U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES OFFICE

Research & Development Opportunities for Joining Technologies in HVAC&R

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Preface

The Department of Energy's (DOE) Building Technology Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy (EERE) engaged Navigant Consulting, Inc., (Navigant) to develop this report on research and development (R&D) opportunities in heating, ventilation, air-conditioning, and refrigeration (HVAC&R) joining technologies.

The initiatives identified in this report are Navigant's recommendations to BTO for pursuing in an effort to achieve DOE's greenhouse gas emission (GHG) reduction goals. Inclusion in this report does not guarantee funding; individual initiatives must be evaluated in the context of all potential activities that BTO could undertake to achieve its goals.

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List of Acronyms

BTO	Building Technologies Office (Department of Energy, part of EERE)
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FDD	Fault Detection and Diagnostics
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HVAC&R	Heating, Ventilation, Air Conditioning, and Refrigeration
O&M	Operations and Maintenance
PVC	Polyvinyl Chloride
R&D	Research and Development
TXV	Thermostatic Expansion Valve
WAAM	Wire-Arc Additive Manufacturing

Executive Summary

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) within the Office of Energy Efficiency and Renewable Energy works with researchers and industry partners to develop and deploy technologies that can substantially reduce energy consumption and greenhouse gas (GHG) emissions in residential and commercial buildings. This opportunity assessment aims to advance BTO's energy savings, GHG reduction, and other program goals by identifying research and development (R&D) initiatives for joining technologies in heating, ventilation, air-conditioning, and refrigeration (HVAC&R) systems. Improving joining technologies for HVAC&R equipment has the potential to increase lifetime equipment operating efficiency, decrease equipment and project cost, and most importantly reduce hydroflourocarbon (HFC) refrigerant leakage to support HFC phasedown and GHG reduction goals.

This opportunity assessment identifies and characterizes R&D opportunities with HVAC&R joining technologies for BTO to pursue. The investigation scope covers joining technologies common for a wide variety of residential and commercial HVAC&R systems, and focuses on three cross-cutting topic areas:

- Brazing and Joining Technologies and Processes
- Advanced Component Design and Materials
- Installation, Operation, and Maintenance.

To gather input for this opportunity assessment, BTO hosted a one-day workshop of experts with wide-ranging backgrounds, including university researchers, manufacturers (HVAC, refrigeration, heat exchangers, fittings, and more), and design engineers. Stakeholders emphasized the need for R&D investment to better understand and improve current joining practices and develop the next generation of joining techniques for advanced HVAC&R systems and components. Key themes arose from stakeholder discussion, including:

- **Reducing the number of joints in HVAC&R systems and components:** Heat exchanger, fitting, and overall system design strategies that eliminate the number of joints and potential leakage points.
- **Consistent methodologies to inspect, measure, and benchmark leakage from different joining techniques:** Research studies into common joining practices and the development of advanced joint-verification techniques to improve the way that manufacturers, technicians, and system designers select and employ joining techniques for HVAC&R systems.
- **Alternative joining technologies for factory and field installation, servicing, and repair:** Developing novel joining technologies and techniques or adapting strategies from other industries to improve joining time, cost, reliability, and other attributes, while also preparing for field servicing of HVAC&R equipment using next-generation refrigerants.
- **Material compatibility for next-generation HVAC&R systems and components:** Developing fittings and joining technologies that improve the connections between dissimilar materials found in advanced HVAC&R systems (e.g., copper-aluminum, copper-polymer).

In all, stakeholders provided 19 challenges and barriers facing HVAC&R joining technologies and 35 unique ideas for R&D initiatives. Following the stakeholder workshop, we investigated and characterized the full set of initiatives and evaluated them using several qualitative prioritization steps. Table ES-1 outlines the resulting nine higher-priority initiatives for HVAC&R joining technologies. These initiatives represent some of the key areas in which BTO could advance the current generation of HVAC&R joining technologies. Because each initiative only targets a specific issue, no single initiative can solve the multi-faceted problems manufacturers, contractors, and building owners experience with current HVAC&R joining technologies, and a multi-initiative approach could provide the best pathway.

Table ES-1: Higher-Priority R&D Initiatives

Category	Initiative
Brazing and Joining Technologies	Identify and develop specific adhesives with targeted chemistries for HVAC&R joining applications
Brazing and Joining Technologies	Conduct a research study to evaluate the effectiveness of various joining methods
Brazing and Joining Technologies	Research and develop hybrid joining connections that combine a torque fitting with a secondary non-mechanical joining technique
Brazing and Joining Technologies	Research and develop low-temperature, non-torque-based joining technologies and techniques
Brazing and Joining Technologies	Develop an improved, consistent evaluation process or technology for verifying joints in both factory and field applications
Component and Materials	Develop advanced heat exchanger designs that reduce the number of required joints
Component and Materials	Develop coatings, compounds, or tapes that improve joint connections and leakage rates during installation and servicing
Component and Materials	Develop HVAC&R systems that limit the refrigerant charge lost through leakage events
Installation, Operations, and Maintenance	Develop on-board fault detection and diagnostics (FDD) systems to detect leakage from packaged HVAC&R systems

The report that follows provides background on BTO's role in improving HVAC&R joining technologies, discussion of key trends facing the HVAC&R industry, and detailed descriptions for higher-priority R&D initiatives. The report is organized as follows:

1. **Introduction/Background:** Impacts of HVAC joining technologies on HFC phasedown goals, BTO's role, report objectives
2. **Project Approach:** R&D opportunity assessment development process steps

3. **Market Overview:** Market trends and current barriers for HVAC&R joining technologies
4. **R&D Opportunities:** Detailed discussion of higher-priority initiatives, as well as general discussion of themes; Higher-priority initiative characterizations include discussion of initiative's purpose and goals, potential impacts on existing technical and market barriers, and key stakeholder roles throughout different initiative stages.

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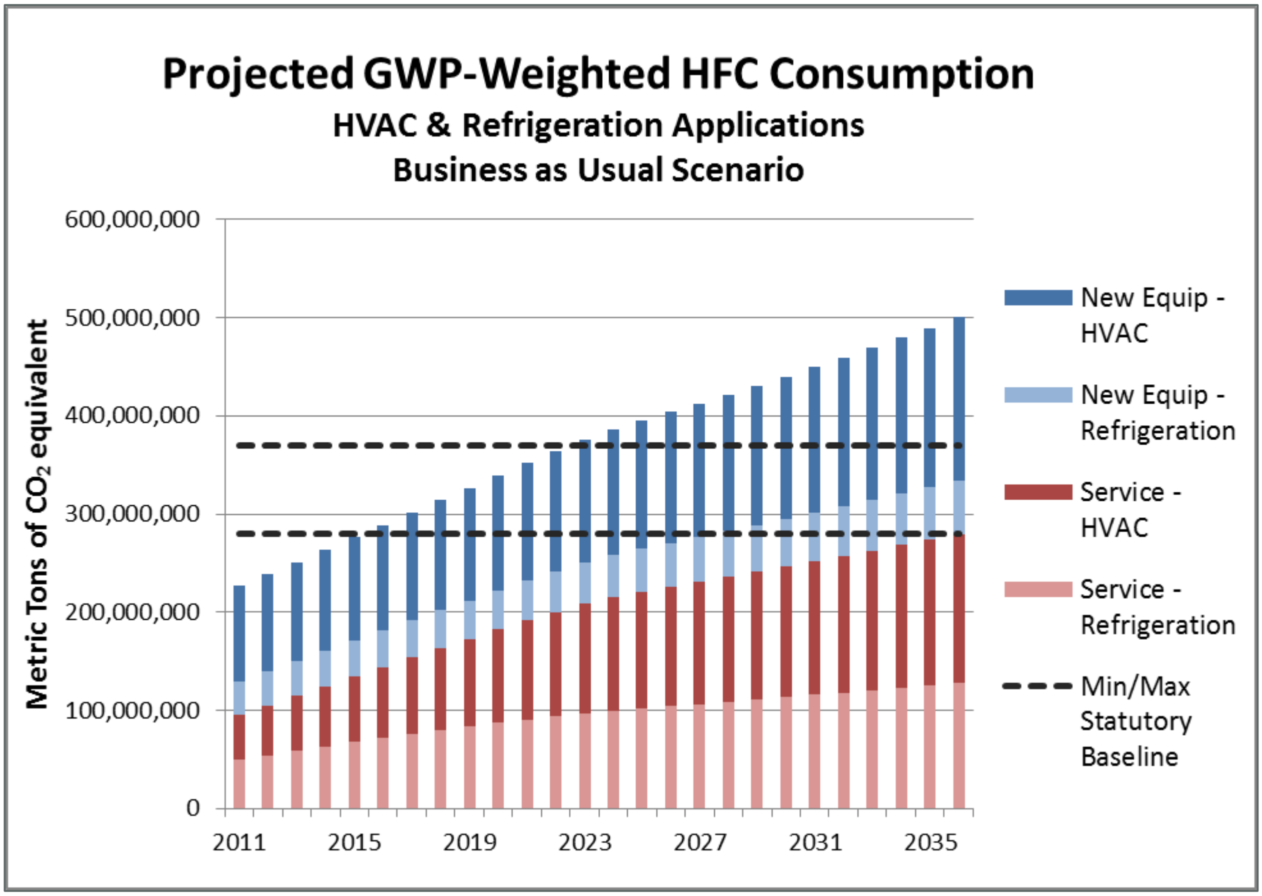
1 Introduction

1.1 Background

The Building Technologies Office (BTO) within the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy works with researchers and industry to develop and deploy technologies that can substantially reduce energy consumption and greenhouse gas (GHG) emissions in residential and commercial buildings. Heating, ventilation, air-conditioning, and refrigeration (HVAC&R) systems contribute GHG emissions both directly through hydrofluorocarbon (HFC) refrigerant leakage and indirectly through fossil fuel and electricity consumption. In an amendment to the U.S.'s proposed submission to the Montreal Protocol, the U.S. Environmental Protection Agency (EPA) targets global warming potential (GWP) weighted HFC consumption reductions of 85% during the period of 2016–2035.[1] BTO aims to facilitate research and development (R&D) on next-generation HVAC&R joining technologies that support the government's HFC phasedown goal, as articulated by the EPA.

HVAC&R systems consume HFC refrigerants both through initial product manufacturing and installation as well as regular servicing to replace refrigerant lost during normal operation through leakage. Absent improved refrigerant management, Navigant modeling predicts that servicing new and existing HVAC&R equipment will account for over 55% of HFC consumption in the U.S by 2035. Figure 1-1 provides the projected GWP-weighted HFC consumption attributed to new equipment and equipment servicing under a business as usual scenario.

[1] UNEP. 2015. "Proposed Amendment to the Montreal Protocol Submitted by Canada, Mexico and the United States of America." March 8, 2015. Open-Ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. Thirty-Fifth Meeting. March 2015.

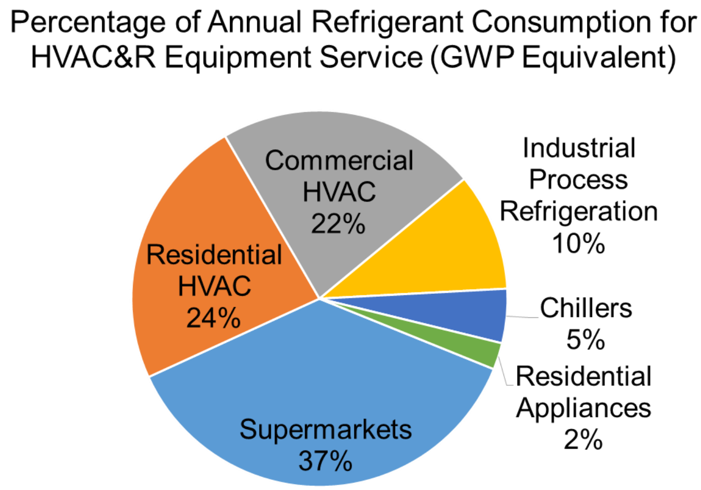


Source: Navigant Refrigerant Consumption Model[2]

Figure 1-1: Projected GWP-weighted HFC consumption for HVAC&R systems

As Figure 1-2 shows, supermarket refrigeration, residential AC, and commercial unitary AC account for over 80% of annual HVAC&R refrigerant consumption for service purposes. BTO primarily focuses on residential and commercial building technologies, which comprise 90% of the HFC consumption for HVAC&R equipment.

[2] Navigant Refrigerant Consumption Model is an internal analysis tool based on EPA Inventory of Greenhouse Gas Emissions and Sinks reports. EPA. 2015. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013." U.S. Environmental Protection Agency. EPA 430-R-15-004. April 15, 2015.



Source: Navigant Refrigerant Consumption Model[3]

Figure 1-2: Breakdown of GWP-weighted HFC consumption for equipment service by HVAC&R equipment category

Many HVAC&R equipment types have leakage rates of 10% per year or more due to limitations in joining techniques, system designs, operations and maintenance (O&M) practices, etc.[4] Table 1-1 summarizes estimated annual HFC leakage rates for common HVAC&R equipment categories. These leakage rates vary with the operating environment of the system, the number of individual fittings and components, the amount of field installed joints, and other considerations.

Table 1-1: Estimated Annual HFC Leakage Rates for HVAC&R Equipment Categories

Equipment Category	Estimated Annual HFC Leakage Rates[5]	Within BTO Scope
Supermarkets and Other Retail	1–25%	✓
Mobile Air Conditioners	2–18%	
Cold Storage	15%	
Residential Unitary AC	12%	✓
Industrial Process Refrigeration	4–12%	
Centrifugal Chillers	2–11%	✓
Commercial Unitary AC	8–9%	✓
Packaged Terminal AC / Heat Pump	4%	✓
Refrigerated Appliances	1%	✓

Beyond HFC emissions, refrigerant leakage adversely affects cooling capacity, energy efficiency, system reliability, and equipment lifetime. A 2000 study modelling the effect of refrigerant leakage on a 3-ton (10.6 kW) rooftop unit with a fixed-orifice expansion device found

[3] Ibid
[4] EPA. 2015. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013." U.S. Environmental Protection Agency. EPA 430-R-15-004. April 15, 2015.
[5] Ibid

that a 14% leakage reduced system capacity and efficiency by 8% and 5%, respectively. Although thermostatic expansion valves (TXVs) can somewhat reduce these effects, significant refrigerant leakage will nevertheless adversely affect HVAC&R system performance and lifetime. This performance degradation also impact building owners and occupants through inadequate comfort, expensive repair calls to service technicians, and potential loss of refrigerated products.

1.2 BTO Emerging Technologies Program Mission and Goals

The BTO has a critical stake in supporting research, development, and demonstration activities that lead to reduced leakage of refrigerants from HVAC&R equipment. BTO's mission is to[6]:

> *Develop and promote efficient, affordable, and environmentally friendly technologies, systems, and practices for our nation's residential and commercial buildings that will foster economic prosperity, lower greenhouse gas emissions, and increase national energy security, while providing the energy-related services and performance expected from our buildings.*

The BTO Multi-Year Work Plan for 2011–2015 articulates BTO's mission and program goals as follows[7]:

- Promote efficiency
- Promote affordability (cost reduction)
- Promote "environmentally friendliness"
- Lower GHG emissions
- Conduct R&D to advance innovative technologies
- Conduct R&D for integrated buildings approaches
- Accelerate adoption of new products on the market
- Increase private sector collaboration in developing new technologies
- Develop innovations in HVAC
- Develop innovations in working fluids

This study on R&D opportunities for HVAC&R joining technologies impacts each of BTO's program goals due to the cross-cutting nature of the topic. Improving joining technologies for HVAC&R equipment has the potential to increase equipment operating efficiency, decrease equipment and project cost, and most importantly reduce HFC refrigerant leakage to support HFC phasedown goals. The initiatives described in this report provide potential pathways to meeting these goals, as identified by key stakeholders in the HVAC&R industry.

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[6] Building Technologies Program Multi-Year Work Plan, 2011-2015. Available at http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/myp11.pdf.
[7] Ibid.

1.3 Technology and Market Scope

This opportunity assessment focused on three primary topics that have applicability for most HVAC&R system categories. Each topic area offers a unique set of opportunities to reduce refrigerant leakage, improve reliability, and lower system cost around a specific area of the HVAC&R supply chain. Table 1-2 highlights some of the technology areas under each of the three topics. In line with BTO's program mission, this study focuses on HVAC&R equipment common in residential and commercial buildings and does not consider mobile or industrial applications (as outlined in Table 1-1). Nevertheless, most HVAC&R systems share common joining techniques, system architectures, and other attributes, so the recommended initiatives of this study will impact these areas as well.

Table 1-2: Estimated Annual HFC Leakage Rates for HVAC&R Equipment Categories

Opportunity Assessment Topic	Example Technology Areas (Not Exhaustive)
Brazing and Joining Technologies and Processes	• Advanced brazing techniques • Brazing materials • Factory vs. field brazing • Compression fittings • Torque or threaded fittings • Quick-connect fittings
Advanced Component Design and Materials	• New heat exchanger designs • Copper and aluminum alloys • Leakage rates of specific valves or other components • Polymer-based components
Installation, Operation, and Maintenance	• Field installation techniques • Leak detection and location techniques • Field repair for inaccessible leakage points • Loss of equipment efficiency and/or capacity

The initiatives discussed in this study were identified and prioritized by industry stakeholders and Navigant experts, in consultation with BTO. Therefore, not all topic areas and technologies are emphasized equally or even included in the articulated initiatives in Section 1. The recommended initiatives in this report showed promising opportunity to help meet BTO goals and fits with BTO mission and capabilities.

BTO focuses their efforts on innovative initiatives that accelerate development of technologies. However, in select cases, BTO also supports initiatives that can drive innovation broadly throughout the industry or provides foundational information on industry practices to enable future breakthroughs. This opportunity assessment does not address early stage science research that is more suitable for the Office of Science, or late-stage market development activities that may be more suitable for industry or for the commercial or residential building integration teams (separate from the Emerging Technologies group) within BTO. (See Section 1 for additional detail on the process).

1.4 Objective of this Study

The objective of this report is to identify and highlight higher-priority R&D activities that DOE could support to help reduce refrigerant leakage at piping, heat exchanger, and other joints in HVAC&R equipment in residential and commercial buildings. In this report we aim to identify and prioritize R&D initiatives that provide the best opportunities for accelerating development and commercialization of these technologies.

2 Project Approach

Figure 2-1 outlines the three stages for developing this R&D opportunity assessment.

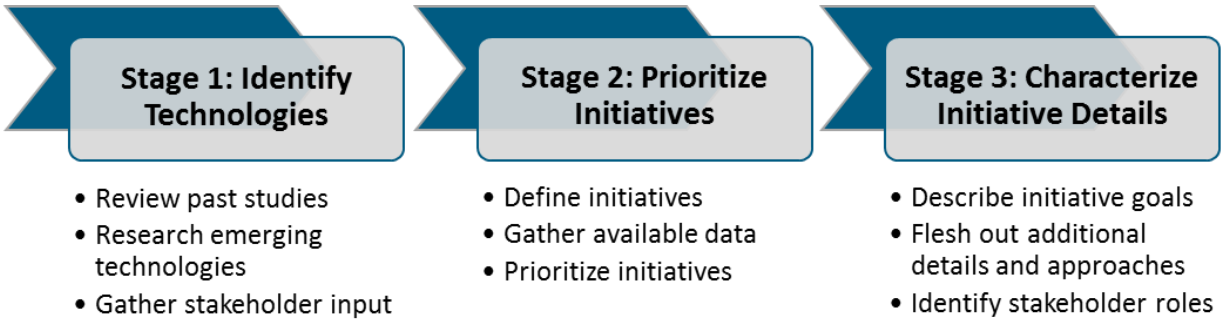

Figure 2-1: Project steps

The following subsections describe each stage in greater detail.

2.1 Stage 1: Identify Technologies and Define Initiatives

We conducted research on joining technologies used in HVAC&R applications in both commercial and residential applications. The process began with secondary research of available academic studies of joining technologies, their prevalence in the marketplace, and each technology's potential to leak under various circumstances. Later, primary research via one-on-one interviews added additional depth to the technical and market characterizations of these technologies.

On June 4, 2015 BTO hosted a one-day workshop of experts with wide-ranging backgrounds, including university researchers, manufacturers (HVAC, refrigeration, heat exchangers, fittings, and more) and design engineers.[8] The objective of the workshop was to refine our understanding of the key barriers in reducing leakage, as well as gather expert insights into areas of research that need additional attention. The participants helped generate the majority of the R&D concepts that we then developed into clear initiatives and prioritized for BTO. For additional information on the forum, see Appendix A – HVAC&R Joining R&D Workshop Summary.

2.2 Stage 2: Prioritize Initiatives

To prepare for initiative prioritization, we developed a comprehensive list of suggested initiatives and refined the list to eliminate duplicates and combine those ideas that naturally fit together.

In consultation with BTO, we prioritized the initiatives to identify the most promising for BTO to pursue. We used the comprehensive prioritization process described below, which scores each initiative based on qualitative metrics and the votes from the stakeholder forum.

[8] See the Acknowledgements for a list of participants.

The prioritization approach was as follows:

1. Score and rank the selected initiatives using a qualitative prioritization process
2. Select a top tier of initiatives for deeper review and detailed characterization

The qualitative prioritization used five different metrics, each scored on a scale of 1 to 5. The weighted average of these scores determined the ranking. Table 2-1 shows the definitions of each metric.

Table 2-1: Initiative Scoring Metrics – Definitions

Metric	Definition
Impact	Expected impact on developing new technology or performing research that addresses a critical knowledge gap or overcomes a key barrier to high-performance, cost-effective, and leak-free joining technologies for HVAC&R systems
Fit with BTO Mission	Relevance of topic area to BTO areas of expertise and the nature of the initiative (e.g., high-risk, disruptive R&D is core to DOE's mission, while incremental, low-risk R&D is not). BTO's mission is also focused on supporting technologies that are near (5 years or less) market ready.
Criticality of DOE Involvement	Importance for DOE to participate or whether industry will be successful without DOE's participation
Level of Required Investment	Funding level that may be expected for the initiative to be successfully demonstrated in a relevant environment or developed to the pre-commercialization stage and ready for industry partnerships to bring the technology to market

Table 2-2 shows the scoring and weighting values.

Table 2-2: Initiative Scoring Metrics – Scores

Metric	5	4	3	2	1	Weight
Impact	Significant	Semi-Significant	Moderate	Modest	Minimal	**40%**
Fit with BTO Mission	Core to mission	Semi-core to mission	Relevant to mission	Semi-relevant to mission	Outside scope / mission	**30%**
Criticality of DOE Involvement	Critical to success	Semi-critical to success	Beneficial to success	Semi-beneficial to success	Unnecessary for success	**20%**
Level of Required Investment	< $1M	$1M – $3M	$3M – $5M	$5M – $10M	> $10M	**10%**

Two members of the project team independently scored each initiative on each metric. Averages of the scores determined the output score for each metric. In order to incorporate industry voting on each initiative from the stakeholder forum (see section 2.1, above), we assigned an industry-input score (1-3) to each initiative, depending on the relative number of votes. Each point on the industry-input score corresponded to a boost in final score of 0.20 (applied after scoring of prioritization metrics from above). For example, an initiative with a post-prioritization score of 3 and an industry-input score of 2 would receive a final score of 3.40 (e.g., $3 + (0.20 * 2) = 3.40$).

2.3 Stage 3: Develop Report

We developed descriptions as a starting point for BTO to use should they choose to execute any of the top nine initiatives. Each initiative description includes the following components:

- Discuss of the initiative's purpose and goals
- Outline initiative's potential impact on existing technical and market barriers
- Recognize key stakeholder roles and responsibilities throughout different initiative stages

Section 1 contains the detailed recommendations and characterizations for each higher-priority initiative.

3 Market Overview

3.1 State of the Market – Trends

Every HVAC&R system consists of many individual components joined together in subassemblies (e.g., individual tubes in a heat exchanger), connected to other major components (e.g., compressors in supermarket refrigeration racks), and finally attached to a piping system or other method to distribute thermal energy. At every point where two components meet, joining technologies create a mechanical bond that connects the components, supports their weight and operational stresses of the system, and allows working fluids to continue their path throughout the system. While brazing is the most common joining technology for HVAC&R systems, recent and future trends towards torque-based connections, microchannel heat exchangers, alternative materials, and the next-generation of refrigerants will change how manufacturers and technicians join HVAC&R systems.

Brazing Technologies

Most HVAC&R systems consist of metallic components, usually copper or aluminum, and use one of several brazing techniques. During brazing, a filler metal is melted between the two metal components at temperatures greater than 840°F. The liquid metal flows into the gap between the base metals through capillary action. Most connections between two pieces of piping use a coupling that has a slightly larger diameter than the pipe itself so that a portion of the pipe may enter the coupling and the filler material establishes an overlapping or "lap" joint within the coupling. Alternatively, the two components can be connected directly without an overlapping coupling to form a butt joint. In any joint, the filler metal establishes a metallurgical bond to each of the base metal components, forming a strong connection.

The most common brazing techniques for HVAC&R systems are furnace brazing and flame brazing. Furnace brazing is a manufacturing process where components and subassemblies enter a continuous or batch furnace to uniformly melt the filler material and create the brazing joints. Flame brazing occurs in both factory and field installations where a technician uses a handheld oxyacetylene torch to melt the filler material and create the brazing joint. Several other brazing techniques exist, including: induction, resistance, dip, diffusion, infrared, and laser. Every brazing technique can create strong and reliable joints when employing industry best-practices. One stakeholder at the workshop (see section 2.1) noted that typical HVAC&R joining processes for new packaged equipment are better than six sigma in terms of leakage rates, i.e., with less than 3.4 defects per million joints. However, leaks still occur due to the high volume of joints required in this equipment as well as difficult installation environments or configurations, material imperfections, the limited available verification techniques, contaminant corrosion, and other issues.

Torque-based and Other Physical Joining Technologies

Several manufacturers and fitting vendors have developed physical joining technologies that use torque-based, clamp-based, press-connect, or other connection techniques to connect two pipes together using a specialized coupling and without the use of a flame. While still a small part of the market, torque-based joining systems are now common for ductless mini-split systems and hydronic distribution systems. To expand their use in HVAC&R systems, several companies are developing products to meet the material compatibility, pressure, reliability, and other requirements for refrigerant applications. While brazing typically creates the strongest mechanical joint between two materials, several of these physical joining technologies offer increased flexibility, quicker installation, and fewer safety risks. For example, for field-joined pipes, the high-temperature brazing flame requires careful technician consideration to safely create brazing joints around combustible materials in tight spaces – all these considerations are reduced or eliminated by using physical joining technologies.

Microchannel Heat Exchangers

Manufacturers increasingly employ microchannel heat exchangers to meet rising energy efficiency standards for several HVAC&R applications. Microchannel systems use a substantially higher number of smaller diameter flow channels, compared to the traditional fin-and-tube heat exchangers that use fewer, but larger flow channels. With a higher number of tubes in microchannel systems, the number of joints and potential leakage points increases. Joint verification also becomes more difficult as the size of each joint decreases and the joint density increases.

Alternative Materials

HVAC&R systems traditionally use copper piping and components. Residential refrigeration has been somewhat of an outlier, having employed aluminum heat exchangers for decades.[9] Only recently have manufacturers employed aluminum in larger HVAC&R systems, such as aluminum microchannel heat exchangers for residential split-system ACs. Joining dissimilar materials requires careful consideration since each metal reacts differently to the filler material at different temperatures. While the practice of copper-to-aluminum joining is increasing, few options exist to join other dissimilar, alternative materials. Several emerging heat exchanger designs for vapor-compression, absorption, heat recovery, and other systems utilize polymer-based membrane materials. Technologies using these alternative materials encounter significant issues when connecting to conventional HVAC&R systems and components, which limits their further development and adoption.

Next-Generation Refrigerants

Joining technologies are not only important for the initial manufacture and installation of HVAC&R systems, but also throughout equipment's life. Technicians must often disconnect and reconnect fittings during equipment servicing and repair. For brazed joints, the technician will remove the refrigerant from the system before heating the coupling to melt the filler material and break the joint. Several alternatives to replace HFCs refrigerants introduce flammability, toxicity, and pressure risks for technicians and building occupants. Technicians servicing equipment using mildly flammable A2L or flammable A3 hydrocarbon refrigerants must follow additional safety protocols to ensure safe operation.[10] Additionally, alternative refrigerants with higher pressures require more robust joints to ensure safe and reliable operation of the HVAC&R system.

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[9] Lundin, Eric. 2013. "Fabricator Follows Forming Trend in HVAC Industry." The Tube and Pipe Journal. June 2013. http://www.thefabricator.com/article/shopmanagement/fabricator-follows-forming-trend-in-hvac-industry

[10] ASHRAE refrigerant safety classes indicate the toxicity (A, B, C) and the flammability (1, 2, 2L, 3) for each refrigerant, where the lowest risk refrigerant is class A1. See ASHRAE Standard 34 for additional discussion of refrigerant safety risks.

3.2 Barriers to Reducing Refrigerant Leakage in HVAC&R Joints

Although manufacturers and technicians use best practices when joining system components, refrigerant leakage is still an issue that reduces efficiency and performance, and increases operating cost and GHG emissions for HVAC&R systems. The HVAC&R industry faces numerous challenges to reduce refrigerant leakage today and in the future as the industry adjusts to the trends discussed above. Table 3-1 lists some of the key barriers and challenges to reducing refrigerant leakage in HVAC&R systems.

Table 3-1: Barriers and Challenges to Reducing Refrigerant Leakage in HVAC&R Systems

Category	Technical and Market Barriers and Challenges
Manufacturing & Installation Processes	Creating reliable, consistent, and cost-effective brazing connections in factory and field settings
Manufacturing & Installation Processes	Overcoming cultural aversion to developing and employing new joining technologies
Manufacturing & Installation Processes	Reducing joint contamination and corrosion in non-ideal environments
Advanced Materials	Ensuring safe and reliable joints for HVAC&R systems using alternative materials with compatibility issues (e.g., dissimilar metals, polymers) and refrigerants with pressure, flammability, or toxicity risks.
Verification & Analysis	Understanding the strength, reliability, and leakage rates for different joining technologies in actual factory and field application
Verification & Analysis	Validating the effectiveness of compression-based, torque-based, and other advanced joining techniques and fittings for HVAC&R systems
Verification & Analysis	Cost-effective methodologies for joint inspection, evaluation, and verification to improve quality-control practices
System Design	Reducing the high number of potential leakage points in current heat exchangers and HVAC&R systems layouts
Diagnostic Tools & Repair Methods	Overcoming limitations with current leak detection, location, and repair methods

4 Research & Development Opportunities

This R&D opportunity assessment contains five sections below:

- *Central Themes (Section 4.1)*: Summary of themes that emerged during opportunity assessment development that carry common threads through many (if not all) of the prioritized initiatives
- *R&D Initiative Summary (Section 4.2)*: Summary of higher-priority technology initiatives
- *Priority Brazing and Joining Technology Initiatives (Section 4.3)*: Detailed descriptions for higher-priority R&D initiatives that support the investigation and development of improved joining techniques for HVAC&R systems
- *Priority Component and Material Initiatives (Section 4.4)*: Detailed descriptions for higher-priority R&D initiatives focused on improved heat exchanger designs, fittings, couplings, and other components in HVAC&R systems
- *Priority Installation, Operations, and Maintenance Initiatives (Section 4.5)*: Detailed descriptions for higher-priority R&D initiatives targeting advanced methods of field installation, leak detection, and servicing for HVAC&R systems.

The sections do not specifically distinguish between the various end-use and market sector subcategories of HVAC&R technologies. The various higher-priority initiatives, detailed below, broadly cover the various sectors and market sectors as applicable, though this R&D opportunity assessment makes no specific effort to cover each category evenly.

4.1 Central Themes

The stakeholder forum in Washington D.C., in addition to providing valuable input on specific initiatives, also uncovered some key themes that undercut much of the work that BTO may pursue. Stakeholders emphasized the need for R&D investment to better understand and improve current joining practices and develop the next generation of joining techniques for advanced HVAC&R systems and components. Figure 4-1 provides general context to the individual opportunity assessment activities listed in the subsequent sections.

Key Themes for HVAC&R Joining Technology R&D Needs

Reducing the number of joints in HVAC&R systems and components

Heat exchanger, fitting, and overall system design strategies that eliminate the number of joints and potential leakage points.

Related initiatives:

- Low joint-intensity heat exchanger designs
- Charge-loss-limiting HVAC&R systems
- Eliminate intermediate tube for heat exchangers

Alternative joining technologies for factory and field installation, servicing, and repair

Developing novel joining technologies and techniques or adapting strategies from other industries to improve joining time, cost, reliability, and other attributes, while also preparing for field servicing of HVAC&R equipment using next-generation refrigerants.

Related initiatives:

- Hybrid joining techniques
- Low-temperature joining technologies
- Secondary joining tapes and materials
- Next generation of brazing materials

Consistent methodologies to inspect, measure, and benchmark leakage from different joining techniques

Research studies into common joining practices and the development of advanced joining verification techniques to improve the way that manufacturers, technicians, and system designers select and employ joining techniques for HVAC&R systems.

Related initiatives:

- Research study on joining technique effectiveness
- Joint-verification technologies
- Expand certifications and training for technicians
- Next-generation leak detection techniques

Material compatibility for next-generation HVAC&R systems and components

Developing fittings and joining technologies that improve the connections between dissimilar materials found in advanced HVAC&R systems (e.g., copper-aluminum, copper-polymer).

Related initiatives:

- Adhesives for HVAC&R joining
- Joining technologies for membrane-metal connections
- Additive manufacturing joining techniques

Figure 4-1: Key themes for HVAC&R joining technology R&D needs

4.2 R&D Initiative Summary

We prioritized the list of initiatives to provide guidance to BTO on which initiatives showed greater potential impact, closer fit with BTO's mission, higher importance with stakeholders, and other considerations (see section 2.2, above, for prioritization criteria). These initiatives represent some of the key areas in which BTO could advance the current generation of HVAC&R joining technologies. Because each initiative only targets a specific issue, no single initiative can solve the multi-faceted problems manufacturers, contractors, and building owners experience with current HVAC&R joining technologies, and a multi-initiative approach could provide the best pathway. Lower-priority initiatives could offer a substantial opportunity to reduce refrigerant leakage and improve performance, and are worth considering further if BTO sees an interesting R&D opportunity.

The prioritized list in Table 4-1 identifies the most promising initiatives in each of the three categories: Brazing and Joining Technologies (Section 4.3), Component and Materials (Section 4.4), and Installation, Operations, and Maintenance (Section 4.5). The sections that follow detail the higher-priority initiatives in greater detail, with lower-priority initiatives described further in Appendix B – Summary of Lower-Priority Initiatives.

Table 4-1: Prioritized List of R&D Initiatives

ID	Description	Category
1	Identify and develop specific adhesives with targeted chemistries for HVAC&R joining applications	Brazing & Joining Technologies (section 4.3.1)
2	Conduct a research study to evaluate the effectiveness of various joining methods	Brazing & Joining Technologies (section 4.3.2)
3	Research and develop hybrid joining connections that combine a torque fitting with a secondary non-mechanical joining technique	Brazing & Joining Technologies (section 4.3.3)
4	Research and develop low-temperature, non-torque-based joining technologies and techniques	Brazing & Joining Technologies (section 4.3.4)
5	Develop an improved, consistent evaluation process or technology for verifying joints in both factory and field applications	Brazing & Joining Technologies (section 4.3.5)
6	Develop advanced heat exchanger designs that reduce the number of required joints	Component & Materials (section 4.4.1)
7	Develop coatings, compounds, or tapes that improve joint connections and leakage rates during installation and servicing	Component & Materials (section 4.4.2)
8	Develop HVAC&R systems that limit the refrigerant charge lost through leakage events	Component & Materials (section 4.4.3)
9	Develop on-board fault detection and diagnostics (FDD) systems to detect leakage from packaged HVAC&R systems	Installation, Operations, & Maintenance (section 4.5.1)

4.3 Priority Brazing and Joining Technology Initiatives

4.3.1 (ID #1) Adhesives for HVAC&R Joining

***Initiative**: Identify and develop specific adhesives with targeted chemistries for HVAC&R joining applications*

Under this initiative, BTO would conduct research with adhesives manufacturers to investigate the range of available adhesives for compatibility with HVAC&R systems and refine adhesive chemistries as needed. For promising adhesive options, conduct testing in relevant environments to determine their applicability, effectiveness, safety, and other characteristics with HVAC&R systems. Developing new adhesives and/or transferring adhesive technologies from other industries is an entirely novel approach to HVAC&R joining and has the potential to greatly improve the reliability and cost-effectiveness of HVAC&R systems.

Adhesives create a chemical bond between two materials that join them together, and can be specialty designed for almost any application. The HVAC&R industry uses adhesives for a variety of applications including sealing and taping duct seams, connecting insulation to pipes, and joining polyvinyl chloride (PVC) pipes. For these applications, adhesives offer simple installation, low-temperature application, quick curing time, and other advantages that could be applied to a wider range of HVAC&R joining situations.

While adhesives are available that meet many of the requirements for HVAC&R applications, few are specifically designed as the primary joining method in HVAC&R systems. Historically, adhesives have not been successfully applied to join refrigerant lines as a replacement for brazing due to several challenges. Adhesives are chemical bonding systems and must have material compatibility with both the surface materials (e.g., copper) as well as the fluids (i.e., refrigerant and lubricants). Additionally, early adhesives could not withstand years of thermal cycling and the mechanical stresses from equipment operation, which led the industry away from adhesives as a primary joining option. Once developed, an adhesive joining technique must be cost-effective and reliable relative to other techniques and allow for quick and safe installation and servicing in both factory and field settings.

Table 4-2 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-2: Initiative Impact on Key Barriers – Adhesives for HVAC&R Joining

Key Barrier	Initiative's Impact
Uncertain material compatibility	Investigates the necessary attributes for an adhesive to operate with copper piping and common refrigerants and lubricants over a variety of conditions
Limited performance information	Conducts laboratory testing on promising adhesives to ensure joint effectiveness and durability over time
Uncertain installation and maintenance practices	Laboratory testing would reveal how best to install and service equipment using adhesive joints
Safety and operational risks	The material identification and testing process will reveal whether certain adhesives have safety concerns for factory and/or field technicians (e.g., inhalation or contact with adhesive)

Table 4-3 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-3: Stakeholder Involvement – Adhesives for HVAC&R Joining

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC&R component manufacturers (e.g., fittings, heat exchangers, refrigerants) » Adhesive manufacturers
Laboratory testing and demonstration	» Independent research laboratories » HVAC&R component manufacturers » Adhesive manufacturers » Industry organizations

4.3.2 (ID #2) Research Study on Joining Technique Effectiveness

***Initiative**: Conduct a research study to evaluate the effectiveness of various joining methods*

Under this initiative, BTO would conduct a research study to evaluate the effectiveness of various HVAC&R joining techniques. With this information, manufacturers, technicians, and system designers can select the most appropriate joining method for their products and projects that provides cost-effective installation, and lasting equipment operation with minimal refrigerant leakage.

All HVAC&R systems require joining techniques to connect the refrigerant lines between various subsystems and components during field installation and/or servicing. For example, field technicians can connect the refrigerant lineset between the indoor evaporator and outdoor condenser sections using flame brazing, torque fittings, or a variety of clamp/press fittings. While each of these methods is capable of producing a lasting joint with no refrigerant leakage, actual data on field installation practices would help determine the most effective techniques to prevent leakage over the life of the equipment. As more joining technologies enter the market, this issue becomes more important as manufacturers and technicians must choose from one of many different strategies.

This research study should primarily focus on refrigerant leakage, but also consider connection time, fitting and system/tool costs, ease of installation in difficult geometries, and other aspects that manufacturers and technicians would consider. The study could include 3 parts:

1. Conducting a survey of current HVAC&R joining practices
2. Developing a laboratory test method
3. Evaluating each joining technique with the test method

The subsequent report could provide an accepted method for testing new joining techniques as well as a publically available benchmark to evaluate each new technique against existing methods.

Table 4-4 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-4: Initiative Impact on Key Barriers – Research Study on Joining Technique Effectiveness

Key Barrier	Initiative's Impact
Uncertain installation effectiveness for different joining methods	Survey of joining techniques would gather data on effectiveness, cost, connection time, and other attributes during factory and field installations.
Lack of consistent test method for joining techniques	New test method would provide consistent data on the available joining techniques and allow for industry benchmarks on joining performance and cost-effectiveness.

Table 4-5 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-5: Stakeholder Involvement – Research Study on Joining Technique Effectiveness

Tasks	Key Stakeholder Roles and Responsibilities
Field studies, data analysis, and report publication	» National laboratories – study design, end-use knowledge/support » Independent research firms – protocols, field test design » Surveying organizations – survey design, recruitment, execution » Industry organizations
Laboratory testing, data analysis, and report publication	» Independent research laboratories » HVAC&R component manufacturers » Industry organizations

4.3.3 (ID #3) Hybrid Joining Techniques

***Initiative**: Research and develop hybrid joining connections that combine a torque fitting with a secondary non-mechanical joining technique*

Under this initiative, BTO would support the development of hybrid joining technologies that combine torque-based or other mechanical fittings[11] with a secondary non-mechanical joining technique (potentially including brazing). If successful, these fittings should be demonstrated in HVAC&R systems to evaluate their effectiveness against leakage, speed, cost, and other characteristics.

Flare joints are a type of mechanical torque joint that holds one pipe with threaded connection to a flared second pipe with a threaded nut. Ductless mini-splits and other HVAC&R systems commonly use flared joints to enable simple and versatile installations. When done correctly using specialized torque wrenches, flare joints can provide a reliable and leak proof connection. Nevertheless, improper pipe cutting, under- or over-torqued connections, and other issues can reduce the effectiveness of flared torque fittings. Several manufacturers and vendors have developed strategies to try and increase the reliability and usability of torque fittings by adding redundancy and/or design changes. Examples include gaskets,[12] additional connectors,[13] and flareless designs.[14] Other strategies could combine the advantages of flared and brazed connections by developing a fitting that first connects with a torqued flare joint, and then provides a brazing connection to seal the system further.

This initiative would begin with an investigation into different hybrid joining techniques on the market today and a characterization of promising joining technologies that could potentially work well together. After studying available options, researchers could evaluate the effectiveness of torque-based and other mechanical fittings in actual installations and investigate the potential for current strategies and/or develop new hybrid joining technologies that improve joint

[11] Technically most joining technologies create a mechanical bond between two materials, but non-brazing joining technologies such as torque- or compression-based fittings are commonly called "mechanical" joining technologies.
[12] Flaretite - Flaretite Pty Ltd. 2015. http://www.flaretite.com/
[13] Flexflair - Test Products International. 2012. http://www.testproductsintl.com/flexflair.html#.VY8B4PlViko
[14] Ferulok Flareless Bite Type Fittings - Parker. 2012. https://www.parker.com/literature/Tube%20Fittings%20Division/Ferulok_Flareless_Bite_Type%20Fittings.pdf

reliability. Performing laboratory and limited field testing can then demonstrate the effectiveness of these hybrid joining techniques for adoption by industry.

Table 4-6 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-6: Initiative Impact on Key Barriers – Hybrid Joining Techniques

Key Barrier	Initiative's Impact
Potential for poor reliability during field installations	Developing a hybrid joining technique that combines a torque-based technique with a secondary strategy can overcome the reliability issues of current technologies
Requirements for simple installation in a variety of settings	The hybrid joining technique can maintain the installation flexibility of the torque-based joint and simply add a second technology after the torque joint is made
Limited ability to test effectiveness of torque-based joints	The hybrid joining technique can provide an additional protection against leakage due to common issues (e.g., improper pipe cutting, under- or over-torqued connections)

Table 4-7 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-7: Stakeholder Involvement – Hybrid Joining Techniques

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC&R component manufacturers (e.g., fittings, heat exchangers, refrigerants)
Laboratory and field demonstration	» Independent research laboratories » HVAC&R component manufacturers » Industry organizations
Deployment	» HVAC&R equipment and component manufacturers » Industry organizations » Contractor and technician organizations

4.3.4 (ID #4) Low-Temperature Joining Technologies

Initiative*: Research and develop low-temperature, non-torque-based joining technologies and techniques*

Under this initiative, BTO would support the development of low-temperature joining technologies and techniques for both factory and field installations, and if promising partner with manufacturers and contractor organizations to demonstrate the technologies in relevant environments. This longer-term R&D activity would investigate the potential and develop an entirely new class of joining technologies, rather than incrementally improve current methods. These low-temperature joining techniques would provide the same or better joint effectiveness to traditional brazed joints, but with potential lower energy consumption, greater cost-effectiveness, and improved safety.

Most HVAC&R joints are brazed with an oxyacetylene or other flame torch. Field technicians must often use brazing torches in tight quarters or near flammable materials, which poses a safety issue for technicians, building owners, and occupants. Several promising low-temperature joining systems offer the possibility for greater energy efficiency, more precise heating zones, and improved safety for manufacturers and contractors. These strategies include wider application of mechanical joining techniques, ultrasonic joining, European SafeFlame brazing,[15] magnetic pulse welding,[16] advanced nanosolder,[17] reactive nanofoils,[18] and other techniques. Applying lessons learned from other industries, these techniques could be applied for HVAC&R manufacturing and/or developed for field applications.

Table 4-8 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

[15] The SafeFlame EU Project. 2015. http://www.safeflameproject.eu/technology/

[16] Schafer and Pasquale. 2011. "Material Hybrid Joining of Sheet Metals by Electromagnetic Pulse Technology." PSTproducts GmbH. January 3, 2011. http://www.pstproducts.com/EMPT_sheetwelding_PSTproducts.pdf

[17] Lockheed Martin. 2012. "Lockheed Martin Advanced Technology Center Develops Revolutionary Nanotechnology Copper Solder." Lockheed Martin Corporation. October 24, 2012. http://www.lockheedmartin.com/us/news/press-releases/2012/october/1024-ss-atc.html

[18] Indium Nanofoil. 2015. http://www.indium.com/nanofoil/

Table 4-8: Initiative Impact on Key Barriers – Low-Temperature Joining Technologies

Key Barrier	Initiative's Impact
High cost and energy consumption of flame brazing techniques	Low-temperature joining techniques could use electricity or chemical reactions rather than gaseous tanks to heat the joint.
Flammability and safety concerns of high-temperature joining techniques	The low-temperature joining methods could pose less of a flammability and safety concern than conventional flame brazing due to lower temperature operation, more precise heating area, smaller application tool, and other advantages.
Relatively wide flame area from imprecise torch	Several potential low-temperature joining techniques have a very focused heating area that can improve joining precision and energy efficiency

Table 4-9 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-9: Stakeholder Involvement – Low-Temperature Joining Technologies

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » Joining technology researchers » Industry organizations
Laboratory testing, data analysis, and report publication	» Independent research laboratories » HVAC&R component manufacturers » Industry organizations » Contractor and technician organizations
Deployment	» HVAC&R equipment and component manufacturers » Industry organizations » Contractor and technician organizations » Codes and standards organizations

4.3.5 (ID #5) Joint-Verification Technologies

***Initiative**: Develop a consistent evaluation process or technology for verifying joints in both factory and field applications*

Under this initiative, BTO would support the development of cost-effective evaluation processes and technologies that provide factory and field technicians greater quality assurance on brazed or mechanical joints. Ensuring a proper joint at each connection point through advanced verification methods can significantly reduce the chance of gradual refrigerant leakage over time in HVAC&R systems.

Inspection of brazed or mechanical joints is an important step to ensure that each connection in an HVAC&R system enables leak-free and high efficiency performance. Both field and factory technicians inspect joints primarily through a visual examination looking for a consistent and gap-free joint, no discoloration or scaling, and other characteristics. For mechanical connections, the technician would look for misalignment of the fitting's gaskets or flanges with the piping. Following visual inspection, the technicians may pressurize the system to check whether pressure decreases over time, signaling a leak, but normally does not employ any other means of verifying a sound joint. Several non-destructive inspection methods (e.g., x-ray,[19] ultrasonic[20]) could be helpful in identifying miniature leakage points beyond visual inspection or pressure testing, but these strategies are impractical or costly for everyday use by field technicians. The next generation of verification technologies and practices could provide better assurance for manufacturers, technicians, and building owners that their HVAC&R systems will have leak-free performance during normal operations.

This initiative could include a survey of current verification and inspection techniques across HVAC&R and other industries, evaluation of potential strategies in other industries that may have applicability for HVAC&R systems, as well as potential product and/or process development to adapt the verification strategies for the HVAC&R industry.

Table 4-10 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-10: Initiative Impact on Key Barriers – Joint-Verification Technologies

Key Barrier	Initiative's Impact
Current inspection processes cannot identify minor leaks	Advanced verification technologies can identify small leaks that would normally go undetected through pressure or visual inspection
Advanced verification techniques currently carry high cost and complexity	For promising strategies, this initiative would help adapt the verification techniques and processes to the requirements of the HVAC&R industry, including factory and field installation techniques, technician expertise, cost and time requirements, and other considerations.

Table 4-11 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

[19] Lucas-Milhaupt. 2014. "Inspecting Brazed Joints." Lucas-Milhaupt, Inc. July 11, 2014. http://www.lucasmilhaupt.com/en-US/about/blog/2014/7/inspecting-brazed-joints
[20] Olympus. 2015. "Braze Joint Testing." Olympus Corporation. 2015. http://www.olympus-ims.com/en/applications/braze-joint-testing/

Table 4-11: Stakeholder Involvement – Joint-Verification Technologies

Tasks	Key Stakeholder Roles and Responsibilities
Industry survey	» National laboratories » Industry organizations » HVAC&R equipment and component manufacturers » Other industrial manufacturing partners » Contractor and technician organizations » Surveying organizations – survey design, recruitment, execution
R&D	» National laboratories » Academic researchers » Joining technology researchers » Industry organizations
Deployment	» HVAC&R equipment and component manufacturers » Industry organizations » Codes and standards organizations

4.3.6 Lower-Priority Brazing and Joining Technology Initiatives

The following initiatives, though not articulated in-depth like the higher-priority initiatives, are also valuable opportunities to further BTO goals and should be considered for future action. Table 4-12 lists a short title for each lower-priority Brazing and Joining Technology Initiative. Appendix B – Summary of Lower-Priority Initiatives provides descriptions of each initiative.

Table 4-12: Lower-Priority Brazing and Joining Technology Initiatives

ID	Description
10	Develop torsion-tolerant mechanical joints
11	Develop fiber laser welding system for HVAC&R joining
12	Develop the next generation of brazing materials
13	Expand certifications and training for brazing technicians
14	Improve manufacturing methods that eliminate the need for an intermediate tube at heat exchanger connection points

4.4 Priority Component and Material Initiatives

4.4.1 (ID #6) Low Joint-Intensity Heat Exchanger Designs

Initiative: *Develop advanced heat exchanger designs that reduce the number of required joints*

Under this initiative, BTO would support the development of HVAC&R heat exchanger designs that reduce joint intensity, and if promising, demonstrate the technologies with manufacturers and industry organizations.

Heat exchangers for most HVAC&R systems consist of several rows of copper tubes located within an airstream that transfer heat from the refrigerant flowing within the tubes either to or from the airstream. Each tube connects to supply and collection manifolds and often features several 180° elbow connections that allow the refrigerant to flow evenly across the heat exchanger and several joints to connect the tubes to each manifold. This design typically uses furnace brazing for each connection, creating several dozen brazing points and potential locations for refrigerant leakage. Recently, manufacturers have incorporated aluminum microchannel heat exchangers into their products to achieve greater efficiencies, but this strategy creates a substantially higher number of brazed connection points. Although connected through reliable joining techniques, increasing the number of joints creates greater opportunity for potential leakage locations. Advanced heat exchanger designs can reduce the number of internal joints by employing one or more strategies, including, but not limited to:

- More continuous tube designs (e.g., serpentine domestic refrigerator condenser)
- Seamless heat exchangers (e.g., polymer heat exchanger cast in a mold)
- Tube shape optimizations to reduce the number of rows, (e.g., rolled multi-port tubes[21])
- Incorporating additive manufacturing techniques.

This initiative would investigate the potential for advanced heat exchangers designed to reduce the number of joints within HVAC&R heat exchangers and systems through computational modeling, prototype development, and laboratory testing. The resulting designs must not only reduce joint-intensity, but also meet the performance, cost-effectiveness, and reliability standards of the HVAC&R industry. If these designs employ new shapes and form factors, researchers should test the heat exchanger prototypes as part of the larger HVAC&R system.

[21] Heat Transfer Technologies. 2015. "Roll Bonded Copper Multiport Tube for Heat Exchanger (HX) Applications." International Copper Association, the University of Maryland, and Heat Transfer Technologies. July 2015.

Table 4-13 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-13: Initiative Impact on Key Barriers – Low Joint-Intensity Heat Exchanger Designs

Key Barrier	Initiative's Impact
High number of heat exchanger joints creates potential leakage points	Developing low joint-intensity heat exchangers will inherently reduce the chance for refrigerant leakage during both factory joining and equipment operation
Increasing equipment efficiency standards require larger or more complex heat exchangers	Heat exchangers using alternative designs and materials could potentially provide greater heat transfer effectiveness per unit volume and allow for smaller and cheaper systems
Uncertain or unfamiliar heat exchanger designs	Demonstrating the advanced heat exchanger design as part of prototype HVAC&R systems can prove performance to equipment and component suppliers and suggest areas of further development before high-volume manufacturing

Table 4-14 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-14: Stakeholder Involvement – Low Joint-Intensity Heat Exchanger Designs

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » Industry organizations » HVAC&R equipment and component manufacturers
Deployment	» HVAC&R equipment and component manufacturers » Industry organizations

4.4.2 (ID #7) Secondary Joining Tapes and Materials

Initiative: *Develop coatings, compounds, or tapes that improve joint connections and leakage rates during installation and servicing*

Under this initiative, BTO would support the development and demonstration of various coatings, compounds, or tapes that supplement the primary joining technology. Manufacturers and field technicians could add these materials on the inside or outside of HVAC&R fittings using conventional joining techniques to create more cost-effective and lasting joint connections.

Either through brazing or mechanical connections, joining HVAC&R systems during field installation and servicing requires careful attention by skilled technicians to properly connect and seal refrigerant lines. Similar to Hybrid Joining Techniques (ID#3, see Section 4.3.3), adding an additional sealing technology could improve imperfections in the primary sealing technique caused by chemical residues, improper tightening, and other means. Incorporating coatings, compounds, or tapes either on the inside or outside of the primary joining technique could reduce leakage rates over the life of the equipment. Two examples could be an internal ring on a tube-joint brazing connection,[22,23] or a specialty tape on a threaded mechanical connection, similar to Teflon tape for plumbing systems.

This initiative would investigate potential strategies for internal and external materials that could create a secondary joining connection. Researchers could then develop promising technologies, conduct laboratory testing on HVAC&R equipment using both the primary and secondary joining techniques, and evaluate the effectiveness of the secondary systems. If successful, HVAC&R manufacturers, contractor organizations, and other industry stakeholders could incorporate the secondary joining tapes and materials into their installation practices.

Table 4-15 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-15: Initiative Impact on Key Barriers – Secondary Joining Tapes and Materials

Key Barrier	Initiative's Impact
Availability of secondary joining materials	Investigating a variety of secondary joining materials and developing promising technologies for HVAC&R applications
Unproven performance	Conducting laboratory testing to understand the effectiveness of the secondary joining material relative to conventional joining techniques
Technician experience	Publicizing the availability and effectiveness of secondary joining materials and strategies to contractors and technicians and incorporate techniques in training materials

Table 4-16 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

[22] Lucas-Milhaupt. 2012. "Sil-Fos (Silvaloy) / Sil-Fos Brazing Rings." Lucas-Milhaupt, Inc. May 2012. http://www.silfos.com/products/catalog/Sil-Fos-Brazing-Rings-orderby0-p-1-c-72.html

[23] Ring of Fire - Harris Products Group. 2015. http://www.harrisproductsgroup.com/en/New-Products/ring-of-fire.aspx

Table 4-16: Stakeholder Involvement – Secondary Joining Tapes and Materials

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC&R component manufacturers (e.g., fittings, heat exchangers, refrigerants) » Materials manufacturers (e.g., adhesives, coatings)
Laboratory testing, data analysis, and report publication	» Independent research laboratories » HVAC&R component manufacturers » Material manufacturers » Industry organizations
Deployment	» HVAC&R equipment and component manufacturers » Industry organizations » Contractor and technician organizations

4.4.3 (ID #8) Charge-loss-limiting HVAC&R Systems

Initiative*: Develop HVAC&R systems that limit the refrigerant charge lost through leakage events*

Under this initiative, BTO would support the development of either:

a. More compact HVAC&R systems incorporating advanced components and improved system layouts that reduce the amount of necessary refrigerant charge.

b. HVACR&R systems using a sensor network and specialized valves that isolate the section of a HVAC&R system that shows a leakage location.

Refrigerant leakage not only occurs slowly through small cracks or holes in the refrigerant lines over a long period of time, but also through sudden catastrophic events where most of the refrigerant escapes almost immediately. One way to reduce the amount of refrigerant released to the atmosphere during a total loss event is by incorporating advanced system designs that require less refrigerant charge. While each refrigerant carries its individual specific charge (i.e., charge volume per unit capacity), manufacturers can design HVAC&R equipment and components that require less fluid volume to distribute refrigerant throughout the system,[24] especially on the condenser and liquid-side distribution systems.[25] For example, microchannel and other advanced heat exchangers utilize small hydraulic diameters to provide the same thermal capacity with less fluid volume.

Additionally, manufacturers could add valves and sensors throughout the refrigerant system that shutoff the flow of refrigerant if any of the sensors detect a sudden loss in refrigerant pressure.

[24] Corberan, Jose. 2014. "Refrigerant Charge Reduction in Refrigerating Systems." 25th Informatory Note on Refrigeration Technologies. November 2014.
[25] Jing and Hrnjak. 2014. "Refrigerant Charge Reduction in Small Commercial Refrigeration Systems." International Refrigeration and Air Conditioning Conference. July 2014.

Manufacturers could incorporate this sensor network as part of a larger on-board FDD system (Section 4.5.1).

This initiative would investigate alternative HVAC&R system designs and/or mitigation strategies to limit the amount of refrigerant escaping systems during leakage events. Researchers could develop computational models and then laboratory prototypes to demonstrate the effects that charge-loss-limiting designs have on system performance, initial cost, leakage percentage, and other attributes. If promising, HVAC&R manufacturers and system designer could consider incorporating the advanced system architectures as part of their products and projects.

Table 4-17 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-17: Initiative Impact on Key Barriers – Charge-loss-limiting HVAC&R systems

Key Barrier	Initiative's Impact
Sudden damaging events are not a major concern for manufacturers, contractors, etc.	Research will investigate whether designing for minimal charge can potentially reduce product cost from lower refrigerant consumption, lower repair costs if leakage sections can be isolated, and improve operational safety with alternative refrigerants that may have flammability or other risks.
Uncertain cost and value to building owner	Quantifying the potential value proposition to building owners through equipment repair (rather than replacement), lower upfront costs, and other advantages.

Table 4-18 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-18: Stakeholder Involvement – Charge-loss-limiting HVAC&R systems

Tasks	Key Stakeholder Roles and Responsibilities
R&D and laboratory testing	» National laboratories » Academic researchers » HVAC&R equipment manufacturers » HVAC&R system designers – built-up systems
Deployment	» HVAC&R equipment manufacturers » HVAC&R system designers – built-up systems » Industry organizations

4.4.4 Lower-Priority Component and Material Initiatives

The following initiatives, though not articulated in-depth like the higher-priority initiatives, are also valuable opportunities to further BTO goals and should be considered for future action. Table 4-19 lists a short title for each lower-priority Component and Material Initiative. Appendix B – Summary of Lower-Priority Initiatives provides detailed descriptions of each initiative.

Table 4-19: Lower-Priority Component and Material Initiatives

ID	Description
15	Develop self-healing joints, fittings, and components
16	Research and develop joining technologies for membrane-to-metal connections
17	Develop techniques to incorporate additive manufacturing as an element in joints, couplings, and "joint-free" components
18	Develop servicing valves and instruments that do not leak refrigerant during field servicing

4.5 Priority Installation, Operations, and Maintenance Initiatives

4.5.1 (ID #9) Refrigerant-Leakage FDD Systems

Initiative: *Develop on-board FDD systems to detect leakage from packaged HVAC&R systems*

BTO has supported the development of FDD algorithms targeting refrigerant leakage using virtual sensors,[26] and manufacturers now offer FDD products[27,28] with these capabilities. Under this initiative, BTO would continue to support the development and demonstration of embedded or add-on FDD systems that improve the reliable detection of refrigerant leakage in HVAC&R systems. Because the FDD system can direct maintenance quickly when leakage occurs, incorporating refrigerant-leakage FDD capabilities into more HVAC&R systems can reduce energy consumption and refrigerant emissions in U.S. buildings.

FDD systems consist of a set of sensors and software algorithms that measure the current state of HVAC&R systems and identify if current operations exceed allowable limits. When a fault is detected, the system communicates with the building operator or contractor that the equipment needs inspection and helps direct the technician to the source of the issue. FDD systems use a variety of sensors including pressure and temperature sensors located throughout the system, non-invasive sensors that rely on electrical or acoustic patterns during equipment operation, and other techniques. Refrigerant leakage is a significant fault due to the substantial loss of capacity and efficiency resulting from even minor refrigerant losses. Most methods today use a “virtual

[26] Braun, Jim. 2015. “CBEI – Virtual Refrigerant Charge Sensing and Load Metering.” Purdue University. 2015 Building Technologies Office Peer Review. April 2015.

[27] Alsaleem et al. 2014. “HVAC System Cloud Based Diagnostics Model.” Emerson Climate Technologies. International Refrigeration and Air Conditioning Conference. July 2014.

[28] Pham and Neidlinger. 2013. “CoreSense Fault Detection & Diagnostic (FDD) Technology.” Emerson Climate Technologies. Western HVAC Performance Alliance. October 2013.

sensor" made up of several pressure and temperature sensors placed throughout the system to measure refrigerant charge indirectly because accurate charge sensors are not cost-effective. As discussed in Section 4.4.3, these FDD systems could help prevent refrigerant leakage in catastrophic events by activating shutoff valves by sensing a loss in refrigerant pressure.

This initiative would expand on existing BTO activities to improve the current generation of refrigerant-leakage FDD technologies through laboratory development, field demonstrations, and fostering industry partnerships with HVAC&R equipment manufacturers, sensors and controls vendors, and building owners.

Table 4-20 identifies the impact that the initiative will have on key technical and market barriers in the HVAC&R industry.

Table 4-20: Initiative Impact on Key Barriers – Refrigerant-Leakage FDD Systems

Key Barrier	Initiative's Impact
Costly installation for embedded or add-on systems	The next-generation of refrigerant-leakage FDD can incorporate lower-cost sensor networks and algorithms that reduce hardware costs for each HVAC&R unit
Wide operating characteristics generate false positives	Developing advanced algorithms and self-commissioning software can tailor the FDD system to each HVAC&R unit and its operating patterns
Uncertain payback and benefits to customer	Demonstration of refrigerant-leakage FDD systems can focus on avoided costs such as equipment downtime, longer replacement cycles, etc.

Table 4-21 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-21: Stakeholder Involvement – Refrigerant-Leakage FDD Systems

Tasks	Key Stakeholder Roles and Responsibilities
R&D, laboratory testing	» National laboratories » Academic researchers » HVAC&R equipment manufacturers » Sensors and control manufacturers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design, execution » National laboratories – survey design, end-use knowledge/support » HVAC&R equipment manufacturers » Equipment and sensors manufacturers
Deployment	» BTO or BTO contractor » HVAC&R equipment manufacturers » Equipment and sensors manufacturers » Industry organizations

4.5.2 Lower-Priority Installation, Operations, and Maintenance Initiatives

The following initiatives, though not articulated in-depth like the higher-priority initiatives, are also valuable opportunities to further BTO goals and should be considered for future action. Table 4-22 lists a short title for each lower-priority Installation, Operations, and Maintenance Initiative. Appendix B – Summary of Lower-Priority Initiatives provides detailed descriptions of each initiative.

Table 4-22: Lower-Priority Installation, Operations, and Maintenance Initiatives

ID	Description
19	Develop an injectable substance that can fill in leakage points within refrigerant lines
20	Develop the next generation of leak-detection techniques for field inspection
21	Develop cost-effective field welding techniques

5 Appendix A – HVAC&R Joining R&D Workshop Summary

US Department of Energy's Research and Development Opportunity Assessment for Joining Technologies in Heating, Ventilation, Air-Conditioning, and Refrigeration Technologies

June 4, 2015

Stakeholder Discussion Workshop Summary – Navigant's Washington D.C. Offices

Summary

On June 4, 2015, Navigant Consulting, Inc., on behalf of the U.S. Department of Energy's (DOE) Building Technologies Office (DOE/BTO), hosted a stakeholder discussion workshop to identify research and development (R&D) needs and critical knowledge gaps related to joining technologies for heating, ventilation, air-conditioning, and refrigeration (HVAC&R) technologies. This workshop covered brazing and joining technologies and processes, advanced component design and materials, and installation, operation, and maintenance practices. DOE/BTO is the office through which DOE funds research to support emerging building technologies, with the aim of reducing total building-related energy consumption by 50% by the year 2030 and hydrofluorocarbon (HFC) consumption by 85% by the year 2035.[29]

DOE/BTO hosted the workshop at Navigant's Washington D.C. office. Twenty-eight stakeholders participated, including university researchers, national laboratories, manufacturers, and representatives from industry organizations. A list of attendees and their affiliations is included at the end of this section.

Objective

The objective of this workshop was twofold: 1) Engage participants in a discussion of the key R&D technologies and processes that have the potential to accelerate improvements in joining technologies, resulting in improved product reliability, reductions in refrigerant leakage, lower cost, and higher performance; and 2) Create a prioritized list of potential R&D activities that can aid DOE/BTO in achieving their goals and that industry stakeholders believe will reduce barriers to greater adoption of these next-generation HVAC&R joining technologies.

Process and Results

Discussions at the workshop included a large group brainstorming session as well as smaller breakout-group sessions. Each attendee participated in two breakout sessions, one of which covered brazing and joining technologies and processes. During the first session, attendees could choose from the following topic areas:

- Brazing and joining technologies and processes

[29] HFC consumption targets weighted by global-warming potential (GWP)

- Advanced component design and materials

During the second breakout session, attendees could choose from the following topic areas:

- Brazing and joining technologies and processes
- Installation, operation, and maintenance

The group brainstorming and breakout sessions together generated a total of 19 unique challenges and barriers and 35 R&D activities or technology suggestions for DOE/BTO to consider (hereafter "initiatives"). At the conclusion of the workshop, Navigant posted all of the initiatives on the wall and asked the participants to prioritize the initiatives by voting on the ones that they felt were most valuable and promising for DOE/BTO to undertake. Each participant received 5 votes (stickers) to distribute among the different initiatives as they saw fit (regardless of topic area). Table 23 shows the top initiatives that received 5 or more total votes.[30]

Table 23: Higher-Priority R&D Initiatives

Session	Initiative	Votes
Brazing and Joining Tech	Identify and develop specific adhesives with targeted chemistries for HVAC&R joining applications	10
Brazing and Joining Tech	Develop a consistent evaluation process (or technology) for verifying joints in both factory and field applications	9
Component and Materials	Develop advanced heat exchanger designs incorporating advanced materials that reduce the number of required internal joints	9
Component and Materials	Develop lower temperature thermal joining technology and techniques	8
Brazing and Joining Tech	Develop a laboratory test method for evaluating the effectiveness of various joint methods	7
Installation, Operations, and Maintenance	Develop the next generation of leak detection techniques for field inspection	5
Component and Materials	Develop self-sealing joints, fittings, and components	5
Component and Materials	Investigate and develop a laboratory test method for evaluating component leakage	5

Table 24 shows the list of key challenges and barriers for HVAC&R joining technologies suggested during the group brainstorming session.

[30] The total number of votes does not equal 5 votes/person multiplied by 28 attendees because: 1) Some attendees departed prior to voting; 2) DOE staff and Navigant facilitators did not vote.

Table 24: Challenges and Barriers for HVAC&R Joining Technologies

Challenges and Barriers
Cultural aversion to epoxies and adhesion
Dimensional tolerances for brazing reliability
Understanding leakage by joint type
Reducing the number of joints and joint free assemblies
Automated leak sealing
System contamination during joining – compatibility of materials to refrigerants, oils, and lubricants
Consistent methodology for joint evaluation
Poor perception of mechanical joint connections
Field servicing and repair – especially with flammability concerns
Uncontrollable factors in manual joining
Maintaining adequate fatigue strength
Quality control and inspection of the joint internally for long term durability
Chemical challenges of corrosion on both fins and joints
Focusing on system design rather than on tolerance design and control
Plastic and metal interfaces and joints
Polymer conductivity and hoop stress, causing diffusion of stress through the material
Rapid thermal transients contributing to leaks
Torsional stability of mechanical joints
Flow distribution into tiny channels with low number of joints

The following tables document each proposed R&D initiative along with the number of votes it received; these tables reflect the raw outputs of the workshop. The tables therefore do not perfectly reflect a single category of initiatives, but rather, documentation of the conversations that transpired during the session. The ideas from the workshop are divided by the breakout session where they arose.

Table 25: R&D Initiatives from Brazing and Joining Technology Breakout Session

Initiative	Votes
Identify and develop specific adhesives with targeted chemistries for HVAC&R joining applications	10
Develop a consistent evaluation process (or technology) for verifying joints in both factory and field applications	9
Develop a laboratory test method for evaluating the effectiveness of various joint methods	7
Research and develop hybrid joining connections that combine a torque fitting with a secondary non-mechanical joining technique (e.g., meltable gasket)	3
Develop fiber laser welding system	2
Research and develop low temperature joining techniques incorporating new joining materials and/or cladding layers	2
Develop reactive nanotechnology incorporating multilayer electrojoining	1
Demonstrate the effectiveness, safety, and other characteristics of epoxies/adhesives with refrigerants in HVAC&R applications	1
Develop torsion tolerant mechanical joints	1
Improve manufacturing methods that eliminate the need for an intermediate tube at heat exchanger connection points	0
Expand certifications and training for brazing technicians	0
Develop the next generation of brazing materials	0
Improve field-applied epoxies, including development of application-specific compounds	0

Table 26: R&D Initiatives from Advanced Component Design and Materials Breakout Session

Initiative	Votes
Develop advanced heat exchanger designs incorporating advanced materials that reduce the number of required internal joints	9
Develop lower temperature thermal joining technology and techniques	8
Develop self-sealing joints, fittings, and components	5
Investigate and develop a laboratory test method for evaluating component leakage	5
Develop techniques to build "joint-free" components through additive manufacturing	4
Develop advanced heat exchangers designs incorporating advanced materials that reduce the number of required external connections to other components	4
Develop alternative refrigerant manifold designs that reduce the number of joints	4
R&D of joining technologies for membrane-metal connections	3
Develop techniques to incorporate additive manufacturing as an element in joints and couplings	2
Develop alternative mechanical connection systems	1
Investigate and develop cold-spray and WAAM joining techniques for HVAC&R applications	1
Develop compact HVAC&R systems that reduce refrigerant charge and amount of potential leakage	1
Development of a sealing tape or compound to apply around joints during field installations and servicing	0
Develop servicing valves and instruments that do not leak refrigerant during field servicing	0
Develop methods for overcasting heat exchangers, manifolds, and other components	0
Develop lower cost resistance welding techniques for field applications	0

Table 27: R&D Initiatives from Installation, Operation, and Maintenance Breakout Session

Initiative	Votes
Develop the next generation of leak detection techniques for field inspection	5
Develop internal coatings or tapes that improve connections and leakage rates with mechanical joints	4
Develop on-board fault detection and diagnostics (FDD) systems to detect leakage from packaged HVAC&R systems	2
Develop cost-effective field welding techniques	1
Develop an injectable substance that can fill in leakage points within refrigerant lines	0
Conduct research study on field installation practices to understand the effectiveness of different joining techniques in the field	0

Next Steps

Navigant, in consultation with BTO, will continue to refine and develop these R&D initiatives though additional research and follow-up interviews with individual stakeholders who were unable to attend the workshop. Navigant will combine any duplicate or overlapping initiatives to ensure that all initiatives are unique. We will use a combination of qualitative criteria and stakeholder voting in developing final recommendations of the top R&D initiatives for DOE to consider. The prioritization will consider some or all of the following criteria:

- Fit with DOE/BTO mission
- Criticality of DOE involvement
- Technical and market risks
- Market readiness
- Level of required DOE investment
- Stakeholder input (including voting results)

DOE/BTO will consider the recommended outputs of these prioritization processes for funding in parallel with other priorities in other building end-use areas. Therefore, no recommended output from this opportunity assessment is guaranteed to receive DOE support.

The opportunity assessment will serve as a guide for DOE and its partners in improving joining technologies for HVAC&R systems, while maintaining the competitiveness of American industry.

Workshop Attendees

Navigant and DOE wish to thank all of the workshop participants. The suggestions, insights, and feedback provided during the workshop are critically important to identifying and prioritizing HVAC&R joining R&D initiatives.

The stakeholder discussion workshop brought together 28 individuals representing a range of organizations across the industry. Table 28 lists all the attendees and their affiliations.

Table 28: Stakeholder Workshop Attendee List

Attendee Name	Organization
Omar Abdelaziz	ORNL
Vikrant Aute	University of Maryland
David Beers	GE
Antonio Bouza	U.S. Department of Energy
David Brown	ARPA-E
Mark Davis	Office of Naval Research
Serguei Dessiatoun	University of Maryland
Bill Goetzler	Navigant
Alison Gotkin	United Technologies Research Center
Matt Guernsey	Navigant
Shaobo Jia	Heatcraft Worldwide Refrigeration
Andrew Kireta	Copper Development Association Inc.
Shari Loushin	3M
Saeed Moghaddam	University of Florida
Jay Peters	RLS, LLC
Pat Phelan	U.S. Department of Energy
Reinhard Radermacher	University of Maryland
Neha Rustagi	U.S. Department of Energy
Ashwin Salvi	ARPA-E
Marc Scancarello	Emerson Climate Technologies, Inc.
Ray Schafer	Ingersoll Rand
Yoram Shabtay	Heat Transfer Technologies LLC
Amir Shooshtari	University of Maryland
Hal Stillman	International Copper Association, Ltd.
Charles Stout	Mueller Industries
Xudong Wang	AHRI
Brian Westfall	Ingersoll Rand
Jim Young	Navigant

6 Appendix B – Summary of Lower-Priority Initiatives

The subsections that follow provide descriptions of each lower-priority initiative. We scored these initiatives during the prioritization process (see Section 2.2) and present them here in ranked order in their respective category.

6.1 Brazing and Joining Technology Initiatives

6.1.1.1 (ID #10) Develop torsion-tolerant mechanical joints

Mechanically joined tubes (e.g., crimped) suffer from limited torsional strength for some HVAC applications. For example, a refrigerant line that is connected to a compressor will be subject to torsional forces as the compressor moves and vibrates during operation, particularly during startup and shutdown. This motion imparts torsional and other stresses on a joint, stresses that a brazed joint handles well, but most mechanical joint are not as well suited to bear over the life of the equipment. R&D is needed to (1) evaluate current mechanical joining techniques to determine options for increasing torsional strength, and (2) to identify potential alternative joining technologies, perhaps from other industries, that could be refined or further developed for use in HVAC&R applications.

6.1.1.2 (ID #11) Develop fiber laser welding system for HVAC&R joining

Laser welding is a joining process that uses the high powered and highly focused energy of a laser to join metals for industrial applications. Although capital intensive, laser welding offers a number of advantages over other joining techniques because the laser is very precise with a narrow focus area and controllable depth. Further, the systems offer high reliability and reproducibility, easy maneuverability around joints, and easy automation with robotics for high-volume manufacturing.

Laser welding techniques using solid-state, gas, or fiber lasers commonly join various steels, aluminum, and titanium for automotive, aerospace, medical, and other industries.[31] Because most systems use copper connections and piping, the HVAC&R industry has not employed laser welding extensively since the most common techniques (e.g., carbon dioxide and other gas lasers) are ineffective with copper's high reflectivity and conductivity.[32] Nevertheless, laser manufacturers and their industrial customers[33] have developed advanced lasers using green or green-red wavelengths[34] to utilize laser welding for copper joining for electronics, battery, electric motor, and other applications. BTO could investigate the potential for these next-generation laser welding systems in copper and aluminum HVAC&R applications. If promising, BTO could partner with major HVAC&R manufacturers to conduct pilot demonstrations in their factories and evaluate the effectiveness of laser welding techniques compared to conventional brazing and joining methods.

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[31] Stiles, Eric. 2010. "Fiber Lasers: The Flexible Tool for High Power Laser Welding." IPG Photonics. AWS New Welding Technologies Conference. June 2010.
[32] Herrmann and Herzog. 2013. "Laser Welding of Copper." Industrial Laser Solutions for Manufacturing. January 2013.
[33] Mada. 2015. "Green Laser Welding." Amada Miyachi Europe. http://www.amadamiyachieurope.com/technologies/green-laser-welding/
[34] Ruettimann et al. 2013. "Reproducible Copper Welding." Industrial Laser Solutions for Manufacturing. September 2013.

6.1.1.3 (ID #12) Develop the next generation of brazing materials

Brazing joints comprise the majority of connections within HVAC&R refrigerant systems due to brazing's good compatibility with copper, the strong bonds between the filler material and two pipes, applicability to both factory and field installations, ability to adjust joints in the field as needed, and other characteristics. Nevertheless, the current generation of brazing materials still leaves the opportunity for incomplete joints or the opportunity for degradation over time through formicary and pitting corrosion, dirt or contaminant buildup, vibration and thermal expansion over time, field damage, and other issues. Advanced filler materials or alternative filler architectures could improve the brazing connections by offering greater capillary flow through the joint, high surface tension for bonding, and high pliability to handle vibration over time. For example, several brazing materials vendors have developed rings of filler material that can be placed within the female fitting in a lap joint to perform inside-out capillary action rather than the outside-in brazing process of using a filler stick[22,23]. BTO could support the development of the next generation of brazing materials, application methods, filler architectures, and other strategies to improve the long-term performance of brazed connections for HVAC&R systems. While it is unclear today which strategies could yield promising results, researchers could present new materials or ideas in the future for BTO to consider.

6.1.1.4 (ID #13) Expand certifications and training for brazing technicians

A well-executed braze joint should provide leak-free functionality for the life of the product. In a factory environment, most variables can be closely controlled to create six-sigma-level (or better) quality processes. In the field, the greatest variable determining the quality of the joint is the technician. A well-trained and focused technician can produce thousands of leak-free joints. However, a technician that is insufficiently trained, or who takes shortcuts or otherwise does not pay sufficient attention to detail may produce leak-prone joints. Expanding training and certification programs for brazing technicians can help reduce variability in the quality of braze joint produced in the field. To determine specific improvements or expansions that are required, BTO could conduct research to determine which topic areas and techniques could have the greatest impact in training and certifying technicians.

6.1.1.5 (ID #14) Improve manufacturing methods that eliminate the need for an intermediate tube at heat exchanger connection points

Many HVAC&R equipment manufacturers purchase fin-and-tube heat exchangers for evaporators and condensers from specialized suppliers. Because the heat exchanger manufacturer supplies products to numerous equipment manufacturers, the supplier does not specifically design the heat exchanger connection points for any one product or model. Rather, the heat exchanger manufacturer leaves a short connection point that can be adapted to meet the needs of all their customers through the use of an intermediate tube. This extra fitting or pipe connector introduces several additional brazing connections that could be sources of refrigerant leakage. BTO could support the coordination between HVAC&R equipment and heat exchanger manufacturers on developing improved manufacturing methods that reduce the number of required brazing points, intermediate tubes, and other connections.

6.2 Component and Material Initiatives

6.2.1.1 (ID #15) Develop self-healing joints, fittings, and components

When leakage occurs in joints, the operating conditions around that joint could change sufficiently to activate an automatic sealing system at that joint. Depending on the joint's location in the refrigerant system (e.g. high or low pressure), changes in normal temperature, pressure, flow direction, or chemical composition could signal the presence of a leak. Specific phase change materials or shape memory alloys could be developed to lie within the joint of a valve or other component and activate when a leakage signal occurs (e.g., infiltration of moisture). Nevertheless, these self-sealing systems would need to have a high enough threshold that they do not activate from the normal range of operating conditions an HVAC&R system experience throughout the seasons, the presence of minor imperfections or contaminants, and other normal conditions, such that they do not adversely affect system performance from false positives. BTO could investigate the potential for self-healing joints, fittings, and components that utilize a specialty material that activates to certain refrigerant leakage markers.

6.2.1.2 (ID #16) Research and develop joining technologies for membrane-to-metal connections

Several emerging heat exchanger designs for vapor-compression, absorption, heat recovery, and other HVAC systems utilize polymer-based and other membrane materials. These specially designed membranes could offer greater efficiency, reduced cost, and other advantages, but encounter significant issues when connecting to conventional HVAC&R systems and components. Currently, few options exist to reliably and cost-effectively connect these alternative materials to conventional metal piping systems (e.g., copper, aluminum). Because many of these alternative systems use low- or zero-GWP working fluids, successful development of membrane-based HVAC&R technologies could have a substantial impact on overall refrigerant emissions. BTO could support these advanced HVAC&R systems by conducting research on different membrane-metal joining techniques and technologies.

6.2.1.3 (ID #17) Develop techniques to incorporate additive manufacturing as an element in joints, couplings, and "joint-free" components

Additive manufacturing involves the systematic layering of materials to build up a three-dimensional object in a continuous process, and have been used in for manufacturing in the aerospace, medical, and other industries where complex geometries require solutions beyond conventional manufacturing or repair methods. Additive manufacturing is a generic term for several different techniques including fused deposition, selective laser sintering, cold spray deposition, wire-arc additive manufacturing (WAAM),[35] and many other techniques. When applied to HVAC&R, additive manufacturing could construct entire heat exchangers or components layer by layer. In this process, manufacturers could design an entire component without any internal connections requiring brazing. Alternatively, manufacturers could use additive manufacturing techniques to join major sections of equipment, e.g., heat exchangers to compressor sections. Without any brazing connections, HVAC&R systems using additive manufacturing techniques could conceptually reduce the number of brazing connections required in both the factory and field. BTO could support the development of additive manufacturing techniques for the HVAC&R industry by investigating how current methods could apply to

[35] Gu et al. 2014. "Wire-Arc Additive Manufacturing of Aluminum." International Solid Freeform Fabrication Symposium. August 2014.

copper and other HVAC&R components, and then demonstrating promising techniques in relevant applications and environments.

6.2.1.4 *(ID #18) Develop servicing valves and instruments that do not leak refrigerant during field servicing*

During seasonal equipment servicing or when faults occur, HVAC&R technicians connect a set of hosed gauges to the refrigerant lines to determine whether the system has proper operating pressures. The manifold of gauges uses hoses to connect to Schrader and other servicing valves on the refrigerant lines to measure the pressure of refrigerant lines. While this practice is effective in diagnosing the HVAC&R system and refrigerant charge levels, this connection method can increase risk of future refrigerant leakage by wearing down the valve connections (Schrader valves have shown to be one of the most likely contributors to system leakage.[36]) While technicians now have inexpensive techniques to replace Schrader valves, new diagnostic tools or alternative connection systems could reduce the chance of refrigerant leakage. Additionally, once the pressure gauges are attached to the Schrader valve, a small amount of refrigerant travels through the hose to reach the gauge. After disconnection, this refrigerant escapes to the atmosphere. While minor relative to other sources of system leakage, this is a standard practice occurs with great frequency. BTO could support the development and demonstration of alternative servicing valves, instruments, and techniques to monitor the high- and low-side refrigerant pressures in field servicing and repair.

6.3 Installation, Operations, and Maintenance Initiatives

6.3.1.1 *(ID #19) Develop an injectable substance that can fill in leakage points within refrigerant lines*

Refrigerant leakage often occurs in parts of the HVAC&R system that are not easily detectable or repairable, and the technician may have to replace certain components or piping lengths without actually finding the source of leakage. A more cost-effective means of repairing difficult leakage points could be to inject a sealant material into the refrigerant line to fill in the leakage point. Several aftermarket vendors offer injectable sealants for service technicians, but few, if any, independent studies have shown their effectiveness in a controlled setting. Any substance entering the refrigerant lines could cause problems with heat transfer, clogging of TXVs and other components, and other complications, and requires careful consideration. BTO could investigate the effectiveness of injectable sealants that can fill in leakage points for HVAC&R systems, and if promising, conduct laboratory and field demonstrations to monitor long-term performance relative to other repair techniques.

6.3.1.2 *(ID #20) Develop the next generation of leak-detection techniques for field inspection*

When a technician determines that refrigerant leakage has occurred, they inspect the HVAC&R system to repair the location and prevent future refrigerant loss. Because most leaks cannot be seen by the naked eye, the technician will employ one or more leak-detection techniques if the cause and location of leakage is not immediately apparent either through damage or corrosion. Common detection methods include: soap-bubble test, water immersion, nitrogen pressure hold, UV dye injection, and a variety of ultrasonic, infrared, and other sensors.[37] Nevertheless, these

[36] Clodic and Yu. 2014. "Joining Techniques Assessment." AHRTI Report No. 09006. March 2014.
[37] Appler, Paul. 2012. "Trends in Refrigerant-Leak Detection." RSES Journal. May 2012.

techniques are sometimes ineffective due to inaccessibility or lack of line-of-site to the leak location, cost/complexity of sensor systems, poor sensitivity or calibration, etc.[38] If the leaks are not found and repaired, refrigerant will continue to leave the system, contributing to greater refrigerant consumption and poor performance. BTO could support the development of next-generation refrigerant-leak-detection techniques that are simple, rugged, effective, and economical for use by HVAC&R technicians.

6.3.1.3 (ID #21) Develop cost-effective field welding techniques

As discussed previously, welding differs from brazing in that both the two base metals and any filler materials melt rather than only the filler material in brazing. Welding does not rely on the capillary action of the secondary material to fill the joint, as is the case for brazing, and can form stronger joints that are less likely to leak refrigerant. The high conductivity of copper poses fundamental issues during welding because the heat of the welder rapidly dissipates away from the weld location, especially compared to steel, aluminum, or other metals. As a result, copper welding is limited to a small number of highly-controllable applications in industry. While most welding techniques reach temperatures that could distort the thin walls of many copper tubes, larger HVAC&R systems with thicker piping could handle the process with acceptable levels of distortion. Manufacturers could employ welding processes for joining their larger equipment in the factory, but field welding would be difficult except on large construction sites where the large electrical generators required for copper welding would not interfere with building operation and electrical infrastructure. BTO could support the development of cost-effective welding techniques for technicians to use on HVAC&R systems.

[38] DuPont. 2005. "Leak Detector Guidance for DuPont Suva Refrigerants." Technical Information ARTD-27A. 2005.

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