20: Next Steps for the Development of Standalone Liquid Desiccant Air Conditioners

| Initiatives |
|--|
| Develop and evaluate noncorrosive liquid desiccants |
| R&D of high-efficiency regenerating components |
| Develop air-cooled prototypes |
| Research and develop improved processes for wetting and rewetting contact surfaces of the LDAC |
| Develop active management systems for managing the desiccant |
| Further testing of large-scale prototypes and optimization of their materials, packaging, design to accommodate manufacturing, and costs |

References

7AC. 2012. 7AC Technologies. Retrieved from <http://www.7actech.com/site/index.html>.

Advanced Research Projects Agency – Energy (ARPA-e), date unknown.¹⁶ “United Technologies Research Center (UTRC): Nano-Engineered Porous Hollow Fiber Membrane-Based Air Conditioning System.” Building Energy Efficiency through Innovative Thermodevices (BEETIT) Project Description. Retrieved November 19, 2013 from <http://arpa-e.energy.gov/?q=arpa-e-projects/liquid-desiccant-air-conditioners>.

AIL Research, Inc. 2011. “LD Tutorial.” 2011. Retrieved from http://www.ailr.com/liquid_desiccant_tutorial.htm.

Dean et al. 2012. “Solar-Powered, Liquid-Desiccant Air Conditioner for Low-Electricity Humidity Control.” AIL Research, Coolerado, Mountain Energy Partnership, and NREL. NREL Report No. NREL/TP-7A40-56437-1. November 2012.

Dieckmann et al. “Liquid Desiccant Air Conditioners.” Emerging Technologies – ASHRAE Journal. October 2008.

Kozubal et al. 2011. “Desiccant Enhanced Evaporative Air-Conditioning (DEVap): Evaluation of a New Concept in Ultra Efficient Air Conditioning.” NREL Report No. NREL/TP-5500-49722. January 2011.

Lowenstein and Miller. 2008. “The Field Operation of a Thermally Driven Liquid-Desiccant Air Conditioner.” AIL Research, Inc. May 2008.

¹⁶ No publication date is listed on the ARPA-e website.

Lowenstein et al. “A zero carryover liquid-desiccant air conditioner for solar applications.” AIL Research, Inc. and NREL. ASME International Solar Energy Conference, July 8-13, 2006. ISEC2006-99079.

Lowenstein, Andrew. “Review of Liquid Desiccant Technology for HVAC Applications.” HVAC&R Research Vol. 14, Number 6. November 2008.

Munters. 2012. “Desiccant Wheels.” Munters Corporation. 2012. Available at <http://www.munters.com/upload/DocumentLibrary/MuntersDesiccantWheels.pdf>.

Sachs et al. 2009. “Emerging Energy-Saving HVAC Technologies and Practices for the Buildings Sector (2009).” American Council for Energy-Efficient Economy. December 2009.

C.3.8 Standalone Solid Desiccant Air Conditioner

| | | |
|----------------------------|---|------------------------|
| Brief Description | Desiccants are materials that have a high affinity for water, and can remove water from moist air when exposed to an airstream. In HVAC systems, solid desiccant air conditioners use solid desiccant materials to dry the incoming air, thereby facilitating a secondary sensible cooling step accomplished with a different cooling technology. Unless coupled with other technologies, however, desiccants cannot provide sensible cooling and, therefore, do not provide a complete space-cooling function in most climates and applications. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| 0% | Available | Moderate |

| Technology Characteristics | Value | Comments |
|---|-------------|--|
| Unit Energy Savings | 0% | Unless coupled with waste or solar heat, standalone solid desiccant systems have COPs less than 1 because they consume at least as much thermal energy to expel the moisture the capture to regenerate the desiccant in addition to electrical fan energy and other losses (Vineyard et al. 2000). |
| Fuel Type(s) | Natural gas | Heat can be supplied via a gas burner, waste heat, or solar heat. |
| Working Fluid(s) | None | Use several desiccant materials including silica gels and lithium chloride salts. |
| Complexity/Size | Moderate | Systems are generally larger in size and shape than vapor-compression systems, to accommodate the necessary airflow. |
| Projected Cost | Moderate | <ul style="list-style-type: none"> In general, solid desiccant systems carry a cost/complexity premium and require additional sensible cooling systems. By serving latent cooling loads, solid desiccant systems can offset their cost through smaller sensible cooling systems in some instances. |
| Threshold Attributes | Moderate | Equivalent threshold attributes to vapor compression are projected. |
| Excitement Attributes | High | Projected improved indoor air quality, facilitates independent control of temperature and humidity, when combined with sensible cooling system. |
| Ability to Utilize Low-Temperature Thermal Sources | High | Waste or solar heat can be used to heat the airstream that will regenerate the desiccant. |
| Technical Maturity | High | Desiccant wheel technology is mature and has been successfully utilized to supplement commercial HVAC applications for many years. |

| | | |
|-------------------------------------|------------------|--|
| Market Maturity | High | Solid desiccant components have been commercialized for about two decades. |
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> • Expected support by gas utilities as a gas-fired technology for cooling, and improved heating efficiency • Electric utilities will potentially oppose gas-fired solid desiccant A/C technology because it requires a fuel switch from electricity to natural gas. |
| Fit with BTO Mission | Moderate | Moderate potential as stand-alone technology, more likely to achieve broad market success as a component for vapor-compression systems. |

Background

Technology Description

Air contains both sensible heat (temperature) and latent heat (the energy required to condense or evaporate water), both of which must be removed from either ventilation air or return air to provide suitable indoor conditions. A typical vapor-compression cooling system decreases the temperature of the indoor heat-exchanger surface below the dew point, condensing the water vapor and therefore removing latent heat from the air. Desiccants are materials that have a high affinity for water and can remove water from moist air when exposed to an airstream. A solid desiccant air conditioner uses solid desiccants to absorb moisture from air, thereby drying it. After capturing moisture, the desiccant is regenerated by a heat source, which releases the water vapor to the outdoor air. Once the desiccant is regenerated, it can be used again in the dehumidification process.

Solid desiccants have traditionally been employed as components within vapor-compression systems. Solid desiccant are commonly utilized as energy recovery systems to capture the sensible and latent energy of the exhaust airstream and precondition the incoming outdoor air through a heat exchanger. Typically, a honeycomb-like material coated with a desiccant such as silica gel or lithium chloride transfers heat and moisture between the air streams in a stationary column (typically used only in industrial drying processes), fixed-plate, or a rotating wheel configuration (Munters 2012).

- In the fixed-plate configuration, incoming and exiting air streams travel through a counter-flow heat exchanger, where they are separated by a porous membrane filled with desiccant. The desiccant transfers both sensible and latent energy across the membrane and is continuously regenerated by the exhaust air from the building, which is heated by a gas burner. This style is used extensively for residential and light-commercial ERVs.
- In the desiccant wheel configuration, depicted in Figure C-20, intake air is drawn through a specific portion of the wheel, dried, and subsequently directed to a vapor-compression system for further sensible cooling as the wheel rotates. Exhaust air from the building, further heated by a gas burner, is blown through the other portion of the wheel, regenerates the desiccant by absorbing water, and is ultimately rejected to the outdoors as hot, humid air. This style is used for commercial applications ranging from a rooftop unit to a large-commercial ventilation system.

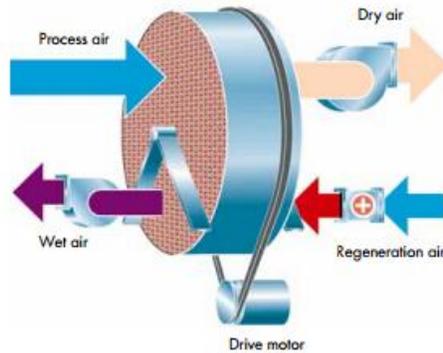


Figure C-20: Solid desiccant wheel

Source: Munters (2012)

Without additional subsystems to cool the dried air stream, solid desiccant systems are only capable of meeting the latent load of incoming air and do not provide sensible cooling. Most solid desiccant systems will provide supplemental dehumidification or energy recovery capabilities to a vapor-compression air conditioners or chillers. Similar to liquid desiccant technology, solid desiccant air conditioners can incorporate several sensible cooling methods to serve as a complete air conditioning system, including many non-vapor-compression technology options. For example, solid desiccant systems can be enhanced through the use of chilled water from ground-coupled loops. See further details in Section C.3.6.

Technical Maturity and Current Developmental Status

Solid desiccant wheels, as utilized in ERVs, have been commercialized in both residential and commercial applications for over two decades and are produced by many major HVAC manufacturers, including Munters, Lennox, and Honeywell. However, these products utilize solid desiccant technology for dehumidification or energy recovery to supplement a vapor-compression system and therefore do not represent standalone solid desiccant air conditioners.

Barriers to Market Adoption

By only addressing latent cooling loads, standalone solid desiccant air conditioners require additional sensible cooling systems to satisfy building space conditioning loads. Except in hot-humid climates and buildings with high moisture loads (e.g., ice rinks, supermarkets) or specialized indoor air quality loads, standalone solid desiccant air conditioners typically pose unfavorable cost and complexity relative to energy or cost savings.

Energy Savings Potential

Potential Market and Replacement Applications

Solid desiccant air-conditioning technology is technically applicable to space-cooling applications for residential and commercial buildings in hot-humid climate zones. As described above, solid desiccants typically supplement existing vapor-compression cooling systems.

Energy Savings

Typical vapor-compression systems sometimes overcool the air to remove humidity and then reheat it to reach desired interior conditions. In contrast, a solid desiccant air-conditioning system acting as a dehumidification technology provides greater independent control of latent and sensible loads, making it potentially more energy efficient to achieve desired indoor air conditions. In hot-humid climates, standalone solid desiccant air conditioners may offer significant energy and cost savings to satisfy large latent loads, but for most systems, the low COP of standalone solid desiccant systems offers no primary energy savings over vapor-compression systems.

By their nature, standalone solid desiccant systems can only achieve a maximum COP of 1 because any latent capacity absorbed by the desiccant must be desorbed by a thermal energy source to regenerate the system. Once accounting for losses in the desiccant's absorption/desorption process, generation of thermal energy, fan power requirements, and other attributes, the source COP of standalone systems is significantly lower.

Vineyard et al. (2000) found standalone solid desiccant systems provided maximum system COPs of 0.3–0.4 over a range of operating conditions.

Energy and Environmental Analysis, Inc. (2004) analyzed several solid desiccant air conditioning systems and calculated thermal COPs between 0.65–0.68, but their analysis does not include fan energy consumption—full-system COPs will be lower than these values.

Cost, Size, and Complexity

Solid desiccant air conditioners require a second cooling system to satisfy both sensible and latent cooling loads, increasing the complexity over technologies that can perform both space conditioning tasks. Depending on the sensible heat ratio of the application, solid desiccant systems can partially offset their cost by decreasing the required capacity of the sensible cooling system.

Solid desiccant air conditioners require a low-grade heat source for general space-cooling applications. In certain applications, this heat could be obtained from the sun or from the waste-heat streams; in others, fossil fuels (usually natural gas) provide this heat. More humid climates can achieve significant cost savings due to the energy savings and increased use of inexpensive thermal energy compared to electrically driven vapor-compression equipment. Applications in more moderate climates may still achieve cost savings from switching to gas-driven cooling.

Peak-Demand Reduction and Other Non-Energy Benefits

As thermally driven systems, solid desiccant air conditioners obtain most of their energy from fossil fuels or sources of waste heat, and thus have significant potential for peak-demand reduction. Solid desiccants are generally non-toxic and have no ODP or GWP. Because solid desiccants facilitate independent control of temperature and humidity, systems can provide improved air quality.

Next Steps for Technology Development

Although standalone solid desiccant air conditioners cannot directly replace vapor-compression systems due to their inability to provide sensible cooling, they are nevertheless an important space-conditioning technology. By satisfying latent cooling loads, solid desiccant systems can supplement conventional vapor-compression systems for improved efficiency and indoor air quality. Additionally, solid desiccant systems can potentially enable other non-vapor-compression technologies that more readily provide sensible cooling (see Section C.3.6).

Table C-21 presents the potential next steps to advance solid desiccant cooling technology.

Table C-21: Next Steps for the Development of Standalone Solid Desiccant Air Conditioners

| Initiatives |
|---|
| Develop higher efficiency solid desiccant air conditioners utilizing advanced desiccants materials, bed designs, lower pressure drops, etc. |

References

Energy and Environmental Analysis, Inc. 2004. “Distributed Energy Technology Characterization.” January 2004.

Holcomb et al. 2000. “Desiccant Cooling Technology – Resource Guide.” Office of the Secretary of Defense. January 2000.

Mei et al. 1992. “An Assessment of Desiccant Cooling and Dehumidification Technology.” Oak Ridge National Laboratory. ORNL/CON-309. July 1992.

Munters. 2009. “DryCool Dehumidification System (DDS) – Engineering Catalog.” Munters Corporation. 2009. Available at <http://www.munters.us/upload/Related%20product%20files/Engineering%20Catalog-%20DDS.pdf>

Munters. 2012. “Desiccant Wheels.” Munters Corporation. 2012. Available at <http://www.munters.com/upload/DocumentLibrary/MuntersDesiccantWheels.pdf>.

Pesaran, Ahmad. 1999. “A Review of Desiccant Dehumidification Technology.” National Renewable Energy Laboratory. NREL/TP-472-7010. June 1993.

Sachs et al. 2009. “Emerging Energy-Saving HVAC Technologies and Practices for the Buildings Sector (2009).” American Council for Energy-Efficient Economy. December 2009.

Vineyard et al. 2000. “Parametric Analysis of Variables that Affect the Performance of a Desiccant Dehumidification System.” Oak Ridge National Laboratory. Available at <http://web.ornl.gov/~webworks/cpr/pres/106025.pdf>.

C.3.9 Vuilleumier Heat Pump

| | | |
|-----------------------------|---|------------------------|
| Brief Description | Similar to Stirling heat pumps, the Vuilleumier heat pump cyclically compresses and expands a gaseous working fluid between different volumes to produce a hot and cold side. With a high-temperature heat source, such as a gas burner, the system can provide space heating and cooling as well as service water heating. | |
| Unit Energy Savings | Technical Maturity | Cost/Complexity |
| Heating: 26% Cooling: 0% | Emerging | Moderate |

| Technology Characteristics | Value | Comments |
|---|--|--|
| Unit Energy Savings | Heating: 26% Cooling: 0% (fossil-fuel-fired) | <ul style="list-style-type: none"> Estimated COPs for heating and cooling of 1.6 and 0.8, respectively (ThermoLift 2013). Approx. 26% savings for heating |
| Fuel Type(s) | Natural gas | Some electricity for parasitic loads such as fans and pumps. |
| Working Fluid(s) | Helium | Long-term potential for other working fluids, including: hydrogen, and hydrogen-helium mixtures |
| Complexity/Size | Moderate | <ul style="list-style-type: none"> Compact size estimated for products currently under development Products would have relatively simple installation with self-contained systems that require water/glycol connections. |
| Projected Cost | N/A | Cost estimates for HVAC applications are unavailable. |
| Threshold Attributes | Moderate | Sealed design with few moving parts could offer long lifetimes and low maintenance requirements. |
| Excitement Attributes | Moderate | Gas-fired heat pump with heating COP over unity that utilizes non-toxic working fluid. |
| Ability to Utilize Low-Temperature Thermal Sources | Low | Requires high temperatures (500°C and higher). |
| Technical Maturity | Moderate | Performance has been demonstrated in laboratory, but market-ready prototypes have not been built. |
| Market Maturity | Low | Vuilleumier heat pumps are not yet commercialized. |
| Level of Stakeholder Support | Moderate-to-High | <ul style="list-style-type: none"> Gas utilities are likely to support this technology as a gas-fired technology for cooling, and improved heating efficiency Electric utilities will potentially oppose this technology because it requires a fuel switch from electricity to natural gas |
| Fit with BTO Mission | Moderate | Potentially an attractive thermally activated heat-pump technology that does not use toxic working fluids or require significant maintenance. |

Background*Technology Description*

Comprising of both a heat engine and a heat pump, the Vuilleumier cycle transfers heat from a high-temperature source, such as a gas burner, to a medium-temperature heat source for space heating, and a low-temperature heat sink for space cooling. Similar to the Stirling cycle, a sealed volume of gas, usually high-pressure helium, undergoes cyclic compression and expansion. Whereas the Stirling-cycle heat pump utilizes a common piston with separated working volumes, the Vuilleumier heat pump circulates the working fluid through three volumes¹⁷ of different temperatures separated by two displacers, as outlined in Figure C-21.

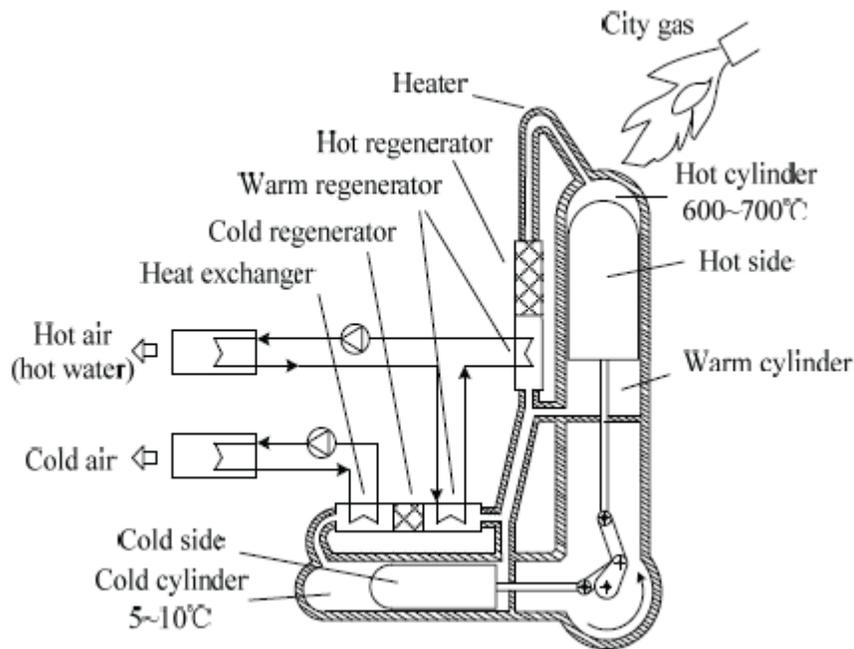


Figure C-21: Schematic of kinematic Vuilleumier heat pump

Source: Xie et al. (2008)

The displacers may operate as a kinematic (as shown in Figure C-21) or free-piston machine (where the displacers share a common vertical shaft), and may require an electrical source to overcome minor frictional and pressure losses. Driven by the high-temperature heat source in the heat-engine portion, the displacers oscillate the working fluid among the hot, warm, and cold volumes. The system achieves high heating COPs by capturing waste heat from the engine portion in addition to the thermal energy generated by the heat pump. A regenerator, made of a porous metal mesh, stores a portion of the thermal energy to pre-heat or pre-cool the gas throughout the cycle for improved efficiency. To deliver the heating and cooling energy to the space, a secondary working fluid, usually water, circulates through the warm and cold heat exchangers.

¹⁷ Three volumes refer to the hot volume, cold volume, and warm volume. Because the warm volume is split between both the hot and cold side of the cycle, some literature refers to four volumes, two of which are at the warm temperature. Because the working fluid is shared between each, it is a matter of preference.

Technical Maturity and Current Developmental Status

Although several groups have studied the Vuilleumier heat pump and its potential for gas-fired space conditioning, no products currently exist on the market. These past and current efforts include:

- Researchers in Germany and Denmark developed several prototypes for space heating and cooling in a residential home (7.5 kW) and fishing vessels (20 kW). Using a lower heating value (LHV) calculation, the units achieved approx. COPs of 1.6 for heating and 0.35 for cooling. (Carlsen 1989). Converting these values to the higher heating value (HHV) of natural gas results in COPs of approx. 1.4 for heating and 0.32 for cooling.
- Sanyo and several Japanese gas utilities investigated Vuilleumier heat pumps for residential space conditioning and service water heating, but the work did not continue (Bakker et al. 2010). Several prototypes were developed, which achieved COP values of 0.56 for cooling and 1.33 for heating (Toshikazu et al. 1999).
- ThermoLift, a start-up associated with Stony Brook University, is currently developing a gas-fired Vuilleumier heat pump for residential and commercial space conditioning and service water heating. The company has received several grants from DOE and NYSERDA to build a demonstration prototype and expects heating COPs of 1.6–2.2 and cooling COPs of 0.8–1.2 (ThermoLift 2013). Their technology improves upon earlier mechanically controlled designs by utilizing a magnetic actuation system to precisely control the amplitude and timing of the oscillating displacers. This control mechanism allows the system to optimize efficiency and performance for different operating modes and ambient conditions.

Barriers to Market Adoption

Currently no products on the market utilize Vuilleumier heat pumps. Because cooling COPs are low, energy savings are not expected during the cooling season. For heating-dominated climates, the higher heating efficiency and cost savings may offset the lower cooling efficiency.

Energy Savings Potential

Potential Market and Replacement Applications

The Vuilleumier heat pump would be technically suitable for most residential and commercial applications once developed. The heat pump operates as a sealed system with water heat exchangers that could condition the space directly through a radiant system, or operate through an air-side heat exchanger for ducted systems. The gas burner would require an exhaust vent, similar to other gas-heating equipment.

Energy Savings

At current performance estimates, a fossil-fuel-fired Vuilleumier heat pump would only offer potential source energy savings for space- and service-water-heating applications compared to conventional vapor-compression equipment. Estimating heating COPs of 1.6 (ThermoLift 2013) and parasitic electric consumption (kW) of 0.023 per heating capacity (kW) for distribution systems, fossil-fuel-fired Vuilleumier heat pumps could provide source energy savings for heating of 26% over vapor-compression heat pumps.

Cost, Size, and Complexity

We found only limited cost and operating information for Vuilleumier heat pumps. By utilizing natural gas as the energy source, Vuilleumier heat pumps would have lower operating costs in space- and service-water-heating mode, and potentially in cooling mode. The sealed design could allow for easy installation, requiring only water connections and exhaust vents in the field.

Peak-Demand Reduction and Other Non-Energy Benefits

As a gas-fired technology, the Vuilleumier heat pump would offer peak-demand savings during the cooling season, although the exact benefit will depend on the parasitic loads. Helium is a non-toxic and environmentally benign refrigerant. With minimal moving parts, systems could have long lifetimes and low maintenance requirements.

Next Steps for Technology Development

Table C-22 presents the potential next steps to advance Vuilleumier heat pumps.

Table C-22: Next Steps for the Development of Vuilleumier Heat Pumps

| Initiatives |
|--|
| Continue development of demonstration prototypes to benchmark space-heating, space-cooling, and service-water-heating COPs and understand the parasitic energy consumption |

References

Bakker et al. 2010. “Gas Heat Pumps.” GasTerra. December 2010.

Carlsen, Mikael. 1989. “Development of a Gas Fired Vuilleumier Heat Pump for Residential Heating.” International Energy Conversion Engineering Conference. 1989.

Näslund, Mikael. 2008. “Residential Gas-Fired Sorption Heat Pumps – Test and Technology Evaluation.” Dansk Gasteknisk Center A/S. December 2008.

ThermoLift. 2013. “Comparative Analysis of Current Thermally Driven Refrigeration Devices.” ThermoLift Inc. <http://www.tm-lift.com/index.html>.

Toshikazu et al. 1999. “Development of a Vuilleumier Cycle Heat Pump System.” Sanyo Electric Company, Ltd. Symposium on Stirling Cycle Vol. 3. 1999.

Xie et al. 2008. “Investigation on the Performance of the Gas Driven Vuilleumier Heat Pump.” International Refrigeration and Air Conditioning Conference. July 2008.

Appendix D Methodology to Estimate Technical Energy Savings Potential

General Methodology

In general, technical energy savings potential is the product of the estimated percent unit energy savings and the total annual energy consumption attributed to the technology across the following market segments:

- Space conditioning end use (e.g., heating, cooling)
- Building type (e.g., residential, commercial)
- Equipment categories (e.g., unitary heat pumps, chillers, etc.)
- Climate regions (e.g., Cold, Hot-Dry, etc.).

$$TESP \left(\frac{\text{Quads}}{\text{yr}} \right) = UES (\%) \times AEC \left(\frac{\text{Quads}}{\text{yr}} \right)$$

TESP = Technical energy savings potential

UES = Unit energy savings percentage over baseline technology

AEC = Annual energy consumption of relevant U.S. market segments

Estimate of Baseline Equipment Efficiency

The analysis assumes that the equipment efficiencies for each baseline technology meet current codes and standards (or current typical practice for new equipment installations) for U.S. residential and commercial buildings. For comparison to non-electric technology options, each baseline-efficiency metric was converted to a source energy COP assuming a site-to-source ratio of 3.11 for electricity. For ease of comparison, this analysis averaged the source energy COPs for residential and light commercial equipment types. For example, the assumed cooling COP is the average of the cooling COPs for residential and light commercial air conditioners. Table D-1 presents the baseline equipment efficiency information and Table D-2 provides the final site and source energy COPs used for baseline equipment types.

Table D-1: Baseline Equipment Efficiency Information (Site Energy)

| Equipment Type | Capacity / Description | Source | Cooling Efficiency Metric | | | | Heating Efficiency Metric | | | |
|-----------------------------|---|--------|---------------------------|------|--------|------|---------------------------|------|-----|------|
| | | | SEER | EER | kW/ton | COP | EER | HSPF | COP | COP |
| Res. Air Conditioner | 3–5 tons | 1 | 13 | 11.1 | - | 3.25 | - | - | - | - |
| Res. Heat Pump | 3–5 tons | 1 | 14 | 12.0 | - | 3.52 | - | 8.2 | - | 3.35 |
| Light Comm. Air Conditioner | 11.5–20 tons | 2 | - | 10.8 | - | 3.17 | - | - | - | - |
| Light Comm. Heat Pump | 11.5–20 tons | 2 | - | 10.4 | - | 3.05 | - | - | 3.2 | 3.20 |
| Large Comm. Chiller | > 300 tons, water cooled, positive displacement | 3 | - | - | 0.62 | 5.67 | - | - | - | - |

1. DOE. 2004. “Energy Conservation Program for Consumer Products; Central Air Conditioners and Heat Pumps Energy Conservation Standards.” U.S. Department of Energy. 69 FR 50997. August 17, 2004.

2. DOE. 2012. “Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment.” U.S. Department of Energy. 77 FR 71340. May 16, 2012.

3. ASHRAE. 2013. “Energy Standard for Buildings Except Low-Rise Residential Buildings.” ANSI/ASHRAE/IES Standard 90.1–2013.

Where applicable, cooling and heating efficiency metrics were converted to site COPs through the following:

- Cooling SEER to EER using de-rating estimates from Table 6 of Cutler et al. (2013)¹⁸
- Cooling EER to COP using the conversion factor of $COP = \frac{EER (\frac{Btu/h}{W})}{3.412}$
- Cooling kW/ton to COP using the conversion factor of $COP = \frac{3.516}{kW/ton}$
- Heating HSPF to COP using de-rating estimates from Table 11 of Cutler et al. (2013)¹⁸

¹⁸ Cutler et al. 2013. “Improved Modeling of Residential Air Conditioners and Heat Pumps for Energy Calculations.” National Renewable Energy Laboratory (NREL). NREL/TP-5500-56354. January 2013.

Table D-2: Baseline Equipment Site and Source Energy COPs

| Equipment Type | Site Energy COPs | | Source Energy COPs ¹ | |
|--------------------------------|-------------------|-------------------|---------------------------------|---------|
| | Cooling | Heating | Cooling | Heating |
| Residential / Light Commercial | 3.21 ² | 3.28 ³ | 1.03 | 1.05 |
| Large Commercial | 5.67 | - | 1.82 | - |

¹ Site-to-source energy ratio of 3.11 for electricity

² Average of cooling COPs for residential and light commercial air conditioners

³ Average of heating COPs for residential and light commercial heat pumps

Source Energy Consumption Estimate for Thermotunneling

The published COPs of thermotunneling, one of the solid-state technologies analyzed in this report, do not include the parasitic electric consumption required to operate fans, pumps, and other components needed to distribute thermal conditioning to the space, reject excess heat, etc. Because standard rating methods for conventional technologies include these parasitic electricity loads, the COPs for thermotunneling technology must be adjusted before evaluating its energy savings potential. With limited data available, we estimated parasitic electricity consumption based on our knowledge of the parasitics associated with air conditioners and heat pumps. We estimated that parasitic electric consumption would account for 30% of the total energy consumption of thermotunneling technology, although this estimate may be optimistic because this technology option offers limited heat transfer surfaces and thus may require disproportionate parasitic energy consumption to overcome.

Source Energy Consumption Estimate for Non-Electric Technology Options

Efficiencies for thermally activated technology options are commonly reported as thermal COPs, which do not take into account parasitic electric consumption, as defined above. Because standard rating methods for conventional technologies include these parasitic electricity loads, the thermal COPs for non-electric technologies must be adjusted before evaluating their savings potential. With limited data available for early-stage and emerging technology options, we estimated parasitic electricity consumption using commercially available information for residential and light commercial absorption heat pumps. Our analysis of non-electric heat pumps revealed cooling efficiencies lower than conventional vapor-compression systems, so we developed estimates for parasitic loads for heating-mode only. We estimated parasitic electric consumption (kW) of 0.023 kW per kW of heating capacity, summarized in Table D-3.

Table D-3: Reported Parasitic Electric Consumption for Available Absorption Heat Pumps

| Manufacturer | Model | Heating Output (kW) | Electrical Input (kW) | Elec. Input to Thermal Output (kW/kW) |
|------------------------|--------------|---------------------|---------------------------|---------------------------------------|
| Buderus ¹ | GWPL 38 | 41.1 | 1.09 | 0.027 |
| FireChill ² | AHP40 | 39.6 | 0.75 | 0.019 |
| Fulton ³ | IVS-095-A | 40.8 | 0.75 | 0.018 |
| Robur ⁴ | GAHP-ALT | 41.7 | 0.9 | 0.022 |
| Robur ⁵ | RTAR 180-360 | 105.9 | 3.21 | 0.030 |
| | | | Arithmetic Average | 0.023 |

¹ Buderus. 2012. "GWPL 38 Gas Absorption Heat Pump 38.3 kW." Bosch Thermotechnology, Ltd. March 2012.

² FireChill. 2011. "Product Data AHP40." FireChill Trading LLP. January 2011.

³ Fulton. 2012. "Invictus - Hydronic Heating and Cooling Systems with Gas Absorption Heat Pumps." Fulton Heating Solutions, Inc. December 2012.

⁴ Robur. 2013. "Integrated Heating and Cooling Solutions with Absorption Heat Pumps Powered by Natural Gas and Renewable Energy." Robur S.p.A.

⁵ Robur. 2007. "Air Conditioning Systems with Gas Absorption Heat Pumps - Messaggerie del Garda S.p.A." Robur S.p.A. June 2007.

We then calculate total site energy COP for non-electric technology options as follows:

$$Total\ Site\ Energy\ COP = \frac{Output_{therm}\ (kW)}{Input_{therm}\ (kW) + Input_{elec}\ (kW)} = \frac{COP_{therm}}{1 + (k \times COP_{therm})}$$

where k is the estimated ratio of electricity input to thermal output (i.e., $0.023 \frac{Input_{elec}(kW)}{Output_{therm}(kW)}$) and COP_{therm} is the thermal COP estimate for the technology option.

Total source energy COP is then calculated by incorporating the site-to-source conversion factors for electricity (3.11) and natural gas (1.01):

$$Total\ Source\ Energy\ COP = \frac{COP_{therm}}{(1 \times 1.01) + (k \times COP_{therm} \times 3.11)}$$

Unit Energy Savings Estimate for Non-Electric Technology Options

We estimate the unit energy savings for a non-vapor-compression technology option by comparing the estimated total source energy COP of the technology with the source energy COP of the baseline vapor-compression equipment:

$$UES\ (\%) = \frac{Total\ Source\ Energy\ COP_{tech} - Source\ Energy\ COP_{baseline}}{Source\ Energy\ COP_{baseline}}$$

Heating-Mode Source Energy Consumption

Many of the technology options we analyzed can provide both space heating and space cooling; however, as described in Appendix C, much of the research conducted to date on these technology options has focused solely on space-cooling applications, so space-heating performance is less certain. Therefore, for technology options that are technically suitable for efficient space heating, but for which space-heating performance is not well-documented, we used the first law of thermodynamics to convert their cooling COP (as adjusted to include parasitic energy consumption, as described above) to heating COPs. We then adjusted these heating COPs based on the assumption that 10 percent of the total heat produced would be lost to the ambient and 90 percent would provide useful heating:

$$COP_{heat} = (COP_{cool} + 1) * 0.90$$

Appendix E Comparison of U.S. Census Regions and Building America Climate Zones

As mentioned in Section 1.2, the P-Tool does not distinguish geographic regions based on climate zone. It instead uses nine census regions as defined by the U.S. Census Bureau. A map of these census regions is presented in Figure E-1 below.

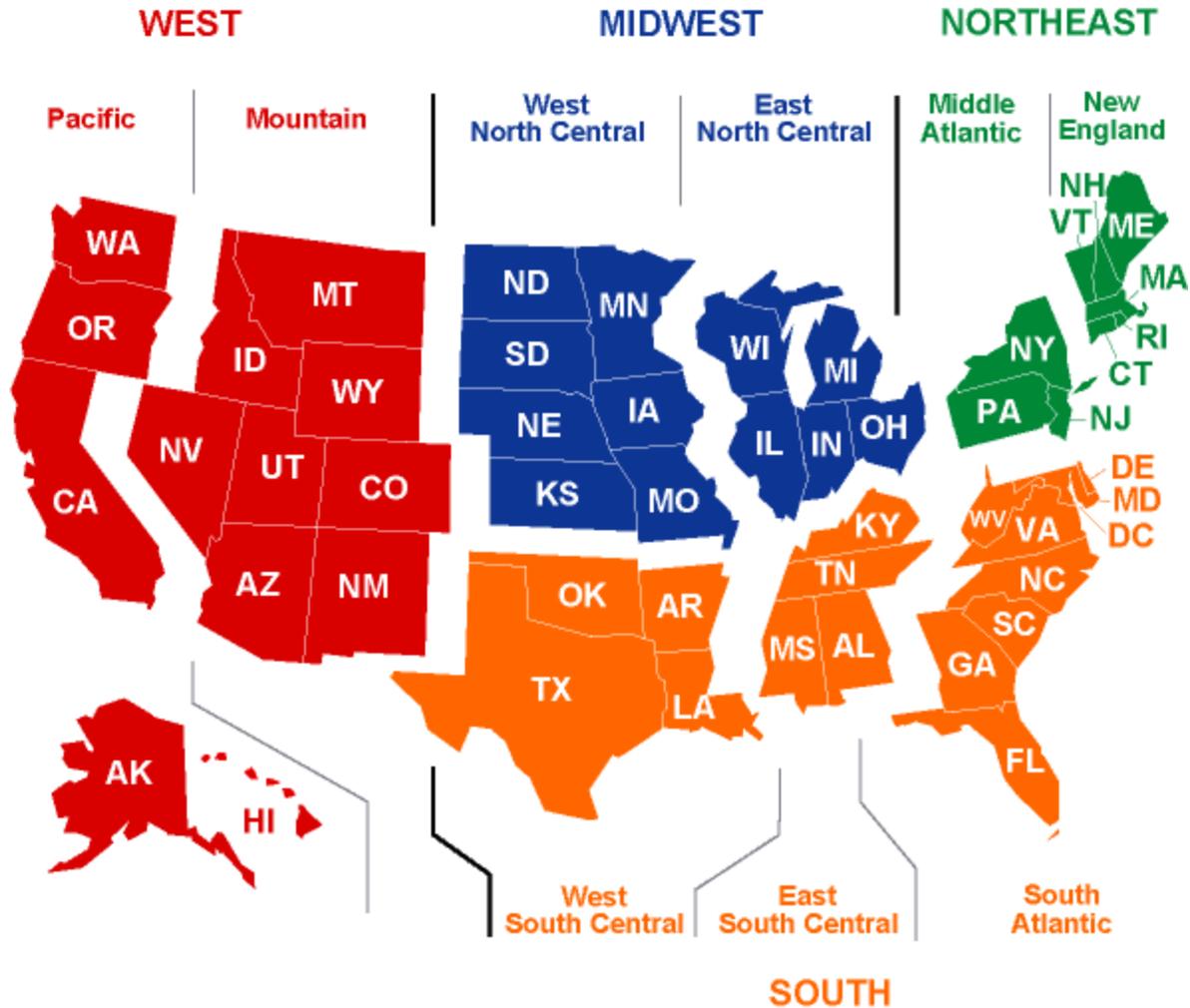


Figure E-1: U.S. census regions
Source: EIA (2013)

Some of the technology options that we considered in this report can only be used in specific climate regions. For example, evaporative cooling technologies are only applicable in hot-dry regions, while most desiccant-based air conditioners are only applicable in hot-humid regions. Building America (BA) defines five climate zones for the United States based on their typical temperatures and humidity levels. The BA climate zones are presented in Figure E-2.

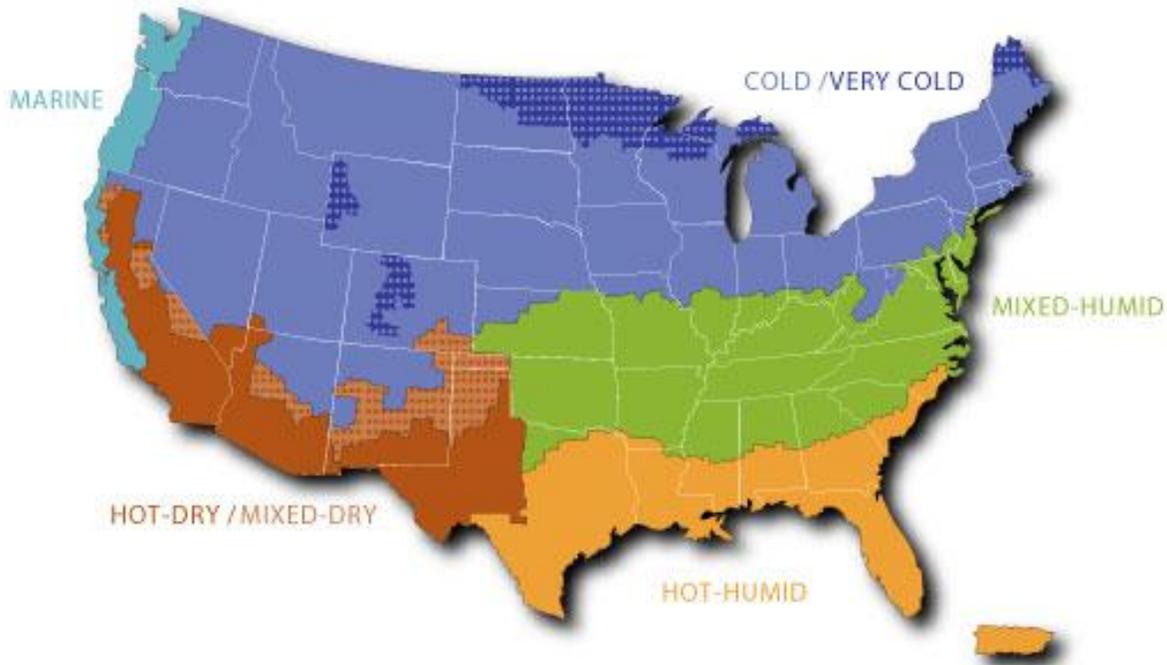


Figure E-2: Building America climate zones

Source: Source: EIA (2013)

To estimate the energy savings associated with technologies specific to certain climate zones, we made the following assumptions about how the U.S. census regions map to the BA climate zones:

1. The Hot-Humid climate zone maps to the South Atlantic, East South Central, and West South Central census regions (numbered as census regions 5, 6, and 7 in the P-Tool).
2. The Hot-Dry/Mixed-Dry climate zone maps to the Mountain census region (numbered as census region 8 in the P-Tool).

References

EIA. 2013. "Residential Energy Consumption Survey (RECS) – Maps." U.S. Energy Information Administration. Accessed December 2013. Available at: <http://www.eia.gov/consumption/residential/maps.cfm>

Appendix F Technical Energy Savings Potential of the 17 Viable Non-Vapor-Compression Technology Options

| Technology Options | Heating Unit Energy Savings | Cooling Unit Energy Savings | Applicable Market | Technical Potential (Quads) |
|---|-----------------------------|-----------------------------|-------------------|-----------------------------|
| Absorption Heat Pump | 17% | 0% | 1 | 0.24 |
| Adsorption Heat Pump | 8% | 0% | 1 | 0.11 |
| Brayton Heat Pump | 0% | 0% | 1 | - |
| Duplex-Stirling Heat Pump | 4% | 0% | 1 | 0.06 |
| Ejector Heat Pump | 0% | 0% | 1 | - |
| Evaporative Cooling | 0% | 75% | 3 | 0.25 |
| Evaporative Liquid Desiccant A/C | 0% | 61% | 1 | 2.64 |
| Ground-Coupled Solid Desiccant A/C | 0% | 43% | 2 | 1.21 |
| Magnetocaloric | 27% | 20% | 1 | 1.25 |
| Membrane Heat Pump | 0% | 50% | 1 | 2.16 |
| Standalone Liquid Desiccant A/C | 0% | 0% | 2 | - |
| Standalone Solid Desiccant A/C | 0% | 0% | 2 | - |
| Thermoacoustic | 8% | 0% | 1 | 0.11 |
| Thermoelastic | 48% | 47% | 1 | 2.68 |
| Thermoelectric | 14% | 0% | 1 | 0.19 |
| Thermotunneling | 14% | 1% | 1 | 0.22 |
| Vuilleumier Heat Pump | 26% | 0% | 1 | 0.36 |
| <p>Market #1: All residential and commercial space-cooling applications (excluding gas-fired chillers, as explained in Section 1.2) and all residential and commercial space-heating applications that use electricity as their main input.</p> <p>Market #2: All residential and commercial space-cooling applications in U.S. census regions 5, 6, and 7.¹⁹ This is the target market for cooling-only technologies that are most applicable in hot-humid climates.</p> <p>Market #3: All residential and commercial space-cooling applications in census region 8. This is the target market for cooling-only technologies that are most applicable in hot-dry climates.</p> | | | | |

¹⁹ The P-Tool uses census regions rather than climate zones to distinguish geographic areas of the United States. Maps indicating how U.S. census regions compare to climate zones can be found in Appendix E.

Appendix G Supplementary Technologies for Vapor-Compression Systems

Several non-vapor-compression technology options can augment the efficiency of conventional vapor-compression systems by serving as a component. Evaluating applications as subsystems to vapor-compression equipment was beyond the scope of this assignment. The following list summarizes the potential supplementary applications for non-vapor-compression technology options for future reference.

- **Condenser subcooling** with solid-state devices offers the potential to increase the evaporator capacity and COP of vapor-compression systems by lowering the temperature of liquid refrigerant. Because they have high efficiency at low temperature differences, solid-state devices can provide this additional cooling capacity more efficiently than the compressor alone. Relevant technology options include: Thermoelectric and potentially other solid-state technology options (Schoenfeld et al. 2012).
- **Desiccant pre-cooling** lowers the energy consumption of vapor-compression systems by more efficiently removing latent heat from the supply air stream. By serving only the sensible cooling load, the vapor-compression system avoids the process of successively overcooling and reheating the air to remove moisture. Additionally, sensible and latent energy from exhaust air streams can be transferred to incoming air streams to precondition the air. Relevant technology options include: Standalone Liquid Desiccant A/C (Dieckmann 2008), Standalone Solid Desiccant A/C (Munters 2012), and potentially other desiccant technology options such as Evaporative Liquid Desiccant A/C.
- **Evaporative pre-cooling** sprays water onto a heat exchanger located upstream of the condenser or supply air flow to reduce the temperature and pressure requirements of the compressor, and thereby reduce energy use in vapor-compression systems. For dry climates, the incoming air evaporates the water from the heat exchanger surface, which provides sensible cooling to the air stream. Relevant technology options include: Evaporative Cooling (Faramarzi et al. 2010), and potentially other evaporative technology options such as Evaporative Liquid Desiccant A/C.
- **Alternative expansion devices** can recover a portion of the throttling or friction losses caused by the conventional expansion valve in a vapor-compression system. Reducing the losses associated with refrigerant expansion improves system COP. Relevant technology options include: Ejector Heat Pump (Weissler 2009, Pottker et al. 2010), Vortex-Tube Cooling (Li et al. 2000).
- **Secondary compression devices** reduce the required pressure ratio across the primary, electrically driven compressor, and thereby improve COP of vapor-compression systems. These secondary systems utilize thermal energy to compress the refrigerant, decreasing the electricity consumption of the vapor-compression cycle. Relevant technology options include: Ejector Heat Pump (Bergander 2006).

References

- Bergander, Mark. 2006. "Refrigeration Cycle with Two-Phase Condensing Ejector." International Refrigeration and Air Conditioning Conference. July 2006.
- Berchowitz et al. 2008. "CO₂ Stirling Heat Pump for Residential Use." International Refrigeration and Air Conditioning Conference. July 2008.
- Dieckmann et al. "Liquid Desiccant Air Conditioners." Emerging Technologies – ASHRAE Journal. October 2008.
- Faramarzi et al. 2010. "Performance Comparison of Evaporatively Cooled Condenser versus Air-Cooled Condenser Air Conditioners." 2010 ACEEE Summer Study on Energy Efficiency in Buildings.
- Li et al. 2000. "Thermodynamic Analysis of Vortex Tube and Work Output Devices for the Transcritical Carbon Dioxide Cycle." Preliminary Proceedings of the 4th IIR-Gustav Lorentzen Conference on Natural Working Fluids. 2000.
- Munters. 2012. "Desiccant Wheels." Munters Corporation. 2012. Available at <http://www.munters.com/upload/DocumentLibrary/MuntersDesiccantWheels.pdf>.
- Pottker et al. 2010. "Experimental Investigation of an R410A Vapor Compression System Working with an Ejector." International Refrigeration and Air Conditioning Conference. July 2
- Schoenfield et al. 2012. "CO₂ Transcritical Vapor Compression Cycle with Thermoelectric Subcooler." HVAC&R Research. Volume 18, Issue 3. June 11, 2012.
- Weissler, Paul. 2009. "2010 Prius First with Ejector-Cycle Air Conditioning." SAE International. August 10, 2009. Retrieved from <http://articles.sae.org/6741/>.

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