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Building Technologies Office

Research & Development Roadmap for Next-Generation Appliances

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NOTICE

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Research & Development Roadmap for Next-Generation Appliances

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Executive Summary

The Building Technologies Program (BTP) within the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy is responsible for developing and deploying technologies that can substantially reduce energy consumption in residential and commercial buildings. Residential appliances such as refrigerator/freezers, dishwashers, laundry equipment, and cooking equipment account for over 12 percent of U.S. residential sector primary energy consumption. The appliance sector has seen substantial innovation in recent years; however, energy efficiency measures, while significant, have generally involved incremental improvements to meet new DOE efficiency standards. Little research has focused on radical innovations that might dramatically reduce energy consumption. By leveraging resources, the appliance industry may be able to work cooperatively with the DOE to develop and commercialize products and technologies that could make dramatic improvements feasible. In order to guide such activities and ensure the best possible outcomes, a research & development (R&D) roadmap is necessary.

The objective of this roadmap is to advance DOE's goal of reducing the energy consumption of residential appliances by accelerating the commercialization of high-efficiency appliance technologies, while maintaining the competitiveness of American industry.

This roadmap targets high-priority R&D, demonstration, and commercialization activities that, if pursued by DOE and its partners, could significantly reduce residential appliance energy consumption. The roadmap prioritizes those technologies with the highest energy savings potential and greatest likelihood of being embraced by both manufacturers and consumers. The schedule of proposed activities ranges from near-term activities in the 6-month to 2-year time frame, to longer-term research initiatives that may span 3-5 years or longer.

This R&D roadmap focuses on the following residential appliances: **refrigerator/freezers**, **clothes washers**, **clothes dryers**, **cooking equipment,** and **cross-cutting** appliance technologies. Microwaves and dishwashers were eliminated from consideration in this report due to their low annual energy consumption and a lack of identified technologies that could significantly decrease energy consumption below current best-in-class levels. This roadmap does not cover heating, ventilation, and air-conditioning (HVAC) systems, water heaters, or building envelope components.

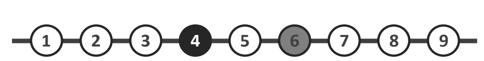
Table 1. summarizes the recommended R&D activities for each technology option. Specifically, for each technology, the table provides the following:

- Summary of overall R&D objectives
- Estimate of development status after achieving R&D objectives
- Summary of specific R&D tasks
- Identification of possible performers and their respective roles
- Estimate of the duration of each R&D activity and the types of resources required
- Summary of the key risks associated with each technology option

Table 1. Summary of R&D Recommendations for Each Appliance Technology Option

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Tier 1 (Higher Priority)						
Refrigerator/ Freezer: Magnetic refrigeration	Demonstrate the required cooling capacity of residential refrigerators.		• Further understand magnetic refrigeration cooling principles • Optimize individual components of the system • Test optimized prototype to demonstrate required cooling capacity	• BTP: provide funding, manage test program, develop test protocols • Ames Laboratory: expand on previous research and prototype	 **Duration: 3-5 years** • Materials & supplies for component development and system integration • Research and development staff	• Ability to scale down components to fit within residential-size cabinet • Fully-functional prototype will require years of additional R&D • Future availability of exotic magnetic materials
Refrigerator/ Freezer: Vacuum insulation panels	Understand the causes of inconsistent results among multiple manufacturers' products and to reduce overall costs.		• Perform characterization tests on products known to have inconsistent performance • Reverse-engineer products to determine root causes for performance inconsistencies • Analyze the supply chain of all materials and processes used in the manufacture of VIPs • Determine major cost drivers and identify strategies for reducing costs	• BTP: provide funding, manage test program, perform supply chain analysis • Third-party laboratory: perform energy tests using DOE test procedure, perform reverse-engineering analysis of VIPs • Manufacturers: Partnership with DOE/BT research efforts	 **Duration: 2-3 years** • Refrigerator/freezer products with VIPs • VIP samples from multiple manufacturers • Third-party laboratory for testing • ORNL research staff to test and analyze results	• Requires more costly manufacturing methods • Low degree of certainty on longevity of VIPs • Uncertain consumer willingness to pay higher upfront cost
Clothes Dryer: Heat pump (electric only)	Support a pilot testing program for pre-commercial heat pump clothes dryers, and support the development of ENERGYSTAR criteria for heat pump dryers.		• Support pilot testing program of pre-commercial heat pump clothes dryers • Support development of ENERGY STAR criteria for high-efficiency clothes dryers	• BTP: provide technical support to ENERGY STAR program; support and manage pilot test program • Manufacturers: develop technology to pre-commercial readiness level; collaborate with DOE on pilot test program • EPA: management of ENERGY STAR program specifications	 **Duration: 2 years** • Funding for program technical staff • Test equipment & materials required for pilot testing	• Technology not yet proven for large U.S. laundry load sizes • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost
Cross-Cutting Technologies: Integrated energy and water recovery & transfer between appliances	Measure and validate the energy savings potential of the ZEHcore concept by performing laboratory tests simulating real-world usage patterns, and through a pilot demonstration project in a residential setting.		• Develop fully functional prototype system • Characterize system performance and compare to modeled predictions • Perform preliminary laboratory testing using actual appliances • Modify/optimize internal components based on preliminary testing • Further refine design to produce fully functional prototype system • Conduct further laboratory tests simulating real-world usage patterns • Conduct pilot demonstration in a residential setting	• BTP: provide funding, manage test program, manage pilot program • ORNL: development and refinement of ZEHcore system • Pilot users: operate under real-world conditions	 **Duration: 3-5 years** • Funding for research staff • Materials & supplies for further system development • Test equipment & materials required for testing (including appliances) • Funding and program support for small-scale pilot testing	• Would require total redesign of typical kitchen appliance layouts • Feasibility not yet proven for energy/water recover and transfer concepts • Unproven energy/water savings • Would likely require changes to manufacturing processes • Uncertain consumer acceptance • Marketing changes required to shift away from single-appliance focus

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Tier 2 (Medium Priority)						
Refrigerator/ Freezer: Improved linear compressor	Improve energy efficiency of linear compressors through optimization of design, material selection, and lubricants.		• Reverse engineer commercially available linear compressors • Increase compressor efficiency through improved designs, materials, and lubricants to optimize performance • Test optimized compressor to demonstrate improved energy efficiency	• BTP: provide funding, manage test program • Third-party laboratory: perform reverse-engineering analysis • National Laboratory: design and testing	**Duration: 2 years** • Materials to build and test improved compressors • Research staff to build, test, and analyze compressors	• May involve proprietary compressor designs
Clothes Washer: Polymer bead cleaning	Demonstrate technology viability in commercial-scale laundry facilities; support the development of a prototype for residential use, and assess any environmental or safety hazards.		• Support pilot testing program of commercial-scale washers at on-premise and off-premise laundry facilities • Support ongoing development of a residential prototype that would be relevant in the U.S. market • Demonstrate residential prototype functionality under laboratory conditions • Assess any environmental risks or safety hazards associated with polymer beads in a residential setting.	• Xeros, Ltd: manufacturer of pilot test units and prototypes, cooperation with DOE project • BTP: provide funding, coordinate pilot test program, manage R&D of residential prototypes • National Laboratory: cooperative R&D agreement with manufacturer; funding & support for development of residential prototype • Large-scale gas utility: coordinate pilot test program of commercial-scale units	**Duration: 3-5 years** • BTP project staff to manage test program • National Laboratory staff for prototype development and testing • Funding and program support for pilot testing of commercial-scale units	• Suitability of technology for residential laundry not yet demonstrated • Cleaning ability of technology not yet proven to AHAM standards • Uncertain consumer acceptance of new plastic particle technology • Potential environmental and safety concerns associated with polymer beads
Clothes Dryer: Inlet air preheat	Adapt currently available technology to residential clothes dryers, determine the energy-savings potential, and assess the viability of inlet air preheating technology for residential clothes dryers.		• Develop smaller-scale design that could be applicable to residential dryers • Modify residential clothes dryer cabinet with air inlets/outlets to work with heat wheel technology • Perform testing to determine energy savings potential • Investigate the feasibility of installing heat exchanger inside dryer cabinet	• BTP: provide funding, manage R&D program • National Laboratory: design and build prototype system, perform prototype testing • Rototherm Corp.: provide samples of current heat wheel technology, cooperate and/or collaborate with DOE project	**Duration: 1 year** • Funding for research staff • Materials & supplies for developing modified components • Test equipment & materials required for internal testing	• Unproven energy savings potential • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Potential impacts on installation procedures • Potential safety issues with lint handling
Clothes Dryer: Mechanical steam compression (electric only)	Validate the technology concept by developing a complete working prototype and performing testing under laboratory conditions.		• Develop remaining components required for fully functional system • Integrate components to develop functional prototype • Characterize system performance and compare to modeled predictions	• BTP: provide funding, monitor R&D progress • Center for Energy Studies, Ecole des Mines de Paris (Mines ParisTech): expand on previous research and prototypes • U.S. university or National Laboratory: joint research activities with Center for Energy Studies	**Duration: 2 years** • Funding for research staff • Materials & supplies for component development and system integration • Test equipment & materials required for testing	• Technology not yet proven in integrated prototype • Increased manufacturing cost compared to traditional dryers • Increased manufacturing cost compared to heat pump dryers with little or no additional benefit • Uncertain consumer willingness to pay higher upfront cost

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Cooking Equipment: Induction cooktops	Verify energy savings, incorporate into DOE's cooking equipment test procedure, and support the development of an ENERGY STAR specification for cooktops.		• Test commercially available units to determine energy savings potential • Create test method to incorporate into the DOE test procedure • Support development of ENERGY STAR criteria for cooktops	• BTP: provide funding, manage test program, develop test protocols • Third-party laboratory: perform energy tests • EPA: Management of ENERGY STAR program specifications	 **Duration: 1 year** • Procurement of units for testing • Third-party laboratory for testing	• Requires specialized cookware • Uncertainty regarding wide-scale consumer demand for this technology • Unverified energy savings in real-world residential settings
Cooking Equipment: Specialized cookware	Quantify the energy savings potential and support the development of an ENERGY STAR specification for specialized cookware.		• Perform energy testing of commercially available products to verify energy efficiency potential. • Support development of ENERGY STAR criteria for cooktops	• BTP: provide funding, manage test program, develop test protocols • Third-party laboratory: perform energy tests • Cookware manufacturers: assist in developing ENERGY STAR specifications • EPA: Management of ENERGY STAR program specifications	 **Duration: 1 year** • Procurement of units for testing • Third-party laboratory for testing	• Uncertainty regarding wide-scale consumer demand for specialty cookware • Unverified energy savings in real-world residential settings
Tier 3 (Lower Priority)						
Refrigerator/ Freezer: Stirling cycle refrigeration	Determine the energy savings potential of stirling cycle refrigerator/freezers by developing and testing a working prototype.		• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• BTP: provide funding, manage test program, develop test protocols • Purdue University: provide knowledge and expertise on stirling cycle refrigeration R&D	 **Duration: 2-3 years** • Research staff to develop and test prototype • Materials required to build prototype	• Unproven energy savings potential compared to vapor-compression systems • Challenges regarding how to transfer heat away from refrigerated compartments
Refrigerator/ Freezer: Thermoelastic refrigeration	Demonstrate the cooling capacity that would be required for a residential refrigerator.		• Further understand thermoelastic refrigeration cooling principles • Optimize individual components of the system • Test optimized prototype to demonstrate required cooling capacity	• BTP: provide funding, manage test program, develop test protocols • University of Maryland: expand on previous research and prototype development	 **Duration: 3-5 years** • Materials & supplies for component development and system integration • University of Maryland research staff to test and analyze results	• Concept is proven, but low degree of certainty that the technology is feasible in a residential setting • Unproven energy savings potential • Challenges regarding how to transfer heat away from refrigerated compartments
Refrigerator/ Freezer: Thermoelectric refrigeration	Determine the potential energy savings of a full-sized residential thermoelectric refrigerator/freezer by developing prototypes for laboratory testing.		• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• BTP: provide funding, manage test program, develop test protocols • Manufacturers: Partnership with DOE/BT research efforts • National Laboratory: design, testing, and development of prototypes	 **Duration: 2-3 years** • Small thermoelectric refrigerators to analyze • Materials to build full-sized prototype • Research staff to build, test, and analyze prototypes	• Unproven energy savings potential compared to vapor-compression refrigeration • Uncertainty regarding ability to scale up manufacturing process

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Clothes Washer: Sanitizing agents	Assess environmental and health risks of certain sanitizing agents that would enable lower-temperature wash cycles.		• Assess environmental risks associated with wastewater discharge of sanitizing agents • Assess human health risks associated with certain sanitizing agents	• BTP: provide funding, coordination of environmental and health assessments • EPA: coordination and review of environmental and health assessments	 **Duration: 1 year** • BTP project staff to manage program • Funding for environmental and health assessments	• Certain sanitizing agents may pose environmental or human health risks • Perceived risks may limit consumer acceptance • Perceived risks and potential liability concerns may limit manufacturer interest
Clothes Dryer: Indirect heating	Determine the energy savings potential of indirect (hydronic) clothes dryer technology with back-to-back dryer cycles.		• Procure several working units • Perform testing of back-to-back dryer cycles • Determine energy savings potential • Assess any risks associated with clothing cool-down period	• Hydromatics Technologies: provide units for testing • BTP: provide funding, manage test program, develop test protocols • Third-party accredited laboratory: perform energy & performance tests • DOE Standards team: provide background/insights, help evaluate test results	 **Duration: 6 months** • Procurement of units for testing • BTP project staff to manage test program • Third-party laboratory for testing • DOE Standards staff to help analyze results	• Unproven energy savings potential • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Lack of a cool-down phase before the load comes to rest could pose a safety hazard
Clothes Dryer: Microwave (electric only)	Assess various methods for alleviating major safety concerns, and develop a working prototype for laboratory testing.		• Investigate feasibility of eliminating major safety concerns • Refine previous prototype models to address safety concerns • Demonstrate testing under laboratory conditions	• BTP: provide funding, manage R&D program • National Laboratory: design and build prototype system, perform pilot testing • Manufacturers: collaborate with DOE to leverage prior design and testing experience	 **Duration: 2-3 years** • Funding for research staff • Materials & supplies for prototype development • Test equipment & materials required for internal testing	• Potential safety issues associated with metal zippers, coins, and other metallic objects • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Uncertain consumer acceptance of microwave dryer technology

[1] Black fill numbers indicate current TRL status; grey fill numbers indicate target TRL status after achieving the overall R&D objective. See Appendix B for details on the TRL system.

#: Current TRL status

#: Target TRL status after R&D activities

The following sections summarize the R&D roadmaps for each appliance type. For technologies with time-sensitive R&D tasks, the timelines are shown on a fiscal year (FY) basis beginning with FY 2012. For technologies with R&D tasks that are less sensitive to the absolute date, the R&D timelines are shown on a relative year basis, beginning at Year 0.

Refrigerator/Freezers

The technologies with the greatest potential for improving energy efficiency are those that can generate the required amount of cooling more efficiently than traditional vapor-compression systems, as well as technologies that help reduce the amount of heat transfer into the refrigerated food compartments. Figure 1 shows the finalized R&D roadmaps for refrigerator/freezer technologies. The roadmap shows the various recommended technology options identified for refrigerator/freezers, as well as estimated timelines for each task.

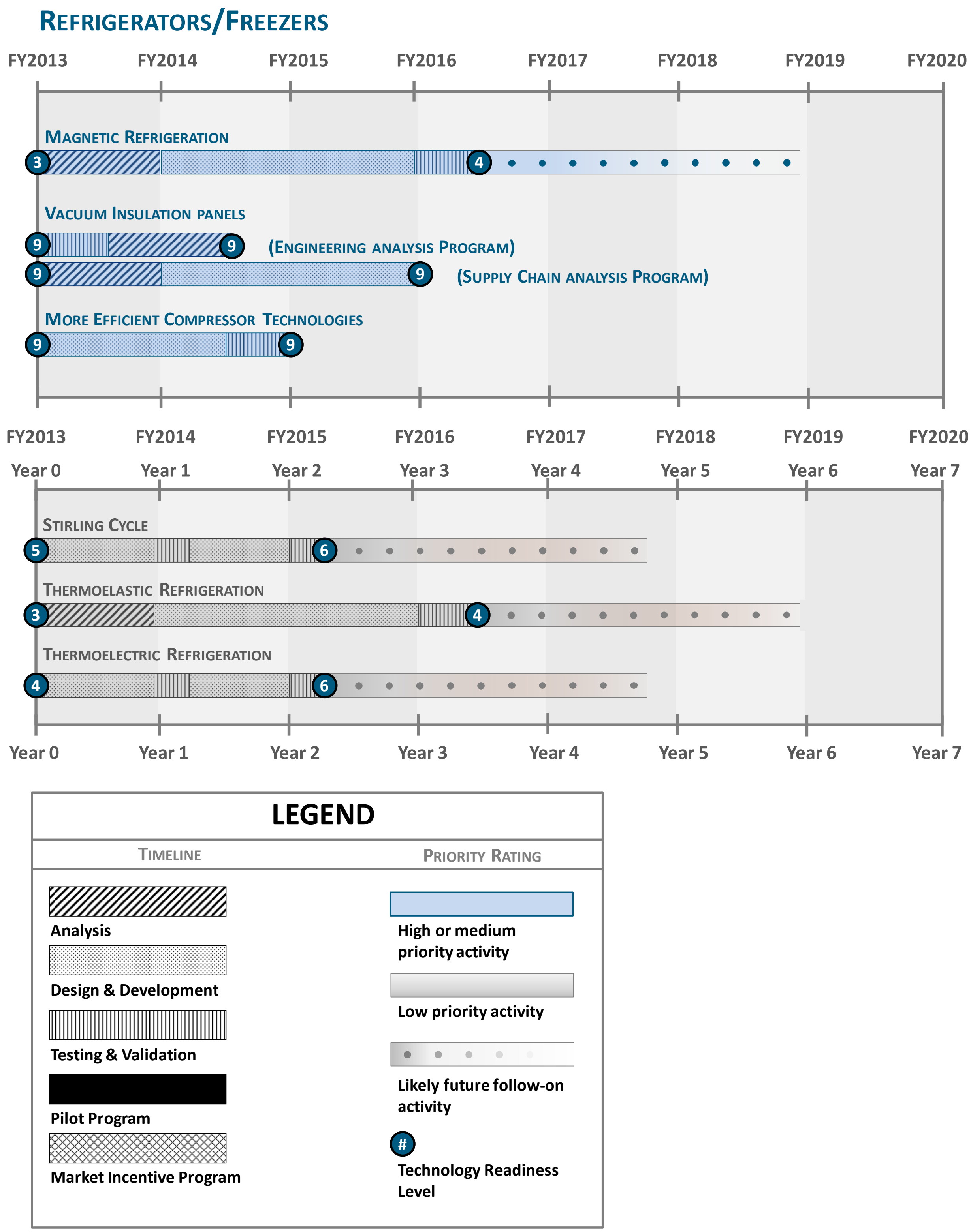


Figure 1. R&D Roadmap for Refrigerator/Freezer Technologies

Clothes Washers

The technologies with the greatest potential for improving energy efficiency are those that enable lower water temperatures and/or less overall hot water consumption. Figure 2 shows the finalized R&D roadmaps for clothes washer technologies. The roadmap shows the two recommended technology options identified for clothes dryers, as well as estimated timelines for each task.

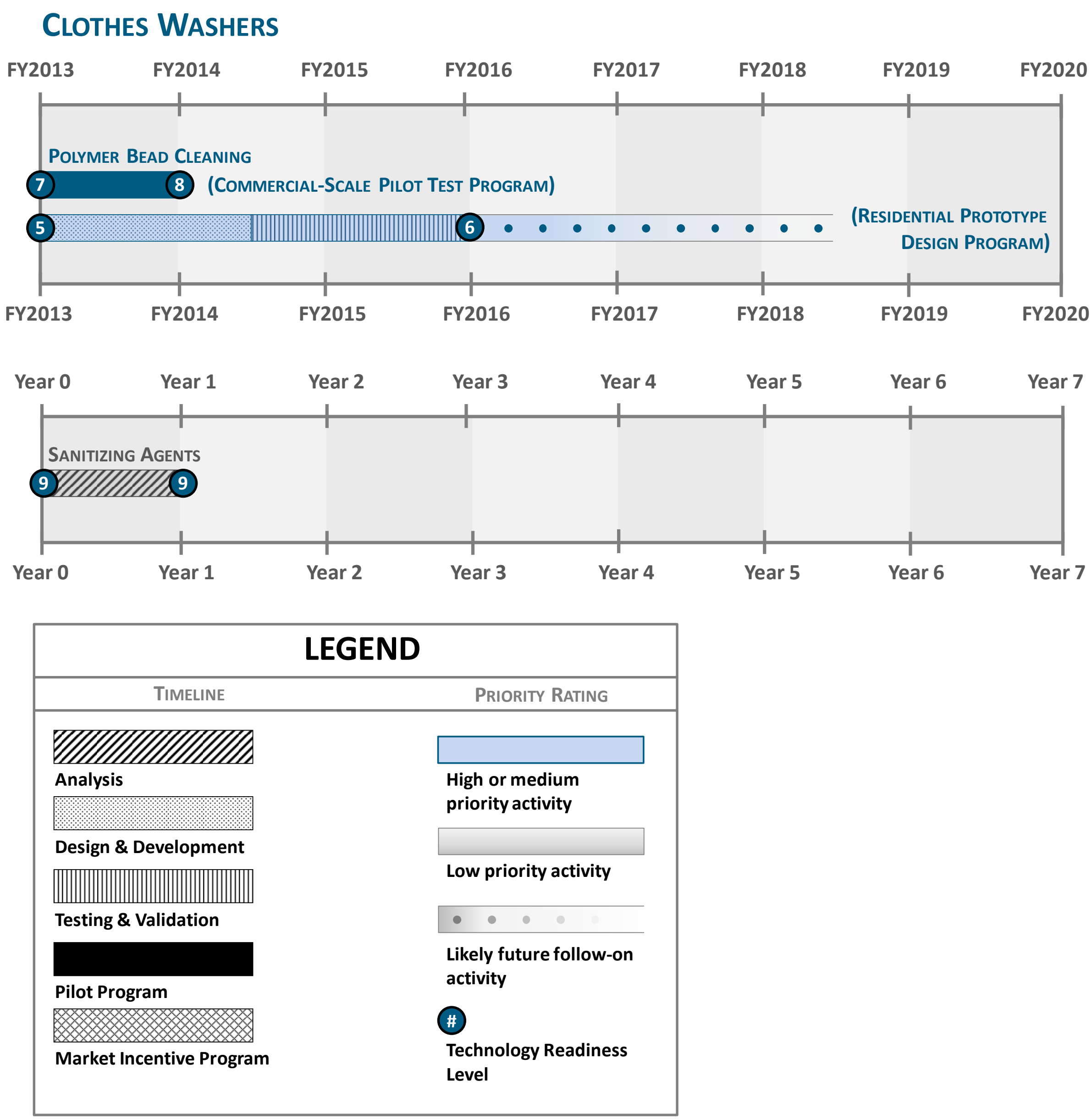


Figure 2. R&D Roadmap for Clothes Washer Technologies

Clothes Dryers

The technologies with the greatest potential for improving energy efficiency are those that provide more efficient methods for creating heat as well as technologies that help reduce the amount of wasted heat. Figure 3 shows the finalized R&D roadmaps for clothes dryer technologies. The roadmap shows the various recommended technology options identified for clothes dryers, as well as estimated timelines for each task.

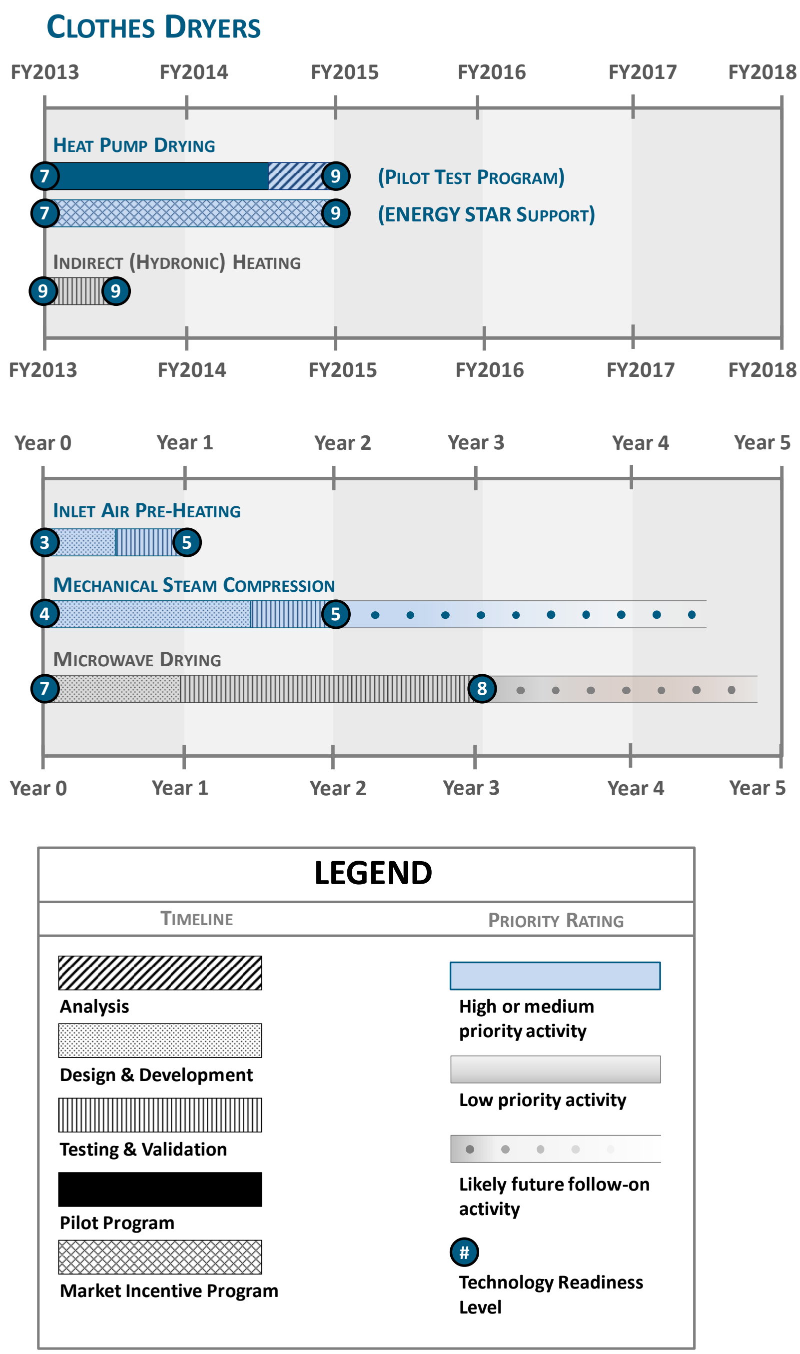


Figure 3. R&D Roadmap for Clothes Dryer Technologies

Cooking Equipment

The technologies with the greatest potential for improving energy efficiency are those that use more efficient means for generating heat, as well as technologies that help improve heat transfer to the cooking vessel or directly to the food. Figure 4 shows the finalized R&D roadmaps for cooking technologies. The roadmap shows the various recommended technology options identified for cooking equipment, as well as estimated timelines for each task.

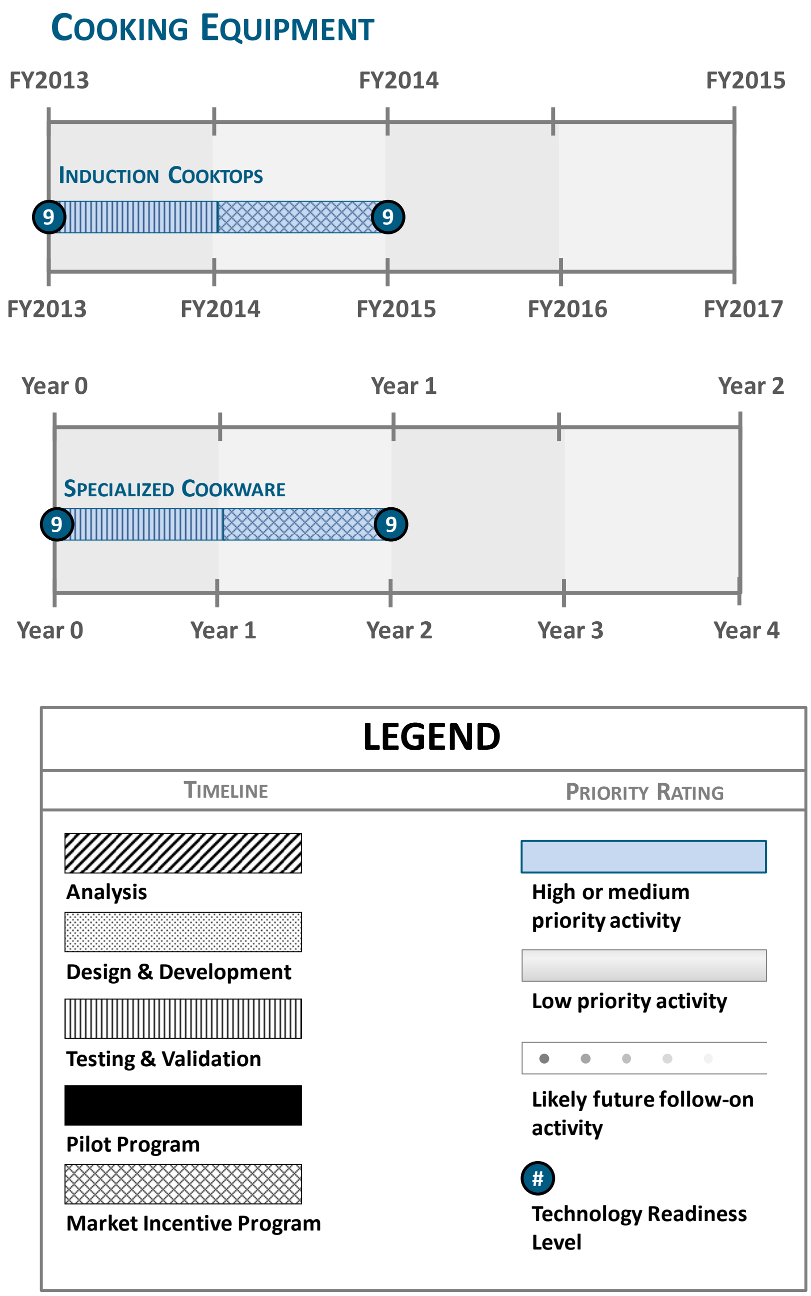


Figure 4. R&D Roadmap for Cooking Equipment Technologies

Cross-Cutting Appliance Technologies

Cross-cutting technologies are those technologies that offer the potential for integrated energy and water recovery and/or transfer between appliances. For example, waste heat from a refrigerator could be used to preheat the incoming water for the dishwasher; similarly, latent heat from a clothes dryer exhaust vent could be used to preheat incoming water for the clothes washer. Figure 5 shows the finalized R&D roadmap for cross-cutting appliance technologies. The roadmap shows the estimated timelines for each R&D task.

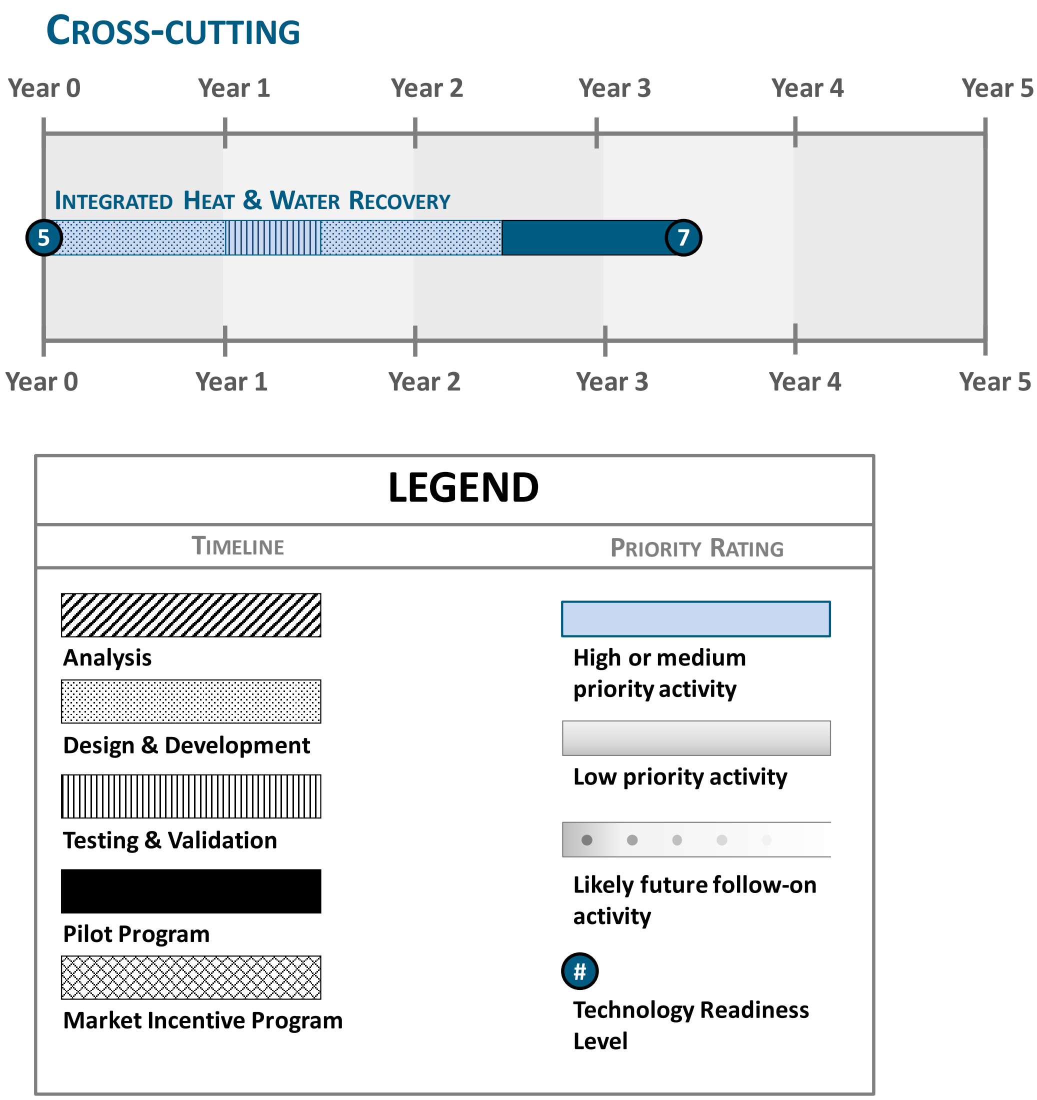


Figure 5. R&D Roadmap for Cross-Cutting Technologies

1 Introduction

1.1 Background

The Building Technologies Program (BTP) within the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy is responsible for developing and deploying technologies that can substantially reduce energy consumption in residential and commercial buildings. Activities in recent years have included technical pathways to achieve net zero energy homes. Most recently, particular attention has been focused on energy savings potential in existing buildings, because the impacts are more immediate due to the slow turnover of the residential building stock. Because appliances are less expensive and are replaced more regularly than heating, ventilation, and air-conditioning (HVAC) systems or building envelope components, they present an opportunity for near-term energy savings.

Residential appliances such as refrigerator/freezers, dishwashers, laundry equipment, and cooking equipment account for over 12 percent of U.S. residential sector primary energy consumption. The appliance sector has seen substantial innovation in recent years; however, energy efficiency measures, while significant, have generally involved incremental improvements to meet new DOE efficiency standards. Little research has focused on radical innovations that might dramatically reduce energy consumption. By leveraging resources, the appliance industry may be able to work cooperatively with the DOE to develop and commercialize products and technologies that could make significant improvements feasible. In order to guide such activities and ensure the best possible outcomes, a research & development (R&D) roadmap is necessary.

1.2 Objective of This Roadmap

The objective of this roadmap is to advance DOE's goal of reducing the energy consumption of residential appliances by accelerating the commercialization of high-efficiency appliance technologies, while maintaining the competitiveness of American industry.

This roadmap targets high-priority R&D, demonstration, and commercialization activities that, if pursued by DOE and its partners, could significantly reduce residential appliance energy consumption. The roadmap prioritizes those technologies with the highest energy savings potential and greatest likelihood of being embraced by both manufacturers and consumers. The schedule of proposed activities ranges from near-term activities in the 6-month to 2-year time frame, to longer-term research initiatives that may span 3-5 years.

This R&D roadmap focuses on the following residential appliances: **refrigerator/freezers**, **clothes washers**, **clothes dryers**, **cooking equipment,** and **cross-cutting** appliance technologies. This roadmap does not cover heating, ventilation, and air-conditioning (HVAC) systems, water heaters, or building envelope components.

1.3 Roadmap Development Process

This R&D roadmap was developed by Navigant Consulting, Inc., in cooperation with Oak Ridge National Laboratory (ORNL). The following provides a summary of each task completed during the process of developing this roadmap:

1.3.1 Task 1: Identify and Evaluate Potential Technical Innovations

Objectives
In Task 1, we determined which appliances should be included in our assessment and identified possible technical innovations that could be applied to improve energy efficiency. We then completed a preliminary feasibility assessment of each identified technology and evaluated performance and approximate cost relative to today's baseline equipment.

Approach
Through literature searches and discussions with industry experts, we identified technology options for each appliance. Next, we applied a preliminary screening to eliminate technologies that offered only incremental improvements in energy efficiency. The remaining technologies included only those that could provide significant improvements in appliance energy efficiency. We then developed a set of scoring criteria to further evaluate the remaining technology options. The criteria included technical energy savings potential, fit with DOE/BT mission, cost and complexity, and non-energy benefits. We assigned a weighting factor to each criterion to reflect its relative importance. Using a 1–5 scale, we rated each technology option against each criterion and calculated an overall rating score. We used the quantitative scoring and other qualitative considerations to assess the feasibility of each technology option and to prioritize each option for further in-depth analysis.

Conclusions
The analysis indicated that the appliances with the best combination of high energy savings potential and strong fit with the DOE/BT mission are **refrigerator/freezers**, **clothes washers**, **clothes dryers,** and **cross-cutting** appliance technologies.

The analysis indicated that **cooktops**, **ovens**, **microwaves**, and **dishwashers** had relatively little national energy savings potential, although some of the technology options could be a strong fit with the DOE/BT mission. In addition, the annual energy cost to the consumer is so low for these appliances that even a moderate increase in appliance cost would likely have an unacceptably long payback period.

1.3.2 Task 2: Define Research Needs

Objectives
In Task 2, we defined the research and development needs to be addressed in order to accelerate commercialization of each of the down-selected technology options identified in Task 1. We also prioritized these research and development needs.

Approach
To help facilitate planning, we first prioritized the technology options into tiers using the scoring results from Task 1. Next, we reviewed additional literature and held additional discussions with industry experts to determine the current state of each technology option. We then categorized

the current state of each technology option using the Technology Readiness Level (TRL) system. Based on the current TRL status, we then determined the research and development needs of each technology option that, if supported, would help accelerate its commercialization. We also determined the key risks associated with each technology option.

Conclusions
The results from Task 2 reaffirmed the preliminary conclusions from Task 1; specifically, that the appliance categories with the highest-priority, highest energy savings potential, and strongest fit with the DOE/BT mission are **refrigerator/freezers, clothes washers**, **clothes dryers,** and **cross-cutting** appliance technologies.

The analysis confirmed that **cooktops**, **ovens**, and **dishwashers** are lower priority with relatively little national energy savings potential, although some of the technology options have a moderately strong or very strong fit with the DOE/BT mission.

1.3.3 Task 3: Create Preliminary Research & Development Roadmap

Objectives
In Task 3, we created a preliminary R&D roadmap for each appliance technology with goals and timetables, priorities, identification of possible performers and their respective roles, and a relative comparison of the resources required to achieve the goals.

Approach
Using the R&D needs identified in Task 2, we first defined the overall R&D objective for each technology option. Next, we determined the R&D tasks that would be required to achieve each objective. We then identified possible performers and their respective R&D roles for each technology option. We also estimated the approximate duration and resources required to achieve the R&D objectives for each technology option. Finally, we created preliminary research and development roadmaps for each appliance technology and developed work breakdown structures for the highest-priority technology options.

Conclusions
The R&D roadmaps developed during Task 3 provided a foundation for discussions with key stakeholders during Task 4.

1.3.4 Task 4: Obtain Stakeholder Feedback

Objectives
In Task 4, we obtained feedback on the preliminary R&D roadmaps from key stakeholders such as manufacturers, national laboratories, and industry experts.

Approach
We conducted a series of one-on-one discussions with key stakeholders to review the preliminary roadmaps for each appliance technology. We received feedback from manufacturers representing over 85 percent of the core major appliances[1] market. Due to the sensitive nature of R&D programs, private discussions with manufacturers were conducted under non-disclosure agreements. In addition, we interviewed home appliance industry experts and lead researchers who are involved with some of the high-priority technology options identified in the roadmaps.

[1] Core major appliances include refrigerator/freezers, clothes washers, clothes dryers, dishwashers, and ranges.

Conclusions

Stakeholders generally expressed the strongest interest in **refrigerator/freezer** and **clothes dryer** technologies, and moderate interest in **clothes washer** technologies. Stakeholders generally expressed little interest in **dishwasher** and **cooking equipment** technologies due to the limited energy savings potential and the unlikelihood of consumer acceptance of those particular technologies.

1.4 Final Report Organization

This final report is organized as follows:

- Section 2 presents the finalized R&D roadmaps for each appliance type. This section provides a brief summary description of each appliance technology, a description of the R&D needs, and a discussion of the proposed R&D activities.
- Section 3 provides a brief summary and conclusions from this roadmap effort.
- Appendix A provides the key summary tables from previous task reports.
- Appendix B provides a description of the Technology Readiness Level (TRL) system referenced throughout the report.
- Appendix C provides detailed technical descriptions of each technology option, including current development status and links to relevant source information.

2 Research and Development Roadmaps

The following sections present the research and development roadmaps for each appliance type. Each roadmap highlights the activities that, with DOE support, would accelerate the commercialization of each technology. DOE support may involve any combination of financial, technical, or programmatic resources. Each section contains a table summarizing the recommended R&D activities for each technology option. Specifically, for each technology, the table provides the following:

- Summary of overall R&D objectives
- Estimate of development status after achieving R&D objectives
- Summary of specific R&D tasks
- Identification of possible performers and their respective roles
- Estimate of duration of each R&D activity and types of resources required
- Summary of key risks associated with each technology option

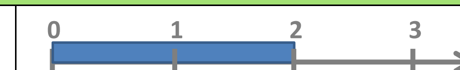
The roadmaps include two categories of technologies: The first category includes technologies with time-sensitive R&D tasks. For these technologies, the timelines are shown on a fiscal year (FY) basis beginning with FY 2012. The second category includes technologies with R&D tasks that are less time-sensitive (i.e., less sensitive to the absolute date when the activities would begin). For these technologies, the R&D timelines are shown on a relative year basis, beginning with Year 0.

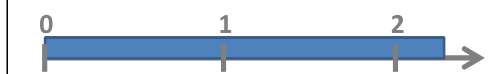
2.1 Refrigerator/Freezers

The primary driver of energy consumption in refrigerator/freezers is the energy required to power the vapor-compression cycle, which uses a compressor and multiple heat exchangers to transfer heat from inside the food compartments to outside the refrigerator/freezer. Accordingly, the technologies with the greatest potential for improving energy efficiency are those that can generate the required amount of cooling more efficiently than traditional vapor-compression systems, as well as technologies that greatly reduce the amount of heat transfer between the walls of the refrigerated food compartments.

Table 2 summarizes the recommended R&D objectives and tasks identified for the highest-potential refrigerator/freezer technologies, possible performers and their respective roles, and estimated duration of each R&D activity.

Table 2. Refrigerator/Freezers – Summary of Technology Options

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Tier 1 (Higher Priority)						
Refrigerator/ Freezer: Magnetic refrigeration	Demonstrate the required cooling capacity of residential refrigerators.		• Further understand magnetic refrigeration cooling principles • Optimize individual components of the system • Test optimized prototype to demonstrate required cooling capacity	• BTP: provide funding, manage test program, develop test protocols • Ames Laboratory: expand on previous research and prototype	 **Duration: 3-5 years** • Materials & supplies for component development and system integration • Research and development staff	• Ability to scale down components to fit within residential-size cabinet • Fully-functional prototype will require years of additional R&D • Future availability of exotic magnetic materials
Refrigerator/ Freezer: Vacuum insulation panels	Understand the causes of inconsistent results among multiple manufacturers' products and to reduce overall costs.		• Perform characterization tests on products known to have inconsistent performance • Reverse-engineer products to determine root causes for performance inconsistencies • Analyze the supply chain of all materials and processes used in the manufacture of VIPs • Determine major cost drivers and identify strategies for reducing costs	• BTP: provide funding, manage test program, perform supply chain analysis • Third-party laboratory: perform energy tests using DOE test procedure, perform reverse-engineering analysis of VIPs • Manufacturers: Partnership with DOE/BT research efforts	 **Duration: 2-3 years** • Refrigerator/freezer products with VIPs • VIP samples from multiple manufacturers • Third-party laboratory for testing • ORNL research staff to test and analyze results	• Requires more costly manufacturing methods • Low degree of certainty on longevity of VIPs • Uncertain consumer willingness to pay higher upfront cost
Tier 2 (Medium Priority)						
Refrigerator/ Freezer: Improved linear compressor	Improve energy efficiency of linear compressors through optimization of design, material selection, and lubricants.		• Reverse engineer commercially available linear compressors • Increase compressor efficiency through improved designs, materials, and lubricants to optimize performance • Test optimized compressor to demonstrate improved energy efficiency	• BTP: provide funding, manage test program • Third-party laboratory: perform reverse-engineering analysis • National Laboratory: design and testing	 **Duration: 2 years** • Materials to build and test improved compressors • Research staff to build, test, and analyze compressors	• May involve proprietary compressor designs
Tier 3 (Lower Priority)						
Refrigerator/ Freezer: Stirling cycle refrigeration	Determine the energy savings potential of stirling cycle refrigerator/freezers by developing and testing a working prototype.		• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• BTP: provide funding, manage test program, develop test protocols • Purdue University: provide knowledge and expertise on stirling cycle refrigeration R&D	 **Duration: 2-3 years** • Research staff to develop and test prototype • Materials required to build prototype	• Unproven energy savings potential compared to vapor-compression systems • Challenges regarding how to transfer heat away from refrigerated compartments
Refrigerator/ Freezer: Thermoelastic refrigeration	Demonstrate the cooling capacity that would be required for a residential refrigerator.		• Further understand thermoelastic refrigeration cooling principles • Optimize individual components of the system • Test optimized prototype to demonstrate required cooling capacity	• BTP: provide funding, manage test program, develop test protocols • University of Maryland: expand on previous research and prototype development	 **Duration: 3-5 years** • Materials & supplies for component development and system integration • University of Maryland research staff to test and analyze results	• Concept is proven, but low degree of certainty that the technology is feasible in a residential setting • Unproven energy savings potential • Challenges regarding how to transfer heat away from refrigerated compartments

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Refrigerator/ Freezer: Thermoelectric refrigeration	Determine the potential energy savings of a full-sized residential thermoelectric refrigerator/freezer by developing prototypes for laboratory testing.		• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• BTP: provide funding, manage test program, develop test protocols • Manufacturers: Partnership with DOE/BT research efforts • National Laboratory: design, testing, and development of prototypes	 **Duration: 2-3 years** • Small thermoelectric refrigerators to analyze • Materials to build full-sized prototype • Research staff to build, test, and analyze prototypes	• Unproven energy savings potential compared to vapor-compression refrigeration • Uncertainty regarding ability to scale up manufacturing process

[1] Black fill numbers indicate current TRL status; grey fill numbers indicate target TRL status after achieving the overall R&D objective. See Appendix B for details on the TRL system.

#: Current TRL status

#: Target TRL status after R&D activities

Figure 6 shows the finalized R&D roadmap for refrigerator/freezer technologies. The roadmap shows the various recommended technology options identified for refrigerator/freezers, as well as estimated timelines for each task. For technologies with time-sensitive R&D tasks, the timelines are shown on a fiscal year basis beginning with FY 2012. For technologies with R&D tasks that are less time-sensitive (i.e., less sensitive to the absolute date on which the activities would begin), the R&D timelines are shown on a relative year basis, beginning with Year 0.

REFRIGERATORS/FREEZERS

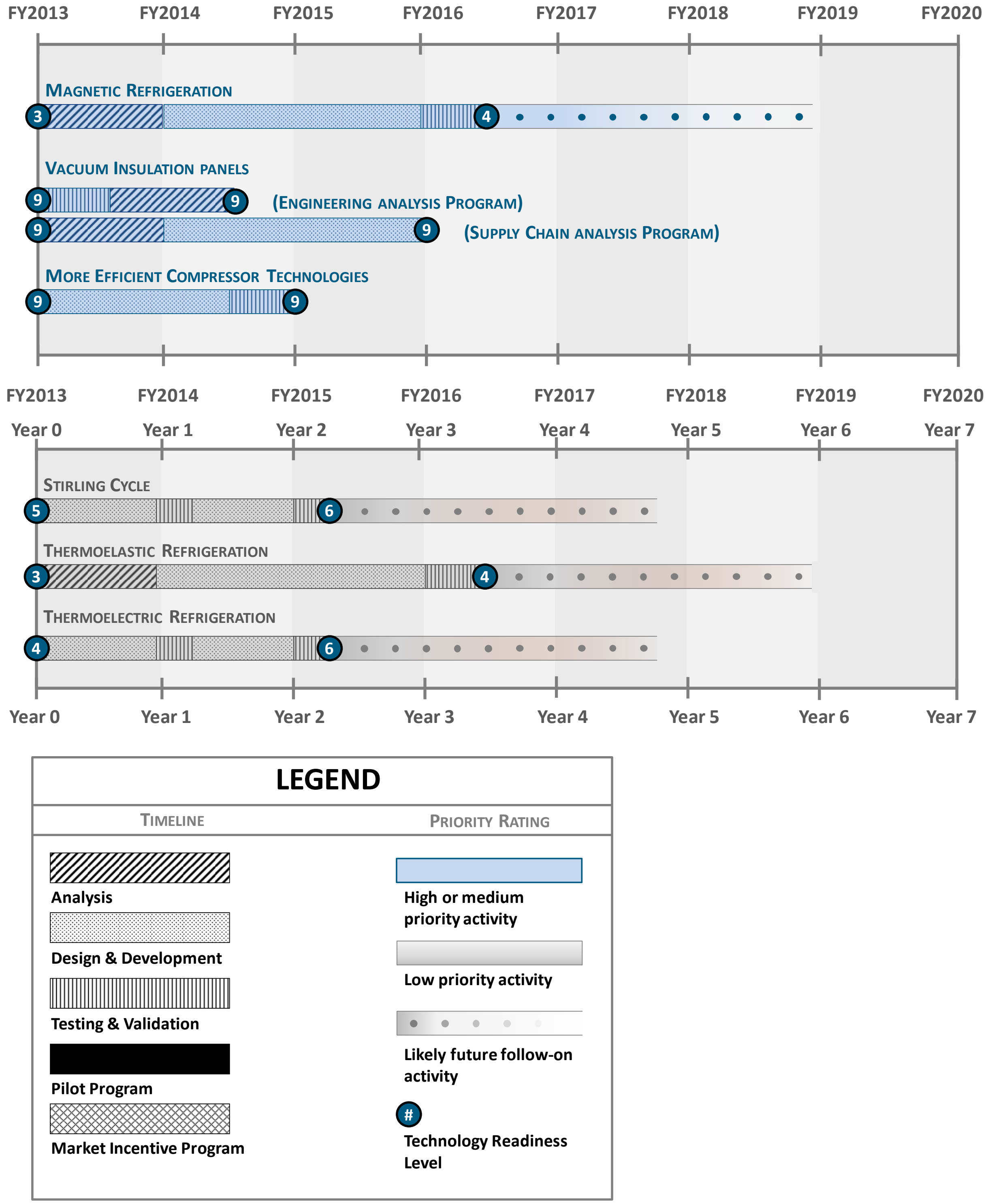


Figure 6. R&D Roadmap for Refrigerator/Freezer Technologies

The following sections provide additional details regarding our recommended R&D activities for each of these refrigerator/freezer technologies. Target work breakdown structures (WBS) are also provided for the highest-priority technologies.

2.1.1 Magnetic Refrigeration

Magnetic refrigeration is based on the magneto-caloric effect, in which changing magnetic fields are used to create a reversible change in temperature of a paramagnetic material. A working prototype has been developed at the Ames Laboratory. However, due to the size of the components and the high magnetic field required, the system is not applicable for use in residential settings. Additionally, existing prototypes do not yet demonstrate the cooling performance required for a residential refrigerator/freezer. This technology is currently at TRL 3.

The recommended R&D activities include a multi-year program to further understand the principles of magnetic cooling, optimize individual components of the system, and demonstrate the required cooling capacity of a residential refrigerator/freezer. In the long-term, magnetic refrigeration shows the potential to be a viable replacement for traditional vapor-compression systems, with greater energy efficiency. Therefore, this is a high-priority technology option that DOE should continue to support over the next several fiscal years. Many more years of additional R&D will be required to create a fully functional residential magnetic refrigerator/freezer.

The recommended program of research and component development could advance this technology to TRL 4.

Magnetic Refrigeration

- **Priority:** High
- **Current Status:** Concept of magnetic refrigeration is proven and a working prototype has been built.
- **R&D Objective:** Demonstrate the cooling capacity that would be required for a residential refrigerator.
- **Recommended R&D Activities:**
    - Further understand magnetic refrigeration cooling principles
    - Optimize individual components of the system
    - Test optimized prototype to demonstrate required cooling capacity
- **Program Duration:** 3-5 years

Figure 7 shows a target WBS for magnetic refrigeration development.

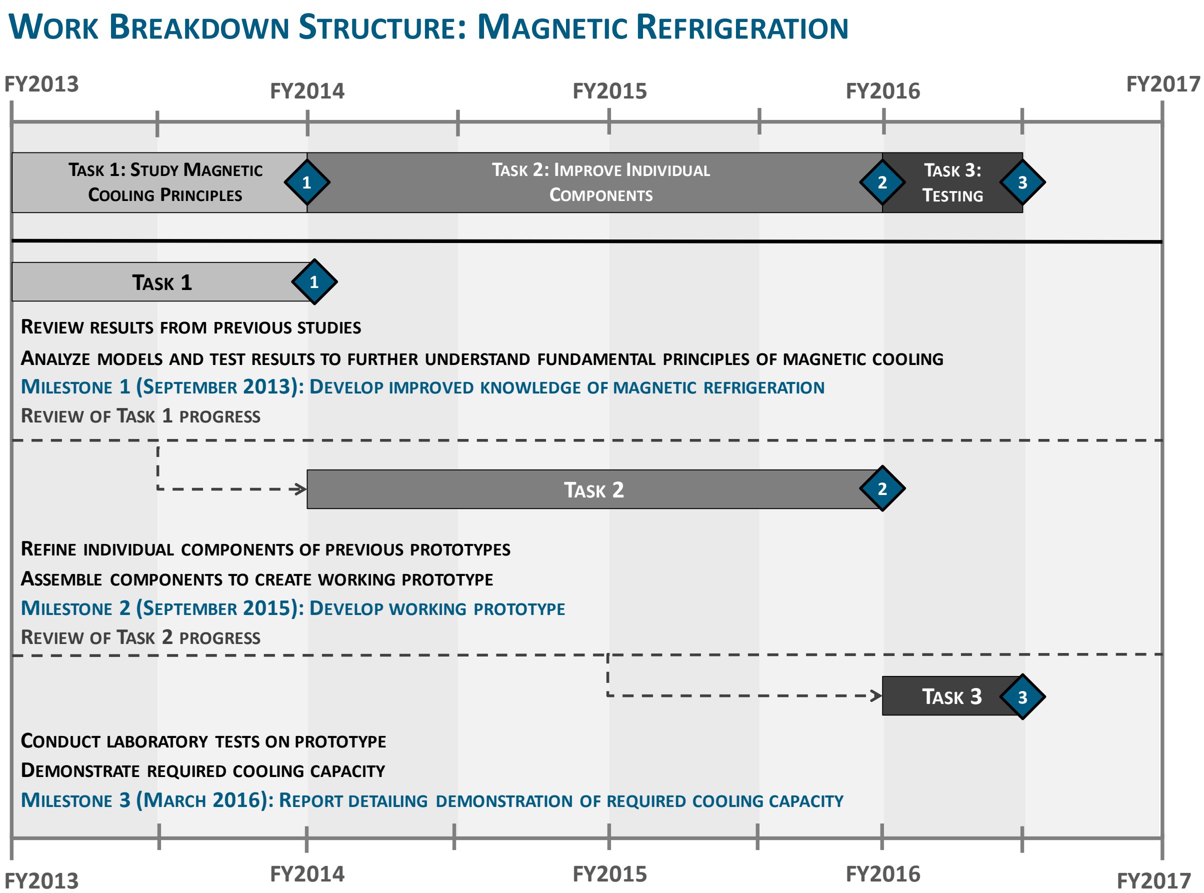


Figure 7. Work Breakdown Structure for Magnetic Refrigeration R&D Activities

2.1.2 Vacuum Insulation Panels

Vacuum-insulated panel (VIP) technology is based on the reduction in conductivity that occurs in a low vacuum. VIPs used in refrigeration products consist of a sealed package with a fill material that provides support to prevent the panel from collapsing and interferes with the molecular mean free path, as the intermolecular spacing increases at lower vacuum levels. VIPs are currently commercially available, but their performance is inconsistent among manufacturers. In addition, the cost is substantial compared to traditional insulation techniques. Currently, this technology is at TRL 9.

The first recommended R&D program includes a testing and reverse-engineering program to identify the root causes of performance inconsistencies in VIPs. The second recommended program is an analysis of the manufacturing supply chain for VIPs to identify the primary drivers of cost and to implement strategies for cost reduction.

By improving reliability and lowering the cost, these recommended programs would keep VIP technology at TRL 9 and would significantly increase the prevalence of this technology option in the residential refrigerator/freezer market. Because VIPs have the potential to significantly improve energy efficiency in the short-term, this is a high-priority technology option that DOE should continue to support over the next few fiscal years.

Vacuum Insulation Panels

- **Priority:** High
- **Current Status:** VIPs are commercially available from some manufacturers.
- **R&D Objective:** Understand the causes of inconsistent results among manufacturers' products and reduce overall costs.
- **Recommended R&D Activities:**
    - Perform characterization tests on products known to have inconsistent performance
    - Determine root causes for performance inconsistencies
    - Analyze the supply chain of all materials and processes used in the manufacture of VIPs
    - Determine major cost drivers and identify strategies for reducing costs
- **Program Duration:** 2-3 years

Figure 8 shows a target WBS for VIP research activities.

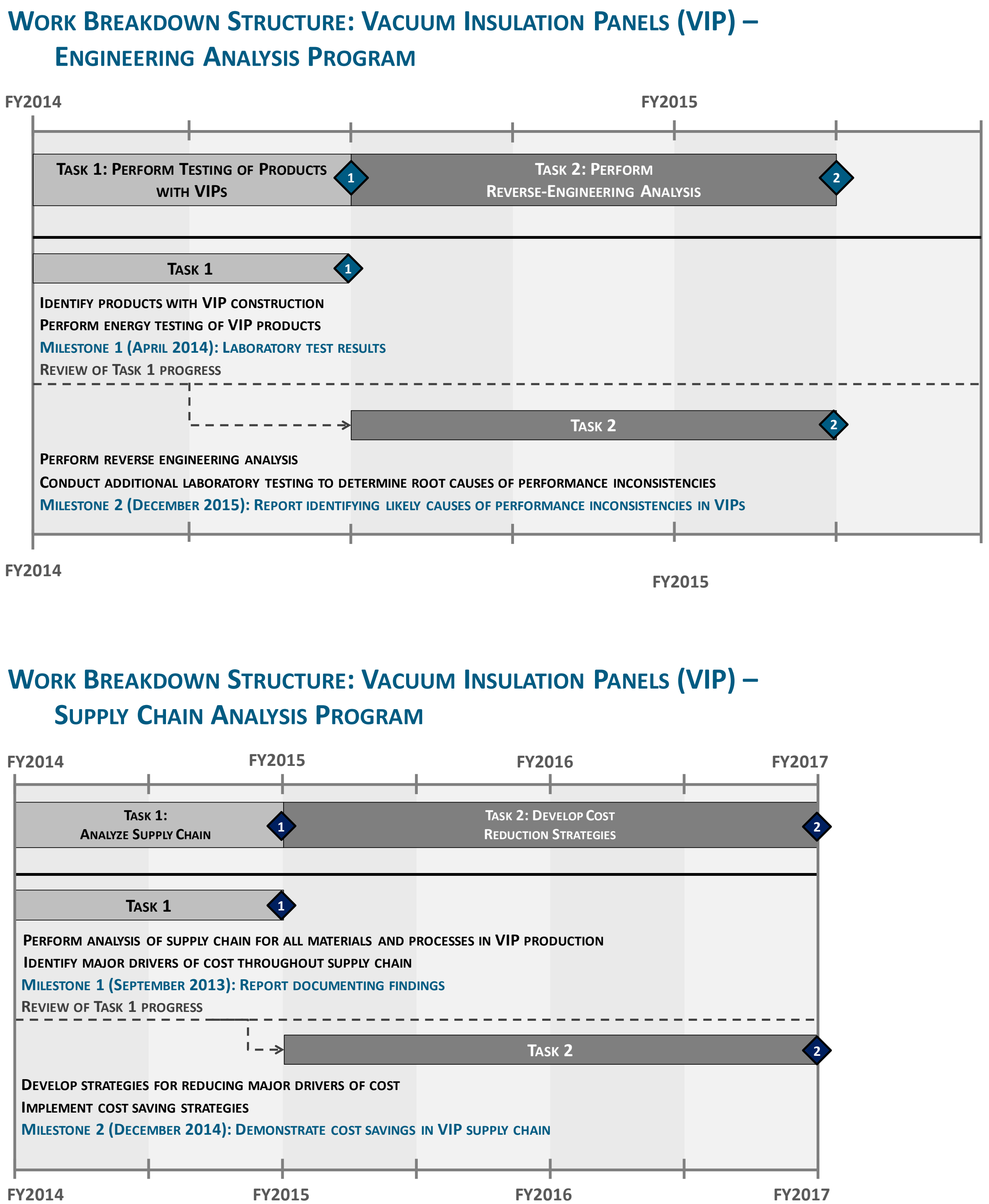


Figure 8. Work Breakdown Structures for Vacuum Insulation Panel R&D Activities

2.1.3 Improved Linear Compressors

Linear compressors employ a different design than either reciprocating or rotary compressors and are reportedly more efficient than both. Linear compressors use a linear rather than rotary motor, thus eliminating the crankshaft and linkage that converts the rotary motion to the linear motion of the piston of a reciprocating compressor. High efficiency linear compressors exist on the market, but could benefit from improved design, materials, and lubricants. Currently, this technology is at TRL 9.

In the short-term, the improvement of compressor technologies can increase the energy efficiency of traditional vapor-compression systems. The recommended R&D program includes developing and testing an optimized compressor to demonstrate improved energy efficiency over currently available products.

These R&D activities would help keep linear compressor technology at TRL 9 and could significantly increase the prevalence of this technology option in the refrigerator/freezer market.

Improved Linear Compressors

- **Priority:** Medium
- **Current Status:** More efficient compressors are commercially available from some manufacturers.
- **R&D Objective:** Improve energy efficiency of linear compressors through optimization of design, material selection, and lubricants.
- **Potential R&D Activities:**
    - Reverse engineer commercially available linear compressors
    - Increase compressor efficiency through improved designs, materials, and lubricants to optimize performance
    - Test optimized compressor to demonstrate improved energy efficiency
- **Program Duration:** 2 years

2.1.4 Stirling Cycle Refrigeration

A Stirling cycle machine is a device that operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperature levels. The flow of the working fluid is controlled by volume changes, so that there is a net conversion of heat to work, or vice versa. A Stirling refrigeration cycle compresses and expands an inert gas in a single cylinder. Heat is rejected at one end of the cylinder and absorbed at the opposite end. In the absence of all thermodynamic losses, the efficiency could be higher than for vapor compression systems. Various technical difficulties have so far limited the use of Stirling cycle cooling to small prototype residential refrigerators. Currently, this technology is at TRL 5. Stirling cycle technology is well known, but has not been shown to be more efficient than vapor compression. Thus, manufacturers have not pursued this technology. The recommended R&D program includes developing and testing a full-sized residential prototype.

This recommended R&D program could advance Stirling cycle refrigeration to TRL 6.

Stirling Cycle Refrigeration

- **Priority:** Low
- **Current Status:** Working prototypes have been developed, but limited to small residential refrigerators.
- **R&D Objective:** Determine the energy savings potential of a Stirling cycle refrigerator by developing and testing a working prototype.
- **Recommended R&D Activities:**
  - Create a full-sized residential prototype
  - Determine energy performance
  - Modify/optimize internal components based on preliminary testing
  - Conduct further testing
- **Program Duration:** 2-3 years

2.1.5 Thermoelastic Refrigeration

Thermoelastic cooling is based on a thermoelastic shape memory alloy that releases heat when compressed and returns to its original shape when heated. Researchers are developing a 0.01-ton prototype with the goal of establishing the commercial viability of thermoelastic cooling. Currently, this technology is at TRL 3.

The recommended R&D program includes refining individual components to improve the cooling capacity. Many years of research will be required to create a full-size residential refrigerator/freezer using thermoelastic cooling technology.

These R&D activities could advance thermoelastic refrigeration technology to TRL 4.

Thermoelastic Refrigeration

- **Priority:** Low
- **Current Status:** Concept has been proven, and a prototype is being developed.
- **R&D Objective:** Demonstrate the cooling capacity required for a residential refrigerator/freezer.
- **Recommended R&D Activities:**
  - Further understand thermoelastic refrigeration cooling principles
  - Optimize individual components of the system
  - Test optimized prototype to demonstrate required cooling capacity
- **Program Duration:** 3-5 years

2.1.6 Thermoelectric Refrigeration

Thermoelectric cooling occurs when a current is passed across the junction of two dissimilar metals. One side of the device becomes hot and the other becomes cold. Several compact refrigerators and wine coolers using thermoelectric cooling are currently available on the market, including several models offered by Avanti Products. However, their efficiency is lower than traditional vapor-compression models, and the technology is not yet suitable for standard-size residential refrigerator-freezers. Therefore, for standard-size refrigerator/freezers, we consider this technology to be at TRL 4.

The recommended R&D program includes development of a full-sized prototype, energy performance testing, and additional design and development based on preliminary test results.

This R&D program could advance this technology to TRL 6 for full-size residential refrigerator/freezers.

Thermoelectric Refrigeration

- **Priority:** Low
- **Current Status:** Small thermoelectric refrigerators are commercially available from some manufacturers.
- **R&D Objective:** Determine the energy savings potential (if any) of a full-sized residential thermoelectric refrigerator/freezer by developing prototypes for laboratory testing.
- **Recommended R&D Activities:**
    - Create a full-sized residential prototype
    - Determine energy performance
    - Modify/optimize internal components based on preliminary testing
    - Conduct further testing
- **Program Duration:** 2-3 years

2.2 Clothes Washers

The primary driver of energy consumption in residential clothes washers is the energy required to heat the hot water. The machine electrical energy represents less than one quarter of total energy consumption. Accordingly, the technologies with the greatest potential for improving energy efficiency are those that enable lower water temperatures and/or less overall hot water consumption.

Table 3 summarizes the recommended R&D objectives and tasks identified for the highest-potential clothes washer technologies, possible performers and their respective roles, and estimated duration of each R&D activity.

Table 3. Clothes Washers – Summary of Technology Options

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Tier 1 (Higher Priority)						
(none)						
Tier 2 (Medium Priority)						
Clothes Washer: Polymer bead cleaning	Demonstrate technology viability in commercial-scale laundry facilities; support the development of a prototype for residential use, and assess any environmental or safety hazards.		• Support pilot testing program of commercial-scale washers at on-premise and off-premise laundry facilities • Support ongoing development of a residential prototype that would be relevant in the U.S. market • Demonstrate residential prototype functionality under laboratory conditions • Assess any environmental risks or safety hazards associated with polymer beads in a residential setting.	• Xeros, Ltd: manufacturer of pilot test units and prototypes, cooperation with DOE project • BTP: provide funding, coordinate pilot test program, manage R&D of residential prototypes • National Laboratory: cooperative R&D agreement with manufacturer; funding & support for development of residential prototype • Large-scale gas utility: coordinate pilot test program of commercial-scale units	**Duration: 3-5 years** • BTP project staff to manage test program • National Laboratory staff for prototype development and testing • Funding and program support for pilot testing of commercial-scale units	• Suitability of technology for residential laundry not yet demonstrated • Cleaning ability of technology not yet proven to AHAM standards • Uncertain consumer acceptance of new plastic particle technology • Potential environmental and safety concerns associated with polymer beads
Tier 3 (Lower Priority)						
Clothes Washer: Sanitizing agents	Assess environmental and health risks of certain sanitizing agents that would enable lower-temperature wash cycles.		• Assess environmental risks associated with wastewater discharge of sanitizing agents • Assess human health risks associated with certain sanitizing agents	• BTP: provide funding, coordination of environmental and health assessments • EPA: coordination and review of environmental and health assessments	**Duration: 1 year** • BTP project staff to manage program • Funding for environmental and health assessments	• Certain sanitizing agents may pose environmental or human health risks • Perceived risks may limit consumer acceptance • Perceived risks and potential liability concerns may limit manufacturer interest

[1] Black fill numbers indicate current TRL status; grey fill numbers indicate target TRL status after achieving the overall R&D objective. See Appendix B for details on the TRL system.

#: Current TRL status

#: Target TRL status after R&D activities

Figure 9 shows the finalized R&D roadmaps for clothes washer technologies. The roadmap shows the two recommended technology options identified for clothes dryers, as well as estimated timelines for each task. For technologies with time-sensitive R&D tasks, the timelines are shown on a fiscal year (FY) basis beginning with FY 2012. For technologies with R&D tasks that are less sensitive to the absolute date, the R&D timelines are shown on a relative year basis, beginning at Year 0.

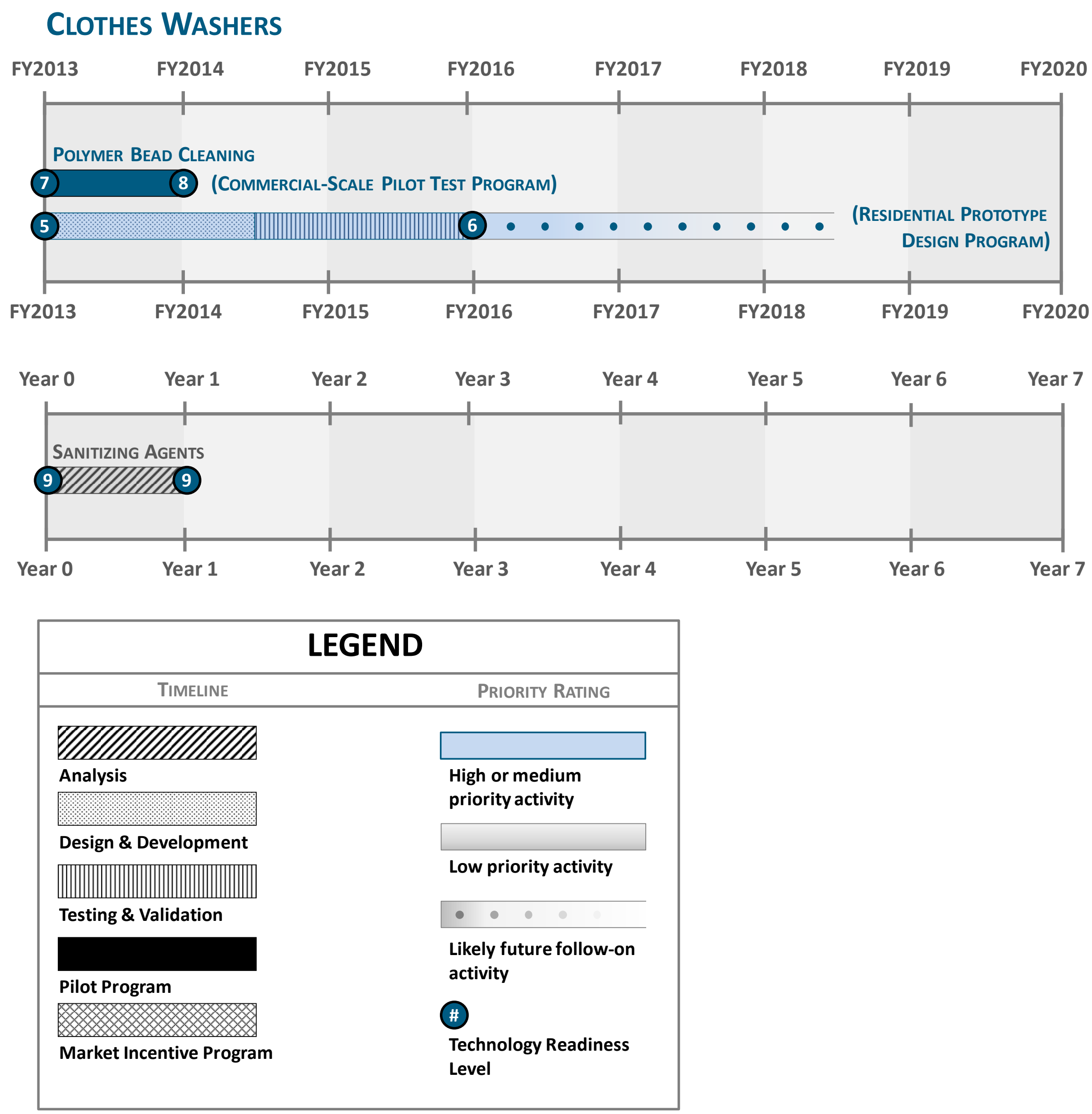


Figure 9. R&D Roadmap for Clothes Washer Technologies

The following sections provide additional details regarding our recommended R&D activities for each of these clothes washer technologies.

2.2.1 Polymer Bead Cleaning

Polymer bead cleaning technology is currently in development by Xeros Ltd. in the United Kingdom. Xeros Ltd. has successfully concluded two field trials of this technology: One field study was in a commercial-scale dry cleaning setting and the other was in an industrial laundry setting. Development is ongoing to create prototypes for residential use. For clothes washers in a residential setting, this technology is currently at TRL 5.

The recommended R&D program includes supporting future pilot testing program of commercial-scale washers at on-premise and off-premise laundry facilities in the U.S. To accelerate the development of this technology for residential application, we recommend creatine a cooperative research agreement with the manufacturer to support the ongoing development of a residential prototype that would be relevant to the U.S. laundry consumers. This R&D effort would culminate in the demonstration of a residential prototype under laboratory conditions. In addition, we recommend investigating any environmental or human health and safety risks associated with the usage and disposal of polymer beads in a residential setting.

This recommended R&D program could advance the state of this technology for residential settings to TRL 6.

Polymer Bead Cleaning

- **Priority:** Medium
- **Current Status:** Pilot tests have been performed at commercial-scale laundry facilities in the UK; development of a residential prototype is ongoing.
- **R&D Objective:** Demonstrate viability in commercial-scale laundry facilities in the U.S., support the development of a prototype for residential use, and assess any environmental or safety hazards.
- **Recommended R&D Activities:**
    - Support pilot testing program of commercial-scale washers at on-premise and off-premise laundry facilities in the U.S.
    - Support ongoing development of a residential prototype that would be relevant in the U.S. market.
    - Demonstrate residential prototype functionality under laboratory conditions.
    - Assess any environmental risks or safety hazards associated with the usage and disposal of polymer beads in a residential setting.
- **Program Duration:** 3-5 years

2.2.2 Sanitizing Agents

Certain sanitizing agents, such as chemical or ionic compounds, can be added to the incoming cold wash water to reduce the need for hot water washing. A clothes washer using such sanitizing agents could offer cooler wash cycles that provide sanitization of the clothing; such wash cycles typically require hot water temperatures up to 140°F.

One example of a sanitizing agent is the addition of silver ions to the cold wash water. Silver is a natural disinfectant and can provide sanitization during a cold water wash. Samsung previously introduced this technology to the market; therefore, this technology is at TRL 9. However, concerns about potential health and environmental risks arose after these clothes washers entered the market. This technology has since been withdrawn from the market.

The recommended R&D program includes assessing the environmental and human health risks associated with silver ion and other sanitizing agents that may be added to the wash water. The assessment would include an investigation of the risks associated with sanitizing agents in wastewater discharge. This recommended research program could alleviate concerns associated with various sanitizing agents and could help promote the usage of cold water wash cycles.

This recommended research program could allow this technology to remain at TRL 9 and enable cold-water sanitizing agents to be reintroduced to the market by any interested manufacturer.

Sanitizing Agents

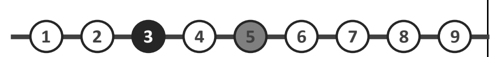
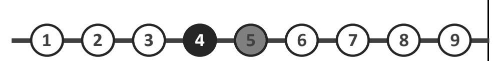
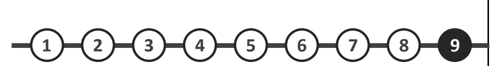
- **Priority:** Low
- **Current Status:** Previously available on the market, but since withdrawn.
- **R&D Objective:** Assess the environmental and health risks of certain sanitizing agents that would enable the usage of lower-temperature wash cycles.
- **Recommended R&D Activities:**
    - Assess environmental risks associated with wastewater discharge of sanitizing agents.
    - Assess human health risks associated with certain sanitizing agents.
- **Program Duration:** 1 year

2.3 Clothes Dryers

The primary driver of energy consumption in residential clothes dryers is the energy required to heat the air inside the drum. Accordingly, the technologies with the greatest potential for improving energy efficiency are those that provide more efficient methods for creating heat as well as technologies that help reduce the amount of wasted heat.

Table 4 summarizes the recommended R&D objectives and tasks identified for the highest-potential clothes dryer technologies, possible performers and their respective roles, and estimated duration of each R&D activity.

Table 4. Clothes Dryers – Summary of Technology Options

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Tier 1 (Higher Priority)						
Clothes Dryer: Heat pump (electric only)	Support a pilot testing program for pre-commercial heat pump clothes dryers, and support the development of ENERGYSTAR criteria for heat pump dryers.		• Support pilot testing program of pre-commercial heat pump clothes dryers • Support development of ENERGY STAR criteria for high-efficiency clothes dryers	• BTP: provide technical support to ENERGY STAR program; support and manage pilot test program • Manufacturers: develop technology to pre-commercial readiness level; collaborate with DOE on pilot test program • EPA: management of ENERGY STAR program specifications	 **Duration: 2 years** • Funding for program technical staff • Test equipment & materials required for pilot testing	• Technology not yet proven for large U.S. laundry load sizes • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost
Tier 2 (Medium Priority)						
Clothes Dryer: Inlet air preheat	Adapt currently available technology to residential clothes dryers, determine the energy-savings potential, and assess the viability of inlet air preheating technology for residential clothes dryers.		• Develop smaller-scale design that could be applicable to residential dryers • Modify residential clothes dryer cabinet with air inlets/outlets to work with heat wheel technology • Perform testing to determine energy savings potential • Investigate the feasibility of installing heat exchanger inside dryer cabinet	• BTP: provide funding, manage R&D program • National Laboratory: design and build prototype system, perform prototype testing • Rototherm Corp.: provide samples of current heat wheel technology, cooperate and/or collaborate with DOE project	 **Duration: 1 year** • Funding for research staff • Materials & supplies for developing modified components • Test equipment & materials required for internal testing	• Unproven energy savings potential • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Potential impacts on installation procedures • Potential safety issues with lint handling
Clothes Dryer: Mechanical steam compression (electric only)	Validate the technology concept by developing a complete working prototype and performing testing under laboratory conditions.		• Develop remaining components required for fully functional system • Integrate components to develop functional prototype • Characterize system performance and compare to modeled predictions	• BTP: provide funding, monitor R&D progress • Center for Energy Studies, Ecole des Mines de Paris (Mines ParisTech): expand on previous research and prototypes • U.S. university or National Laboratory: joint research activities with Center for Energy Studies	 **Duration: 2 years** • Funding for research staff • Materials & supplies for component development and system integration • Test equipment & materials required for testing	• Technology not yet proven in integrated prototype • Increased manufacturing cost compared to traditional dryers • Increased manufacturing cost compared to heat pump dryers with little or no additional benefit • Uncertain consumer willingness to pay higher upfront cost
Tier 3 (Lower Priority)						
Clothes Dryer: Indirect heating	Determine the energy savings potential of indirect (hydronic) clothes dryer technology with back-to-back dryer cycles.		• Procure several working units • Perform testing of back-to-back dryer cycles • Determine energy savings potential • Assess any risks associated with clothing cool-down period	• Hydromatics Technologies: provide units for testing • BTP: provide funding, manage test program, develop test protocols • Third-party accredited laboratory: perform energy & performance tests • DOE Standards team: provide background/insights, help evaluate test results	 **Duration: 6 months** • Procurement of units for testing • BTP project staff to manage test program • Third-party laboratory for testing • DOE Standards staff to help analyze results	• Unproven energy savings potential • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Lack of a cool-down phase before the load comes to rest could pose a safety hazard

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Clothes Dryer: Microwave (electric only)	Assess various methods for alleviating major safety concerns, and develop a working prototype for laboratory testing.		• Investigate feasibility of eliminating major safety concerns • Refine previous prototype models to address safety concerns • Demonstrate testing under laboratory conditions	• BTP: provide funding, manage R&D program • National Laboratory: design and build prototype system, perform pilot testing • Manufacturers: collaborate with DOE to leverage prior design and testing experience	 **Duration: 2-3 years** • Funding for research staff • Materials & supplies for prototype development • Test equipment & materials required for internal testing	• Potential safety issues associated with metal zippers, coins, and other metallic objects • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Uncertain consumer acceptance of microwave dryer technology

[1] Black fill numbers indicate current TRL status; grey fill numbers indicate target TRL status after achieving the overall R&D objective. See Appendix B for details on the TRL system.

#: Current TRL status

#: Target TRL status after R&D activities

Figure 10 shows the finalized R&D roadmaps for clothes dryer technologies. The roadmap shows the various recommended technology options identified for clothes dryers, as well as estimated timelines for each task. For technologies with time-sensitive R&D tasks, the timelines are shown on a fiscal year (FY) basis beginning with FY 2012. For technologies with R&D tasks that are less sensitive to the absolute date, the R&D timelines are shown on a relative year basis, beginning at Year 0.

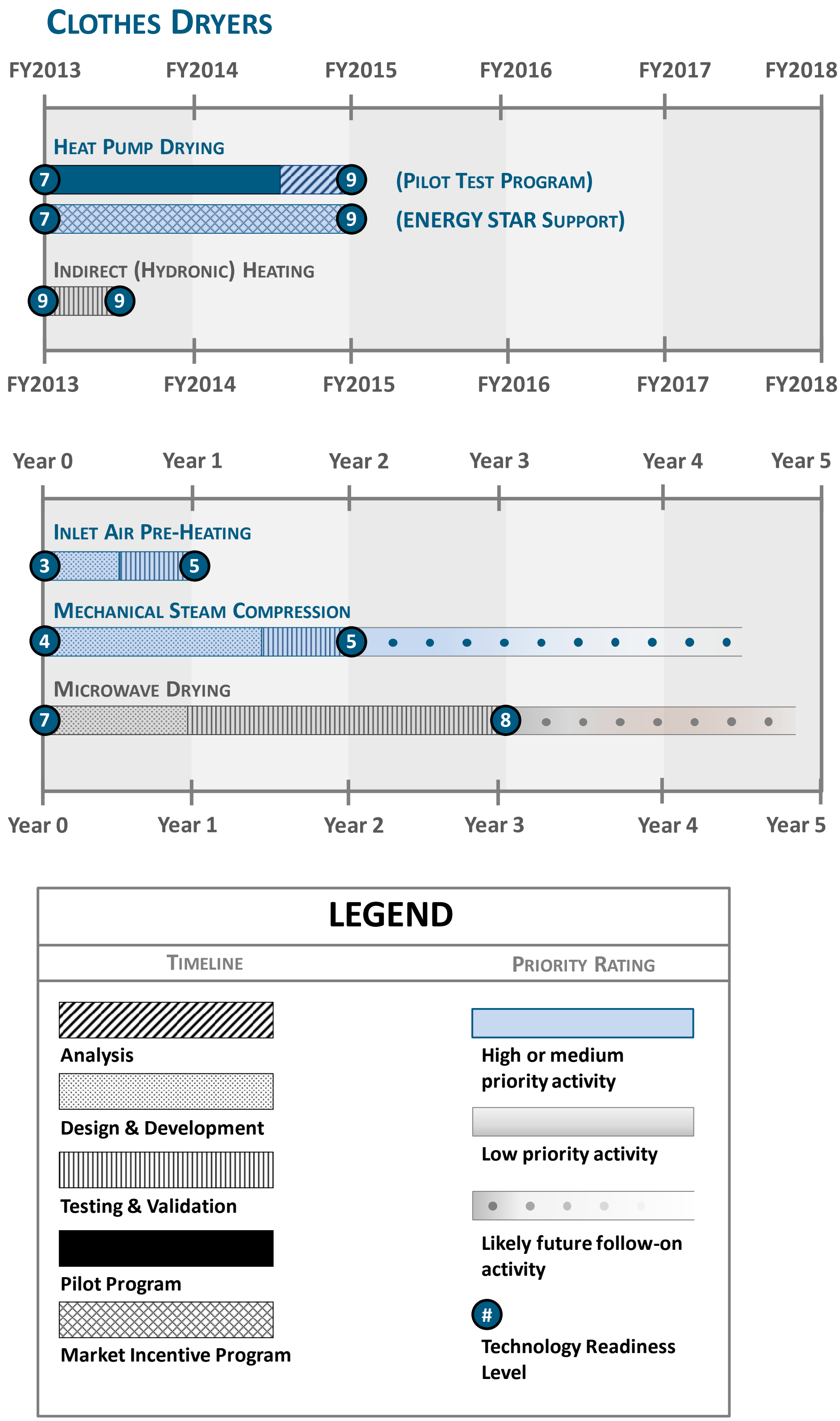


Figure 10. R&D Roadmap for Clothes Dryer Technologies

The following sections provide additional details regarding our recommended R&D activities for each of these clothes dryer technologies. A target work breakdown structure (WBS) is also provided for the pilot test program for heat pump drying, which is the highest-priority technology for clothes dryers.

2.3.1 Heat Pump Clothes Dryer

Several prototype heat pump clothes dryers have been developed previously through DOE funding and partnerships. Heat pump dryers have been on the market in Europe for several years; however, heat pump dryers are not currently unavailable in the U.S. It is widely expected that heat pump dryers will become commercially available in the U.S. in the near future. This technology is currently at TRL 7.

The recommended program involves providing program support and funding for pilot testing of pre-commercial heat pump dryer demonstration units. A pilot demonstration program would allow manufacturers to understand consumer usage habits and any address any technical hurdles that might remain before wide-scale commercial availability.

In anticipation of entry into the market, the Environmental Protection Agency (EPA) has chosen advanced clothes dryers as one of the ENERGY STAR Emerging Technology Award categories for 2012[2]. It is anticipated that heat pump technology would be one of the few clothes dryer technologies able to achieve the energy factor requirements established by ENERGY STAR. We recommend that DOE continue to provide support to ENERGY STAR clothes dryer initiatives to help accelerate the commercialization and consumer adoption of heat pump clothes dryers when they become commercially available.

These recommended testing and program activities could advance heat pump dryer technology to TRL 9.

Heat Pump Clothes Dryer

- **Priority:** High
- **Current Status:** Working prototypes have been developed; technology available in Europe but not yet available in the U.S.
- **R&D Objective:** Support a pilot testing program for pre-commercial heat pump clothes dryers, and support the development of ENERGYSTAR criteria for heat pump dryers.
- **Recommended R&D Activities:**
    - Support pre-commercial pilot testing program with manufacturer collaboration.
    - Support EPA/DOE development of ENERGY STAR criteria for clothes dryers.
- **Program Duration:** 2 years

[2] More information on the ENERGY STAR 2012 Emerging Technology Award for Advanced Clothes Dryers can be found at the program's website: http://www.energystar.gov/index.cfm?c=pt_awards.pt_clothes_dryers

Figure 11 shows a target WBS for the pilot test program for heat pump clothes dryer development.

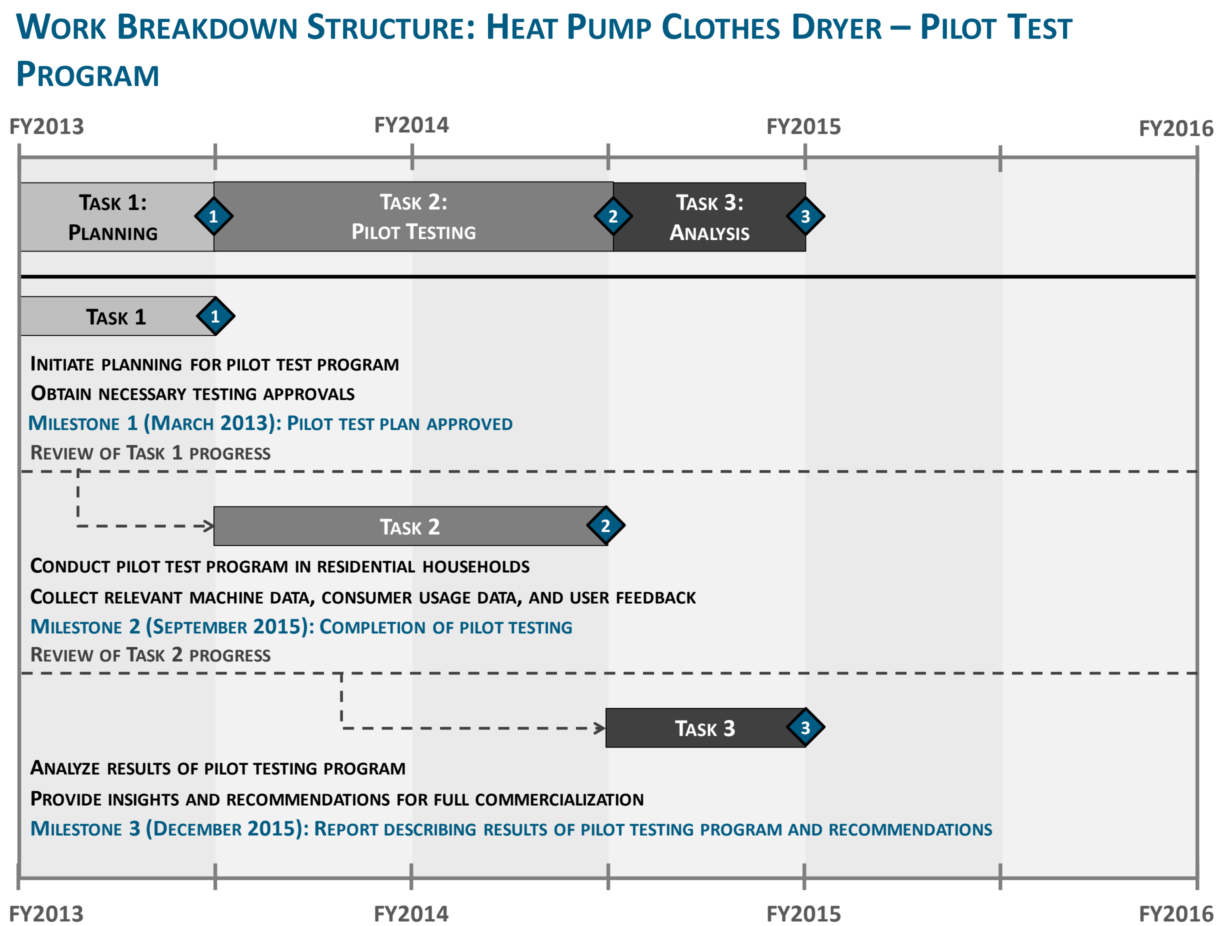


Figure 11. Work Breakdown Structure for Heat Pump Clothes Dryer R&D Activities

2.3.2 Inlet Air Preheating

One company, Rototherm Corporation, has developed a heat recovery wheel that provides dryer inlet air preheating in a commercial laundry setting. Limited testing has been performed to provide energy savings estimates in a commercial setting. However, we are unaware of any adaptations of this technology for use with residential clothes dryers. Therefore, currently, this technology is at TRL 3 for residential clothes dryers.

The recommended R&D program includes developing a smaller-scale version of the heat recovery wheel that could be applied to residential clothes dryers. The external cabinet of a residential clothes dryer would be modified with an air inlet to be compatible with the heat wheel. The prototype system would be tested to determine the energy savings potential of heat wheel technology in a residential setting. Further design work could be performed to investigate the feasibility of installing the heat exchange system inside the dryer cabinet.

This recommended program of prototype development could advance inlet air preheating technology to TRL 5.

Inlet Air Preheating

- **Priority:** Medium
- **Current Status:** Technology available for commercial laundry setting, but not for residential clothes dryers.
- **R&D Objective:** Adapt currently available technology to residential clothes dryers, determine the energy-savings potential, and assess the viability of inlet air preheating technology for residential clothes dryers.
- **Recommended R&D Activities:**
    - Develop smaller-scale design that could be applicable to residential dryers.
    - Modify residential clothes dryer cabinet with air inlets/outlets to be compatible with heat wheel technology.
    - Perform testing to determine energy savings potential.
    - Investigate the feasibility of installing heat wheel system inside dryer cabinet.
- **Program Duration:** 1 year

2.3.3 Mechanical Steam Compression Clothes Dryer

The Center for Energy Studies (CES) in Paris, France has developed a super-heated steam dryer concept using mechanical steam compression. The CES has completed preliminary performance testing on a compressor that could be used in such a system. Computer simulations have been conducted to model the performance of a complete working system; however, we are unaware of any fully-assembled working laboratory prototype. Currently, this technology is at TRL 4.

The recommended R&D program includes development of the remaining components required in the system, integration into a fully functional prototype, and preliminary energy performance testing. Because the laboratory developing this technology is located in France, a cooperative research agreement would need to be reached with a national laboratory or academic institution in the U.S.

This recommended program of research and prototype development could advance mechanical steam compressor drying technology to TRL 5.

Mechanical Steam Compression Clothes Dryer

- **Priority:** Medium
- **Current Status:** Individual components have been developed; fully working prototype not yet developed.
- **R&D Objective:** Validate the technology concept by developing a working prototype and performing testing under laboratory conditions.
- **Recommended R&D Activities:**
    - Develop remaining components required for fully functional system.
    - Integrate components to develop functional prototype.
    - Characterize system performance and compare to modeled predictions.
- **Program Duration:** 2 years

2.3.4 Indirect Heating (Hydronic) Clothes Dryer

Hydromatics Technologies Corp. has developed a hydronic heating system for electric dryers, marketed under the Safe-Mates brand. The company claims that its clothes dryer uses 50 percent less energy compared to a conventional clothes dryer; however, these estimates have not been independently confirmed. In addition, the hydronic dryer may benefit from back-to-back laundry cycles, which are not accounted for in the DOE energy efficiency test procedure. This technology is currently at TRL 9.

The recommended program involves conducting testing to evaluate the energy savings potential of this technology when back-to-back laundry cycles are conducted. This testing program would resolve specific questions that arose during the most recent energy efficiency standards rulemaking for clothes dryers. In addition, an assessment would be made of any potential safety risks associated with the clothing cool-down period. Lack of an adequate cool-down period could pose a fire hazard.

This recommended testing program could allow this technology to remain at TRL 9 and would help resolve outstanding questions regarding the energy savings potential of indirect (hydronic) clothes dryer technology.

Indirect Heating (Hydronic) Clothes Dryer

- **Priority:** Low
- **Current Status:** Technology is commercially available, but energy savings potential is unverified.
- **R&D Objective:** Determine the energy savings potential associated with back-to-back drying cycles using hydronic clothes dryer technology.
- **Recommended R&D Activities:**
  - Procure several working units from manufacturer.
  - Perform testing of back-to-back dryer cycles.
  - Determine energy savings potential.
  - Assess any risks associated with clothing cool-down period.
- **Program Duration:** 6 months

2.3.5 Microwave Clothes Dryer

Previous research by the Electric Power Research Institute (EPRI) led to the development and testing of prototype microwave dryers. Serious safety concerns were raised due to electrical arcing between metallic objects in the microwave dryer. EPRI investigated some approaches to mitigating the risk of arcing; however, the persistence of safety concerns has resulted in the abandonment of any major R&D activities related to microwave drying. This technology is currently at TRL 7.

The recommended R&D program includes investigating techniques for eliminating the major safety concerns associated with microwave clothes drying, such as through the use of advanced sensors or by creating a hybrid system that combines microwave drying with traditional drying. If the major safety concerns can be resolved, R&D efforts would continue with the development of demonstration units that could be tested in a pilot test program in residential settings.

This recommended program of research and prototype development could advance microwave clothes drying TRL 8.

Microwave Clothes Dryer

- **Priority:** Low
- **Current Status:** Prototypes have been developed previously, but safety concerns remain the key barrier to further development.
- **R&D Objective:** Assess various methods for alleviating major safety concerns, and develop a working prototype for laboratory testing.
- **Recommended R&D Activities:**
  - Investigate the feasibility of eliminating major safety concerns.
  - Refine previous prototype models to address safety concerns.
  - Demonstrate successful testing under laboratory conditions.
- **Program Duration:** 2-3 years

2.4 Cooking Equipment

The primary driver of energy consumption in cooking equipment is the generation of heat and the subsequent transfer of heat from the heat source to the cooking vessel and the food. Accordingly, the technologies with the greatest potential for improving energy efficiency are those that can generate heat more efficiently, as well as technologies that help improve heat transfer to the cooking vessel or directly to the food.

Table 5 summarizes the recommended R&D objectives and tasks identified for the highest-potential cooking technologies, possible performers and their respective roles, and estimated duration of each R&D activity.

Table 5. Cooking Equipment – Summary of Technology Options

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Tier 1 (Higher Priority)						
(none)						
Tier 2 (Medium Priority)						
Cooking Equipment: Induction cooktops	Verify energy savings, incorporate into DOE's cooking equipment test procedure, and support the development of an ENERGY STAR specification for cooktops.	1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – **9**	• Test commercially available units to determine energy savings potential • Create test method to incorporate into the DOE test procedure • Support development of ENERGY STAR criteria for cooktops	• BTP: provide funding, manage test program, develop test protocols • Third-party laboratory: perform energy tests • EPA: Management of ENERGY STAR program specifications	 **Duration: 1 year** • Procurement of units for testing • Third-party laboratory for testing	• Requires specialized cookware • Uncertainty regarding wide-scale consumer demand for this technology • Unverified energy savings in real-world residential settings
Cooking Equipment: Specialized cookware	Quantify the energy savings potential and support the development of an ENERGY STAR specification for specialized cookware.	1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – **9**	• Perform energy testing of commercially available products to verify energy efficiency potential. • Support development of ENERGY STAR criteria for cooktops	• BTP: provide funding, manage test program, develop test protocols • Third-party laboratory: perform energy tests • Cookware manufacturers: assist in developing ENERGY STAR specifications • EPA: Management of ENERGY STAR program specifications	 **Duration: 1 year** • Procurement of units for testing • Third-party laboratory for testing	• Uncertainty regarding wide-scale consumer demand for specialty cookware • Unverified energy savings in real-world residential settings
Tier 3 (Lower Priority)						
(none)						

[1] Black fill numbers indicate current TRL status; grey fill numbers indicate target TRL status after achieving the overall R&D objective. See Appendix B for details on the TRL system.

#: Current TRL status

#: Target TRL status after R&D activities

Figure 12 shows the finalized R&D roadmaps for cooking technologies. The roadmap shows the various recommended technology options identified for cooking equipment, as well as estimated timelines for each task. For technologies with time-sensitive R&D tasks, the timelines are shown on a fiscal year (FY) basis beginning with FY 2012. For technologies with R&D tasks that are less sensitive to the absolute date, the R&D timelines are shown on a relative year basis, beginning at Year 0.

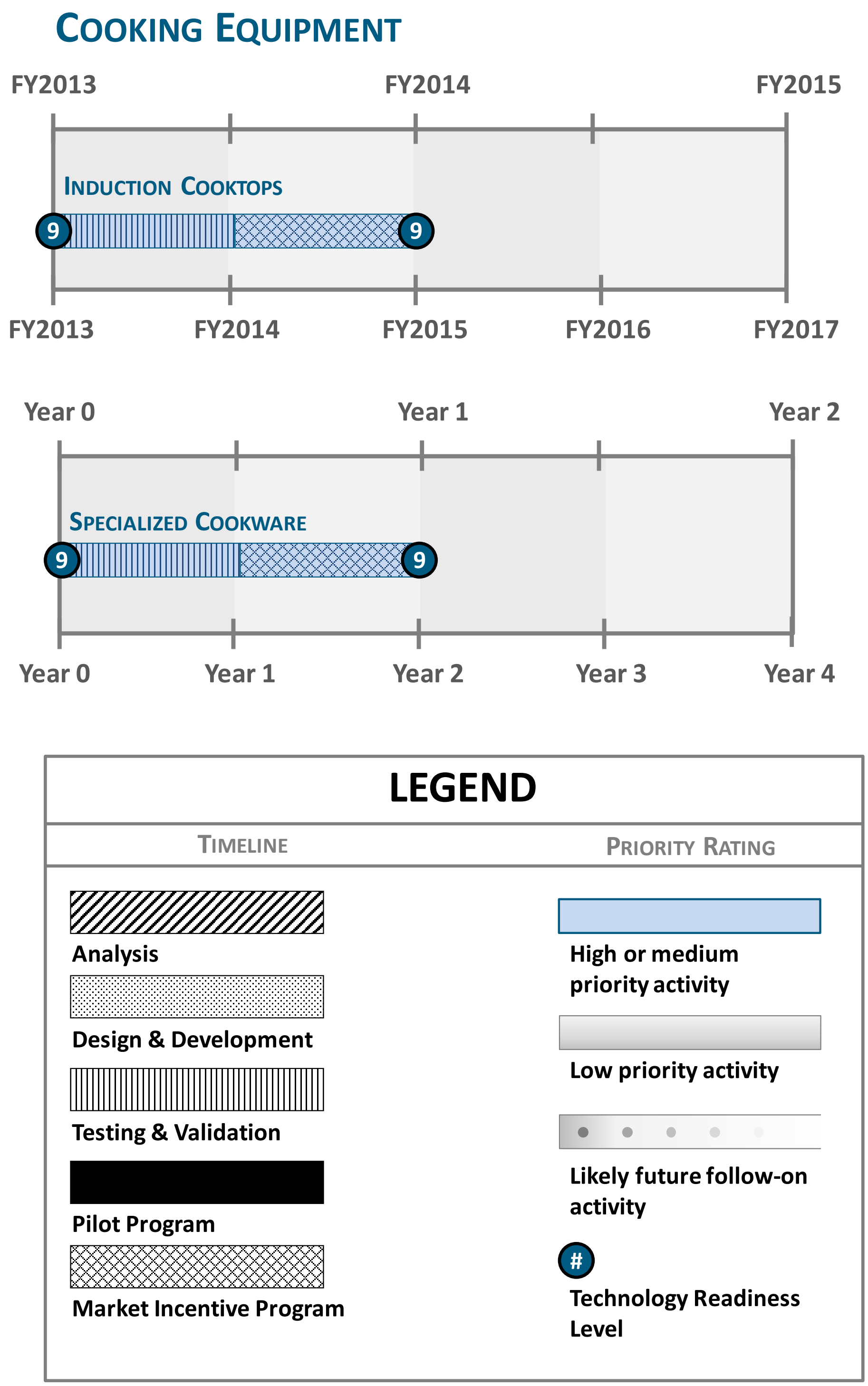


Figure 12. R&D Roadmap for Cooking Equipment Technologies

The following sections provide additional details regarding our recommended R&D activities for each of these cooking equipment technologies.

2.4.1 Induction Cooktops

Induction cooktops uses an inductor and the creation of magnetic fields to generate heat from specialized cooking vessels. Induction cooktops are currently available on the market; therefore, this technology is at TRL 9. Although induction cooktops are significantly more efficient than both gas and electric cooktops, the technology is not accommodated by the current DOE test procedure for cooking equipment.

The recommended activities include testing commercially available units to verify expected energy savings, creating a test method to incorporate into the DOE test procedure, and supporting the development of an ENERGY STAR rating for residential cooktops.

These recommended programs would keep induction cooktop technology at TRL 9 and could significantly increase the prevalence of this technology in the residential cooking equipment market.

Induction Cooking

- **Priority:** Medium
- **Current Status:** Induction cooktops are commercially available from some manufacturers.
- **R&D Objective:** Verify energy savings potential, incorporate into the DOE cooking equipment test procedure, and support the development of an ENERGY STAR specification for residential cooktops.
- **Recommended R&D Activities:**
    - Test commercially available units to determine energy savings potential
    - Create test method to incorporate into the DOE test procedure
    - Support development of ENERGY STAR criteria for cooktops
- **Program Duration:** 1 year

2.4.2 Specialized Cookware

Cookware modified with fins or grooves along the bottom surface have been shown to significantly increase cooktop efficiency. Heat-up times are substantially reduced and production capacities increased. Eneron, Inc. has developed two unique pot designs that use aluminum fins to increase the surface area exposed to the burner flame, thereby increasing the rate of heat transfer to the bottom of the pot. This technology is currently at TRL 9.

This type of cookware may also be well-suited for commercial cooking applications, where larger quantities of food are prepared and the annual energy consumption of the cooking equipment is much more substantial.
The recommended program involves quantifying the energy efficiency potential of specialized cookware in a residential setting, and supporting the development of an ENERGY STAR specification for specialized cookware.

These activities would keep specialized cookware technology at TRL 9 and could significantly increase the prevalence of this technology in the residential cookware market.

Specialized Cookware

- **Priority:** Medium
- **Current Status:** Specialized cookware is commercially available.
- **R&D Objective:** Quantify the energy savings potential and support the development of an ENERGY STAR specification for specialized cookware.
- **Recommended R&D Activities:**
  - Perform energy testing of commercially available products to verify energy efficiency potential.
  - Support development of ENERGY STAR criteria for cooktops.
- **Program Duration:** 1 year

2.4.3 Steam Cooking

With steam cooking, energy is transferred to the food load by means of the condensation of steam on the food surface. This may occur at essentially atmospheric pressure, or the cavity may be pressurized in order to allow higher steam temperatures and thus higher energy transfer to the food. Ovens with steam cooking capabilities are available on the market; thus, this technology is currently at TRL 9.

In the Task 4 report, we had proposed keeping steam cooking as one of the recommended technologies for DOE to support. However, after additional analysis and discussion with industry experts, we have removed steam cooking from consideration. The energy savings potential is incremental compared to traditional oven cooking, and the technology would likely be used infrequently due to U.S. consumers' food and cooking preferences.

2.4.4 Advanced Oven Coatings

The self-cleaning cycle in an oven uses approximately 17% of the total annual energy consumption (assuming four self-clean cycles per year). Innovative oven coatings could reduce the energy consumption of the self-clean cycle by releasing food particles at lower temperatures. The reduced self-clean temperatures would thus reduce the annual energy consumption of self-clean ovens.

In the Task 4 report, we had proposed adding advanced oven coatings as one of the recommended technologies for DOE to support. However, after additional literature review, we discovered that Maytag recently introduced an advanced oven coating, marketed under tha name "AquaLift," that requires much lower self-cleaning temperatures (200°F rather than 800°F for a traditional self-clean cycle). Because this technology has already been commercialized by a major manufacturer, and its energy saving benefits are well-understood, we do not believe there is an appropriate role for DOE in further development of this technology. Therefore, we have removed advanced oven coatings from consideration.

2.5 Cross-Cutting Technologies

Cross-cutting technologies are those technologies that offer the potential for integrated energy and water recovery and/or transfer between appliances. For example, waste heat from a refrigerator could be used to preheat the incoming water for a dishwasher; similarly, latent heat from a clothes dryer exhaust vent could be used to preheat incoming water for a clothes washer.

Table 6 summarizes the recommended R&D objectives and tasks identified for the highest-potential cross-cutting appliance technologies, possible performers and their respective roles, and estimated duration of each R&D activity.

Table 6. Cross-Cutting Technologies – Summary of Technology Options

Technology Option	R&D Objective	Outcomes of Achieving Objective (TRL Advancement)[1]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required	Key Risks
Tier 1 (Higher Priority)						
Cross-Cutting Technologies: Integrated energy and water recovery & transfer between appliances	Measure and validate the energy savings potential of the ZEHcore concept by performing laboratory tests simulating real-world usage patterns, and through a pilot demonstration project in a residential setting.		• Develop fully functional prototype system • Characterize system performance and compare to modeled predictions • Perform preliminary laboratory testing using actual appliances • Modify/optimize internal components based on preliminary testing • Further refine design to produce fully functional prototype system • Conduct further laboratory tests simulating real-world usage patterns • Conduct pilot demonstration in a residential setting	• BTP: provide funding, manage test program, manage pilot program • ORNL: development and refinement of ZEHcore system • Pilot users: operate under real-world conditions	**Duration: 3-5 years** • Funding for research staff • Materials & supplies for further system development • Test equipment & materials required for testing (including appliances) • Funding and program support for small-scale pilot testing	• Would require total redesign of typical kitchen appliance layouts • Feasibility not yet proven for energy/water recover and transfer concepts • Unproven energy/water savings • Would likely require changes to manufacturing processes • Uncertain consumer acceptance • Marketing changes required to shift away from single-appliance focus
Tier 2 (Medium Priority)						
(none)						
Tier 3 (Lower Priority)						
(none)						

[1] Black fill numbers indicate current TRL status; grey fill numbers indicate target TRL status after achieving the overall R&D objective. See Appendix B for details on the TRL system.

#: Current TRL status

#: Target TRL status after R&D activities

Figure 13 shows the finalized R&D roadmap for cross-cutting appliance technologies. The roadmap shows the estimated timelines for each R&D task. The development of this technology is not particularly time-sensitive, so the R&D timelines are shown on a relative year basis, beginning at Year 0.

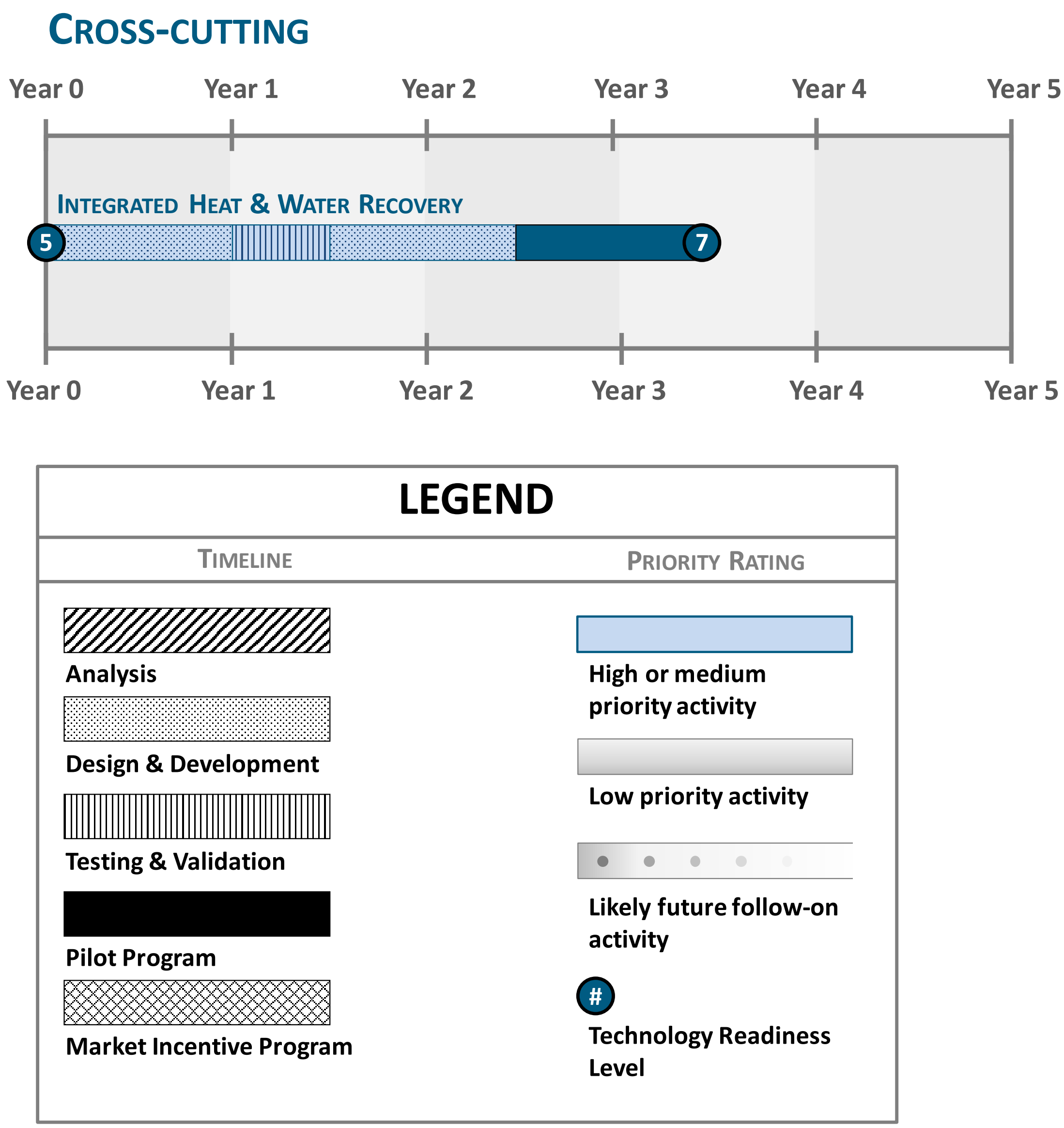


Figure 13. R&D Roadmap for Cross-Cutting Technologies

The following section provides additional details regarding our recommended R&D activities for cross-cutting appliance technologies.

2.5.1 Integrated Heat and Water Recovery

ORNL has developed a ZEHcor Interior Utility Wall concept designed to reduce hot water distribution losses and enable a high level of integration between appliances. The ZEHcore wall concept is a pre-fabricated wall to which all kitchen and laundry appliances would be connected, including major bathroom fixtures. Currently, this technology is at TRL 5.

The recommended R&D program includes laboratory testing with simulated and actual appliances, additional design and development, and a pilot demonstration program. This R&D program could advance this technology to TRL 7.

Integrated Heat and Water Recovery

- **Priority:** High
- **Current Status:** Prototype integrated wall concept has been developed; technology still in early development stages.
- **R&D Objective:** Measure and validate the energy savings potential of the ZEHcore concept by performing laboratory tests simulating real-world usage patterns, and through a pilot demonstration project in a residential setting.
- **Recommended R&D Activities:**
    - Develop fully functional prototype system.
    - Characterize system performance and compare to modeled predictions.
    - Perform preliminary laboratory testing using actual appliances.
    - Modify/optimize internal components based on preliminary testing.
    - Conduct further laboratory tests simulating real-world usage patterns.
    - Conduct pilot demonstration in a residential setting
- **Program Duration:** 3-5 years

Figure 14 shows a target WBS for further development of integrated heat and water recovery technology.

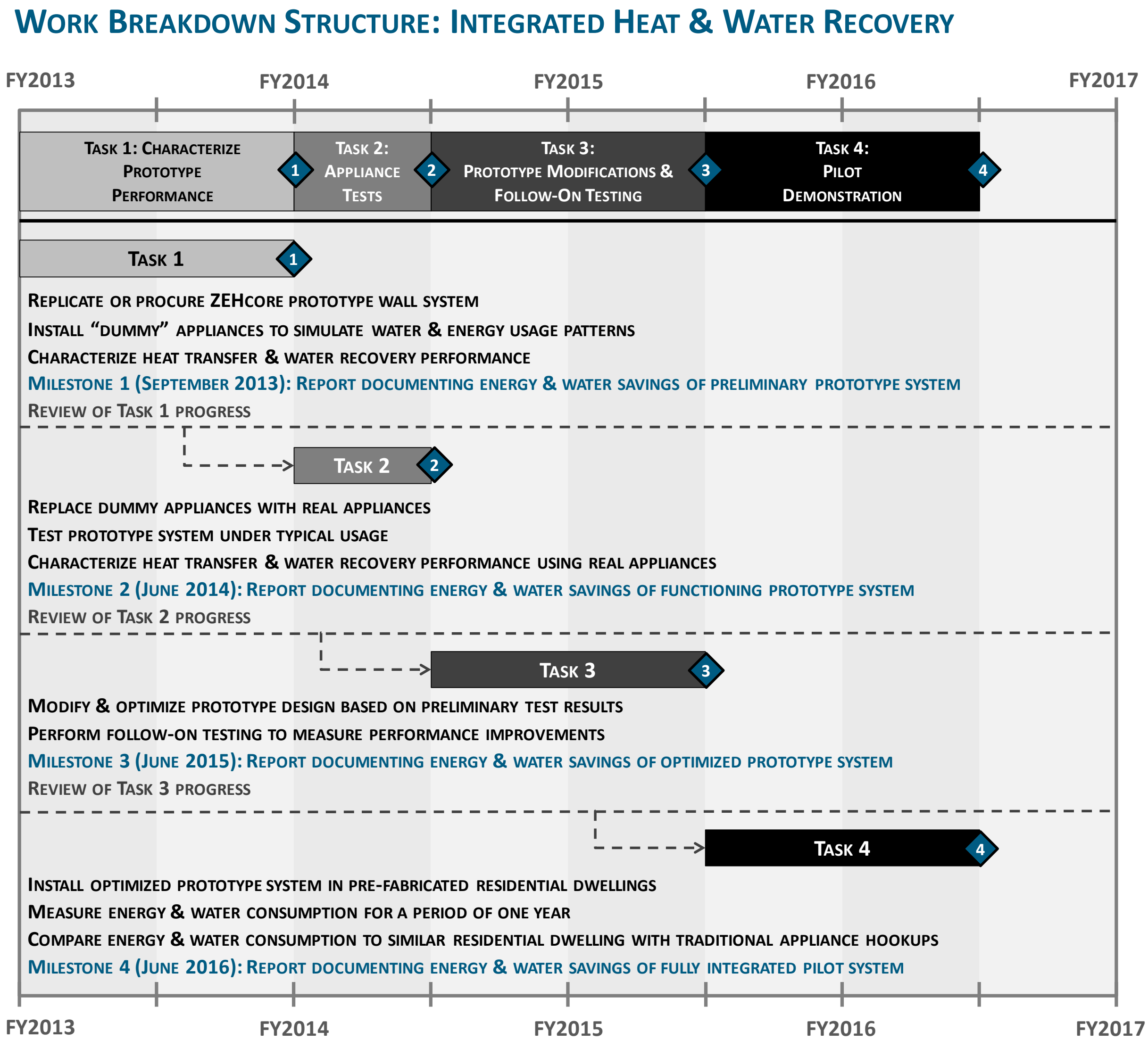


Figure 14. Work breakdown structure for integrated heat and water recovery

3 Summary and Conclusion

The appliance R&D roadmaps presented in this report target high-priority R&D, demonstration, and commercialization activities that, if pursued by DOE and its partners, could significantly reduce residential appliance energy consumption. The roadmap prioritizes those technologies with the highest energy savings potential and greatest likelihood of being embraced by both manufacturers and consumers.

The results of our study indicate that the appliance categories with the highest-priority, highest energy savings potential, and strongest fit with the DOE/BT mission are **refrigerator/freezers, clothes washers**, **clothes dryers,** and **cross-cutting** appliance technologies.

The analysis showed that **cooking equipment** appliances are lower priority with relatively little national energy savings potential, although some of the technology options would have a moderately strong or very strong fit with the DOE/BT mission.

The R&D roadmaps presented in this report will advance DOE's goal of reducing energy consumption of residential appliances by accelerating the commercialization of high-efficiency appliance technologies, while maintaining the competitiveness of American industry.

Appendix A Summary Tables from Previous Task Reports

This Appendix provides the key summary tables from previous task reports.

Table 7. Task 1 - Technology Scoring Matrix

Screening Criteria	Wt. Factor	Score				
		1	2	3	4	5
Technical Energy Savings Potential	**35%**	< 100 TBtu/yr	100 – 300 TBtu/yr	300 – 500 TBtu/yr	500 – 700 TBtu/yr	> 700 TBtu/yr
Fit with DOE/BT Mission	**35%**	Very weak fit	Moderately weak fit	Neither strong nor weak fit	Moderately strong fit	Very strong fit
Cost/Complexity	**15%**	Much higher cost/ complexity	Moderately higher cost/ complexity	Slightly higher cost/ complexity	Potential for similar cost/ complexity	Potential for lower cost/ complexity
Other Non-Energy Benefits	**15%**	Potential negative effects	Provides few or no benefits	Likely to provide some modest benefits	Potential for significant benefits, but not well understood	Provides extensive, quantifiable benefits

Table 8. Task 1 - Scoring of Each Technology Option

Technology Option	Energy Savings	Fit with DOE	Cost / Complexity	Non-Energy Benefits	Weighted Score
Dishwashers					
1. Advanced controls and sensors	1	5	4	3	**3.2**
2. Supercritical carbon dioxide washing	1	4	1	2	**2.2**
3. Ultrasonic washing	1	4	3	1	**2.4**
Cooktops					
1. Catalytic burners (gas only)	1	4	3	2	**2.5**
2. Pulse combustion (gas only)	1	3	3	2	**2.2**
3. Radiant gas burners (gas only)	1	3	3	1	**2.0**
4. Reduced excess air at burner (gas only)	1	3	2	1	**1.9**
5. Specialized cookware (gas only)	1	4	3	3	**2.7**
Conventional Ovens					
1. Bi-radiant oven (electric only)	2	3	4	1	**2.5**
2. Steam cooking (electric only)	1	2	3	3	**2.0**
Clothes Washers					
1. Ionization	5	3	1	4	**3.6**
2. Plastic particle cleaning	4	4	1	4	**3.6**
3. Ultraviolet laundering	5	3	1	4	**3.6**
Clothes Dryers					
1. Heat pump (electric only)	3	4	3	2	**3.2**
2. Indirect (hydronic) heating (electric only)	2	4	2	3	**2.9**
3. Inlet air preheating	2	4	4	2	**3.0**
4. Mechanical steam compression (electric only)	3	5	2	3	**3.6**
5. Microwave (electric only)	2	5	3	1	**3.1**
Refrigerators/Freezers					
1. Improved compressor efficiency	2	3	4	2	**2.7**
2. Magnetic refrigeration	3	5	3	2	**3.6**
3. Nanoparticle additives to refrigerants	2	5	4	2	**3.4**
4. Stirling cycle	2	4	3	2	**2.9**
5. Thermoacoustic refrigeration	2	4	3	2	**2.9**
6. Thermoelectric refrigeration	3	4	4	2	**3.4**
7. Vacuum insulation panels	2	5	4	2	**3.4**
Cross-Cutting Technologies					
1. Integrated energy and water recovery and transfer between appliances	5	4	1	2	**3.6**

Table 9. Task 2 – Summary of R&D Needs and Key Risks

Appliance	Technology Option	Technology Readiness Level	R&D Needs	Key Risks
Tier 1				
1. Clothes Washers	Plastic particle cleaning	TRL 5 – Laboratory Prototype	• First working prototypes to be built by Xeros • Partnerships needed to test first operational prototypes • Prototype testing in operational environment • Prototype testing to confirm cleaning capabilities using AHAM test methods	• Cleaning ability of technology not yet proven to AHAM standards • Uncertain consumer acceptance of new plastic particle technology • Logistics of requiring period replacement of plastic beads • Ability of technology to accommodate large U.S. laundry load sizes
2. Cross-Cutting	Integrated energy and water recovery and transfer between appliances	TRL 5 – Laboratory Prototype	• Laboratory tests of ZEHcore concept • Measure and validate energy savings potential • Additional tests simulating real-world usage patterns • Pilot demonstration in a residential setting	• Would require total redesign of typical kitchen appliance layouts • Feasibility not yet proven for energy/water recover and transfer concepts • Unproven energy/water savings • Would likely require changes to manufacturing processes • Uncertain consumer acceptance • Marketing changes required to shift away from single-appliance focus
3. Clothes Dryers	Mechanical steam compression (Electric only)	TRL 4 – System Proof of Concept	• Development of operational prototype • Prototype testing of complete system under lab conditions	• Technology not yet proven in integrated system-level prototype • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost
4. Refrigerator/Freezers	Magnetic refrigeration	TRL 4 – System Proof of Concept	• Reduce size of technology • Create integrated prototype for laboratory testing • Create working prototype for field testing	• Concept is proven, but there is a low degree of certainty that the technology is feasible in a residential setting • Magnetic field of prototype was too high for use in residential homes
5. Refrigerator/Freezers	Nanoparticle additives	TRL 4 – System Proof of Concept	• Develop prototype refrigerator with nanoparticle additives in laboratory conditions • Acquire energy data from fully functional system	• Has not been tested in fully integrated system • Uncertain energy saving benefits for residential refrigerators
6. Refrigerator/Freezers	Vacuum insulation panels	TRL 5 – Laboratory Prototype	• Develop prototype for field testing to prove energy savings in residential environment • Improve long-term integrity of insulation properties • Reduce manufacturing costs	• Requires different manufacturing methods • Low degree of certainty on longevity of VIPs • Uncertain consumer willingness to pay higher upfront cost
7. Refrigerator/Freezers	Thermoelectric	TRL 4 – System Proof of Concept	• Demonstrate energy savings potential of thermoelectric technology • Develop prototypes for lab testing • Develop prototype for operational testing	• Unproven energy savings compared to vapor-compression refrigeration (small-scale models on the market show low energy efficiency) • Requires different manufacturing methods • Uncertainty regarding ability to scale up manufacturing process
8. Clothes Dryers	Heat pump (Electric only)	TRL 8 – Commercial Demonstration	• Revival of previous prototypes • Additional design and development • Additional laboratory testing • Pilot testing of redesigned prototype	• Technology not yet proven for large U.S. laundry load sizes • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost
Tier 2				
1. Clothes Washers	Ionization	TRL 2 – Applied R&D	• Evaluation of negative ion technology as a method for laundering typical clothing • Proof of concept demonstration to show technology viability • Investigate feasibility of laundering more than one garment at a time with this technology	• Unproven feasibility of technology to adequately clean clothes • Unproven energy savings potential • Ability of technology to accommodate large U.S. laundry load sizes • Significantly different manufacturing processes required • Increased manufacturing cost compared to traditional clothes washers • Uncertain consumer acceptance of new ionization technology
2. Clothes Washers	Ultraviolet laundering	TRL 2 – Applied R&D	• Evaluation of ultraviolet + "free radical oxygen" technology as a method for laundering typical clothing • Proof of concept demonstration to show technology viability • Investigate feasibility of laundering more than one garment at a time with this technology	• Unproven feasibility of technology to adequately clean clothes • Unproven energy savings potential • Ability of technology to accommodate large U.S. laundry load sizes • Significantly different manufacturing processes required • Increased manufacturing cost compared to traditional clothes washers • Uncertain consumer acceptance of new ultraviolet laundering technology
3. Dishwashers	Advanced cleaning sensors	TRL 2 – Applied R&D	• Identification of possible sensors that could be used • Evaluation of existing sensor technologies in other products • Proof of concept laboratory designs	• Unproven feasibility of new sensor technologies • Unproven energy/water savings potential • Increased manufacturing cost compared to traditional dishwasher sensors

Appliance	Technology Option	Technology Readiness Level	R&D Needs	Key Risks
4. Clothes Dryers	Microwave (Electric only)	TRL 7 – Operational System Pilot	• Reduction of upfront costs • Refinements to improve energy efficiency • Partnership with reputable brand name	• Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Uncertain consumer acceptance of microwave dryer technology • Potential safety issues
5. Clothes Dryers	Inlet air preheat	TRL 4 – System Proof of Concept	• Lab testing of technology integrated into residential-style dryer	• Unproven energy savings potential • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost • Potential impacts on installation procedures • Potential safety issues with lint handling
6. Refrigerator/Freezers	Thermoacoustic	TRL 3 – Component Proof of Concept	• Package components to fit within refrigerator dimensions • Development of fully integrated system for lab testing • Development of operational prototype	• Very early stages of development with very rudimentary laboratory prototypes • Low degree of certainty that technology is feasible • Significantly different manufacturing processes required
7. Refrigerator/Freezers	Stirling cycle	TRL 5 – Laboratory Prototype	• Design refinements to improve energy efficiency • Validation of energy savings potential • Development of operational prototype	• Unproven energy savings potential • May require different manufacturing methods
8. Clothes Dryers	Indirect heating	TRL 9 – Full Commercial Deployment	• Acquire energy efficiency data from current products on the market	• Unproven energy savings potential • Increased manufacturing cost compared to traditional dryers • Uncertain consumer willingness to pay higher upfront cost
9. Refrigerator/Freezers	Improved compressor efficiency	TRL 6 – Operational Prototype	• Further develop technology to determine commercial feasibility • Acquire additional performance data • Incorporation into commercial designs	• Patent protection could diminish competition in the market • Limited performance data on high-efficiency compressors
10. Cooktops	Specialized cookware	TRL 7 – Operational Pilot System	• Investigate consumer acceptance • Develop programs to increase consumer awareness and acceptance	• Unsure if cookware will be accepted by consumers • Unproven energy savings in real world
Tier 3				
1. Ovens	Bi-radiant oven (Electric only)	TRL 5 – Laboratory Prototype	• Address practicality concerns • Develop prototype for field testing	• Technical and feasibility issues arose with 1970s prototypes • Low degree of certainty that technology is feasible with modern cookware • Durable lining materials may add costs to consumers
2. Cooktops	Catalytic burners (Gas only)	TRL 4 – System Proof of Concept	• Integrate technology into fully functional prototype for lab testing • Develop prototype for operational field testing	• Technical hurdles still remain • Different manufacturing methods required • High production costs • Uncertain consumer willingness to pay higher upfront cost
3. Dishwashers	Ultrasonic washing	TRL 4 – System Proof of Concept	• Evaluation of current Indian product • Evaluation of suitability for translating technology to U.S. residential needs • Development of residential-style functioning prototype	• Unproven feasibility of technology to adequately clean dishes • Unproven energy savings potential • Ability of technology to accommodate U.S. residential dish loads • Significantly different manufacturing processes required • Increased manufacturing cost compared to traditional clothes washers • Uncertain consumer acceptance of new ultrasonic technology
4. Dishwashers	Supercritical carbon dioxide washing	TRL 2 – Applied R&D	• Evaluation of CO_2 dishwashing technology as a method for cleaning household dishes • Proof of concept demonstration to show technology viability • Investigate feasibility of packaging into residential-size unit	• Unproven feasibility of technology to adequately clean dishes • Unproven energy savings potential • Ability of technology to accommodate U.S. residential dish loads • Significantly different manufacturing processes required • Increased manufacturing cost compared to traditional clothes washers • Uncertain consumer acceptance of technology
5. Cooktops	Pulse combustion (Gas only)	TRL 5 – Laboratory Prototype	• Develop prototype for field testing	• Different manufacturing methods required • Unproven energy savings potential
6. Cooktops	Radiant gas burners (Gas only)	TRL 5 – Laboratory Prototype	• Develop prototype for field testing	• Different manufacturing methods required • Unproven energy savings in real world
7. Ovens	Steam cooking	TRL 9 – Full Commercial Deployment	• Acquire energy efficiency data from current products on the market	• Unsure of consumer acceptance • No energy efficiency data available • Some models require plumbing lines to supply water

Appliance	Technology Option	Technology Readiness Level	R&D Needs	Key Risks
8. Cooktops	Reduced excess air at burner (Gas only)	TRL 3 – Component Proof of Concept	• Determine energy savings potential of this technology • Integrate components into full scale prototype for lab testing	• Low degree of certainty that technology is feasible • Unproven energy savings potential • No prototypes exist

Table 10. Task 3 - Summary of R&D Objectives, Tasks, Possible Performers, and Resources Required

Appliance	Technology Option	R&D Objective	Outcomes of Achieving Objective [a]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required
Tier 1						
1. Clothes Washers	Plastic particle cleaning	To assess the energy savings potential and cleaning performance by procuring a working prototype and performing tests using the DOE test procedure (adapted if necessary) and AHAM test procedures.	• Reliable estimates of energy savings potential 1 2 3 4 5 6 7 8 9	• Procure a working prototype unit • Perform testing using an adapted version of the DOE test procedure • Perform cleaning performance testing using AHAM test procedures • Estimate unit energy savings potential based on results	• Xeros, Ltd: manufacturer of prototype, cooperation with DOE project • BTP: provide funding, manage test program, develop test protocols • National laboratory: perform energy & performance tests • DOE Standards & Test Procedure team: provide background/insights, help evaluate test results	0 1 2 **Duration: 1 year** • Procurement of a prototype unit • BTP project staff to manage test program • National laboratory staff for testing • DOE Standards & Test Procedure staff to help analyze results
2. Cross-Cutting	Integrated energy and water recovery & transfer between appliances	To measure and validate the energy savings potential of the ZEHcore concept by performing laboratory tests simulating real-world usage patterns, and through a pilot demonstration project in a residential setting.	• Validation of integrated appliances concept • Preliminary estimates of energy savings potential • Feedback and experience from pilot installation 1 2 3 4 5 6 7 8 9	• Develop fully integrated prototype system • Characterize system performance and compare to modeled predictions • Perform preliminary laboratory testing using actual appliances • Modify/optimize internal components based on preliminary testing • Further refine design to produce fully functional prototype system • Conduct further laboratory tests simulating real-world usage patterns • Conduct pilot demonstration in a residential setting	• BTP: provide funding, manage test program, manage pilot program • ORNL: development and refinement of ZEHcore system • Pilot users: operate under real-world conditions	0 1 2 **Duration: Multi-year** • Funding for research staff • Materials & supplies for further system development • Test equipment & materials required for testing (including appliances) • Funding and program support for small-scale pilot testing
3. Clothes Dryers	Mechanical steam compression (electric only)	To validate the technology concept by developing a working prototype and performing testing under laboratory conditions.	• Fully functional prototype that could be further tested • Preliminary estimates of energy savings potential 1 2 3 4 5 6 7 8 9	• Develop fully integrated prototype system • Characterize system performance and compare to modeled predictions • Perform preliminary testing using clothing loads • Modify/optimize internal components based on preliminary testing • Further refine design to produce fully functional prototype system	• BTP: provide funding, monitor progress • Center for Energy Studies, Ecole des Mines de Paris (Mines ParisTech): expand on previous research and prototypes • U.S. university: joint research activities with Center for Energy Studies	0 1 2 **Duration: 1 year** • Funding for research staff • Materials & supplies for component development and system integration • Test equipment & materials required for testing
4. Refrigerator/Freezers	Magnetic refrigeration	To demonstrate the required cooling capacity of residential refrigerators.	• Working prototype for further coefficient of performance testing • Validation of cooling performance of magnetic refrigeration 1 2 3 4 5 6 7 8 9	• Further understand magnetic refrigeration cooling principles • Optimize individual components of the system • Test optimized prototype to demonstrate required cooling capacity	• BTP: provide funding, manage test program, develop test protocols • Ames Laboratory: expand on previous research and prototype	0 1 2 **Duration: Multi-year** • Materials & supplies for component development and system integration • Ames staff to test and analyze results
5. Refrigerator/Freezers	Nanoparticle additives	To confirm preliminary energy savings estimates using a residential refrigerator on the U.S. market and the DOE test procedure.	• Reliable estimates of energy savings potential 1 2 3 4 5 6 7 8 9	• Test optimum solution from previous studies in a residential refrigerator using the DOE test procedure • Estimate energy savings potential from laboratory test results	• BTP: provide funding, manage test program, develop test protocols • Researchers involved with preliminary prototypes: provide knowledge and experience from development of initial prototypes • third-party laboratory: perform energy tests using DOE test procedure	0 1 2 **Duration: 1 year** • Materials: refrigerants, nanoparticle additives • Refrigerators in which to test the refrigerants • NIST staff to test and analyze results • Third-party laboratory for testing

Appliance	Technology Option	R&D Objective	Outcomes of Achieving Objective [a]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required
6. Refrigerator/Freezers	Vacuum insulation panels	To understand the causes of inconsistent results among multiple manufacturers' products and to reduce overall costs.	• Understanding of the technical reasons for inconsistent performance across products • Understanding of the primary cost drivers, and strategies for creating a more cost-effective product 1 2 3 4 5 6 7 8 9	• Perform characterization tests on products known to have inconsistent performance • Reverse-engineer products to determine root causes for performance inconsistencies • Analyze the supply chain of all materials and processes used in the manufacture of VIPs • Determine major cost drivers and identify strategies for reducing costs	• BTP: provide funding, manage test program, perform supply chain analysis • third-party laboratory: perform energy tests using DOE test procedure, perform reverse-engineering analysis • Manufacturers: R&D partnership with manufacturers who already produce VIPs	0 1 2 **Duration: Multi-year** • Refrigerator products with VIPs • Third-party laboratory for testing • ORNL staff to test and analyze results
7. Refrigerator/Freezers	Thermoelectric	To determine the potential energy savings of a full-sized residential thermoelectric refrigerator by developing prototypes for laboratory testing.	• Working prototype for further testing • Preliminary estimates of energy savings potential 1 2 3 4 5 6 7 8 9	• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• BTP: provide funding, manage test program, develop test protocols • Manufacturers: R&D partnership with manufacturers who already produce small thermoelectric refrigerators • National laboratory: aide in R&D	0 1 2 **Duration: Multi-year** • Small thermoelectric refrigerators to analyze • Materials to build full-sized prototype • Research staff to build, test, and analyze prototype
8. Clothes Dryers	Heat pump (electric only)	To support the development of ENERGYSTAR criteria for heat pump dryers.	• ENERGYSTAR certification for heat pump dryers 1 2 3 4 5 6 7 8 9	• Collaborate with EPA and stakeholders to develop ENERGYSTAR criteria for heat pump dryers • Perform energy testing and analysis to support ENERGYSTAR program	• BTP: provide program support, manage test program	0 1 2 **Duration: Multi-year** • Funding for program staff • Test equipment & materials required for testing
Tier 2						
1. Clothes Washers	Ionization	To assess the viability of using ionization cleaning technology in a residential laundry setting.	• Validation of technology concept • Development of key system components • Preliminary estimates of potential energy savings 1 2 3 4 5 6 7 8 9	• Verify development status of negative ion technology for clothes laundering • Develop individual components of the system • Demonstrate proof-of-concept of individual components • Investigate feasibility of technology as a method for residential laundering • Determine preliminary estimates of energy savings potential	• BTP: provide funding, monitor progress • Electrolux: provide information & background on technology concept from design competition • National Laboratory: conduct R&D and testing of individual components	0 1 2 **Duration: 1 year** • Funding for research staff • Materials & supplies for component development • Test equipment & materials required for testing
2. Clothes Washers	Ultraviolet laundering	To assess the viability of using ultraviolet cleaning technology in a residential laundry setting.	• Validation of technology concept • Development of key system components • Preliminary estimates of potential energy savings 1 2 3 4 5 6 7 8 9	• Verify development status of ultraviolet technology for clothes laundering • Develop individual components of the system • Demonstrate proof-of-concept of individual components • Investigate feasibility of technology as a method for residential laundering • Determine preliminary estimates of energy savings potential	• BTP: provide funding, monitor progress • Electrolux: provide information & background on technology concept from design competition • National Laboratory: conduct R&D and testing of individual components	0 1 2 **Duration: 1 year** • Funding for research staff • Materials & supplies for component development • Test equipment & materials required for testing
3. Clothes Dryers	Microwave (electric only)	To demonstrate a safe microwave dryer by developing a pre-commercial demonstration unit.	• Development of a safe commercial-ready dryer that would be feasible for the US market • Reliable estimates of energy savings potential 1 2 3 4 5 6 7 8 9	• Refine previous prototype models to address safety concerns • Develop pre-commercial demonstration unit • Perform pilot testing in residential settings • Perform testing using an adapted version of the DOE test procedure • Estimate unit energy savings potential based on results	• BTP: provide funding, manage R&D program • National Laboratory: conduct R&D and design improvements • Pilot users: operate under real-world conditions	0 1 2 **Duration: Multi-year** • Funding for research staff • Materials & supplies for component development • Test equipment & materials required for internal testing

Appliance	Technology Option	R&D Objective	Outcomes of Achieving Objective [a]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required
4. Clothes Dryers	Inlet air preheat	To demonstrate a viable inlet air preheating technology for residential dryers.	• Demonstration of feasibility of heat transfer technology for residential dryers • Preliminary estimates of energy savings potential	• Perform testing to characterize energy benefits of current "heat wheel" technology • Demonstrate smaller-scale design that could be applicable to residential dryers • Develop modified residential dryer with air inlets/outlets to work with heat wheel technology • Investigate the potential for installing heat exchanger inside dryer cabinet	• BTP: provide funding, manage R&D program • National Laboratory: conduct R&D and design improvements • Rototherm company: provide samples of current technology, cooperate with DOE project	**Duration: 1 year** • Funding for research staff • Materials & supplies for testing current system • Materials & supplies for developing modified components • Test equipment & materials required for internal testing
5. Refrigerator/Freezers	Thermoacoustic	To demonstrate a thermoacoustic refrigerator with the same coefficient of performance as commercially available residential refrigerators.	• Working prototype for further testing • Demonstrated feasibility for residential refrigerator applications • Preliminary model of energy savings potential	• Refine previous prototype model to improve coefficient of performance • Test refined prototype to determine performance	• BTP: provide funding, manage test program, develop test protocols • Universities involved with proof of concept: provide knowledge and experience from development of initial prototype • National laboratory: aide in R&D	**Duration: Multi-year** • Procurement of units for testing • BTP project staff to manage test program • Third-party laboratory for testing • DOE Standards staff to help analyze results
6. Refrigerator/Freezers	Stirling cycle	To determine the energy savings potential of stirling cycle refrigerators by developing and testing a working prototype.	• Working prototype for further testing • Preliminary estimates of energy savings potential	• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• BTP: provide funding, manage test program, develop test protocols • Purdue University: provide knowledge and expertise on stirling cycle small refrigeration research	**Duration: Multi-year** • Research staff to develop and test prototype • Materials required to build prototype
7. Clothes Dryers	Indirect heating	To assess the energy savings potential of indirect (hydronic) clothes dryers by testing hydronic clothes dryers currently available on the market.	• Resolve outstanding questions raised during DOE Standards rulemaking • Verification of additional savings from back-to-back laundry cycles • Reliable estimates of energy savings potential	• Procure several working units • Perform testing using DOE test procedure (adapted if necessary) • Determine energy savings potential	• Hydromatics Technologies: provide units for testing • BTP: provide funding, manage test program, develop test protocols • Third-party accredited laboratory: perform energy & performance tests • DOE Standards team: provide background/insights, help evaluate test results	**Duration: 6 months** • Procurement of units for testing • BTP project staff to manage test program • Third-party laboratory for testing • DOE Standards staff to help analyze results
9. Cooktops	Specialized cookware	To verify energy savings potential of residential-sized cookware, and to determine consumer acceptance of specialized cookware by implementing a trial consumer incentive program.	•Verification of energy savings in residential-sized cookware using residential cooking equipment • Knowledge about consumer acceptance of specialized cookware	• Procure residential-sized specialty cookware • Perform investigative energy testing to verify energy efficiency potential • Implement trial consumer incentive program to stimulate purchases of specialized cookware • Determine consumer acceptance rate and feasibility	• BTP: provide funding, manage test program, develop test protocols, design and execute consumer incentive program • Third-party laboratory: perform energy tests • Cookware manufacturers: assist in consumer programs	**Duration: 1 year** • Procurement of units for testing •Third-party laboratory for testing • Staff to carry out consumer programs and analyze results • Funds for incentive program

Appliance	Technology Option	R&D Objective	Outcomes of Achieving Objective [a]	R&D Tasks	Possible Performers & Roles	Duration & Resources Required
Tier 3						
1. Cooktops	Catalytic burners (gas only)	To investigate the viability for use in residential applications and to determine the energy savings potential of catalytic burner technology.	• Demonstrated feasibility for residential applications • Preliminary estimate of energy savings potential 1 – 2 – 3 – **4** – *5* – 6 – 7 – 8 – 9	• Develop integrated bench-top prototype • Test prototype to determine energy savings potential	• BTP: provide funding, manage test program, develop test protocols • Precision Combustion, Inc. : provide product knowledge and expertise	0 1 2 **Duration: 1 year** • Equipment and materials required to build prototype • Research staff to build, test, and analyze prototype results
2. Dishwashers	Ultrasonic washing	To investigate the energy savings potential, cleaning performance, and overall viability of ultrasonic technology in residential dishwashers.	• Validation of technology concept • Assessment of overall concept viability • Preliminary estimates of energy savings potential 1 – 2 – 3 – **4** – *5* – 6 – 7 – 8 – 9	• Procure the model currently available on the Indian market • Perform exploratory testing to verify cleaning performance, energy consumption, sanitization, and safety. • Determine energy savings potential	• Steryl Medi-Equip Systems: provide products from India, cooperate with DOE • BTP: provide funding, manage test program, develop test protocols • National Laboratory: perform exploratory testing	0 1 2 **Duration: 1 year** • Procurement of an Indian product for testing • Research staff to manage test program • Equipment & materials required for testing
3. Dishwashers	Supercritical carbon dioxide washing	To determine the technology's development status, assess its cleaning performance, and assess the viability of using supercritical carbon dioxide technology in residential dishwashers.	• Determination of technology development status • Assessment of cleaning performance • Assessment of overall concept viability 1 – **2** – *3* – 4 – 5 – 6 – 7 – 8 – 9	• Verify development status of supercritical CO_2 dishwasher • Demonstrate proof-of-concept of cleaning performance in benchtop prototype • Investigate feasibility of technology for residential dishwashers	• BTP: provide funding, monitor progress • Electrolux: provide information & background on technology concept from design competition • National Laboratory: conduct feasibility study, laboratory testing	0 1 2 **Duration: 1 year** • Research staff for R&D • Equipment & materials required for testing
4. Cooktops	Pulse combustion (gas only)	To validate the energy savings potential of pulse combustion gas burners.	• Demonstrated feasibility for residential applications • Reliable estimate of energy savings potential 1 – 2 – 3 – 4 – **5** – *6* – 7 – 8 – 9	• Procure/develop working prototype based on patented technology • Test prototype to determine energy savings potential	• BTP: provide funding, manage test program, develop test protocols • GRI: Provide knowledge and expertise • National Laboratory: aide in testing	0 1 2 **Duration: 1 year** • Equipment and materials required to build prototype • Research staff to build, test, and analyze prototype results • Third-party laboratory for testing
5. Cooktops	Radiant gas burners (gas only)	To validate the energy savings potential of radiant gas burners.	• Demonstrated feasibility for residential applications • Reliable estimate of energy savings potential 1 – 2 – 3 – 4 – **5** – *6* – 7 – 8 – 9	• Procure previously developed prototypes • Test prototype to determine energy savings potential	• BTP: provide funding, manage test program, develop test protocols • American Gas Association Laboratories: provide product knowledge and expertise • National Laboratory: aide in testing	0 1 2 **Duration: 6 months** • Procurement of prototypes • Research staff to test and analyze results • Third-party laboratory for testing
6. Ovens	Steam cooking	To assess the energy savings potential of steam-cooking ovens currently on the market.	• Reliable estimates of energy savings potential 1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – **9**	• Procure several working units • Perform testing using adapted DOE test procedure • Determine energy savings potential	• BTP: provide funding, manage test program, develop test protocols • Third-party accredited laboratory: perform energy tests • Manufacturers: provide commercially available steam-cooking ovens	0 1 2 **Duration: 6 months** • Procurement of commercially available steam-cooking ovens • Third-party laboratory for testing • Research staff to test and analyze results
7. Cooktops	Reduced excess air at burner (gas only)	To confirm theoretical energy savings potential by developing and testing a working prototype.	• Proof-of-concept of technology • Working system for further testing and development • Preliminary estimate of energy savings potential 1 – 2 – **3** – *4* – 5 – 6 – 7 – 8 – 9	• Replicate components from previous studies • Integrate components to create a prototype cooktop system • Test system for basic functionality	• BTP: provide funding, manage test program, develop test protocols • National laboratory: aide in R&D • Prior researchers: provide basic knowledge and expertise	0 1 2 **Duration: 1 year** • Equipment and materials required to build prototype • Research staff to build, test, and analyze prototype results

[a] Black fill numbers indicate current TRL status, while grey fill numbers indicate target TRL status after achieving the overall R&D objective.

: Current TRL status

: Projected R&D status after TRL activities

Table 11. Task 4 - Refrigerator/Freezer Summary of Stakeholder Comments

Technology Option	R&D Objective	R&D Tasks	Discussion Summary	Consensus Priority (Change Indicated)
Tier 1 (High Priority)				
Magnetic refrigeration	To demonstrate the required cooling capacity of residential refrigerators.	• Further understand magnetic refrigeration cooling principles • Optimize individual components of the system • Test optimized prototype to demonstrate required cooling capacity	• *A major challenge with this technology is achieving the required temperature lift to obtain necessary cooling capacity* • *Further R&D needed to fully understand the magnetic cooling effect and to develop methods for transferring heat away from the food compartments* • *Fundamentally, this technology holds strong promise as a future alternative to vapor compression.*	HIGH (no change)
Nanoparticle additives	To confirm preliminary energy savings estimates using a residential refrigerator on the U.S. market and the DOE test procedure.	• Test optimum solution from previous studies in a residential refrigerator using the DOE test procedure • Estimate energy savings potential from laboratory test results	• *Nanoparticles may improve the evaporator side of the heat exchanger, but would have little effect on the condensing side. This would limit the overall efficiency gains* • *Overall, this technology unlikely to offer significant energy savings*	REMOVED FROM CONSIDERATION
Vacuum insulation panels	To understand the causes of inconsistent results among multiple manufacturers' products and to reduce overall costs.	• Perform characterization tests on products known to have inconsistent performance • Reverse-engineer products to determine root causes for performance inconsistencies • Analyze the supply chain of all materials and processes used in the manufacture of VIPs • Determine major cost drivers and identify strategies for reducing costs	• *VIPs currently used in a limited number of products* • *Key challenges include long-term performance degradation and manufacturing cost*	HIGH (no change)
Thermoelectric	To determine the potential energy savings of a full-sized residential thermoelectric refrigerator by developing prototypes for laboratory testing.	• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• *Concept is feasible, but may not have the potential to be as efficient as vapor compression* • *Could potentially be used in a hybrid system with vapor compression* • *Useful R&D would investigate the breakthroughs required to make this technology competitive with vapor compression*	LOW (downgrade)
Tier 2 (Medium Priority)				
Thermoacoustic	To demonstrate a thermoacoustic refrigerator with the same coefficient of performance as commercially available residential refrigerators.	• Refine previous prototype model to improve coefficient of performance • Test refined prototype to determine performance	• *Component size and vibration are significant barriers for commercialization* • *Technology not being actively pursued by major manufacturers*	REMOVED FROM CONSIDERATION
Stirling cycle	To determine the energy savings potential of stirling cycle refrigerators by developing and testing a working prototype.	• Create a full-sized residential prototype • Determine energy performance • Modify/optimize internal components based on preliminary testing • Conduct further testing	• *Stirling cycle technology well-known, but has not been shown to be more efficient than vapor compression* • *Technology not being actively pursued by major manufacturers*	LOW (downgrade)
More efficient compressor technologies	Not previously considered	Not previously considered	• *Could be implemented in short-term with traditional vapor compression systems* • *Estimations show linear compressors are more efficient than current fixed speed compressors* • *R&D needed to optimize advanced compressor design, material selection, lubricants, and manufacturing costs*	MEDIUM
Tier 3 (Low Priority)				
Thermoelastic	Not previously considered	Not previously considered	• *Cooling can be obtained from the straining of a thermoelastic shape memory alloy* • *Has drawbacks in its current preliminary form such as low latent heat (~12 kJ/kg) and a limited fatigue life* • *Researchers currently developing a 35kW prototype*	LOW

Table 12. Task 4 - Clothes Washer Summary of Stakeholder Comments

Technology Option	R&D Objective	R&D Tasks	Discussion Summary	Consensus Priority (Change Indicated)
Tier 1 (High Priority)				
Plastic particle cleaning	To assess the energy savings potential and cleaning performance by procuring a working prototype and performing tests using the DOE test procedure (adapted if necessary) and AHAM test procedures.	• Procure a working prototype unit • Perform testing using an adapted version of the DOE test procedure • Perform cleaning performance testing using AHAM test procedures • Estimate unit energy savings potential based on results	• *Concerns persist regarding potential environmental and safety issues with small plastic beads* • *Technology could be better suited for commercial on-premise laundries or dry-cleaning settings* • *Energy savings potential may be less significant compared to the most efficient front-loading clothes washers on the market*	MEDIUM (downgrade)
Tier 2 (Medium Priority)				
Ionization	To assess the viability of using ionization cleaning technology in a residential laundry setting.	• Verify development status of negative ion technology for clothes laundering • Develop individual components of the system • Demonstrate proof-of-concept of individual components • Investigate feasibility of technology as a method for residential laundering • Determine preliminary estimates of energy savings potential	• *No cleaning mechanism has been identified with this technology* • *Unlikely to become a viable replacement for regular home laundering* • *Could be used as a supplement to sanitize clothes*	REMOVED FROM CONSIDERATION
Ultraviolet laundering	To assess the viability of using ultraviolet cleaning technology in a residential laundry setting.	• Verify development status of ultraviolet technology for clothes laundering • Develop individual components of the system • Demonstrate proof-of-concept of individual components • Investigate feasibility of technology as a method for residential laundering • Determine preliminary estimates of energy savings potential	• *No cleaning mechanism has been identified with this technology* • *Unlikely to become a viable replacement for regular home laundering* • *Could be used as a supplement to sanitize clothes*	REMOVED FROM CONSIDERATION
Tier 3 (Low Priority)				
Sanitizing agents	Not previously considered	Not previously considered	• *Sanitizing agents can be added to cold water to reduce the need for hot water washing* • *R&D needed to investigate the safety & environmental effects of certain sanitizing agents*	LOW

Table 13. Task 4 - Clothes Dryer Summary of Stakeholder Comments

Technology Option	R&D Objective	R&D Tasks	Discussion Summary	Consensus Priority (Change Indicated)
Tier 1 (High Priority)				
Mechanical steam compression (electric only)	To validate the technology concept by developing a working prototype and performing testing under laboratory conditions.	• Develop fully integrated prototype system • Characterize system performance and compare to modeled predictions • Perform preliminary testing using clothing loads • Modify/optimize internal components based on preliminary testing • Further refine design to produce fully functional prototype system	• *Technology seems feasible, but not likely to have greater energy savings potential than heat pump dryers* • *Technology will require additional seals and pressurized compartments to accommodate pressurized steam, which will increase cost and complexity over standard heat pump design*	MEDIUM (downgrade)
Heat pump (electric only)	To support the development of ENERGYSTAR criteria for heat pump dryers.	• Collaborate with EPA and stakeholders to develop ENERGYSTAR criteria for heat pump dryers • Perform energy testing and analysis to support ENERGYSTAR program	• *General recognition of heat pump's success in Europe* • *Expectation by industry that heat pump technology will enter the North American market in the future* • *Technology would benefit from ENERGY STAR support, utility/government rebates, and pilot testing upon introduction of first commercial units in the market*	HIGH (no change)
Tier 2 (Medium Priority)				
Microwave (electric only)	To demonstrate a safe microwave dryer by developing a pre-commercial demonstration unit.	• Refine previous prototype models to address safety concerns • Develop pre-commercial demonstration unit • Perform pilot testing in residential settings • Perform testing using an adapted version of the DOE test procedure • Estimate unit energy savings potential based on results	• *Manufacturers generally aware of previous development efforts of this technology* • *Safety concerns remain the key barrier to commercialization*	LOW (downgrade)
Inlet air preheat	To demonstrate a viable inlet air preheating technology for residential dryers.	• Perform testing to characterize energy benefits of current "heat wheel" technology • Demonstrate smaller-scale design that could be applicable to residential dryers • Develop modified residential dryer with air inlets/outlets to work with heat wheel technology • Investigate the potential for installing heat exchanger inside dryer cabinet	• *Manufacturers expressed general interested in the idea* • *Water condensation would require extra plumbing and a drain* • *Uncertainties regarding potential efficiency gains* • *Could be more practical for commercial laundry settings*	MEDIUM (no change)
Indirect heating	To assess the energy savings potential of indirect (hydronic) clothes dryers by testing hydronic clothes dryers currently available on the market.	• Procure several working units • Perform testing using DOE test procedure (adapted if necessary) • Determine energy savings potential	• *Confirmation of uncertainty of potential energy savings of back-to-back dryer cycles* • *Lack of a cool-down phase before the load comes to a rest could pose a safety hazard*	LOW (downgrade)

Table 14. Task 4 - Dishwasher Summary of Stakeholder Comments

Technology Option	R&D Objective	R&D Tasks	Discussion Summary	Consensus Priority (Change Indicated)
Tier 3 (Low Priority)				
Ultrasonic washing	To investigate the energy savings potential, cleaning performance, and overall viability of ultrasonic technology in residential dishwashers.	• Procure the model currently available on the Indian market • Perform exploratory testing to verify cleaning performance, energy consumption, sanitization, and safety. • Determine energy savings potential	• *Technology does not seem realistic in American markets* • *Concerns about amount of water required* • *Technology may not be as useful on plastic dishware*	REMOVED FROM CONSIDERATION
Supercritical carbon dioxide washing	To determine the technology's development status, assess its cleaning performance, and assess the viability of using supercritical carbon dioxide technology in residential dishwashers.	• Verify development status of supercritical CO_2 dishwasher • Demonstrate proof-of-concept of cleaning performance in benchtop prototype • Investigate feasibility of technology for residential dishwashers	• *Unlikely to be accepted by residential consumers due to the need for high-pressure* CO_2	REMOVED FROM CONSIDERATION

Table 15. Task 4 - Cooking Equipment Summary of Stakeholder Comments

Technology Option	R&D Objective	R&D Tasks	Discussion Summary	Consensus Priority (Change Indicated)
Tier 2 (Medium Priority)				
Specialized cookware	To verify energy savings potential of residential-sized cookware, and to determine consumer acceptance of specialized cookware by implementing a trial consumer incentive program.	• Procure residential-sized specialty cookware • Perform investigative energy testing to verify energy efficiency potential • Implement trial consumer incentive program to stimulate purchases of specialized cookware • Determine consumer acceptance rate and feasibility	• *Manufacturers expressed generally interest with the proposal* • *Technology could be more applicable in commercial settings*	MEDIUM (no change)
Induction cooking	Not previously considered	Not previously considered	• *Technology offers much higher efficiency than traditional electric or gas cooktops* • *Technology already available in the market* • *Technology not accommodated by current test procedure for cooking equipment* • *Technology could benefit from ENERGY STAR certification*	MEDIUM
Tier 3 (Low Priority)				
Catalytic burners (gas only)	To investigate the viability for use in residential applications and to determine the energy savings potential of catalytic burner technology.	• Develop integrated bench-top prototype • Test prototype to determine energy savings potential	• *Not likely to be embraced by manufacturers or consumers* • *Little to no energy savings*	REMOVED FROM CONSIDERATION
Pulse combustion (gas only)	To validate the energy savings potential of pulse combustion gas burners.	• Procure/develop working prototype based on patented technology • Test prototype to determine energy savings potential	• *Not likely to be embraced by manufacturers or consumers* • *Little to no energy savings*	REMOVED FROM CONSIDERATION
Radiant gas burners (gas only)	To validate the energy savings potential of radiant gas burners.	• Procure previously developed prototypes • Test prototype to determine energy savings potential	• *Not likely to be embraced by manufacturers or consumers* • *Little to no energy savings*	REMOVED FROM CONSIDERATION
Steam cooking	To assess the energy savings potential of steam-cooking ovens currently on the market.	• Procure several working units • Perform testing using adapted DOE test procedure • Determine energy savings potential	• *Technology may be undesirable from consumer standpoint because consumers like to get crispy sear on food, which steam does not provide*	LOW (no change)
Reduced excess air at burner (gas only)	To confirm theoretical energy savings potential by developing and testing a working prototype.	• Replicate components from previous studies • Integrate components to create a prototype cooktop system • Test system for basic functionality	• *Not likely to be embraced by manufacturers or consumers* • *Little to no energy savings*	REMOVED FROM CONSIDERATION
Oven coatings	Not previously considered	Not previously considered	• *Coatings with innovative materials could reduce the heat required during self-clean cycles* • *Self-clean temperature could potentially be reduced by a few hundred degrees*	LOW
Smart burners	Not previously considered	Not previously considered	• *Technology would adjust flame to keep pot at constant temperature, thus eliminating excess waste heat* • *Technology likely to be embraced by both manufacturers and consumers*	LOW

Table 16. Task 4 - Cross-cutting Summary of Stakeholder Comments

Technology Option	R&D Objective	R&D Tasks	Discussion Summary	Consensus Priority (Change Indicated)
Tier 1 (High Priority)				
Integrated energy and water recovery & transfer between appliances	To measure and validate the energy savings potential of the ZEHcore concept by performing laboratory tests simulating real-world usage patterns, and through a pilot demonstration project in a residential setting.	• Develop fully integrated prototype system • Characterize system performance and compare to modeled predictions • Perform preliminary laboratory testing using actual appliances • Modify/optimize internal components based on preliminary testing • Further refine design to produce fully functional prototype system • Conduct further laboratory tests simulating real-world usage patterns • Conduct pilot demonstration in a residential setting	• *Manufacturers expressed general interest in integrated energy and water recovery and transfer between appliances* • *R&D efforts could focus on highly-insulated flexible tubing between appliances* • *Technology may be easier to implement in traditionally paired appliances (e.g. washer and dryer)*	HIGH (no change)

Appendix B Technology Readiness Level (TRL) System

This Appendix provides a description of the Technology Readiness Level (TRL) system referenced throughout the report.

Table 17. Technology Readiness Level (TRL) System for Categorizing Technology Development Status

Relative Level of Technology Development	Technology Readiness Level (TRL)	TRL Definition	Description
Basic Technology Research	**TRL 1**	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting information includes published research or other references that identify the principles that underlie the technology.
	TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Technology Development	**TRL 4**	Component and/or subsystem validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on-hand equipment and a few special-purpose components that may require special handling, calibration, or alignment to get them to function.

	TRL 5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and TRL 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Demonstration	**TRL 6**	Engineering/ pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and TRL 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
System Commissioning	**TRL 7**	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
	TRL 8	Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system in a realistic environment. Supporting information includes operational procedures that are virtually complete.
System Operations	**TRL 9**	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. Examples include using the actual system with the full range of functionality.

Source: U.S. Department of Energy Technology Readiness Assessment Guide. Publication DOE G 413.3-4. October 12, 2009. (DOE, 2009)

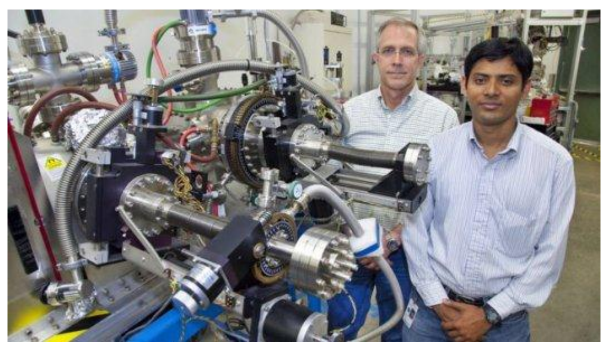
Appendix C Description of Appliance Technology Options

This appendix provides detailed descriptions of each technology option, including current development status and links to relevant source information. The order of technology descriptions corresponds to the order in which the technologies are presented in the final report above.

C.1 Refrigerator/Freezers

C.1.1 Magnetic Refrigeration

Magnetic refrigeration is based on the magneto-caloric effect (MCE). MCE is a magneto-thermodynamic phenomenon in which a reversible change in temperature of a paramagnetic material is caused by exposing it to a changing magnetic field. In the magnetic refrigeration cycle, randomly oriented magnetic spins in a paramagnetic material are aligned via a magnetic field, resulting in a rise in temperature. This heat is removed from the material to ambient by means of heat transfer. Upon removal of the magnetic field, the magnetic spins return to its randomized state thus cooling the material to below ambient temperature. The material is then used to absorb heat from the refrigerated volume thus cooling that space and returning the paramagnetic material to its original state and the cycle starts again. For room temperature applications, materials are needed that have a Curie temperature (the temperature above which ferromagnetic materials loss their permanent magnetism) around 295 K. Gadolinium and Gadolinium alloys have a large MCE around this temperature range and they are among the most widely used materials for room temperature refrigeration and space cooling applications.



A working prototype has been developed at the **Ames Laboratory**. However, due to the high magnetic field, the system is not applicable for use at home. The ultimate goal of this research would be to develop a standard refrigerator for home use.

Sources:
1. United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf
2. Idea Connection, July 2010. http://www.ideaconnection.com/new-inventions/magnetic-refrigeration-03730.html

C.1.2 Vacuum Insulation Panels

Vacuum-insulated panel (VIP) technology is based on the reduction in conductivity that occurs in a low vacuum. VIPs used in refrigeration products consist of a sealed package with a fill material which provides support to prevent the panel from collapsing and interferes with molecular mean free path as the intermolecular spacing increases at lower vacuum levels. VIPs can be foamed in place between the cabinet liner and wrapper to decrease the heat leakage and energy required to maintain the cabinet at low temperature. Different configurations are commercially available through advances in manufacturing technologies. As a result, VIPs are available in a variety of geometries (e.g., flat, curved, cylindrical) with added features (e.g., holes, cut-outs). Typical VIPs generally consist of a core material and an airtight envelope. Some VIPs also include absorber to absorb gas which leaks through the envelope.

Of significant concern for VIPs is their long-term thermal conductivity integrity. VIP thermal conductivity increases dramatically as the pressure within the VIP exceeds 100 Pa (1 mbar). The pressure increase in the VIP over time is related to several factors, including: residual gases in the VIP after vacuum, degassing from the VIP core material, and gas diffusion through the envelope pores. Improved envelopes and absorbers have been developed to prevent pressure increases from occurring in VIPs. **Oak Ridge National Laboratory** (ORNL) analyzed three composite VIPs and measured only a five-percent reduction in overall thermal resistance over a three-year period. ORNL demonstrated that this reduction in thermal resistance was less than the corresponding reduction for a panel without any VIPs, i.e., panels consisting only of PU foam insulation.

VIPs are currently commercially available, but research is ongoing in reducing the cost and longevity of VIPs. Several core materials have been used in the manufacture of VIPs including polystyrene, open-cell PU, silica powder, and glass fiber. Research sponsored by the **European Commission** has evaluated these core materials based on their cost and characteristics, including density and manufacturing time. Additionally, ORNL also has evaluated the performance of three types of VIPs: a silica powder filler encapsulated in a polymer barrier film; a fibrous glass insulation filler encapsulated in a stainless steel barrier; and an undisclosed insulation filler encapsulated in a stainless steel barrier.

Source:
United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf

C.1.3 Improved Linear Compressors

Linear compressors employ a different design than either reciprocating or rotary compressors and are reportedly more efficient than both. These compressors use a linear rather than rotary motor, thus eliminating the crankshaft and linkage which converts the rotary motion to the linear motion of the piston of a reciprocating compressor. Elimination of the mechanical linkage reduces friction and side-forces. The linear motor requires power electronics and a controller to assure proper piston throw. Most linear compressor designs use a free piston arrangement and can be controlled for a range of capacities through adjustment of piston displacement. Early work on the concept suggested that the compressors can operate without requiring oil, which could provide additional energy benefit by improving heat transfer in the evaporator. Refrigerator noise levels can also be reduced by utilizing linear compressors in the same way that this can be done with variable-speed compressors, by operating most of the time at low capacity. Linear compressor may be about 9% more efficient than the best current-technology rotating-shaft reciprocating compressors.

At least one manufacturer, **LG**, uses linear compressors in some of its commercially available refrigerator/freezers. LG claims that the linear compressors emit lower noise levels and require less energy to operate than conventional compressors.

Sources:
1. United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf
2. LG product website: http://www.lg.com/us/kitchen/refrigerator/energy-efficient-refrigerator.jsp
Accessed March 21, 2012.

C.1.4 Stirling Cycle Refrigeration

A Stirling-cycle machine is a device that operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperature levels, and where the flow is controlled by volume changes, so that there is a net conversion of heat to work or vice versa. “Regenerative” refers to the use of an internal heat exchanger, the regenerator, which is an essential part of the Stirling cycle. A Stirling refrigeration cycle compresses and expands an inert gas in a single cylinder. Heat is rejected at one end of the cylinder and absorbed at the opposite end. In the absence of all thermodynamic losses, the efficiency could be higher than for vapor compression systems. Various technical difficulties have so far limited the use of Stirling-cycle cooling to small prototype domestic refrigerators. There is no circulating refrigerant fluid and the hot and cold heat areas are relatively small, which creates heat exchange challenges for any but the lowest-capacity systems.

Source: United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf

C.1.5 Thermoelastic Refrigeration

Thermoelastic cooling is based on a thermoelastic shape memory alloy (SMA) that releases heat when compressed and returns to its original shape when heated. Two or three alloys are combined in precise proportions that permit them to take on two different internal structures, depending on their temperature and pressure. Thermoelastic cooling occurs when an SMA is strained or stretched, resulting in a solid phase change of the material. This phase change is accompanied by a nearly-reversible temperature rise in the material. The material rejects heat to its surroundings in its strained state. When the SMA is relaxed from its strained state, a solid phase change occurs back to its initial phase. This phase change is accompanied by a nearly-reversible temperature drop. In the relaxed state, the SMA absorbs heat from a temperature source.

The efficiency of the thermoelastic cooling process is high, with a coefficient of performance (COP) estimated at 11.8, which is double that of state-of-the-art vapor compression technology. This technology, however, has drawbacks in its current preliminary form; these include a relatively low latent heat (~12 kJ/kg) and a limited fatigue life. The University of Maryland, collaborating with **General Electric Global Research** and the **Pacific Northwest National Laboratory**, is developing a 0.01-ton prototype with the goal of establishing the commercial viability of thermoelastic cooling.

Sources:

1. *Quick, Darren. "'Thermally-elastic' metal to cut summer CO2 emissions and electricity bills". Gizmag July, 2010. http://www.gizmag.com/thermally-elastic-smart-metal/15793/*
2. *Thermoelastic Cooling". Degrees. http://www.reece.com.au/degrees/2011/Apr/thermoelastic.html*
3. *Smart Metals for Solid-State Cooling Nix Greenhouse Gases". Smarter Technology. http://www.smartertechnology.com/c/a/Technology-For-Change/Smart-Metals-for-SolidState-Cooling-Nix-Greenhouse-Gases/*
4. *SBIR Phase I Award Abstract". NSF. http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1143093*
5. *Refrigeration Machines". http://www.machine-history.com/Refrigeration%20Machines*
6. *New 'Smart' Metal Could Mean Cool Cash for Consumers, Less CO2". July 15, 2010. http://www.newsdesk.umd.edu/vibrant/release.cfm?ArticleID=2198*

C.1.6 Thermoelectric Refrigeration

Thermoelectric cooling occurs when a current is passed across the junction of two dissimilar metals. One side of the device becomes hot and the other becomes cold. Semiconductor materials have relatively recently been developed that have allowed for the use of this type of cooling in some applications. Thermoelectric cooling devices have no moving parts and have extremely long lifetimes. There are several compact refrigerators and wine coolers using thermoelectric cooling that are currently on the market, including several models offered by **Avanti Products**. However, their efficiency is lower than traditional vapor-compression models, and the technology is not yet suitable for standard-size residential refrigerator-freezers.

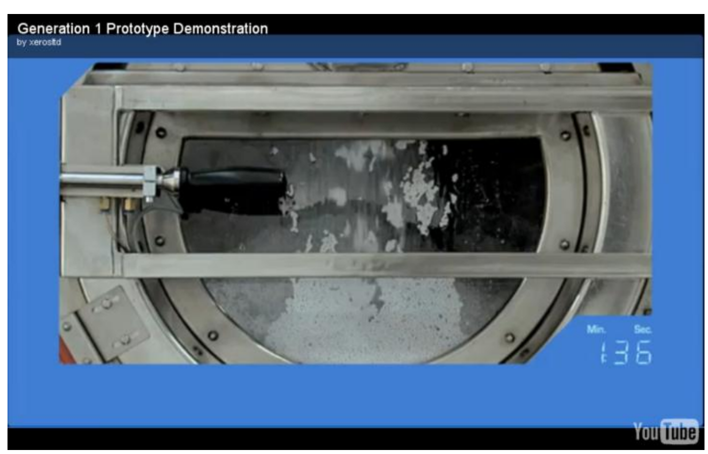
DOE tested a thermoelectric refrigerator from **Haier**, model HRT02WNC, a 1.7 cubic foot all-refrigerator. Testing revealed that the thermoelectric module EER was 0.9 at a temperature lift of at most 33 °F, an order of magnitude less than is achieved by conventional technology.

Sources:
1. United States Department of Energy. Final Rule Technical Support Document: Refrigerators, Refrigerator-Freezers, and Freezers. August 25, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/refrig_finalrule_tsd.pdf
2. Avanti Products, September 2011. http://www.avantiproducts.com/superconductor

C.2 Clothes Washers

C.2.1 Polymer Bead Cleaning

This technology is currently in development by **Xeros Ltd**. in the United Kingdom. Polymer bead cleaning uses the absorbent properties of nylon polymer beads to clean clothes. The nylon beads are added to the wash drum with a small amount of water and detergent to loosen the dirt or stains on the clothing. The clothes are tumbled with the polymer beads for around 45 minutes. The polarity of the nylon polymer attracts stains from the clothing. Under humid conditions, the polymer becomes absorbent. Dirt is



attracted to the surface and then absorbed into the center of the bead. At the end of the cycle, the polymer beads are separated from the clothing through an inner drum/outer drum rotation process.

Research conducted in the United Kingdom has shown that this technology would reduce water consumption by up to 90% compared to a traditional clothes washer. Including lower temperature cleaning and reduced detergent consumption, total laundry carbon footprint would be reduced by up to 40%.

According to the manufacturer's website, Xeros Ltd. has successfully concluded two field trials in the United Kingdom. One field study is in a commercial-scale dry cleaning setting and the other is in a commercial-scale industrial setting. Additionally, development is ongoing to create prototypes for residential use. The company is open to exploring R&D partnership opportunities.

Source: Xerox, Ltd. March 2012. http://www.xerosltd.com/xeros-marketing.htm

C.2.2 Sanitizing Agents

Sanitizing agents, such as chemical or ionic compounds, can be added to the incoming cold wash water to reduce the need for hot water washing. Clothes washers using such sanitizing agents could offer cooler wash cycles that provide sanitization of the clothing; such wash cycles typically require hot water temperatures up to 140°F.

One example of a sanitizing agent is the addition of silver ions to the cold wash water. Silver is a natural disinfectant and can provide sanitization during a cold water wash. **Samsung** previously offered silver ion injection as an alternative to the traditional hot water sanitization cycle in its SilverCare™ line of front-loading residential clothes washers; however, clothes washers with this feature are no longer available on the market. With this feature, silver is electrolyzed during the wash and rinse cycles, and, according to Samsung, the released silver ions penetrate into the fabric, killing bacteria and sanitizing the clothes. Samsung also states that the silver ions eradicate bacteria and mold from inside the clothes washer, disinfecting the drum and other internal parts.

Because the silver ion injection feature can be used for sanitization in cold water, energy savings can be achieved compared to a hot water or steam sanitization cycle. The sanitization of the machine may also eliminate the need for period self-cleaning cycles commonly recommended for front-loading clothes washers.

The long-term health effects of human and environmental exposure to nanoscale silver particles are unknown. In September 2007, the U.S. Environmental Protection Agency (EPA) issued a *Federal Register* notice in which it determined that clothes washers will be regulated as pesticides if the machines contain silver or other substances, and if they generate ions of those substances for express pesticidal purposes. According to this decision, a manufacturer would be required to register a clothes washer with EPA as a pesticide if the product is marketed with claims that it will kill bacteria on clothing.
In May 2008, a group of advocacy organizations sued the EPA asking the agency to issue new rules regulating products containing nanoscale silver particles. The petition claimed that EPA failed to adequately regulate products containing or using nanoscale silver particles. The petition asks EPA to: (1) classify nanoscale silver as a new pesticide; (2) require detailed product registration and data submissions under the Federal Insecticide Fungicide and Rodenticide Act; and (3)analyze the potential environmental, health, and safety risks of nanoscale silver.

Sources:

1. *United States Department of Energy. Draft Final Rule Technical Support Document: Residential Clothes Washers. Draft copy March 21, 2012.*
2. *Samsung 2010. "Silver Nano Health System – Frequently Asked Questions." Samsung website. Accessed March 4, 2010. http://ww2.samsung.co.za/silvernano/silvernano/wash_faq_popup.html*
3. *"Ions and Free Radicals." Appliance Magazine, September 2007. Accessed online at http://www.appliancemagazine.com/editorial.php?article=1820&zone=1&first=1*
4. *EPA Announcement. "Pesticide Registration: Clarification for Ion Generating Equipment." September 21, 2007. Accessed online at http://www.epa.gov/oppad001/ion_gen_equip.htm.*
5. *Monica, John C. "EPA Sued Over Nanoscale Silver." Nanotechnology Law Report. May 3, 2008. Accessed online at http://www.nanolawreport.com/2008/05/articles/epa-sued-over-nanoscale-silver.*

C.3 Clothes Dryers

C.3.1 Heat Pump Clothes Dryer

Heat pump dryers function by recirculating the exhaust air back to the dryer while moisture is removed by a refrigeration-dehumidification system. A heat pump dryer is essentially a dryer and a dehumidifier packaged as one appliance. No heating element is needed. The warm and damp exhaust air of the dryer enters the evaporation coil of the dehumidifier where it cools down below the dew point, and sensible and latent heat are extracted. The heat is transferred to the condenser coil by the refrigerant and reabsorbed by the air, which is moving in a closed air cycle. A drain is required to remove the condensate; however, one is usually available since clothes washers and dryers are typically located side by side.

Heat pump dryers have been unable to penetrate the U.S. market despite showing significant energy savings. The major issue for heat pump dryers has been cost and performance. Heat pump dryer cycle times are typically significantly longer than those associated with standard U.S. electric dryers. More maintenance will probably be required for a heat pump dryer than for a conventional dryer. The traditional heating element is replaced by equipment found in a small room air conditioner— a condenser, evaporator, compressor, expansion valve, etc. Installation costs, though, may be less than for a conventional electric dryer because the heat pump dryer does not require an exhaust vent as does a conventional dryer (although some heat pump dryers may still use a vent). However, heat pump dryers require access to a drain for removal of condensate.

Research conducted on both heat pump dryers and conventional vented dryers on the European market showed that heat pump dryers consumed about 50 percent less energy than conventional dryers. The heat pump dryers tested had energy efficiency values between 0.32 and 0.40 kWh/kg laundry (with 70 percent initial moisture, measured according to test standard EN 61121) whereas conventional dryers had values between 0.6 and 0.8 kWh/kg laundry. Another benefit noted by this research was that the leakage of water vapor into the room was around 20 percent, which is significantly lower than conventional dryers. This research performed a cost comparison of heat pump dryers versus conventional dryers, which showed that the combined sale price and electricity costs over 15 years was about 1900 and 2300 Euros, respectively.

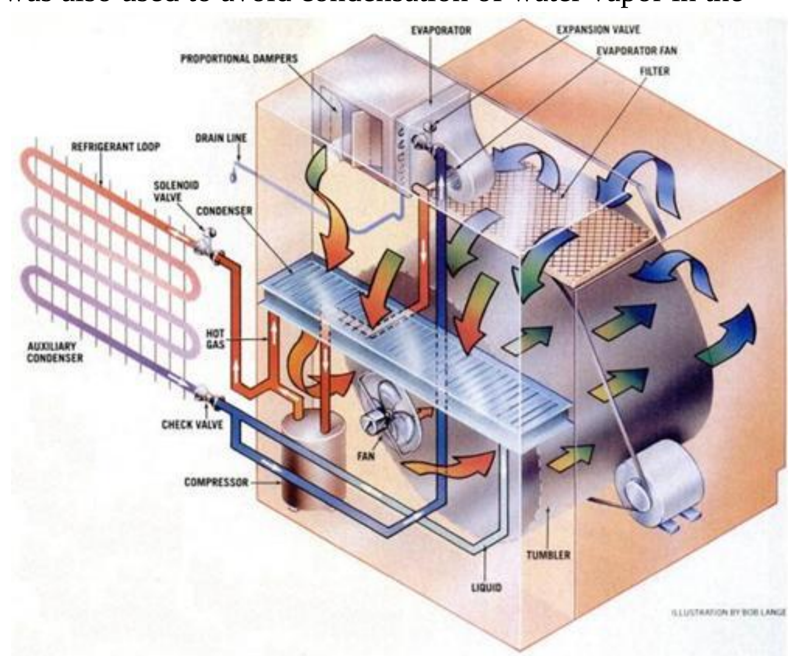
According to the DOE technical support dryer for the clothes dryer energy conservation standards, a heat pump dryer has been developed by a U.S. company which has successfully tested several prototypes and found energy savings of 68 percent as compared to energy use by a conventional electric clothes dryer. The estimated retail cost is approximately twice that of a conventional electric dryer. Drying times were essentially the same as for the conventional dryer, and the dryer operates on standard 120 V line power. The prototype uses a disposable filter to reduce lint in the air system. One inch of polyisocyanurate insulation was used to avoid condensation of water vapor in the recirculated air. In addition, the extension on the back of the prototype dryer to accommodate the added refrigeration components was estimated to be about the same depth as a vent duct, so the cabinet may fit in the same space as a conventional dryer.

Research sponsored by **TIAX** and **Whirlpool** developed a high efficiency, high-performance heat pump clothes dryer for the U.S. market. This different approach to the heat pump system maximized the output capacity and temperature from the heat pump. This design has shown 40 to 50 percent energy savings on large loads along with 35 degree Fahrenheit (°F) lower fabric temperatures and similar drying times as conventional dryers. For delicate loads, the design reduced fabric temperature by 10–30 °F and provide up to 50 percent energy savings and 30–40 percent drying time savings. The heat pump dryer designed by TIAX also exhibited improved fabric temperature uniformity as well as robust performance across a range of vent restrictions in a partially open-loop design.

In order to maximize the air inlet temperature and airflow into the dryer's drum, TIAX replaced the standard refrigerant, R-22, with R-134a in an R-22 air conditioner/heat pump compressor, shifting evaporating and condensing temperatures by 30 °F while maintaining similar operating pressures and power input. TIAX was also able to maximize the capacity of the heat pump system by redesigning the heat exchanger components to optimize space utilization and increasing the airflow in the system as compared to typical dryers.

A key issue in the TIAX design was the venting options of the heat pump dryer. The moisture in the air exiting the drum is removed by the evaporator. This air can then be recirculated back into the drum, which removes the need for a vent. However, some form of heat rejection is required since the heat pump generates more heat than cooling in steady state operation. TIAX used a partially open-loop design in which a portion of the process air is vented outdoors to remove excess heat. In this design, all of the process air is recirculated through the dryer until the system has fully warmed, at which point the exhaust is opened and a portion of the total flow is vented to the outside.

In the late 1980s, the **Nyle Corporation** developed a ventless heat pump dryer, funded through a grant with the Department of Energy. The dryer reportedly used two-thirds less energy than a traditional electric dryer and operated on a 110-volt circuit, rather than the typical 220-volts required by traditional electric dryers. The estimated retail cost was approximately $800, around twice the cost of a conventional dryer at the time. The dryer used a chlorofluorocarbon-based refrigerant loop with a coefficient of performance of approximately 2.6. Drying times were essentially the same as with a conventional dryer. The dryer used a disposable filter to reduce the lint in the air system. Insulation was also used to avoid condensation of water vapor in the recirculated air.



According to DOE dryer rulemaking documents, the prototypes were constructed by modifying a conventional electric dryer. The unit resembled a conventional dryer except that it contained the refrigerant system in the rear of the cabinet, which usually houses the electric heater. The extension on the back of the dryer was approximately the same depth as a vent duct, so the cabinet could fit within the same space as a conventional dryer.

Nyle had arranged for an offshore manufacturer to make the heat pump dryers, but economic problems that developed had prevented commercial units from being made.

Sources:
1. United States Department of Energy. Direct Final Rule Technical Support Document: Residential Clothes Dryers and Room Air Conditioners. April 21, 2011. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/residential/residential_clothes_dryers_room_ac_direct_final_rule_tsd.html

2. E. Bush and J. Nipkow. 2006. Tests and Promotion of Energy-Efficient Heat Pump Dryers. Report Prepared for International Energy Efficiency in Domestic Appliances & Lighting Conference '06.

3. P. Pescatore and P. Carbone. 2005. High Efficiency High Performance Clothes Dryer. Final Report to Department of Energy.

4. V. Elaine Gilmore. November 1989. "Heat-pump clothes dryer." Popular Science. pp.124-126.

C.3.2 Inlet Air Pre-Heating

For this technology option, a heat exchanger is used to recover exhaust heat energy and to preheat inlet air. This system should be feasible for both gas and electric dryers since none of the exhaust air re-enters the dryer. Energy savings are achieved either by a faster drying time or by reducing the required heater input power.

A limitation of this technology option is that a large surface area is required to achieve sufficient heat transfer, and that lint may accumulate on these heat transfer surfaces. Although every dryer is equipped with a lint filter, considerable lint is still contained in the exhaust air. This lint can foul the heat exchanger, decreasing its effectiveness. Additionally, to overcome the increased resistance to air flow, an extra blower is needed at the fresh air inlet or a stronger blower in the exhaust air duct is required.

Manufacturers have also expressed concern that any decrease in exhaust temperature will lead to moisture condensation in the exhaust duct, which could result in damage to the exhaust duct and dryer, as well as water leakage into the home. Water leakage into the home could lead to the health risks from the development of mildew and/or mold.

One example of a technology for recovering dryer exhaust heat is the Rototherm heat recovery wheel, manufactured by **Rototherm Corporation.** Half of the heat recovery wheel is exposed to the dryer air inlet, while the other half is exposed to the dryer exhaust inlet. The wheel is constructed of alternate layers of flat and corrugated aluminum, as shown in the figure below.

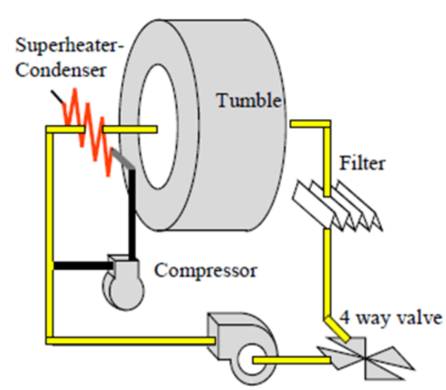
As the heat wheel spins, heat is extracted from the exhaust outlet and transferred to the colder dryer inlet air. A case study featured on the company website claims a fuel reduction of 44-51% using the heat recovery wheel.

Source: Rototherm Corporation. http://www.rototherm.net/index1.html

C.3.3 Mechanical Steam Compression

The **Center for Energy Studies** has developed a super-heated steam (SHS) dryer using mechanical steam compression (MSC). Instead of using hot air to dry the clothing, mechanical steam compression dryers use water recovered from the clothing in the form of steam.

First, the tumbler and its contents are heated to the boiling point of water at 100°C/212°F. The resulting wet steam purges the system of air, and the internal atmosphere is now pure water vapor. As wet steam exits the tumbler, it is mechanically compressed to extract water vapor and transfer the heat of vaporization to the remaining gaseous steam. The extracted water is drained from the compression chamber, and the pressurized gaseous steam is allowed to expand and be superheated before being injected back into the drum. Back in the drum, heat from the super-heated steam causes more water to vaporize from the clothing, creating more wet steam and restarting the cycle.



The considerably higher temperatures used in mechanical steam compression dryers result in a one-hour drying time, roughly half as long as the drying time for a heat pump dryer. The energy consumption of a mechanical steam compression dryer is roughly 55% less than a traditional electric dryer.

The Center for Energy Studies has completed preliminary performance testing on a compressor that could be used in such a system. Computer simulations have been conducted to model the performance of a complete working system; however, a working laboratory prototype has not yet been built.

Source: Palandre and Clodic. "Comparison of Heat Pump Dryer and Mechanical Steam Compression Dryer" http://www-cep.ensmp.fr/francais/innov/pdf/ICR0143SLV%20_IIR_IIF%20Conf.pdf

C.3.4 Indirect Heating (Hydronic) Clothes Dryer

For indirect heating, the clothes dryer heat energy is derived from an external heating system such as the home's hydronic heating system, or a stand-alone supplementary hydronic system. This technology option uses a hydronic heating system to heat water which then flows through a heat exchanger in the dryer, heating the air entering the drum. To use a home's existing heating system, significant plumbing would be required to circulate heated water through the heat exchanger in the dryer. In its clothes dryer rulemaking, DOE was unaware of any data quantifying potential energy efficiency improvements associated with indirect heating.

Hydromatics Technologies Corp. developed a built-in hydronic heating system for electric dryers, marketed under the Safe-Mates brand. In the system, a heat transfer fluids is heated using an immersion element similar to a water heater. The heated fluid passes through a heat exchanger, where the heat is transferred to the air entering the drum, and is then pumped back to the hydronic heater. The company claims that their clothes dryer uses 50 percent less energy compared to a conventional clothes dryer. However, it appears that this estimate refers to the fact that the hydronic heating system draws 2,500 Watts of power, versus a typical electric heater that draws around 5,000 Watts. It is unclear whether the total cumulative energy consumption over a complete cycle is less than a conventional clothes dryer, because the cycle time for the hydronic system may be longer. The website also claims that because the system utilizes a proprietary heat transfer fluid that retains its heat between loads much longer than a gas or electric clothes dryer's heating system can, more energy can be saved when drying back-to-back loads. The Safe-Mates dryer is also marketed as safer than a traditional electric dryer because of the reduced risk of lint fires.

Source: Hydromatic Technology Corporation. http://www.safe-mates.com/products.html

C.3.5 Microwave Clothes Dryer

Microwave energy can be absorbed by water, thereby heating the water enough to cause evaporation. This would be a direct and efficient manner to remove moisture from clothes. Instead of the conventional method of passing warm air over the clothes, microwave energy can be directly absorbed by water retained in the clothing, thereby heating the water enough to cause evaporation. Microwave drying uses the principle of dielectric heating, in which electromagnetic energy is radiated into the dryer drum where it is absorbed by water molecules which have a higher dielectric loss factor than most common fabric materials. Most fabric materials are also relatively transparent to microwave energy, so that the microwaves can penetrate the fabric's interior to heat the water molecules directly. This allows the fabric in a microwave dryer to stay cooler—below 115 °F—as compared to conventional dryers which heat air to approximately 350 °F, with fabric surfaces reaching 150 °F.

Microwave dryer prototypes have been shown to consume about 17 to 25 percent less energy as well as to dry clothes about 25 percent faster than conventional electric dryers.

Early conceptualization of this technology began in the mid-1960s; however, product development was not pursued because of high manufacturing costs and difficulties in overcoming hazards relating to arcing and overheating of clothing. In 1997, the **Electric Power Research Institute** (EPRI) focused on developing a compact countertop dryer based on economic feasibility and market surveys. EPRI market studies and the development of prototypes for in-house evaluation have led to negotiations for technology licensing and indications of serious product development for a residential microwave clothes dryer.

Because of the interaction between the metallic sensor contacts and the electromagnetic field, microwave dryers are incapable of using contact moisture sensors as in conventional dryers. EPRI investigated using sensors to detect the microwave electric field strength and the fabric temperature, which both correlate well with the moisture content. As evaporation nears completion, both measured signal slopes begin to rise in a predictable manner, so that the dryer can be shut off automatically and avoid wasted energy in over-drying clothes.

Microwave drying also introduces a safety concern related to arcing. Arcing is caused by an electric field which induces a voltage differential between metal objects, allowing current to flow within them. The resultant heating and sparking of the metal objects may ignite a fire in the load. EPRI has developed a rapid-response gas sensor to detect small amounts of gaseous by-products of combustion in the exhaust stream. Upon detection, the drying cycle can be shut down immediately, preventing safety hazards and damage. Another technique to avoid arcing is to switch to electric resistance heaters when the clothes are almost dry.

Sources:
1. Ashley, Steven. 1998. "Energy-Efficient Appliances." Mechanical Engineering. Vol. 120, No. 3, pp. 94–97.

2. J. Gerling. 2003. "Microwave Clothes Drying – Technical Solutions to Fundamental Challenges." Appliance Magazine. April 2003.
3. EPRI. "Microwave Drying of Textile Products." October 1999. http://my.epri.com/portal/server.pt?space=CommunityPage&cached=true&parentname=ObjMgr&parentid=2&control=SetCommunity&CommunityID=404&RaiseDocID=000000000001006118&RaiseDocType=Abstract_id

C.4 Cooking Equipment

C.4.1 Induction Cooktops

Induction cooktops use a solid-state power supply to convert 60 hertz alternating line current into a high-frequency (approximately 25 kilohertz) alternating current. This high-frequency current is supplied to an inductor. The inductor is a flat spiral winding located underneath a glass-ceramic panel. The high-frequency current, which is supplied to the inductor, causes it to generate a magnetic field, which passes through the glass-ceramic panel unaffected and produces eddy currents in the bottom of the cooking vessel. The vessel must be made of ferromagnetic material, and the eddy currents that are generated within it cause it to heat up. Thus, the vessel essentially becomes the heating element.

A sensor is placed between the inductor and the glass-ceramic panel, providing a continuous temperature measurement of the vessel bottom. Sensors also enable the inductor to only heat objects of at least 4 inches in diameter. This prevents any small metal objects, such as forks or spoons, from accidentally being heated. In addition, since the glass-ceramic panel is unaffected by the magnetic field, it remains relatively cool, reducing the potential for accidental burns.

The primary advantages of induction elements are their fast response and control of the heat source, their ease of cleaning, and their ability to heat vessels that are not flat. Because these features have usually been associated with gas burners, induction elements are being marketed in competition to them.

As noted above, the cooking vessel used with an induction element must be made from a ferromagnetic material. Since aluminum is not a ferromagnetic material, the current DOE test procedure, which specifies an aluminum test block, cannot be used to rate this equipment. In 1978, the **National Bureau of Standards** (NBS), now called **National Institute of Standards and Technology** (NIST), developed a proposed method of measuring the energy consumption of induction cooktops. The method is a modification of the current DOE test procedure. Energy use is determined by attaching a ferromagnetic material to the bottom of the aluminum test block. This modification was never formally adopted by DOE.

Source:
United States Department of Energy. Final Rule Technical Support Document: Residential Dishwashers, Dehumidifiers, Cooking Products, and Commercial Clothes Washers. Residential Clothes Dryers and Room Air Conditioners. April 8, 2009. Available online at http://www1.eere.energy.gov/buildings/appliance_standards/residential/cooking_products_final_rule_tsd.html

C.4.2 Specialized Cookware

Cookware modified with fins or grooves along the bottom surface have been shown to significantly increase cooktop performance. Heat-up times are substantially reduced and production capacities increased. Energy performance is also significantly improved. By simply using an advanced pot design, the 25–30% energy efficiency of a standard, gas-fired range top can be raised to more than 40%. When used on a range top with energy efficiency in the low 30s, the number can approach 60%.

Eneron Inc. has developed a line of cooking vessels that use aluminum fins to increase the surface area exposed to the burner flame, thereby maximizing the amount of heat transferred to the bottom of the pot.

Sources:
1. Appliance Magazine, August 2009. http://www.appliancemagazine.com/ae/editorial.php?article=2257&zone=215&first=1

2. Eneron, Inc website: http://www.eneron.us/index.html Accessed march 21, 2012.

C.4.3 Steam Cooking

With steam cooking, energy is transferred to the food load by means of the condensation of steam on the food surface. This may take place at essentially atmospheric pressure, or the cavity may be pressurized in order to allow higher steam temperatures and thus higher energy transfer to the food. In order to maintain the proper environment regardless of pressure, a “steam-tight” oven cavity must be maintained. In addition, the use of steam involves considerably higher demands on the oven’s design and materials. Not only are different cavity materials required (e.g., temperature-resistant silicone seals and chrome-nickel steel), but all incorporated elements and accessories must be redesigned and intensively tested. Energy is saved because food items that normally would need to be cooked separately (e.g., a meat roast in an oven and vegetables on a cooktop) can be cooked together.

There are several electric ovens with steam functions currently on the market. **BSH Home Appliances** has recently introduced the Gaggenau Combination Steam and Convection Oven. The oven utilizes a steam injection valve to control steam delivery to the cavity. The temperature and humidity level in the oven are user-selectable to tailor the cooking process as needed. Speed cooking is not advertised as the primary feature of this oven. Rather, food quality and nutrition is the focus. The steam capability is described as allowing vegetables to be cooked while retaining texture and nutritional content, meat to be roasted without drying out, and leftovers to be reheated without the loss of flavor and texture often associated with microwave reheating. Since this is a built-in oven, water delivery and condensate drainage are provided via plumbing lines much like a dishwasher. **Miele**, **Viking**, and **Gaggenau** also market steam convection ovens that do not require any external plumbing. Instead, they include a refillable container for water supply and collection.

Sources:
1. Gaggenau, http://www.gaggenau.com/US_en/products/product-detail.do?contentId=78b1160b-a568-4f52-8a4c-147fba99c97a
2. Miele http://www.mieleusa.com/products/models_pages/3/19/models.html?nav=20&snav=110&tnav=125&oT=38
3. Viking http://www.vikingrange.com/consumer/products/product.jsp?id=prod4840155

C.4.4 Advanced Oven Coatings

The self-cleaning cycle in ovens uses approximately 17% of the total annual energy consumption (using four self-clean cycles per year). Innovative oven coatings could improve the efficiency of the self-clean cycle by releasing food particles at lower temperatures. The reduced self-clean temperatures will reduce the overall oven annual energy consumption.

Maytag recently introduced its "AquaLift" self-clean technology. This self-clean technology is an interior oven that enables low heat and water to release baked-on spills in less than one hour. Temperatures stay below 200 degrees as compared to ovens that require heat of up to 800 degrees during the self-cleaning cycle. In less than an hour, the oven is ready for a final wipe-down to remove food and debris, with no odor or extreme heat like traditional high-temperature self-clean ovens.

Sources:

1. *Maytag, http://www.whirlpoolcorp.com/about/innovation/aqualift.aspx*
2. *Glaze, Ayana. "The Must-Have Self-Cleaning Oven of 2012". http://ext.homedepot.com/community/blog/the-must-have-self-cleaning-oven-of-2012/*

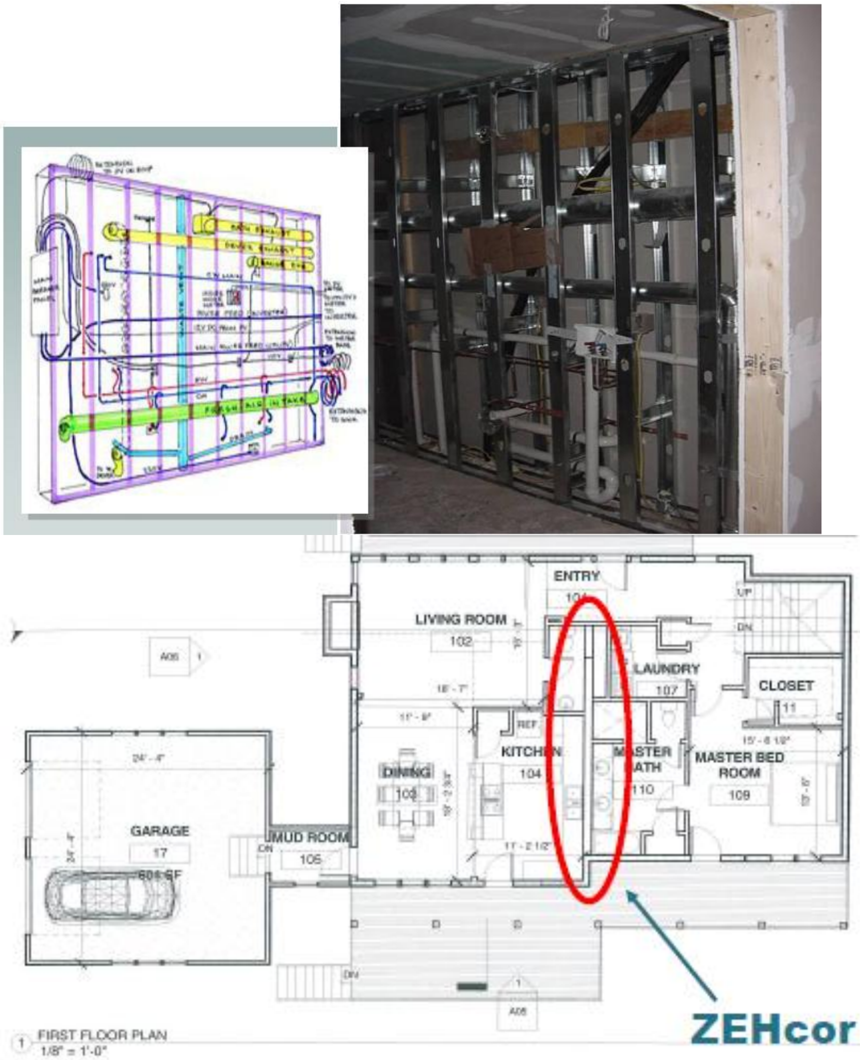
C.5 Cross-Cutting Technologies

C.5.1 Integrated Heat & Water Recovery

Whirlpool has designed a prototype integrated kitchen design concept where wasted water and heat are re-used from one appliance by another. The system captures heat from the refrigerator's compressor and uses it to pre-heat the dishwasher water. 60% of the water in the integrated system is captured, undergoes anti-bacterial treatment and then stored in an external water tank under the sink. This water can be used for the dishwashing cycle. The refrigerator is compartmentalized into drawers to prevent cold air from spill out when the doors are opened. Whirlpool estimates that savings would result in 7 liters (1.8 gallons) of water per cycle and up to 20% savings of electricity with the same washing performance. In total, the concept claims to increased water and energy efficiency by up to 70%.

Another concept, the Propane Energy Pod from the **Propane Education & Research Council** (PERC), is intended to serve as a new energy model for homes. PERC describes it as a research-based solution for home construction that treats five areas of energy use in a home: space heating, water heating, cooking, clothes drying, and fireplaces, all as part of a whole-home energy package. The model is designed for significant reductions in energy consumption and carbon emissions when compared to homes with standard appliances and mechanical systems. The Propane Energy Pod includes mechanical systems with high-efficiency amenities, such as on-demand hot water, professional-grade cooktops, and switch-on fireplaces. According to a study by Newport Partners, a home built using the Propane Energy Pod model can save homeowners about $285 in annual energy costs.

Additionally, **ORNL** has developed a ZEHcor Interior Utility Wall concept. The ZEHcore wall concept is a pre-fabricated wall to which all kitchen and laundry appliances would be connected, including major bathroom fixtures. The wall would be built off-site in a controlled environment. It is designed to reduce hot water distribution losses and enable a high level of integration between appliances that could not otherwise be accomplished reliably on-site. The ZEHcore wall could also be integrated with an external foundation heat exchanger.



Sources:
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2. Appliance Magazine, June 2011.
Source: http://www.appliancemagazine.com/news.php?article=1497114&zone=0&first=101
3. Images: http://www.treehugger.com/files/2008/03/kitchen-design-whirlpool.php
4. Thomas King. May 2009. "Addressing the Future Energy Challenges Through Innovation." Oak Ridge National Laboratory. Presentation available at http://e2s2.ndia.org/pastmeetings/2009/tracks/Documents/8240.pdf

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