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Comparison of Real World Energy Consumption to Models and Department of Energy Test Procedures

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Comparison of Real-World Energy Consumption to Models and Department of Energy Test Procedures

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Executive Summary

Background

DOE efficiency standards rulemaking calculations (e.g. national energy savings, environmental and other benefits, efficiency level impacts), utility incentive programs and rebates, and Building America models all rely on predicted energy consumption of appliances and equipment, often based on DOE test procedures and models. However, do DOE and industry test procedures really replicate real world conditions? Does performance degrade over time? If actual usage in the field is higher than predicted, standards calculations would need to be modified (e.g. higher standards might be justified), utility incentives could be changed, and Building America models would need to be adjusted. Furthermore, if performance degrades over time, then more robust designs could be appropriate.

The objective of our study was to:

- Identify and prioritize equipment to be investigated
- Review existing data and perform tests and measurements to determine whether real world performance differs substantially from predictions
- Identify and analyze the sources of any substantial differences
- Recommend appropriate changes to test procedures, models, or installation and maintenance practices
- Recommend R&D topics such as technology development to overcome deficiencies observed in the field.

Methodology

We followed a three-step methodology for our study.

- First, we identified and prioritized appliances to determine how real world energy consumption compares with models. Based on our prioritization, we selected storage water heaters (electric and gas) and refrigerators for further investigation.
- Second, for both water heaters and refrigerators, we determined whether real world energy consumption differs substantially from predictions and assessed whether performance degrades over time. We also identified the potential causes of any discrepancies we observed.
- Finally, we drew conclusions from our research and recommended test procedure modifications and areas for future research.

Summary of Water Heater Testing and Results

Approach

We followed a four-step approach to investigate the real world energy consumption of water heaters:

1. Conducted a broad literature survey and interviewed industry experts to find that the impact of aging on storage water heater performance was not well understood.
2. Procured used water heaters (in working condition) of different ages from the field.

3. Tested the water heaters using the DOE test procedure at an accredited laboratory and compared the results to rated efficiency metrics.
4. Systematically disassembled the tested sample of water heaters and recorded signs of degradation in key components of the units.

Summary of Literature Review

The literature review on real world energy consumption indicated two prominent areas of study:

1. Investigations of test procedure parameters, including:
    - Water draw patterns
    - Total hot water usage
    - Frequency of water draws.
2. Energy savings of water heaters with new technologies (e.g., tankless water heaters, condensing water heaters, solar heated water heaters).

The literature review did not reveal any significant research on the impact of aging on storage water heater performance. However, interviews with experts indicated strong interest in this topic and we focused our research on this issue.

Results from Performance Tests

We procured 13 used water heaters in working condition for testing. Table 1 provides the equipment characteristics of each unit in our test sample. For each water heater we tested, we determined the energy factor as rated by manufacturers from an Air-Conditioning, Heating, and Refrigeration Institute (AHRI) database[1]. We tested the water heaters at a DOE-accredited laboratory and compared the tested Energy Factor(EF) to the rated EF. We considered a variation of less than five percent from the rated energy factor to be insignificant.

Table 1: Characteristics of Used Water Heater Units

	Manufacturer	Type	Capacity	Age (years)
Unit 1	A.O.Smith	Electric	40 gallons	2
Unit 2	GE	Gas	40 gallons	3
Unit 3	RHEEM	Electric	40 gallons	4
Unit 4	State Select	Gas	50 gallons	4
Unit 5	A.O.Smith	Gas	50 gallons	5
Unit 6	American	Electric	40 gallons	5
Unit 7	Rheem	Gas	50 gallons	6
Unit 8	A.O.Smith	Electric	50 gallons	6
Unit 9	RHEEM	Gas	75 gallons	7
Unit 10	State Industries	Gas	50 gallons	8
Unit 11	A.O.Smith	Gas	40 gallons	11
Unit 12	A.O.Smith	Gas	50 gallons	14
Unit 13	Pioneer Inc	Gas	40 gallons	14

[1] Available at http://www.ahridirectory.org/ahridirectory/pages/rwh/defaultSearch.aspx

While nine out of the eleven water heaters showed a decrease in EF compared to their rated values (Figure 1), there was no clear correlation between age and the magnitude of performance degradation. Furthermore, only two water heaters (Units 6 and 9) showed a decline of five percent or more.

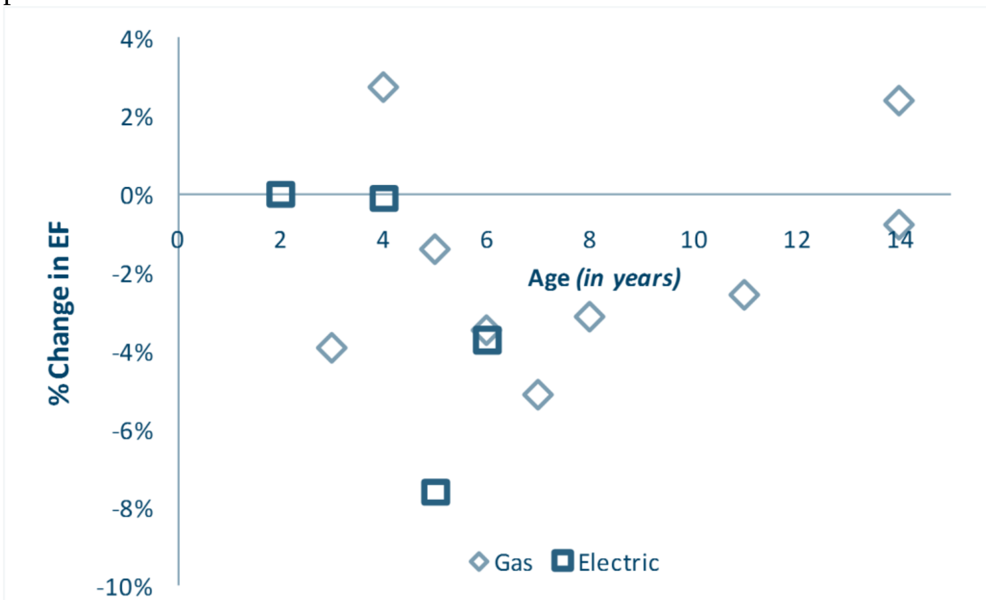


Figure 1: Plot of percent change in Energy Factor with age show no clear correlation between performance decline and age.

Results from Disassembly

We qualitatively judged the state of the components during disassembly of the water heater units. We used the following criteria:

- Excellent: Little or no degradation/scaling/sediment accumulation
- Good: Slight degradation/scaling/sediment accumulation
- Poor: Significant degradation/scaling/sediment accumulation

Table 2 shows the results from the disassembly of each water heater. Analysis of the results showed the following:

- Water heaters degrade significantly after seven years of use[2]
- Scaling on electric water heater heating elements may have a large impact on the performance
- The combustion chamber and insulation around the combustion chamber are prone to corrosion and degradation
- Deposition on the interface of the combustion chamber and the water tank does not have any notable impact on performance
- Significant combustion deposits accumulated on the gas burners after seven years of use
- Anti-corrosion anodes erode after five years of use.

[2] Reference: A.O.Smith warranties Promax residential water heaters the tank for 10 years and parts for 6 years (www.hotwater.com)

Table 2: Results from the Disassembly of Water Heaters

Water Heater Components		Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10	Unit 11	Unit 12	Unit 13
		Electric	Gas	Electric	Gas	Gas	Electric	Gas	Electric	Gas	Gas	Gas	Gas	Gas
	Age	2	3	4	4	5	5	6	6	7	8	11	14	14
	Percent Change from Rated EF	0%	-4%	0%	3%	-1%	-8%	-3%	-4%	-5%	-3%	-3%	-1%	2%
Recovery Efficiency	**Combustion Chamber (CC)**	NA	Good	NA	Good	Good	NA	Good	NA	Poor	Poor	Poor	Good	Poor
Recovery Efficiency	**Burner (B)**	NA	Good	NA	Good	Good	NA	Good	NA	Poor	Poor	Good	Poor	Poor
Recovery Efficiency	**Interface (B/CC)**	NA	Good	NA	Excellent	Good	NA	Good	NA	Excellent	Poor	Poor	Poor	Excellent
Recovery Efficiency	**Spiral Heat Exchanger**	NA	Good	NA	Excellent	Good	NA	Good	NA	Good	Good	Good	Good	Good
Recovery Efficiency	**Upper Element**	Good	NA	Excellent	NA	NA	Poor	NA	Poor	NA	NA	NA	NA	NA
Recovery Efficiency	**Lower Element**	Good	NA	Good	NA	NA	Poor	NA	Poor	NA	NA	NA	NA	NA
Standby Coefficient	**Insulation (Top and Side)**	Good	Excellent	Good	Good	Excellent	Good	Good	Good	Poor	Good	Good	Good	Good
Standby Coefficient	**Insulation(Combustion Chamber)**	Good	Good	Good	Good	Good	Good	Good	Good	Good	Poor	Poor	Poor	Poor
Standby Coefficient	**Cold Water Inlet**	Good	Good	Good	Good	Good	Poor	Good	Poor	Good	Good	Good	Poor	Good
Standby Coefficient	**Hot Water Outlet**	Good	Good	Good	Good	Good	Poor	Good	Good	Good	Good	Good	Poor	Good
Standby Coefficient	**Anti-corrosion Anode**	Excellent	Good	Good	Good	Good	Poor	Poor	Poor	Good	Poor	Poor	Poor	Good
Tank Temp	**Cold Water Dip Tube**	Excellent	Excellent	Excellent	Excellent	Good	Good	Good	Good	Good	Good	Good	Good	Good
Tank Temp	**Thermocouple**	Good	Excellent	NA	Good	Good	NA	Good	Poor	Poor	Good	Poor	Poor	Good
	Water Heater Installation Location	Middlebury, CT	Kingston, RI	Worcester, MA	Melrose, MA	Newton, MA	Needham, MA	Metro Boston, MA	Newton, MA	Battle Creek, MI	Metro Boston, MA	Metro Boston, MA	Metro Boston, MA	Springfield, MA

Scaling on the heating elements of electric water heaters may have a significant impact on the efficiency.

Of particular interest to us were Units 6 and 8. Both had scaling on the heating elements (the scale build up was more pronounced in Unit 6) and both performed lower than rated. Unit 6 with its heavy scaling had the worst performance (- 8% as compared to -4%). However, Unit 8 was within the limits of experimental error (5%) and we cannot be certain about the degree to which scaling impacts performance. Two issues warrant further investigation:

1. Does scaling significantly affect heat transfer from the heating elements in an electric water heater?
2. If the scaling impact is significant, how common is scaling in installed electric water heaters?

While we did not consider water quality within the scope of our study, we noticed extreme sedimentation in a few of the water heaters from Massachusetts.

Conclusions

Performance tests on aged water heaters showed that nine out of thirteen water heaters performed below their rated energy factor, though only very slightly in most cases. No clear trend emerged that would indicate that energy efficiency performance degrades with age. Furthermore, only two water heaters showed a decline in EF of over five percent. Therefore, for our set of water heater samples, there is no correlation of performance degradation with age.

After disassembling the tested water heaters, we found that they degrade significantly after seven years of use. We also noticed a large performance drop in one electric water heater that may result from scaling on the heating elements. We found that deposition on the interface of the combustion chamber and the water tank does not have any notable impact on performance The combustion chamber and insulation around the combustion chamber are prone to corrosion and degradation. In addition, significant combustion deposits accumulated on the gas burners after seven years of use. Lastly, the anti-corrosion anodes erode after five years of use.

Recommendations

Our experiments indicate that water heaters do not typically experience significant performance degradation as they age. We observed the largest performance decline (-8%) with an electric water heater that showed significant scaling on the heating elements. If scaling is responsible for the reduced efficiency, this could decrease energy efficiency in localities with hard water. We recommend further investigation of whether scaling decreases the energy efficiency of electric water heaters, as well as investigating whether scaling is a widespread concern for all electric water heaters.

During disassembly, we also noted severe sedimentation in some water heaters. While deposition did not affect water heater performance in the tests, we recommend regularly draining the tank for sanitary reasons. In addition, changing the sacrificial anode rod after five years of usage will prevent corrosion of the tank.

Summary of Refrigerator Testing and Results

Background

During the recent DOE test procedure rulemaking for residential refrigerators, questions arose regarding the energy consumption of automatic ice makers. Specifically, the previous DOE test procedure for refrigerators did not measure the energy consumption associated with ice production in automatic ice makers. DOE estimated that the energy consumption associated with automatic ice making could represent 10 to 15 percent of the rated energy consumption of a typical refrigerator, a significant amount that should be captured by the test procedure.

Field Study Design

We conducted a field study of refrigerator energy consumption to investigate how real-world energy consumption compares to rated energy consumption, and to measure the additional energy consumption associated with automatic ice makers under real-world conditions. We collected data during separate sessions in the spring and summer seasons so that we could also assess the extent to which seasonal temperature variations affect refrigerator and ice maker energy consumption. During each session, we collected two weeks of data: one week with the ice maker on, the second week with the ice maker off. We compared the energy consumption data collected in our field study to the energy consumption information published in the various reports referenced in our literature review.

Field Study Results

Figure 2 shows a comparison between the rated energy consumption and the energy consumption measured during the field study sessions.

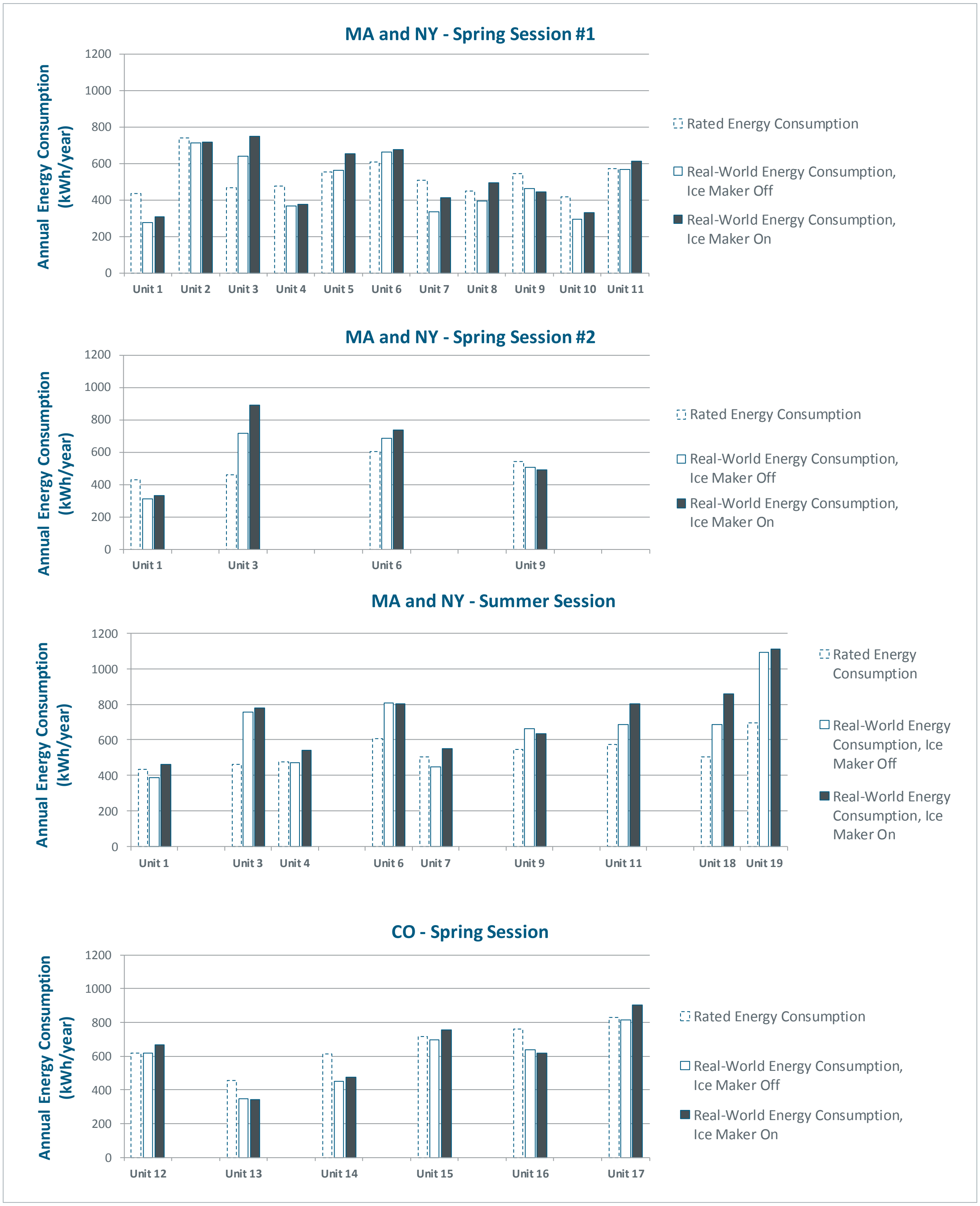


Figure 2. Comparison of rated energy consumption, energy consumption with ice maker off, and energy consumption with ice maker on

During the spring session, the refrigerators in the field study experienced an average of 9 percent lower real-world energy consumption than predicted by their rated values. During the summer session, the refrigerators experienced 26 percent higher real-world energy consumption than predicted by their rated values. The data indicate that energy consumption during the warmer summer months is significantly higher than during the milder spring months, which is to be expected. These results highlight the importance of acquiring energy consumption data across multiple seasons.

Our data indicate a moderate correlation ($R^2 = 0.29$) between ambient air temperature and the difference between real-world and rated energy consumption. The results also indicate that the current DOE test procedure accurately simulates real-world energy consumption at typical ambient temperatures.

The average ice maker energy consumption measured in our field study ranged from 43 kWh/year during the spring session to 61 kWh/year during the summer session. This corresponds to an increase of 8 percent and 9 percent, respectively, over the energy consumption when the ice makers were turned off. The results indicate a wide range of ice maker energy consumption under real-world conditions, from essentially no impact at the low end to an additional 166 kWh/year at the high end. The average ice maker energy consumption from both sessions is less than the average from the AHAM data set (83 kWh/year). Our results are also lower than the estimates provided by NIST (63-223 kWh/year).

For some households, using the automatic ice maker adds a significant amount of energy compared to the energy consumption with the ice maker off. In a few cases, the participants experienced “negative” ice maker energy consumption. In these cases, variables other than the ice maker likely had a greater impact on the energy consumption during the field test measurement periods.

Our study indicated that ice maker energy consumption shows little correlation with the number of household members, the refrigerator model year, the refrigerator’s rated annual energy consumption, the presence of through-the-door ice access, the freezer configuration, or the geographic location.

Conclusions

- **Annual Energy Consumption**
  Our results indicate that the DOE refrigerator test procedure is highly accurate in simulating real-world energy consumption. The results also indicated that the difference between real-world energy consumption and rated energy consumption varies significantly by season, with higher energy consumption during the warmer summer months. Our results showed less difference, however, between real-world energy consumption and rated energy consumption compared to the prior PNNL field study, which showed much more variation between the two.

- **Performance Degradation over Time**
  Our results indicate a weak correlation between performance and model year during the spring season, and a much stronger correlation during the summer months. The stronger

correlation during the summer session indicates that higher ambient temperatures may amplify any age-related performance degradation. Additional testing with a much larger sample size would be required to confirm this correlation.

- **Ice Maker Energy Consumption**
  Our field study indicates a wide range of results for the annual energy consumption associated with ice making, with an average of 43 kWh/year during the spring, and 61 kWh/year during the summer. This represents an increase in energy consumption of between 8-9 percent compared to the energy consumption when the ice maker is turned off. These results justify DOE's conclusion that ice maker energy consumption is significant and should be included in the refrigerator test procedure.

Recommendations

- **Annual Energy Consumption**
  Based on the conduct and results of our study, we propose the following recommendations for additional testing of real-world energy consumption:
    - Use a large sample size. We recommend a minimum of around 50 households.
    - Include a more varied range of household demographics.
    - Capture year-round seasonality, spanning the coldest and warmest months of the year.
    - Include more geographic household distribution, especially hot Southern climates.

- **Performance Degradation over Time**
  Our field study did not specifically measure refrigerator performance degradation over time, and during the summer session we noted a moderate correlation of refrigerator performance degradation with unit age. To study the effects of refrigerator performance degradation over time, we recommend measuring the real-world energy consumption of individual refrigerators over the course of 5-10 years, under roughly the same usage patterns each year. Alternatively, multi-year laboratory tests could be performed on individual units to monitor any performance degradation over time.

- **Additional Testing**
  We propose the following recommendations for additional testing of ice maker energy consumption:
    - Include ice maker energy consumption in the refrigerator test procedure as a measured parameter for each refrigerator, rather than a fixed value.
    - Perform a comparison of ice maker energy consumption under laboratory conditions of both 90°F and 70°F to investigate the effect of ambient air temperature.
    - Perform additional field studies to independently verify AHAM's ice consumption estimates.
    - During field studies, measure the quantity of ice consumption (lb/day) in addition to ice maker energy consumption.
    - Consider alternatives to the one-week-on, one-week-off methodology used in our study.
    - Use the shortest time sampling intervals possible in the data logging system to enable identification of key signatures in the raw energy data.

- Use a larger sample size. We recommend a minimum of around 50 households.
- Include a more varied range of household demographics.
- Consider more geographic household distribution.

1 Introduction

1.1 Background

DOE efficiency standards rulemaking calculations (e.g. national energy savings, environmental and other benefits, efficiency level impacts), utility incentive programs and rebates, and Building America models all rely on predicted energy consumption of appliances and equipment, often based on DOE test procedures and models. But do DOE and industry test procedures really replicate real world conditions? Does performance degrade over time? Do installation patterns and procedures differ from the ideal and inhibit optimal performance? If actual usage in the field is higher than predicted, standards calculations would need to be modified (e.g. higher standards might be justified), utility incentives could be changed, and Building America models would need to be adjusted. Installation and maintenance guidelines might need to be modified. Furthermore, if performance degrades over time, then more robust designs could be appropriate. For example, heat exchangers or water tanks that don't degrade due to dirt, scaling, etc. could be required or encouraged.

The objective of our study was to:

- Identify and prioritize equipment to determine how real world energy consumption compares with models
- Review existing data and perform tests and measurements to determine whether real world performance differs substantially from predictions
- Identify and analyze the sources of any substantial differences
- Recommend appropriate changes to test procedures, models, or installation and maintenance practices
- Recommend R&D topics such as technology development to overcome deficiencies observed in the field.

1.2 Methodology

We followed a three-step methodology for our study. First, we identified and prioritized appliances to be evaluated to determine how real world energy consumption compares with models. Second, for the selected appliances, we determined whether real world energy consumption differs substantially from predictions and assessed whether performance degrades over time. We also identified the potential causes of any discrepancies we observed. Finally, we drew conclusions from our research and recommended test procedure modifications and areas for future research.

2 Equipment Prioritization

2.1 Approach

Our approach involved first developing a list of major household appliances. We created this list by referencing major appliances listed in Table 2.1.16 and Table 2.1.17 of the Buildings Energy Data Book(U.S.DOE, 2009). We also added gas furnaces, room air conditioners, and central air conditioners to this list. For each appliance, we gathered estimates of annual unit energy consumption using data from the 2009 Buildings Energy Data Book(U.S.DOE, 2009) and the 2005 Residential Energy Consumption Survey(EIA, 2005)

Next, we developed a set of criteria to prioritize the equipment for this study. These criteria included the following:

- High annual unit energy consumption
- High annual national energy consumption
- Uncertainty in actual consumer usage patterns
- Questions of whether test procedure is unrepresentative of real world energy use
- Whether installation may affect energy usage
- Potential for performance degradation over time
- Questions exist that could be answered with additional research and development
- Known issues or questions would fall within the scope and manageability of this project

To evaluate each type of equipment against these criteria, we spoke with representatives from the DOE codes and standards rulemaking teams for each product type. These representatives were highly knowledgeable about each product type and provided expert opinions on known or potential discrepancies that may exist between energy models and real world energy usage. Using this information, we assessed the suitability of each type of equipment for inclusion in this study. Based on our assessment, we developed a prioritized list of appliances to include for further study.

2.2 Prioritization Results

Table 1 below shows each type of equipment that was evaluated, an indication of which criteria apply to each equipment type, and summary comments describing some of the particular issues associated with each equipment type.

Table 3: Selection Criteria Matrix

Appliance Type	Annual Unit Energy Consumption (kWh/yr or MMBtu/year)	High Annual Unit Energy Consumption	High Annual National Energy Consumption	Uncertainty in Actual Consumer Usage Patterns	T.P. Unrepresentative of Real World Energy Use?	Installation May Affect Energy Usage	Performance Degradation Over Time	Issue that R&D can Help	Scope / Manageability for this Project	Comments
Water heater (Electric)	4,770	X	X	X	X		X	X	X	• Questions about the ability to compare different technologies to each other (elec. vs. instantaneous vs. heat pump). • How does current TP apply to high efficiency products (e.g. heat pumps)? • Unknown effects of heat pump installation (e.g. whether it's installed in a conditioned or non-conditioned space). • ASHRAE has committee looking at some of these issues, but that may take years.
Water heater (Gas)	19 MMBtu	X	X	X	X	X	X	X	X	• Primary concern – the test procedure draw patterns may not accurately represent residential use. Already have an ASHRAE committee looking at this issue. • The draw patterns in the TP may favor instantaneous gas WH over storage WH. • Storage WH mfgrs's say that residue buildup is a problem with tankless WH. But tankless WH mfgrs's say there is no more concern. • Most installation concerns are regarding safety (e.g. condensate in high-eff. WHs). • LBNL considers many different use characteristics in their rulemaking models.
Furnace (Gas)	50 MMBtu	X	X		X	X	X	X	X	• Concern that the static pressures in TP not representative of real-world use. • Low static pressure in test would reflect lower usage than actual. • Electrical energy consumption of fan represents only 2% of total unit energy.

Appliance Type	Annual Unit Energy Consumption (kWh/yr or MMBtu/year)	High Annual Unit Energy Consumption	High Annual National Energy Consumption	Uncertainty in Actual Consumer Usage Patterns	T.P. Unrepresentative of Real World Energy Use?	Installation May Affect Energy Usage	Performance Degradation Over Time	Issue that R&D can Help	Scope / Manageability for this Project	Comments
Furnace (Oil)	92 MMBtu	X					X	X	?	• Oil furnaces must be periodically cleaned. Buildup of soot on heat exchangers negatively impacts efficiency. • Main concern has been eventual damage to furnace due to buildup; energy efficiency impacts haven't been the focus.
Clothes dryer (Electric)	1,000	X	X	X	X			X	X	• How often do consumers use auto-dry feature? • How much energy does auto-dry save? • DOE planning to conduct its own field survey to collect data • Unknown effects of air infiltration on household energy use.
Clothes dryer (Gas)	4 MMBtu	X	X	X	X			X	X	
Room AC	1,259	X	X	X	X	X	X	X		• What are real-world operating hours? • Full-load vs. part-load? • How much does poor installation affect energy usage? • Unknown effects of air infiltration on household energy use.
Central AC	3,475	X	X	X	X		X	X		• Probably already looked at by others since it's such a big topic.
Dehumidifier	970	X		X	X			X	X	• Total lack of consumer usage data. • How climate- and weather-dependent is energy use? • How often are they emptied? • Do TP conditions mimic real-word? • How does set-point operation compare to continuous operation?
Pool pump	790	X								• No information
Refrigerator	660	X	X		X	X	X	X	X	• Installation can affect air flow • Do TP conditions accurately replicate real-world energy use?

Appliance Type	Annual Unit Energy Consumption (kWh/yr or MMBtu/year)	High Annual Unit Energy Consumption	High Annual National Energy Consumption	Uncertainty in Actual Consumer Usage Patterns	T.P. Unrepresentative of Real World Energy Use?	Installation May Affect Energy Usage	Performance Degradation Over Time	Issue that R&D can Help	Scope / Manageability for this Project	Comments
Freezer (stand-alone)	470	X	X		X		X	X	X	• LBNL looking into real-world issues, numerous field studies. • How does degradation of foam insulation affect energy usage?
Computer & monitor	260	X	X	X				X		• ENERGY STAR program has looked extensively at this.
Television	250	X	X							• No information
Set-top cable box	178									• No information
Microwave	131									• Standards only focused on standby power use now. • Active mode power use very low.
Dishwasher	120		X							• Energy and usage patterns well understood
Clothes washer	110		X	X	X			X		• The only appliance that has large potential water savings. • Numerous questions related to real-world consumer usage. • Complexity of clothes washers requires large sample size in studies.

2.3 Implications

Based on an evaluation of all the criteria, along with other factors listed in the 'Comments' section of the table, we assigned top priority to the following appliance types, in descending order:

1. Water heaters (gas)
2. Water heaters (electric)
3. Furnaces (gas)
4. Room air conditioners
5. Dehumidifiers

Of these five appliance types, we placed the highest priority on gas and electric water heaters.

While refrigerators were not initially considered to be among the highest priorities, during the recent DOE test procedure rulemaking for residential refrigerators, questions arose regarding the energy consumption of automatic ice makers. Specifically, the previous DOE test procedure for refrigerators did not measure the energy use associated with ice production in automatic ice makers. DOE estimated that the energy use associated with automatic ice making could represent 10 to 15 percent of the rated energy use of a typical refrigerator, a significant amount that should be captured by the test procedure.

Therefore, we selected water heaters (electric and gas) and refrigerators for further investigation. This report presents the final results of the water heater study and refrigerator study separately. The results of the water heater study are presented in Section 3 through Section 8; the results of the refrigerator study are presented in Section 9 through Section 14.

3 Water Heaters – Approach

We followed a four-step approach to investigate the real world energy consumption of water heaters.

First, we conducted a broad literature survey and interviewed industry experts to identify the following:

- Past research on real world energy consumption of storage water heaters
- Outstanding research questions and research needs to address future DOE test procedure rulemaking.

We found that the impact of aging on storage water heater performance was not well understood.

Second, we procured used water heaters (in working condition) from the field. To the extent possible, we selected samples that are representative of the most common types of water heaters on the market. The target criteria included the following:

- 40 or 50 gallon capacity
- 2-10 years old
- Units from multiple manufacturers
- Electric or gas.

Third, we tested the water heaters using the DOE test procedure at an accredited laboratory. We compared the energy efficiency metrics calculated from the tests to the metrics published by Air-conditioning Heating and Refrigeration Institute (AHRI)[3].

Fourth, we systematically disassembled the tested sample of water heaters and recorded signs of degradation in key components of the units.

[3] Available at http://www.ahridirectory.org/ahridirectory/pages/rwh/defaultSearch.aspx

4 Water Heaters - Literature Review

4.1 Summary of Review

The literature review on real world energy consumption indicated two prominent areas of study:

1. Investigations of test procedure parameters, including:
    - Water draw patterns
    - Total hot water usage
    - Frequency of water draws.
2. Energy savings of water heaters with new technologies (e.g., tankless water heaters, condensing water heaters, solar heated water heaters).

We discuss below key observations and conclusions from the literature that are pertinent to our study.

The Center for Energy and Environment (Bohac, Lobenstein, & Butcher, 2010) conducted a two-year field-monitoring project to determine if high-efficiency tankless water heaters could significantly improve water heating efficiency. The study showed 37 percent savings of water heating energy per household by replacing a typical natural draft storage water heater with a tankless water heater. The study also noted the inability of the current DOE test procedure to capture real-world performance of various water heater technologies. The water heating community is therefore considering two alternate methods to improve water heater energy factor (EF) tests (Bohac et al., 2010):

a. Updating the water draw profile to more accurately represent real-world hot water usage; or
b. Switching to a modeling approach, where performance is modeled using a standard load profile and an input-output line generated from two-point lab tests.

Another study (Hoeschele & David, 2008) assessed the implications of hot water draw patterns on tankless gas water heater performance. It concluded that differences between field and rated performance occurred because the EF draw profile did not represent actual draw patterns or total hot water use in homes.

A 30-home NRCAN[4] study in Ontario, Canada (Thomas, 2008) indicated an average hot water consumption of 44 gallons per day (gpd), compared to 64 gpd as prescribed in the current test procedure.

The U.S. Environmental Protection Agency (EPA, 2005) collected baseline water usage in 96 homes in Seattle, WA, the East Bay area of California, and Tampa, FL. Each home was then retrofitted with low-flow plumbing products. The study also monitored flow into the water heaters for 20 of the homes. The 20 homes used 55 gpd of hot water prior to the retrofits and 44 gpd after the retrofits. The average draw length was 70 seconds. Typically, households had only one or two large draws per day, with over 95 percent of draws using less than two gallons per draw.

[4] Natural Resources Canada

Lawrence Berkeley National Laboratory ((J. D. Lutz, A Lekov, Qin, & Melody, 2011) analyzed the data collected from ten different research studies covering 142 households. They found that there was very large variation in draw patterns (i.e. volume and frequency of draw) with an asymmetric distribution around the mean (58.7 gpd).

NREL[5] (Hendron & Burch, 2008) has developed a draw-pattern modeling algorithm that simulates a series of event schedules (in six-minute time steps) for five major residential hot water end uses, thereby providing more realistic energy simulations for advanced water heating systems.

The Florida Solar Energy Center conducted a comparative study (Carlos J. Colon Danny S. Parker, 2010) of water heating systems using the NREL draw pattern. Most systems experienced lower measured performance with the NREL draw pattern than with the DOE draw pattern.

Two studies examined the impact of aging on water heaters:

1. The Energy Center of Wisconsin report (Pigg, Cautley, & Mendyk, 2010) monitored the performance of 10 existing natural draft water heaters in southern Wisconsin households. Key findings from the study included:
   - Hot water usage ranged from 27-135 gallons per day
   - Heavy mineral accumulation in two water heaters resulted in a decline in instantaneous combustion efficiency
   - A large fraction of hot water events (water draws of more than five seconds) use under two gallons of water
   - A spike in the draw event data occurs at 10 gallons due to showering
   - Hot water delivery tends to drop off more suddenly in water heaters with disintegrated dip tubes
   - Homeowners frequently increased the temperature set point from the manufacturer default.

2. Battelle (Paul, Gadkari, Evers, Goshe, & Thornton,) conducted an accelerated field test simulation to investigate the benefits of removing water hardness. Thirty water heaters were operated for a period of over 90 days, with both softened and un-softened water under controlled lab conditions. Key results included:
   - The average efficiency of gas storage water heaters dropped from 70.4 percent to 67.4 percent at two years of equivalent field service
   - No effect was observed on electric storage water heaters, despite an observed buildup of scale.

4.2 Implications

The literature review did not reveal any significant research on the impact of aging on storage water heater performance. However, interviews with experts indicated general interest in this topic. Therefore, we focused our study on conducting tests on aged water heaters to investigate whether water heaters experience any performance degradation over time.

[5] National Renewable Energy Laboratory (www.nrel.gov)

5 Water Heaters - Test Results

5.1 Water Heater Characteristics

We procured 13 used water heaters in working condition for testing. Table 4 provides the equipment characteristics of each unit in our test sample.

Table 4: Characteristics of Used Water Heater Units

	Manufacturer	*Type*	*Capacity*	*Age (years)*
Unit 1	A.O.Smith	Electric	40 gallons	2
Unit 2	GE	Gas	40 gallons	3
Unit 3	RHEEM	Electric	40 gallons	4
Unit 4	State Select	Gas	50 gallons	4
Unit 5	A.O.Smith	Gas	50 gallons	5
Unit 6	American	Electric	40 gallons	5
Unit 7	Rheem	Gas	50 gallons	6
Unit 8	A.O.Smith	Electric	50 gallons	6
Unit 9	RHEEM	Gas	75 gallons	7
Unit 10	State Industries	Gas	50 gallons	8
Unit 11	A.O.Smith	Gas	40 gallons	11
Unit 12	A.O.Smith	Gas	50 gallons	14
Unit 13	Pioneer Inc	Gas	40 gallons	14

5.2 Laboratory Testing

5.2.1 Brief Description of DOE Test Procedure

The DOE test procedure[6] measures water heater energy use over a 24-hour period. The procedure specifies six equal hot water draws at one-hour intervals, totaling 64.3 gallons. Each draw occurs at a flow rate of 3.0 gallons per minute. After six hours, the water heater enters standby mode for a period of 18 hours. Based on measurements made during these operating modes, the energy factor (EF) is calculated. Energy factor is defined as the added energy content of the water drawn from the water heater, divided by the energy required to heat and maintain the water heater at the set-point temperature (J. Lutz, Whitehead, Alex Lekov, Rosenquist, & Winiarski, 1999). Water heater manufacturers are required to test and label the EF of every model. The EF metric has been widely used to compare energy efficiency across water heaters.

5.2.2 Test Results

For each water heater we tested, we determined the energy factor as rated by manufacturers from an Air-Conditioning, Heating, and Refrigeration Institute (AHRI) database[7]. We tested the water heaters at a DOE-accredited laboratory and compared the tested EF to the rated EF, as shown in Table 5. While nine out of the eleven water heaters showed a decrease in EF performance compared to their rated values (Figure 3), there was no clear correlation between age and the

[6] 10 CFR Part 430 Subpart B Appendix E: Uniform Test Method for Measuring the Energy Consumption of Water Heaters
[7] Available at http://www.ahridirectory.org/ahridirectory/pages/rwh/defaultSearch.aspx

magnitude of performance degradation (Figure 4). Furthermore, only two water heaters (Units 6 and 9) showed a decline of five percent or more.

An experimental study by Pacific Gas and Electric Company (Spoor, Leni-konig, Davis, & Emanuel, 2008) showed that even new storage water heaters, when tested under laboratory conditions, show a variation in energy factor ranging from three to six percent. The variation can result from different sources – experimental error, test setup etc. DOE Energy Star verification testing also allows a variation of five percent from the rated energy factor, when conducting spot checks[8]. We therefore considered a variation of less than five percent from the rated energy factor to be relatively insignificant.

Table 5: Energy Factor from Laboratory Tests

Unit	Manufacturer	Type	Capacity	Age (years)	Rated EF	Tested EF	Percent Change in Rated EF[9]
Unit 1	A.O.Smith	Electric	40 gal	2	0.92	0.92	0%
Unit 2	GE	Gas	40 gal	3	0.59	0.57	-4%
Unit 3	RHEEM	Electric	40 gal	4	0.92	0.92	0%
Unit 4	State Select	Gas	50 gal	4	0.58	0.60	3%
Unit 5	A.O.Smith	Gas	50 gal	5	0.58	0.57	-1%
Unit 6	American	Electric	40 gal	5	0.92	0.85	-8%
Unit 7	Rheem	Gas	50 gal	6	0.58	0.56	-3%
Unit 8	A.O.Smith	Electric	50 gal	6	0.91	0.88	-4%
Unit 9	RHEEM	Gas	75 gal	7	0.53	0.50	-5%
Unit 10	State Industries	Gas	50 gal	8	0.58	0.56	-3%
Unit 11	A.O.Smith	Gas	40 gal	11	0.55	0.54	-3%
Unit 12	A.O.Smith	Gas	50 gal	14	0.53	0.53	-1%
Unit 13	Pioneer Inc	Gas	40 gal	14	0.58	0.59	2%

[8] See http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/estar_verification_process.pdf detailing verification testing: "A spot check will be performed on the first unit. If the test result of the spot check fails by five percent or more, the additional 3 units will be tested and statistical methods applied to the results for purposes of determining a failure".
[9] Calculated as (Tested EF- Rated EF)/Rated EF x 100

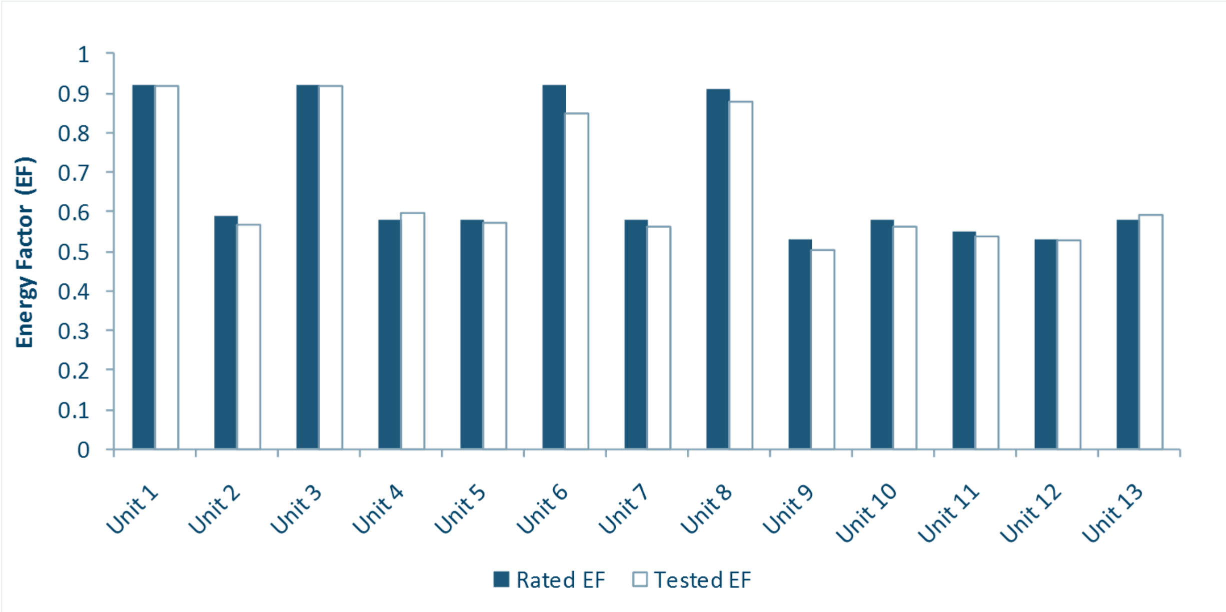


Figure 3: Comparison of Rated and Tested Performance of Water Heater Samples

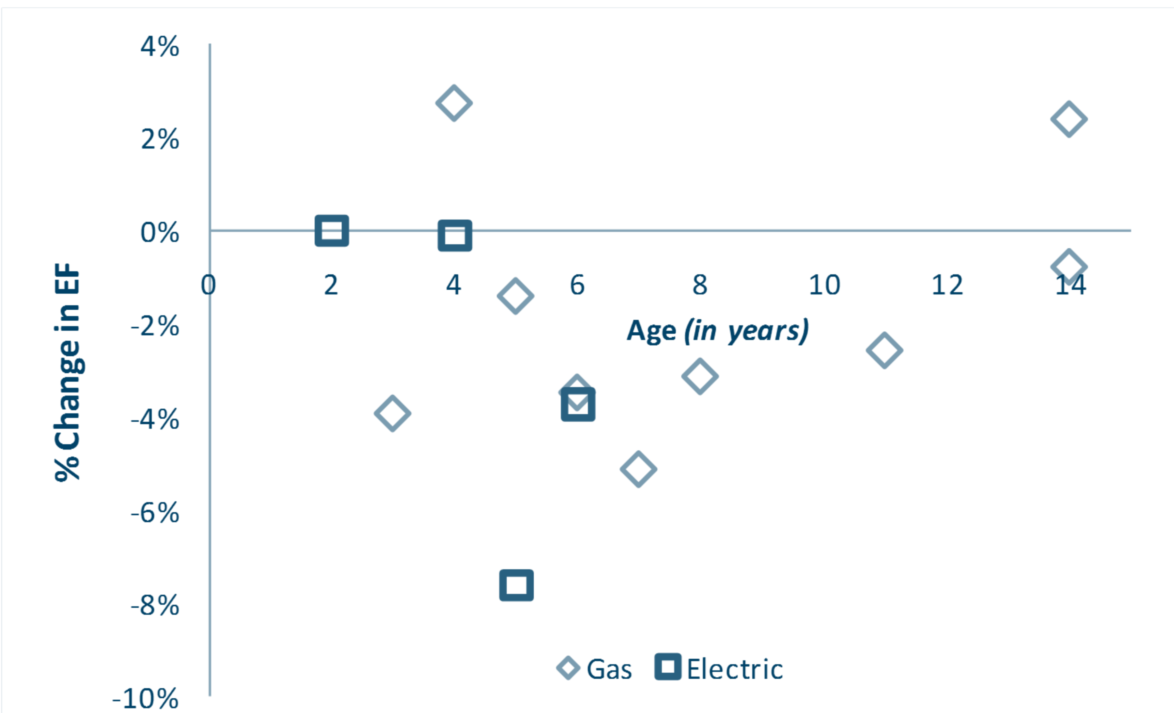


Figure 4: Plot of percent change in Energy Factor with age show no clear correlation between performance decline and age.

6 Water Heaters - Disassembly

6.1 Internal Components of a Storage Water Heater

Storage water heaters work on the principle of convective heating and consist of four basic construction elements (See Figure 5):

1. Inlet and outlet
2. Heater and heat exchanger
3. Storage tank
4. Safety features and controls

Cold water enters through the dip tube at the bottom of the tank. Once heated, hot water rises to the top and exits through the hot water outlet. This maintains temperature stratification in the tank from coldest near the bottom to hottest at the top.

In gas water heaters, the supply gas feeds a gas burner inside the combustion chamber. A pilot flame is the source of ignition. The burner heats the interface of the combustion chamber and the storage tank. The exhaust flue has a spiral heat exchanger that traps heat from the combustion products and heats the water.

In electric water heaters, two heating elements – upper and lower - are immersed in the water in the storage tank. The upper element is used to quickly provide hot water on demand. The lower element brings the entire tank to the set temperature.

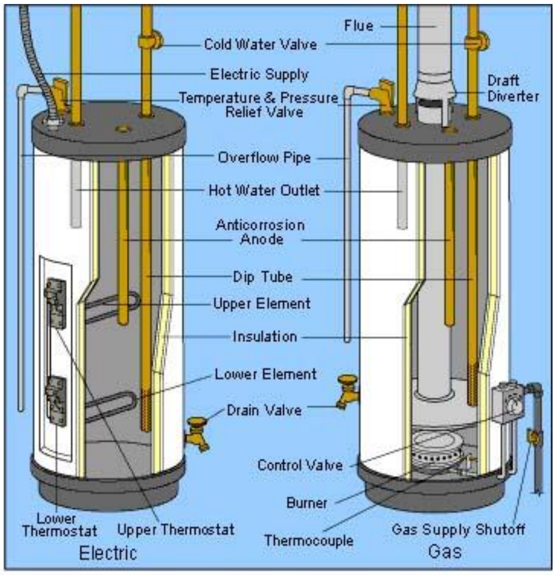


Figure 5: Components of storage water heaters – electric and gas (Source: www.theplumbinginfo.com)

The storage tank is insulated on the outside to prevent standby heat loss. A sacrificial anode rod (usually aluminum or magnesium) bolted to the top of the tank prevents corrosion from rusting. A temperature and pressure relief valve keeps the tank operating under the safe design limits. A drain valve is also provided at the bottom of the tank. Draining the tank prevents sediment build up. The thermostat and control valve is part of a simple control system to regulate the temperature inside the tank.

6.2 The WHAM Equation

6.2.1 Simplified Equation to Calculate Water Heater Energy Input

The Water Heater Analysis Model (WHAM) is an analytical model (J. Lutz et al., 1999) based on the DOE water heater test procedure that characterizes the operating conditions using four variables:

- Daily draw volumes
- Thermostat set-point temperature
- Inlet water temperature
- Ambient air temperature

The water heater performance (i.e. the energy factor) is determined by the rated input (P_{on}), standby heat loss coefficient (UA) and recovery efficiency (RE). Alternatively, the WHAM equation calculates the total water heater consumption (Equation 1) based on the parameters described above.

Equation 1

$$Q_{in} = \frac{vol \times den \times C_p \times (T_{tank} - T_{in})}{RE} \times \left(1 - \frac{UA \times (T_{tank} - T_{amb})}{P_{on}}\right) + 24 \times UA \times (T_{tank} - T_{amb})$$

Where,

Q_{in} = total water heater energy consumption[10]
vol = volume of water drawn in 24 hours
den = density of water
C_p = specific heat of water
T_{tank} = tank temperature
T_{amb} = temperature of ambient air surrounding water heater
T_{in} = inlet water temperature
RE = recovery efficiency
UA = standby heat loss coefficient
P_{on} = rated input power

WHAM is based on the following assumptions:

- The temperature of the water in the tank is always at the thermostat set point
- The water and air temperatures are constant
- The density of water is constant
- P_{on} , RE and UA are constant

6.2.2 Decomposing the WHAM Equation to Identify Key Water Heater Components

The variables within the WHAM equation can be traced to key components of a water heater that can affect its performance in the DOE test as they degrade. We identified several key

[10] Note that the energy factor (EF) = $vol \times den \times C_p \times (T_{tank} - T_{in})/Qin$

components, shown in Table 6. We excluded from the analysis factors external to the system such as piping, ambient air circulation, or improper venting.

Table 6: Decomposing the WHAM Equation to Identify Key Water Heater Components

Parameter	Key Components	Component Degradation Affects Parameter in Performance Test?	Explanation
vol	Storage tank	No	Water draw pattern in the DOE test is constant
den	-	-	-
C_p	-	-	-
T_{tank}	Thermostat	Yes	Faulty thermostat set point
	Dip tube	Yes	Broken dip tube leads to hot and cold water mixing. No stratification and the water temperature may not be equal to thermostat set point.
T_{amb}	-	-	External to water heater
T_{in}	-	-	External to water heater
RE	Burner(B)	Yes	Affects combustion efficiency
	Combustion Chamber (CC)	Yes	Affects combustion efficiency
	Interface (B/CC)	Yes	Sediments may affect heat transfer
	Spiral heat exchanger	Yes	Improper flue-gas flow can lead to poor heat transfer
	Upper element	Yes	Scaling can affect heat transfer
	Lower element	Yes	Scaling can affect heat transfer
UA	Top and side insulation	Yes	Loss of insulation means higher standby heat loss
	CC insulation	Yes	Loss of insulation means higher standby heat loss
	Cold/hot water inlet/outlet	Yes	Poor valve condition may lead to hot water backflow and mixing
	Anti-corrosion anode	Yes	Corroded anode may lead to accelerated degradation of tank
P_{on}	-	No	Rated input power is constant

Table 6 shows that component degradation may considerably affect the following three efficiency parameters: RE, UA and T_{tank}.

6.3 Disassembly Process

We qualitatively judged the state of the components identified in Table 6 during disassembly of the water heater units.

We used the following criterion:

- Excellent: Little or no degradation/scaling/sediment accumulation
- Good: Slight degradation/scaling/sediment accumulation
- Poor: Significant degradation/scaling/sediment accumulation

We also documented each component through photographs and physical measurements. Appendix A provides photographs illustrating how we qualitatively rated the degradation of each component..

6.4 Disassembly Results

Table 7 shows the results from the disassembly of each water heater. Analysis of the results shows the following:

- Water heaters degrade significantly after seven years of use[11]
- Scaling on electric water heater heating elements may have a large impact on the performance
- The combustion chamber and insulation around the combustion chamber are prone to corrosion and degradation
- Deposition on the interface of the combustion chamber and the water tank does not have any notable impact on performance
- Significant combustion deposits accumulated on the gas burners after seven years of use
- Anti-corrosion anodes erode after five years of use.

Scaling on the heating elements of electric water heaters may have a significant impact on the efficiency.

Of particular interest to us were Units 6 and 8. Both had scaling on the heating elements (the scale build up was more pronounced in Unit 6) and both performed lower than rated. Unit 6 with its heavy scaling had the worst performance (- 8% as compared to -4%). However, Unit 8 was within the limits of experimental error (5%) and we cannot be certain about the degree to which scaling impacts performance.

Two issues warrant further investigation:

3. Does scaling significantly affect heat transfer from the heating elements in an electric water heater?
4. If the scaling impact is significant, how common is scaling in installed electric water heaters?

While we did not consider water quality within the scope of our study, we noticed extreme sedimentation in a few of the water heaters from Massachusetts (See Appendix A).

[11] Reference: A.O.Smith warranties Promax residential water heaters the tank for 10 years and parts for 6 years (www.hotwater.com)

Table 7: Results from the Disassembly of Water Heaters

Water Heater Components	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10	Unit 11	Unit 12	Unit 13	Group
	Electric	Gas	Electric	Gas	Gas	Electric	Gas	Electric	Gas	Gas	Gas	Gas	Gas	
Age	2	3	4	4	5	5	6	6	7	8	11	14	14	
Percent Change from Rated EF	0%	-4%	0%	3%	-1%	-8%	-3%	-4%	-5%	-3%	-3%	-1%	2%	
Combustion Chamber (CC)	NA	Good	NA	Good	Good	NA	Good	NA	Poor	Poor	Poor	Good	Poor	Recovery Efficiency
Burner (B)	NA	Good	NA	Good	Good	NA	Good	NA	Poor	Poor	Good	Poor	Poor	Recovery Efficiency
Interface (B/CC)	NA	Good	NA	Excellent	Good	NA	Good	NA	Excellent	Poor	Poor	Poor	Excellent	Recovery Efficiency
Spiral Heat Exchanger	NA	Good	NA	Excellent	Good	NA	Good	NA	Good	Good	Good	Good	Good	Recovery Efficiency
Upper Element	Good	NA	Excellent	NA	NA	Poor	NA	Poor	NA	NA	NA	NA	NA	Recovery Efficiency
Lower Element	Good	NA	Good	NA	NA	Poor	NA	Poor	NA	NA	NA	NA	NA	Recovery Efficiency
Insulation (Top and Side)	Good	Excellent	Good	Good	Excellent	Good	Good	Good	Poor	Good	Good	Good	Good	Standby Coefficient
Insulation(Combustion Chamber)	Good	Good	Good	Good	Good	Good	Good	Good	Good	Poor	Poor	Poor	Poor	Standby Coefficient
Cold Water Inlet	Good	Good	Good	Good	Good	Poor	Good	Poor	Good	Good	Good	Poor	Good	Standby Coefficient
Hot Water Outlet	Good	Good	Good	Good	Good	Poor	Good	Good	Good	Good	Good	Poor	Good	Standby Coefficient
Anti-corrosion Anode	Excellent	Good	Good	Good	Good	Poor	Poor	Poor	Good	Poor	Poor	Poor	Good	Standby Coefficient
Cold Water Dip Tube	Excellent	Excellent	Excellent	Excellent	Good	Good	Good	Good	Good	Good	Good	Good	Good	Tank Temp
Thermocouple	Good	Excellent	NA	Good	Good	NA	Good	Poor	Poor	Good	Poor	Poor	Good	Tank Temp
Water Heater Installation Location	Middlebury, CT	Kingston, RI	Worcester, MA	Melrose, MA	Newton, MA	Needham, MA	Metro Boston, MA	Newton, MA	Battle Creek, MI	Metro Boston, MA	Metro Boston, MA	Metro Boston, MA	Springfield, MA	

7 Water Heaters - Conclusions

Performance tests on aged water heaters showed that nine out of thirteen water heaters performed below their rated energy factor, though only very slightly in most cases. No clear trend emerged that would indicate that energy efficiency performance degrades with age. Furthermore, only two water heaters showed a decline in EF of over five percent. Therefore, for our set of water heater samples, there is no correlation of performance degradation with age.

After disassembling the tested water heaters, we found that they degrade significantly after seven years of use. We also noticed a large performance drop in one electric water heater that may result from scaling on the heating elements. We found that deposition on the interface of the combustion chamber and the water tank does not have any notable impact on performance The combustion chamber and insulation around the combustion chamber are prone to corrosion and degradation. In addition, significant combustion deposits accumulated on the gas burners after seven years of use. Lastly, the anti-corrosion anodes erode after five years of use.

8 Water Heaters - Recommendations

Our experiments indicate that water heaters do not typically experience significant performance degradation as they age. We observed the largest performance decline (-8%) with an electric water heater that showed significant scaling on the heating elements. If scaling is responsible for the reduced efficiency, this could decrease energy efficiency in localities with hard water. We recommend further investigation of whether scaling decreases the energy efficiency of electric water heaters, as well as investigating whether scaling is a widespread concern for all electric water heaters.

During disassembly, we also noted severe sedimentation in some water heaters. While deposition did not affect water heater performance in the tests, we recommend regularly draining the tank for sanitary reasons. In addition, changing the sacrificial anode rod after five years of usage will prevent corrosion of the tank.

9 Refrigerators – Background and Approach

9.1 Background

During the recent DOE test procedure rulemaking for residential refrigerators, questions arose regarding the energy consumption of automatic ice makers. Specifically, the previous DOE test procedure for refrigerators did not measure the energy consumption associated with ice production in automatic ice makers. DOE estimated that the energy consumption associated with automatic ice making could represent 10 to 15 percent of the rated energy consumption of a typical refrigerator, a significant amount that should be captured by the test procedure.

In the revised test procedure, DOE selected a fixed placeholder value for ice making energy consumption based on test results from the Association of Home Appliance Manufacturers (AHAM). AHAM performed these tests under controlled laboratory conditions. Some manufacturers expressed concern that these results may not represent true ice making energy consumption experienced by consumers under real-world conditions. DOE stated that it would continue working on the development of an ice making test procedure with the intent of eventually integrating it into the test procedure in lieu of the fixed placeholder.[12]

9.2 Approach

We followed a four-step approach in this study of real world energy consumption of refrigerators.

First, we conducted a broad literature survey and interviewed industry experts to identify the following:

- Past research on real-world energy consumption of refrigerators and automatic ice makers
- Outstanding research questions and research needs to address future DOE test procedure rulemakings

Second, we conducted a field study of refrigerator energy consumption to investigate how real-world energy consumption compares to rated energy consumption, and to measure the additional energy consumption associated with automatic ice makers under real-world conditions.

Third, we compared the energy consumption data collected in our field study to the energy consumption information published in the various reports referenced in our literature review.

Fourth, we developed a set of recommendations for additional testing that could be performed to further validate the findings of our study.

[12] Energy Conservation Program for Consumer Products: Test Procedures for Refrigerators, Refrigerator-Freezers, and Freezers—Final Rule and Interim Final Rule; December 16, 2010; 75 FR 78810.

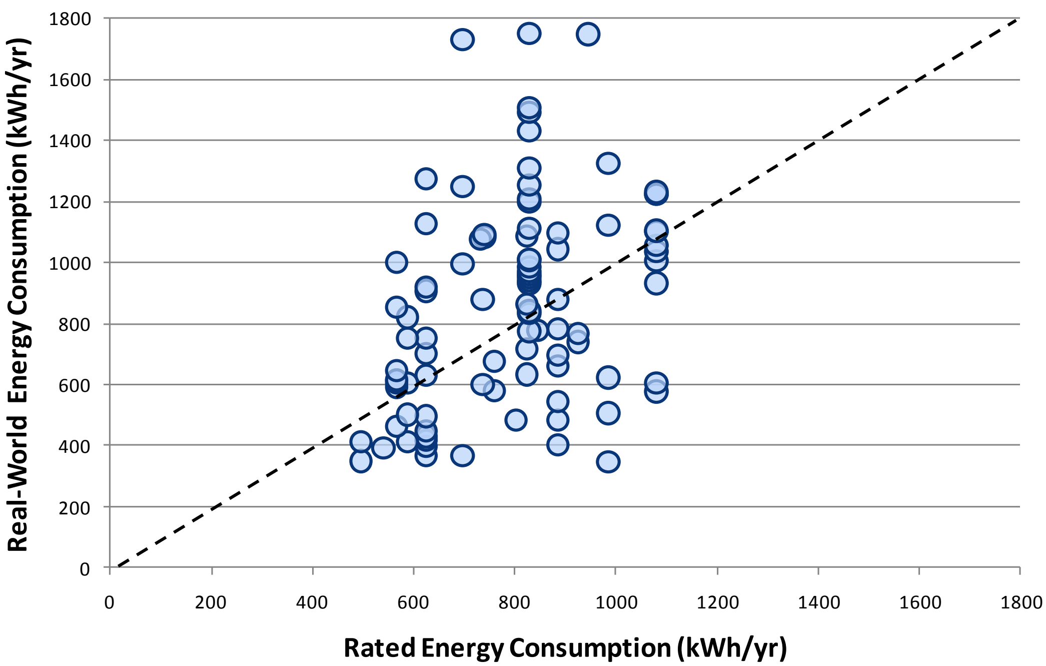
10 Refrigerators - Literature Review

10.1 Summary of Review

To begin this study, we reviewed literature on two specific research areas: 1) comparison of real-world energy consumption of refrigerators to the rated energy consumption; and 2) energy consumption associated with automatic ice makers.

10.1.1 Annual Energy Consumption

Pacific Northwest National Laboratory (PNNL) published a report that examined the possibility of using a regression-model-based approach to estimate energy savings for refrigerators installed in New York City public housing (PNNL 1998). The study monitored the energy consumption of over 100 installed refrigerators, each for a one-week period. Because the study only had seven sets of data acquisition equipment, seven different refrigerators were monitored each week, beginning in April 1997 and ending in November 1997. PNNL noted each refrigerator's rated energy consumption and measured, among other parameters, the actual energy consumption in the field. Figure 6 shows the real-world energy consumption versus the rated energy consumption of each refrigerator.



Note: Points above the dashed line indicate real-world energy consumption greater than the rated value. Data points represent raw data from the PNNL study.

Figure 6. Comparison between real-world energy consumption and rated energy consumption (Source: PNNL 1998)

10.1.2 Performance Degradation over Time

We were unable to find any prior studies investigating whether the performance (i.e., energy efficiency) of residential refrigerators decreases over time.

10.1.3 Ice Maker Energy Consumption

In support of the recent DOE test procedure rulemaking for residential refrigerators, AHAM submitted a presentation containing test results on ice maker energy consumption (AHAM 2009). AHAM collected data on 51 refrigerators spanning seven manufacturers and seven product classes. Tests were performed in controlled laboratory conditions at 90°F, corresponding to the ambient temperature requirement in the DOE refrigerator test procedure. The intent of the DOE refrigerator test procedure is to simulate typical room conditions (approximately 70 °F) with door openings, by testing at 90 °F without door openings[13]. For each test, the ice maker energy consumption was determined by measuring the energy expended to produce ice during the test period (in kWh), dividing by the weight of ice produced during the test period (in lbs), and multiplying by an ice usage factor of 1.8 lbs/day. The ice usage factor represents average household daily ice usage, which AHAM determined using data from three consumer surveys and three field tests. The results of AHAM's tests indicate an average annual ice maker energy consumption of **83 kWh/year**, with a range of **50 – 150 kWh/year**. Figure 7 shows the distribution of ice maker energy consumption from the AHAM study.

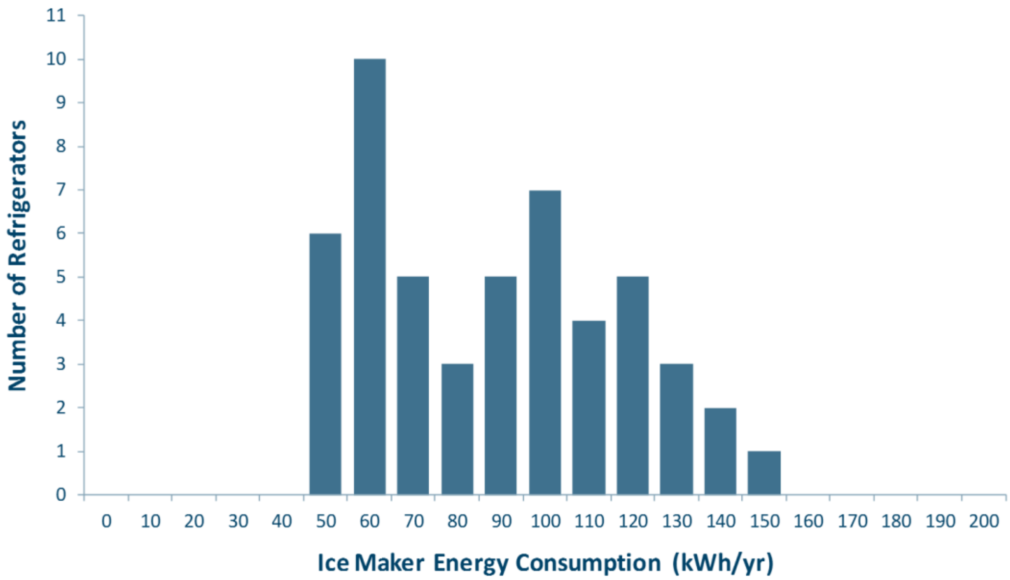


Figure 7. Distribution of Ice Maker Energy Consumption (Source: AHAM 2009)

The National Institute of Standards and Technology (NIST) examined various methods of measuring the energy consumption of automatic ice makers that would generate repeatable and reproducible results (NIST 2011). Each method was evaluated using four different refrigerator/freezer models. The first method replicates AHAM's methodology. The other methods involve mathematical modeling and interpolation. Table 8 and Figure 8 show the results from the first method, which can be compared most directly to AHAM's test results. The results indicate a range of annual ice maker energy consumption of **63–223 kWh/year**.

[13] Reference: Energy Conservation Program for Consumer Products: Test Procedures for Refrigerators, Refrigerator-Freezers, and Freezers; Final Rule and Interim Final Rule. December 16, 2010. Federal Register Vol. 75, p.78850. Available online at: http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/rftp_frnotice_2010-12-21.pdf

Table 8. Ice Maker Energy Consumption (Source: NIST 2011)

Refrigerator/Freezer Type	Annual Ice Maker Energy Consumption (kWh/year)
Top Mount	106
Side-by-Side	223
French Door #1	123
French Door #2	63

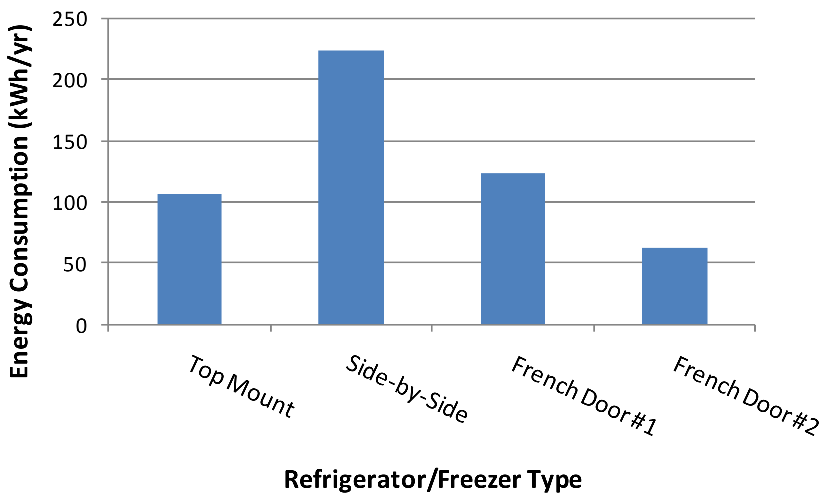


Figure 8. Ice Maker Energy Consumption (Source: NIST 2011)

Finally, Lawrence Berkeley National Laboratory (LBNL) is currently conducting a field survey of refrigerator energy consumption in homes and businesses (LBNL 2010). The study is divided into four phases, with completion of the fourth phase scheduled for 2011 or later. Results from the study will support DOE's energy conservation standards rulemaking for residential refrigerators/freezers.

10.2 Key Implications

10.2.1 Annual Energy Consumption

The results from the PNNL study indicate a wide variation in real-world energy consumption compared to rated values, as shown in Figure 9.

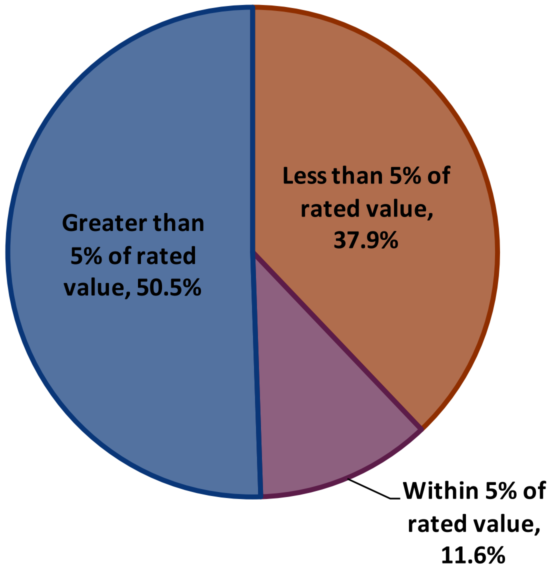


Figure 9. Distribution of Results from PNNL Study (Source: PNNL 1998)

In the PNNL study, 11.6% of refrigerators experienced real-world energy consumption within five percent[14] of the rated value; 50.5% experienced real-world energy consumption at least five percent greater than the rated value; and 37.9% experienced real-world energy consumption at least five percent lower than the rated value.

10.2.2 Performance Degradation over Time

We are unable to draw any conclusions about performance degradation over time based on the results of the literature review.

10.2.3 Ice Maker Energy Consumption

The results from the AHAM and NIST studies indicate a wide variation in ice maker energy consumption. For both studies, units were tested in controlled laboratory conditions, and the final results were normalized and scaled using an ice usage factor derived by AHAM. Neither study measured ice maker energy consumption in real-world residential settings.

[14] DOE Energy Star verification testing allows a variation of five percent from the rated energy efficiency metric. Additional details available at http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/estar_verification_process.pdf.

11 Refrigerators - Field Study Data

The literature review showed relatively little data on the real-world energy consumption of refrigerators or the energy consumption of automatic ice makers. The objective of our field test was to collect refrigerator energy consumption data from approximately 20 different households to calculate annual energy consumption, assess whether refrigerators experience performance degradation over time, and derive the energy consumption associated with automatic ice making. We collected data during the spring and summer seasons so that we could assess the extent to which seasonal temperature variations affect refrigerator and ice maker energy consumption.

11.1 Experiment Design

Due to the limited time and resources to conduct the field study, we designed the experiment so that it could be conducted quickly and relatively inexpensively. Because the results of the study depend on real-world behavior (i.e. real-world ice consumption), we wanted to minimize the extent to which the study would interfere with participants' normal day-to-day usage patterns. Appendix B describes the data acquisition equipment used for this field study. The field data was collected in March, April, and August of 2011.

We conducted the study as follows:

1. Participants were instructed to install the power meter and temperature sensor (see Appendix B) and use their refrigerator/freezers normally for a period of approximately one week, during which time the refrigerator energy consumption and ambient air temperature and humidity were recorded. The automatic ice maker was "on" during this period.

2. At the beginning of the second week, participants switched off their ice makers. During this period, participants were asked to use their refrigerator/freezer normally, except that no new ice would be made. Participants were permitted to use any ice that remained in the ice compartment, or use store-bought ice if they depleted their supply of previously-made ice.

3. After approximately one week of collecting energy data with the ice makers turned off, participants returned the power meters and sensors to Navigant for data extraction and analysis.

We recognized that a number of variables might affect the energy consumption of a household refrigerator, such as the following:

- Number of door openings
- Refrigerator/freezer food content
- Daily usage patterns
- Internal temperature settings

We assumed that by monitoring energy consumption for seven days during each phase, a single atypical event, such as hosting a dinner party, would not significantly affect the cumulative data collected over the entire week. We also assumed that household usage patterns would remain consistent between the first week and second week. Finally, we believed that any changes in energy consumption due to seasonal effects would be minimal over a two-week period.

11.2 Household Data

For the spring sessions, we solicited 23 volunteers to participate in the field study. Eleven volunteers work at Navigant's Burlington, MA office and live in the Boston area and surrounding suburbs. Ten volunteers work at Navigant's Boulder, CO office, and the remaining two volunteers live in upstate New York. The household sizes varied and ranged from one to five household members.

For the summer session, we solicited 10 volunteers to participate in the field study: one of the upstate NY volunteers who previously participated in the spring phase; seven volunteers from the Burlington, MA office who previously participated in the spring phase; and an additional two volunteers from the Burlington, MA office who participated in only the summer phase.

To obtain household data from our field experiment, we requested the following information from each participant:

1. Brand and model of the refrigerator
2. Number of people in the household
3. Total household daily ice usage: Low, Medium, High
    a. Low – Rarely use ice
    b. Medium – Use between one to three glasses worth of ice per day
    c. High – Use more than three glasses worth of ice per day

11.3 Rated Energy Data

We determined the rated energy consumption and other key characteristics of each refrigerator/freezer according to the California Energy Commission (CEC)[15] and ENERGY STAR[16] appliance databases. The rated values are based on the results of the DOE refrigerator test procedure, which requires the ice maker to be turned off for the duration of the test.

Table 9 shows the characteristics of each unit and household in the field test. As explained in the following section, although we solicited a total of 25 volunteer households, our field survey yielded valid data for 19 households.

[15] CEC database available online at http://www.appliances.energy.ca.gov/.
[16] ENERGY STAR database available online at http://www.energystar.gov/.

Table 9. Characteristics of Each Field Test Unit and Household

Field Study Unit	Household Members	Refrigerator Model Year	Freezer Configuration	Through-the-Door Ice Access?	Rated Annual Energy Consumption (kWh/yr)	Rated Daily Energy Consumption (kWh/day)
Unit 1	4	2008	Bottom-mount	No	433	1.19
Unit 2	2	2000	Side-by-side	Yes	741	2.03
Unit 3	3	2004	Bottom-mount	No	464	1.27
Unit 4	2	2006	Bottom-mount	No	476	1.30
Unit 5	2	2009	Bottom-mount	Yes	552	1.51
Unit 6	5	2002	Side-by-side	Yes	606	1.66
Unit 7	5	2010	Side-by-side	Yes	506	1.39
Unit 8	1	2003	Top-mount	No	448	1.23
Unit 9	3	2009	Side-by-side	Yes	545	1.49
Unit 10	2	2008	Top-mount	No	416	1.14
Unit 11	2	2003	Side-by-side	No	572	1.57
Unit 12	2	2005	Side-by-side	Yes	618	1.69
Unit 13	2	2002	Top-mount	No	457	1.25
Unit 14	2	2006	Side-by-side	Yes	615	1.68
Unit 15	1	2005	Side-by-side	Yes	715	1.96
Unit 16	4	2000	Side-by-side	Yes	759	2.08
Unit 17	4	1992	Side-by-side	Yes	828	2.27
Unit 18	2	2010	Side-by-side	Yes	506	1.39
Unit 19	2	2001	Top-mount	No	697	1.91

11.4 Data Validation

Unless otherwise indicated, for households that participated in two spring sessions, we used the average of the two spring sessions in the tables and figures below. In total, we collected data on 40 complete sessions. However, we eliminated data from 10 sessions—five equipment failures occurred during the field experiment, and five participants' self-reported usage patterns differed significantly between the "ice maker off" and "ice maker on" periods. Because we based our test protocol on the assumption that household usage patterns would remain fairly consistent between the first week and second week, we invalidated these five data sets. Therefore, our field survey yielded valid data for 19 households and a total of 30 sessions.

12 Refrigerators - Analysis of Results

Table 10 shows the results of the field measurements. The complete data set from Navigant's field study is found in Appendix C. For each period (ice maker off, ice maker on), we calculated average daily energy consumption and multiplied by 365 to obtain an estimate of the average annual energy consumption for each case.

Following Table 10, Figure 10 shows a comparison between the rated energy consumption and the energy consumption measured during both periods (ice maker on, ice maker off).

Table 10. Refrigerator Field Energy Consumption Data

Field Study Unit	Rated Annual Energy Consumption (kWh/year)	Measured Annual Energy Consumption, Ice Maker Off (kWh/year)	Measured Annual Energy Consumption, Ice Maker On (kWh/year)	Average Ambient Temperature (˚F)
Unit 1 (Spring Session #1)	433	275	305	68.1
Unit 1 (Spring Session #2)	433	314	333	N/A*
Unit 1 (Spring Avg.)	**433**	**295**	**319**	**68.1**
Unit 1 (Summer Session)	**433**	**386**	**461**	**76.2**
Unit 2 (Spring Session #1)	**741**	**712**	**714**	**65.1**
Unit 3 (Spring Session #1)	464	640	746	67.9
Unit 3 (Spring Session #2)	464	715	893	71.7
Unit 3 (Spring Avg.)	**464**	**678**	**820**	**69.8**
Unit 3 (Summer Session)	**464**	**756**	**782**	**69.3**
Unit 4 (Spring Session #1)	**476**	**365**	**374**	**67.6**
Unit 4 (Summer Session)	**476**	**469**	**539**	**72.1**
Unit 5 (Spring Session #1)	**552**	**563**	**653**	**70.1**
Unit 6 (Spring Session #1)	606	661	676	70.0
Unit 6 (Spring Session #2)	606	685	739	N/A*
Unit 6 (Spring Avg.)	**606**	**673**	**708**	**70.0**
Unit 6 (Summer Session)	**606**	**807**	**805**	**74.8**
Unit 7 (Spring Session #1)	**506**	**333**	**411**	**68.3**
Unit 7 (Summer Session)	**506**	**446**	**551**	**73.1**
Unit 8 (Spring Session #1)	**448**	**392**	**492**	**70.1**
Unit 9 (Spring Session #1)	545	464	445	68.3
Unit 9 (Spring Session #2)	545	507	491	72.9
Unit 9 (Spring Avg.)	**545**	**485**	**468**	**70.6**
Unit 9 (Summer Session)	**545**	**662**	**633**	**78.4**
Unit 10 (Spring Session #1)	**416**	**296**	**329**	**66.3**
Unit 11 (Spring Session #1)	**572**	**568**	**611**	**70.0**
Unit 11 (Summer Session)	**572**	**688**	**802**	**77.3**
Unit 12 (Spring Session #1)	**618**	**617**	**668**	**72.6**
Unit 13 (Spring Session #1)	**457**	**349**	**341**	**63.7**
Unit 14 (Spring Session #1)	**615**	**452**	**477**	**63.8**
Unit 15 (Spring Session #1)	**715**	**695**	**754**	**73.2**
Unit 16 (Spring Session #1)	**759**	**637**	**620**	**60.5**
Unit 17 (Spring Session #1)	**828**	**813**	**903**	**70.3**
Unit 18 (Summer Session)	**506**	**687**	**857**	**78.4**
Unit 19 (Summer Session)	**697**	**1094**	**1110**	**74.4**
Average (Spring)	**574**	**525**	**568**	**68.2**
Average (Summer)	**534**	**666**	**727**	**74.6**

Note: Temperature/humidity sensor failures occurred during Session 2 with Unit 1 and Unit 6.

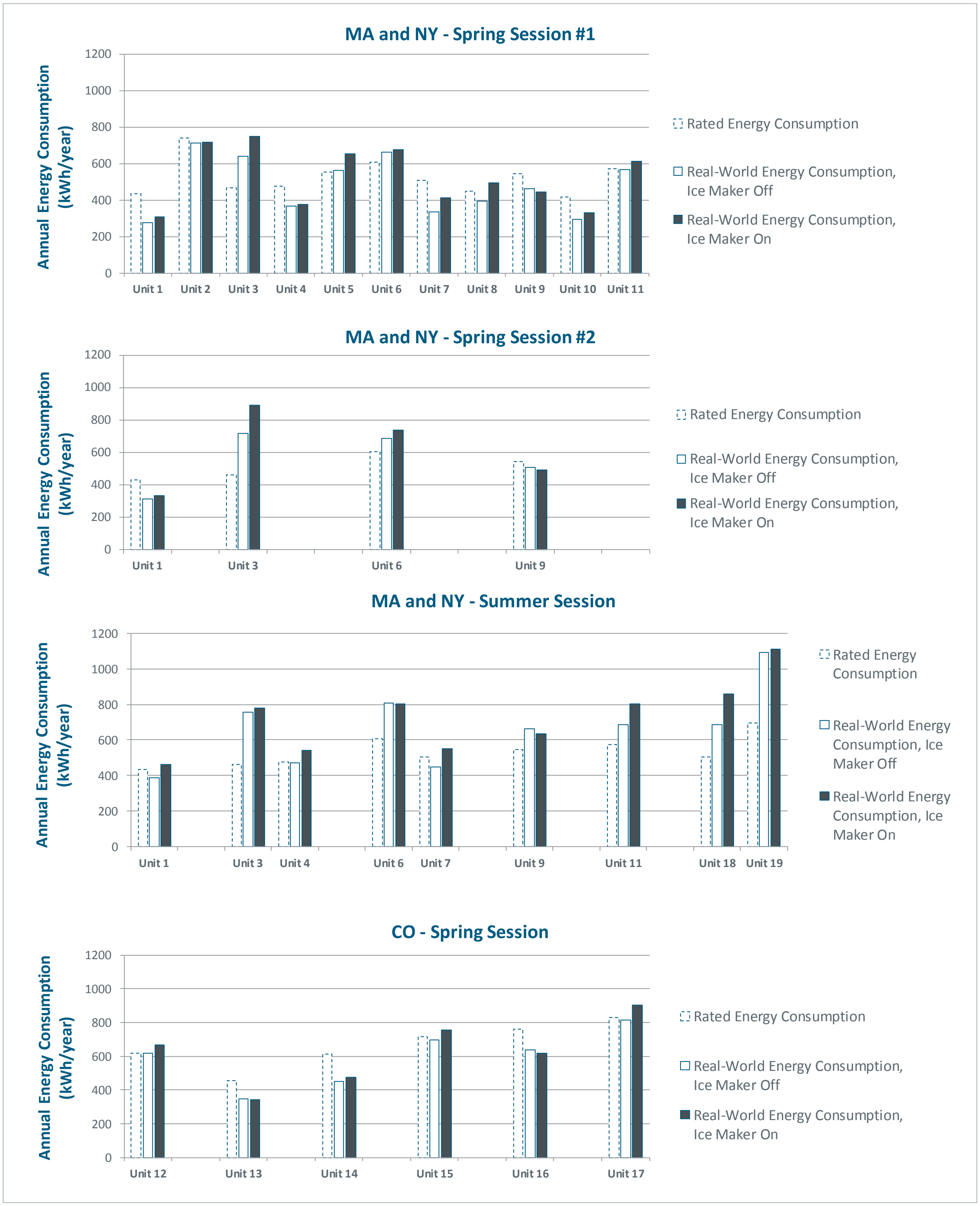


Figure 10. Comparison of rated energy consumption, energy consumption with ice maker off, and energy consumption with ice maker on

12.1 Annual Energy Consumption

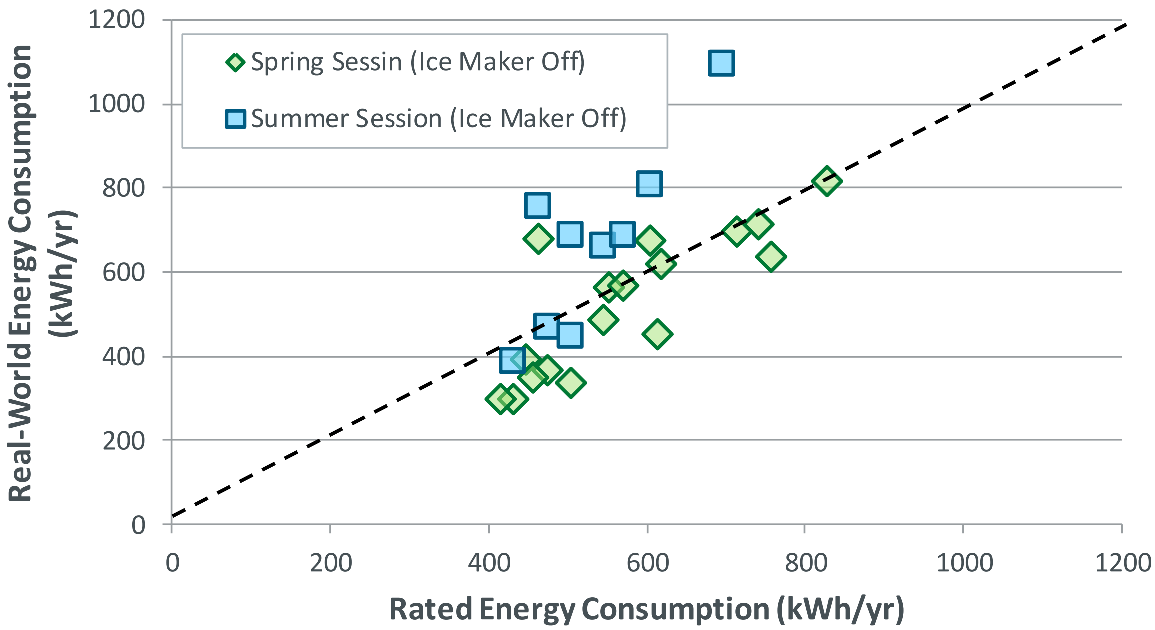
Table 11 shows the rated annual energy consumption and the measured annual energy consumption during the “ice maker off” period. The rated value is based on the unit’s performance under the DOE refrigerator test procedure, which requires the ice maker to be turned off, so the “ice maker off” period should provide the closest match to the rated value.

Table 11. Rated and Measured Annual Energy Consumption

Field Study Unit	Rated Annual Energy Consumption (kWh/year)	Measured Annual Energy Consumption, Ice Maker Off (kWh/year)	Percent Increase over Rated Energy Consumption*
Unit 1 (Spring Session #1)	433	275	-36%
Unit 1 (Spring Session #2)	433	314	-27%
Unit 1 (Spring Average)	**433**	**295**	**-32%**
Unit 1 (Summer Session)	**433**	**386**	**-11%**
Unit 2 (Spring Session #1)	**741**	**712**	**-4%**
Unit 3 (Spring Session #1)	464	640	+38%
Unit 3 (Spring Session #2)	464	715	+54%
Unit 3 (Spring Average)	**464**	**678**	**+46%**
Unit 3 (Summer Session)	**464**	**756**	**+63%**
Unit 4 (Spring Session #1)	**476**	**365**	**-23%**
Unit 4 (Summer Session)	**476**	**469**	**-1%**
Unit 5 (Spring Session #1)	**552**	**563**	**+2%**
Unit 6 (Spring Session #1)	606	661	+9%
Unit 6 (Spring Session #2)	606	685	+13%
Unit 6 (Spring Average)	**606**	**673**	**+11%**
Unit 6 (Summer Session)	**606**	**807**	**+33%**
Unit 7 (Spring Session #1)	**506**	**333**	**-34%**
Unit 7 (Summer Session)	**506**	**446**	**-12%**
Unit 8 (Spring Session #1)	**444**	**392**	**-12%**
Unit 9 (Spring Session #1)	545	464	-15%
Unit 9 (Spring Session #2)	545	507	-7%
Unit 9 (Spring Average)	**545**	**485**	**-11%**
Unit 9 (Summer Session)	**545**	**662**	**+21%**
Unit 10 (Spring Session #1)	**416**	**296**	**-29%**
Unit 11 (Spring Session #1)	**572**	**568**	**-1%**
Unit 11 (Summer Session)	**572**	**688**	**+20%**
Unit 12 (Spring Session #1)	**618**	**617**	**-0%**
Unit 13 (Spring Session #1)	**457**	**349**	**-24%**
Unit 14 (Spring Session #1)	**615**	**452**	**-26%**
Unit 15 (Spring Session #1)	**715**	**695**	**-3%**
Unit 16 (Spring Session #1)	**759**	**637**	**-16%**
Unit 17 (Spring Session #1)	**828**	**813**	**-2%**
Unit 18 (Summer Session)	**506**	**687**	**+36%**
Unit 19 (Summer Session)	**697**	**1094**	**+57%**
Average (Spring)	**573**	**525**	**-8.5%**
Average (Summer)	**527**	**666**	**+26.3%**

*Percent Increase = (Measured Annual Energy Consumption, Ice Maker Off – Rated Annual Energy Consumption) / Rated Annual Energy Consumption

Figure 11 compares the real-world energy consumption (i.e. the measured annual energy consumption during the "ice maker off" period) to the rated energy consumption for each refrigerator. Points above the dashed line indicate real-world energy consumption greater than the rated value.

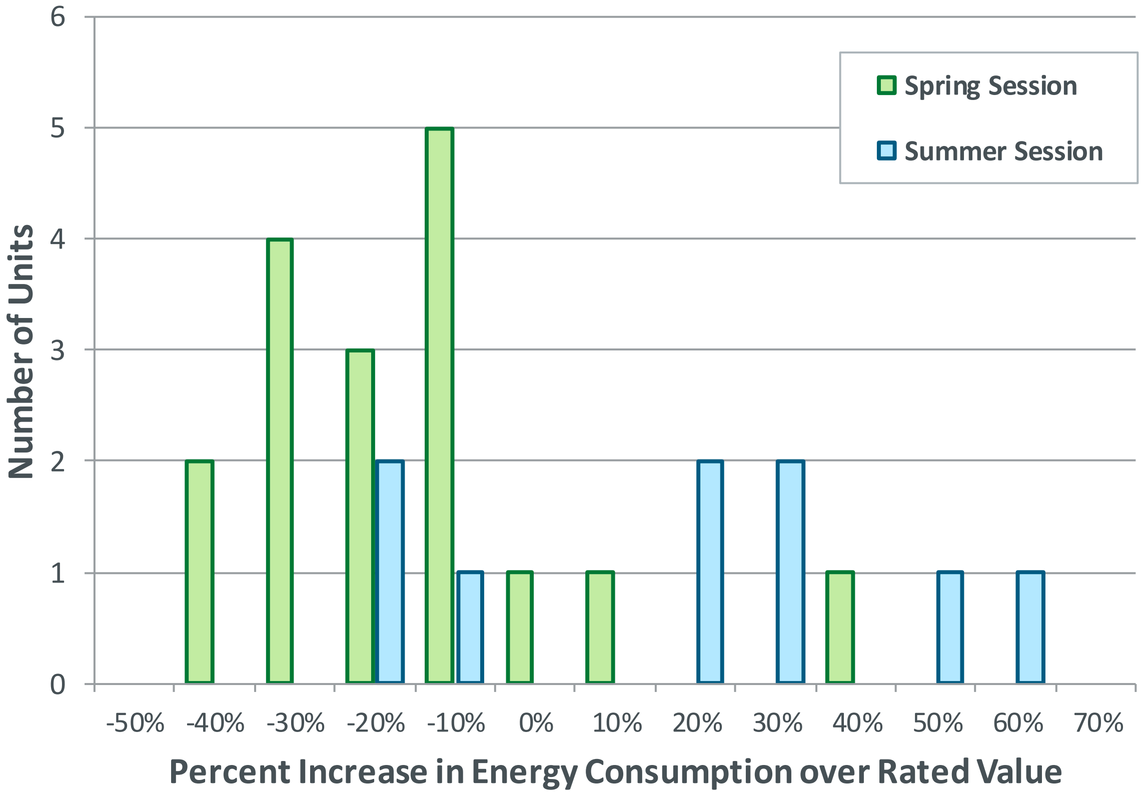


Note: Real-world energy consumption represents the measured annual energy consumption during the "ice maker off" period. Points above the dashed line indicate real-world energy consumption greater than the rated value.

Figure 11. Comparison between real-world energy consumption and rated energy consumption

Figure 11 shows that during the spring season, on average the refrigerators in the field study experienced 9 percent lower real-world energy consumption than predicted by their rated values. Conversely, during the summer session, the refrigerators in the field study experienced 26 percent higher real-world energy consumption than predicted by their rated values. The data indicate that energy consumption during the warmer summer months is significantly higher than during the milder spring months, which is to be expected. These results highlight the importance of acquiring energy consumption data across multiple seasons.

Figure 12 shows the distribution of the percent increase in energy consumption over rated value. In the figure, negative values indicate real-world energy consumption less than the rated value.



Note: Negative values indicate real-world energy consumption less than the rated value.

Figure 12. Distribution of percent increase in energy consumption over rated value

The results indicate that during the spring session, the majority of refrigerators in the field study experience lower real-world energy consumption than predicted by their rated values. Conversely, during the summer session, the majority of refrigerators experienced higher real-world energy consumption than predicted by their rated values.

Figure 13 provides a comparison between the results from our field study and the data from the NY Public Housing field study (PNNL 1998). The figure shows the real-world energy consumption for both the "ice maker on" and "ice maker off" periods in our study. The PNNL study did not indicate the status of the ice maker in each refrigerator.

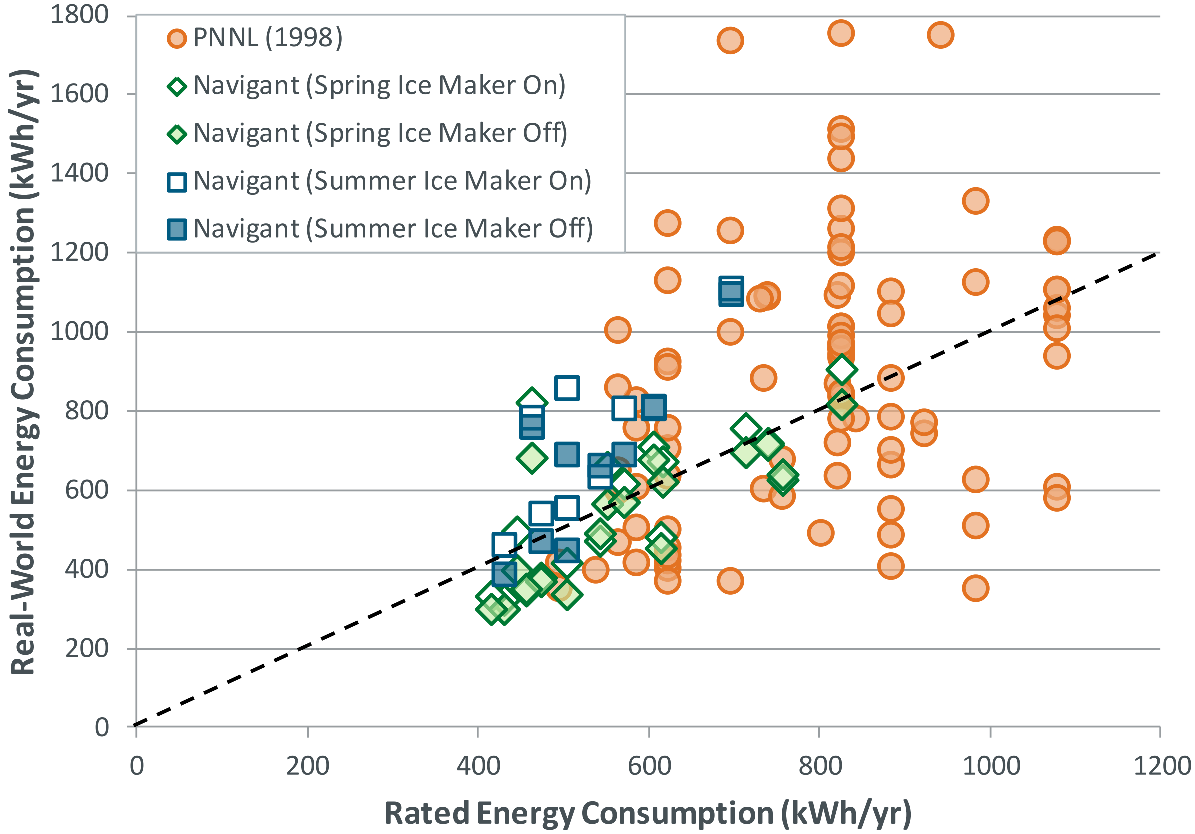


Figure 13. Comparison between real-world energy consumption and rated energy consumption – PNNL vs. Navigant (Source: PNNL 1998)

Figure 13 indicates that the refrigerators in the PNNL field study experienced significantly greater differences between real-world energy consumption and rated energy consumption compared to the refrigerators in the Navigant field study. On average, the refrigerators in the PNNL sample experienced 10 percent greater real-world energy consumption compared to their rated values.

We investigated the correlation between ambient air temperature and the difference between real-world and rated energy consumption. We expect higher ambient air temperature to correlate with higher real-world energy consumption. We also expect that the difference between real-world and rated energy consumption should approach zero at an ambient temperature around 70 °F, because the intent of the refrigerator test procedure is to simulate typical room conditions (approximately 70 °F) with door openings, by testing at 90 °F without door openings[17]. Figure 14 compares the difference between real-world and rated energy consumption as a function of average ambient air temperature for both the Navigant field study and the PNNL field study.

[17] Reference: Energy Conservation Program for Consumer Products: Test Procedures for Refrigerators, Refrigerator-Freezers, and Freezers; Final Rule and Interim Final Rule. December 16, 2010. Federal Register Vol. 75, p.78850. Available online at: http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/rftp_frnotice_2010-12-21.pdf

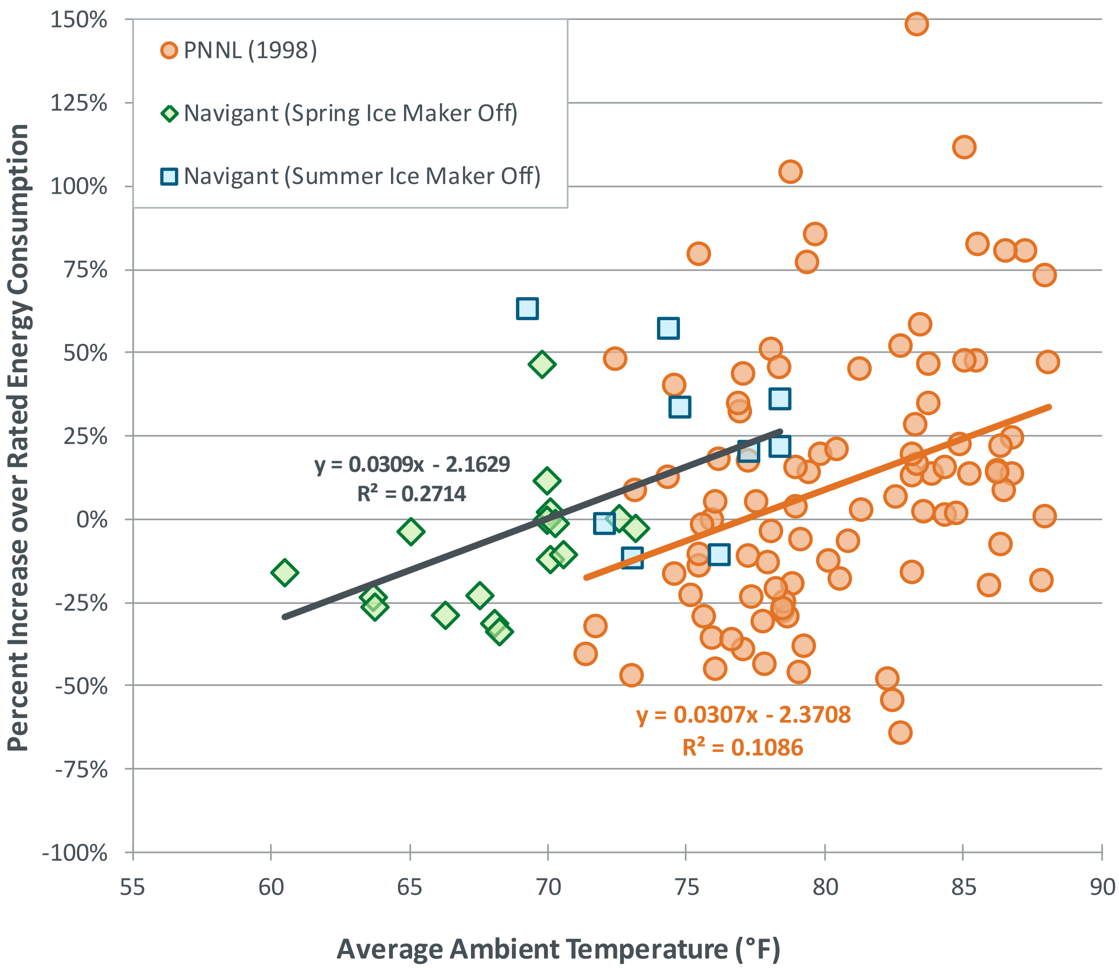


Figure 14. Comparison between rated energy consumption and actual energy consumption vs. average temperature – PNNL vs. Navigant (Source: PNNL 1998)

Figure 14 indicates a moderate correlation (R^2=0.29) between ambient air temperature and the difference between real-world and rated energy consumption. The trendline through the Navigant data sample crosses zero at almost exactly 70 °F, indicating that the current DOE refrigerator test procedure accurately simulates the real-world energy consumption at typical ambient room conditions. The trendline through the PNNL data sample crosses zero at approximately 77 °F.

12.2 Performance Degradation over Time

To address the question of whether refrigerator performance degrades over time, we investigated the correlation between the refrigerator model year and the difference between real-world and rated energy consumption, as shown in Figure 15. If performance degrades over time, we would expect older units to experience a greater increase of real-world energy consumption compared to the rated energy consumption.

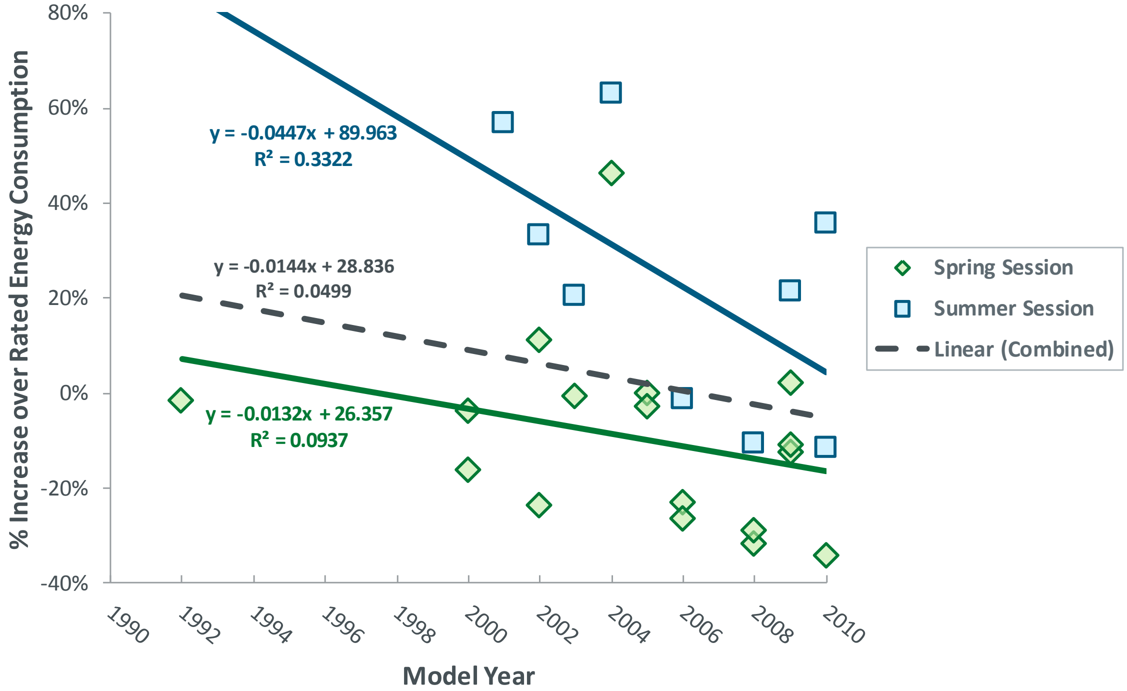


Figure 15. Percent increase over rated energy consumption as a function of model year

Figure 15 shows a weak correlation (R^2=0.09) between performance and model year during the spring session. However, a slightly stronger correlation (R^2=0.19) occurred during the summer session. The correlation is weakest (R^2=0.04) when combining both the spring and summer phases. The stronger correlation during the summer session indicates that higher ambient temperatures may amplify any age-related performance degradation. Due to the small sample size of our experiment, however, we are unable to confirm with certainty whether overall refrigerator performance degrades over time.

12.3 Ice Maker Energy Consumption

Table 12 shows the measured annual energy consumption during the "ice maker off" and "ice maker on" periods, which we used to calculated the annual ice maker energy consumption.

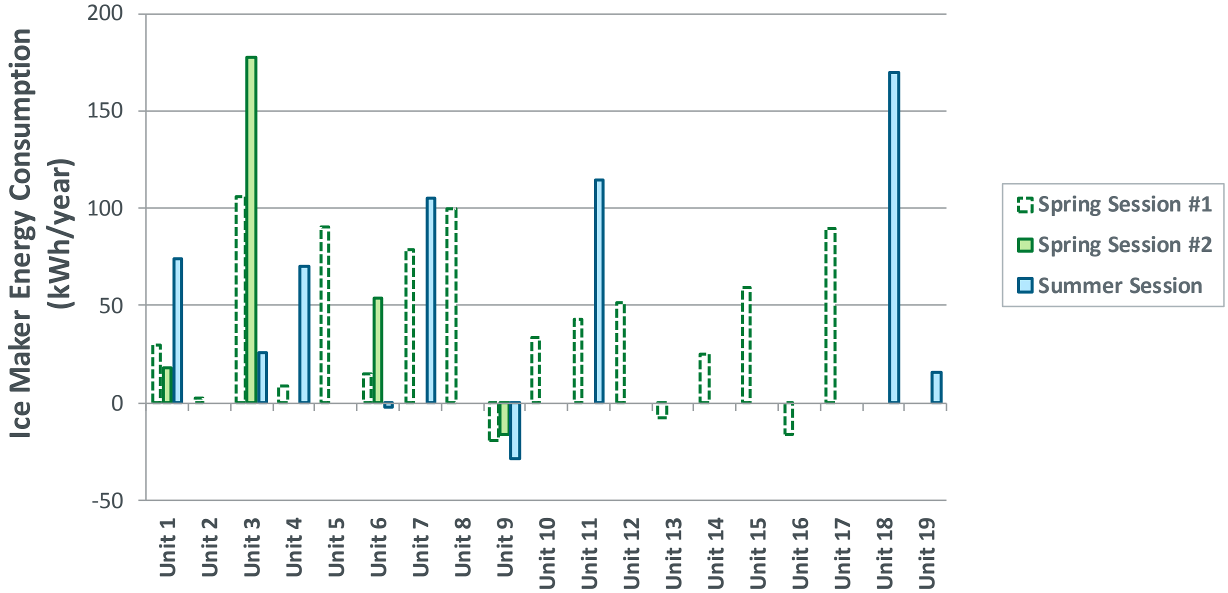
Table 12. Ice Maker Energy Consumption

Field Study Unit	Measured Annual Energy Consumption, Ice Maker Off	Measured Annual Energy Consumption, Ice Maker On	Calculated Annual Ice Maker Energy Consumption (kWh/year)*	Percent Increase in Energy Consumption due to Ice Maker**
Unit 1 (Spring Session #1)	275	305	30	+11%
Unit 1 (Spring Session #2)	314	333	19	+6%
Unit 1 (Spring Average)	**295**	**319**	**24**	**+8%**
Unit 1 (Summer Session)	**386**	**461**	**75**	**+19%**
Unit 2 (Spring Session #1)	**712**	**714**	**2**	**+0%**
Unit 3 (Spring Session #1)	640	746	106	+17%
Unit 3 (Spring Session #2)	715	893	178	+25%
Unit 3 (Spring Average)	**678**	**820**	**142**	**+21%**
Unit 3 (Summer Session)	**756**	**782**	**26**	**+3%**
Unit 4 (Spring Session #1)	**365**	**374**	**9**	+2%
Unit 4 (Summer Session)	**469**	**539**	**70**	**+15%**
Unit 5 (Spring Session #1)	**563**	**653**	**90**	+16%
Unit 6 (Spring Session #1)	661	676	15	+2%
Unit 6 (Spring Session #2)	685	739	54	+8%
Unit 6 (Spring Average)	**673**	**708**	**35**	**+5%**
Unit 6 (Summer Session)	**807**	**805**	**-2**	**+0%**
Unit 7 (Spring Session #1)	**333**	**411**	**78**	**+23%**
Unit 7 (Summer Session)	**446**	**551**	**105**	**+24%**
Unit 8 (Spring Session #1)	**392**	**492**	**100**	**+26%**
Unit 9 (Spring Session #1)	464	445	-19	-4%
Unit 9 (Spring Session #2)	507	491	-16	-3%
Unit 9 (Spring Average)	**485**	**468**	-17	**-4%**
Unit 9 (Summer Session)	**662**	**633**	**-29**	**-4%**
Unit 10 (Spring Session #1)	**296**	**329**	**33**	**+11%**
Unit 11 (Spring Session #1)	**568**	**611**	**43**	**+8%**
Unit 11 (Summer Session)	**688**	**802**	**114**	**+17%**
Unit 12 (Spring Session #1)	**617**	**668**	**51**	**+8%**
Unit 13 (Spring Session #1)	**349**	**341**	**-8**	**-2%**
Unit 14 (Spring Session #1)	**452**	**477**	**25**	**+6%**
Unit 15 (Spring Session #1)	**695**	**754**	**59**	**+8%**
Unit 16 (Spring Session #1)	**637**	**620**	**-17**	**-3%**
Unit 17 (Spring Session #1)	**813**	**903**	**90**	**+11%**
Unit 18 (Summer Session)	**687**	**857**	**170**	**+25%**
Unit 19 (Summer Session)	**1094**	**1110**	**16**	**+1%**
Average (Spring)	**525**	**568**	**43**	**+8%**
Average (Summer)	**666**	**727**	**61**	**+9%**

Note: Calculated values may not add due to rounding.
* Ice Maker Energy Consumption = Energy Consumption, Ice Maker On – Energy Consumption, Ice Maker Off
**Percent Increase = (Energy Consumption, Ice Maker On – Energy Consumption, Ice Maker Off) / Energy Consumption, Ice Maker Off

Table 12 indicates an average ice maker energy consumption of 43 kWh/year during the spring session and 61 kWh/year during the summer session. This corresponds to an increase of 8 percent and 9 percent, respectively, over the energy consumption when the ice maker was turned off. These results are slightly lower than DOE's previous estimate that the energy consumption associated with automatic ice making could represent 10 to 15 percent of the rated energy consumption of a typical refrigerator. The results show that the percentage increase in energy consumption due to ice making is relatively consistent throughout the year at around 8-9 percent.

Figure 16 shows the calculated ice maker energy consumption for each unit in the field study.



Note: Only Units 1, 3, 6, and 9 exhibited valid data in the 2nd session.

Figure 16. Ice maker energy consumption of each unit in the field study

Figure 17 through Figure 22 show how ice maker energy consumption varies according to various refrigerator/freezer and household characteristics

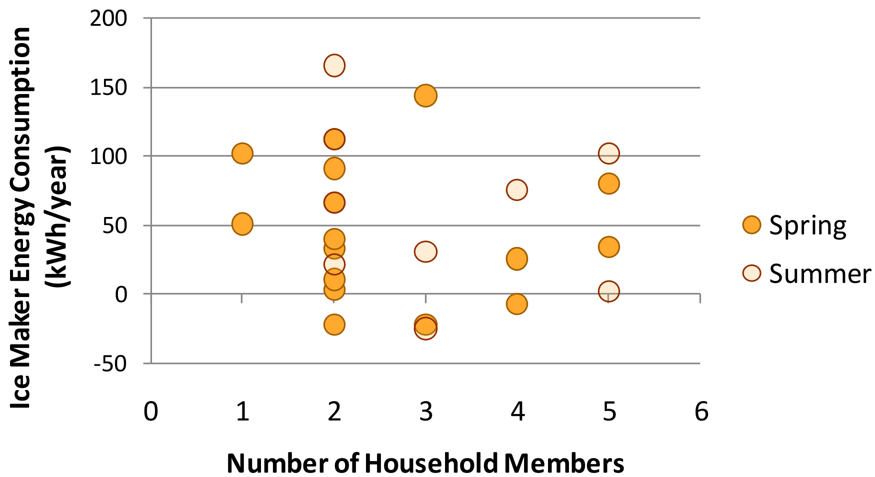


Figure 17. Ice maker energy consumption as a function of number of household members

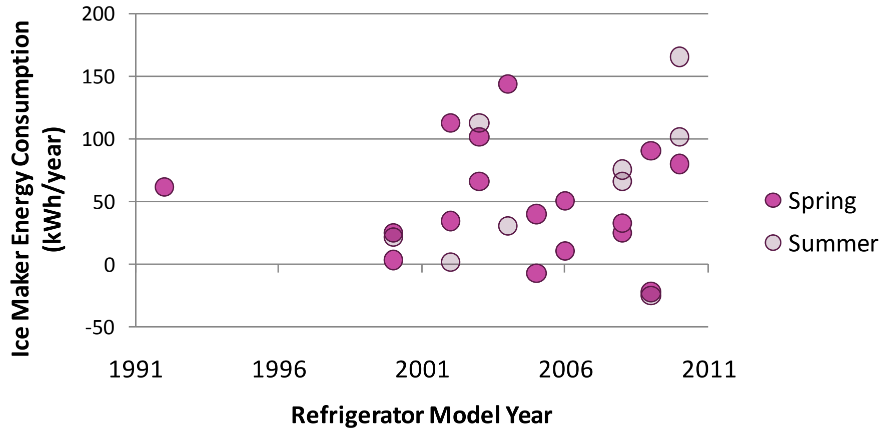


Figure 18. Ice maker energy consumption as a function of refrigerator model year

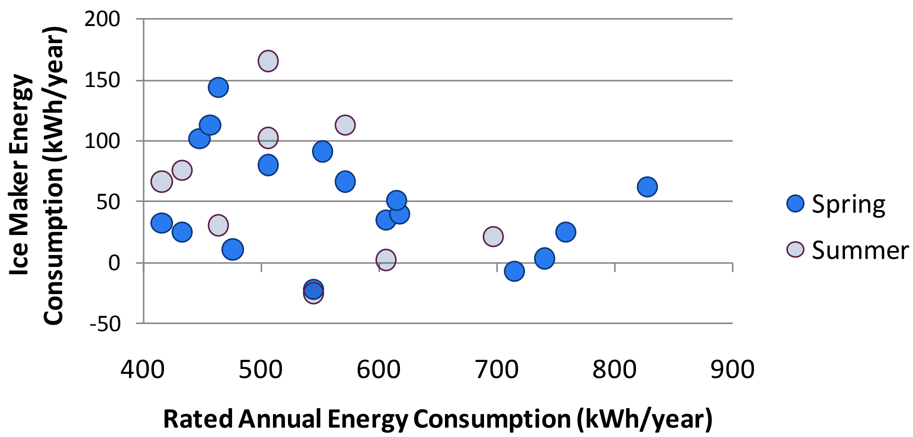


Figure 19. Ice maker energy consumption as a function of refrigerator rated annual energy consumption

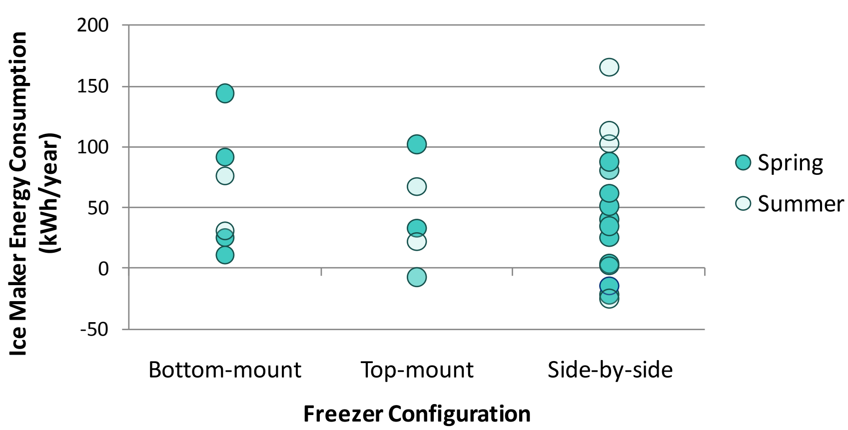


Figure 20. Ice maker energy consumption as a function of freezer configuration

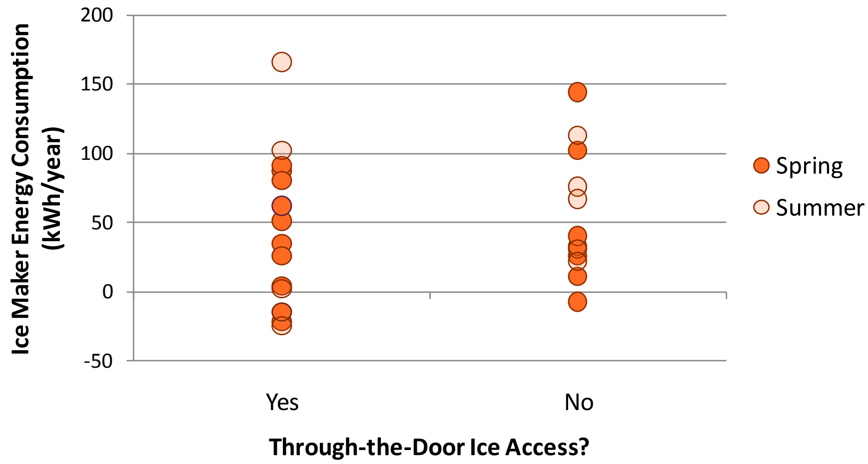


Figure 21. Ice maker energy consumption as a function of through-the-door ice access

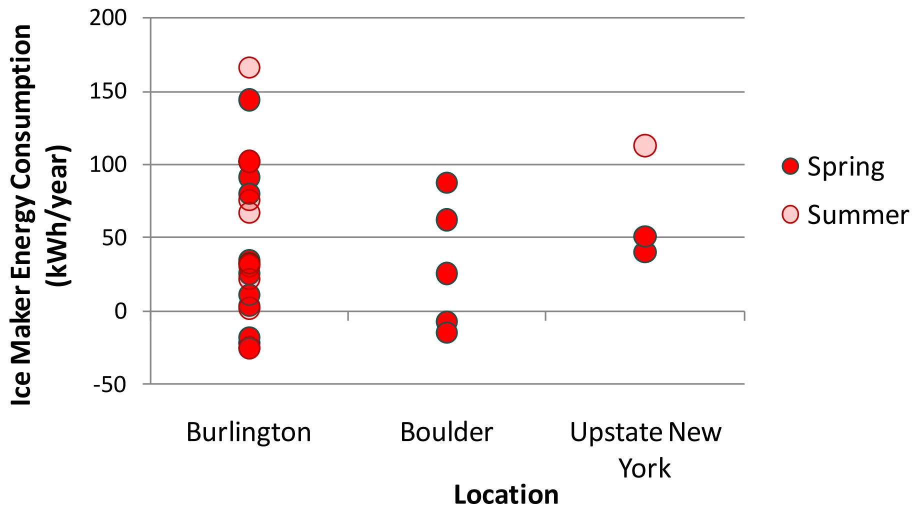


Figure 22. Ice maker energy consumption as a function of geographic location

Figure 23 shows a comparison between AHAM's ice maker energy consumption data and the results from our field study.

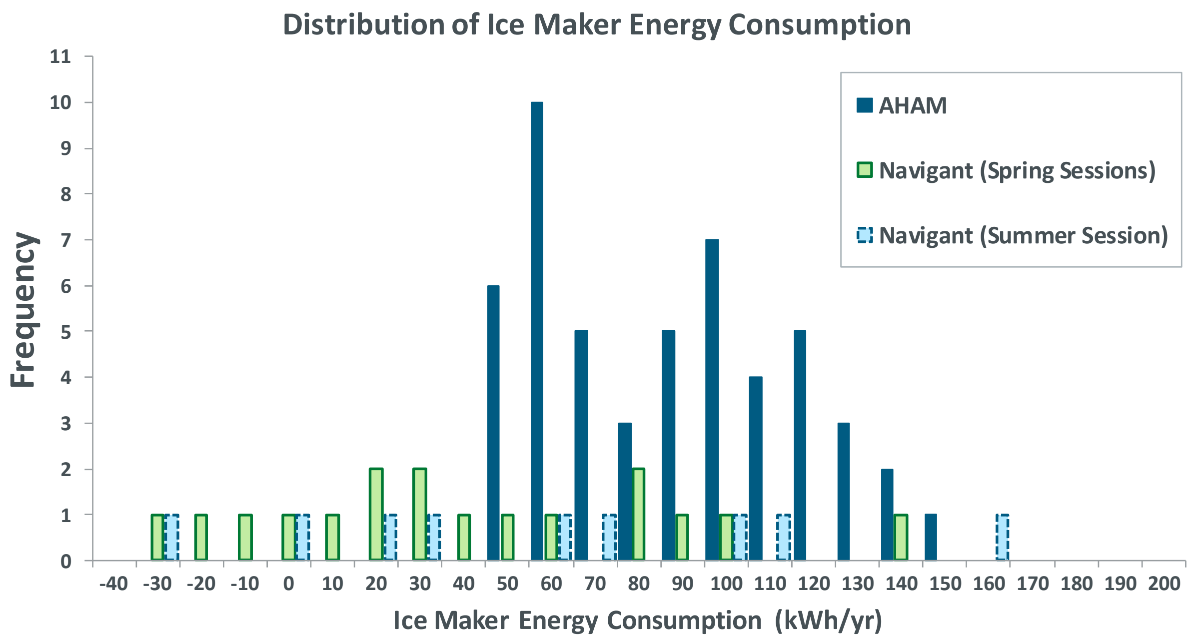


Figure 23. Distribution of ice maker energy consumption – AHAM vs. Navigant (Source: AHAM 2009)

Table 13 shows the average ice maker energy consumption from the AHAM, NIST, and Navigant data sets.

Table 13. Average Ice Maker Energy Consumption

Study	Average Ice Maker Energy Consumption (kWh/year)
AHAM	83
NIST	63-223
Navigant (Spring Session)	43
Navigant (Summer Session)	61

Our field study results indicate a wide range of ice maker energy consumption under real-world conditions. The results span two orders of magnitude difference, from essentially no impact at the low end to an additional 166 kWh/year at the high end. The average ice maker energy consumption from both the spring and summer field studies are less than the average from the AHAM data set. Our results are also lower than the estimates provided by NIST.

For some households, using the automatic ice maker adds a significant amount of energy compared to the energy consumption with the ice maker off. In the most extreme case, the ice maker increased the total energy consumption of the unit by more than 26 percent.

In a few cases, the participants experienced "negative" ice maker energy consumption. In these cases, variables other than the ice maker likely had a greater impact on the energy consumption during the field test measurement periods.

Ice maker energy consumption shows little or no correlation with the number of household members, the refrigerator model year, the refrigerator's rated annual energy consumption, whether the unit features through-the-door ice access, the freezer configuration, or the geographic location.

13 Refrigerators - Conclusions

13.1 Annual Energy Consumption

Our results indicate that the DOE refrigerator test procedure is highly accurate in simulating real-world energy consumption. Our data indicates that the laboratory conditions used by the DOE test procedure (90°F) simulate real-world conditions of approximately 70°F, which matches the intent of the DOE test procedure.

Our field study indicated that the difference between real-world energy consumption and rated energy consumption varies significantly by season, with higher energy consumption during the warmer summer months. Our results showed less difference, however, between real-world energy consumption and rated energy consumption compared to the prior PNNL field study, which showed much more variation between the two. Potential reasons why we experienced less variation with our study include the following:

- Our sample size was small: We had only 21 unique sessions, while the PNNL study had over 100.
- Household characteristics likely differ between the two samples: Our data represents mostly young urban dwellers, whereas the PNNL data represents a large public housing facility.
- Ambient temperature: Our average ambient temperature was 68°F during the spring phase and 75°F during the summer phase, versus 80°F for the PNNL study.
- Year: 2011 (Navigant) vs. 1998 (PNNL)
    - The 1998 units should have higher rated and real-world energy consumption.
    - The difference between rated energy consumption and real-world energy consumption could possibly change over time due to changes in the test procedure or changes in household usage characteristics.

13.2 Performance Degradation over Time

Our results indicate a weak correlation (R^2=0.09) between performance and model year during the spring season, and a slightly stronger correlation (R^2=0.19) during the summer months. The stronger correlation during the summer session indicates that higher ambient temperatures may amplify any age-related performance degradation. Additional testing with a much larger sample size would be required to confirm this correlation.

13.3 Ice Maker Energy Consumption

Our field study indicates a wide range of results for the annual energy consumption associated with ice making, with an average of 43 kWh/year during the spring, and 61 kWh/year during the summer. This represents an increase in energy consumption of between 8-9 percent compared to the energy consumption when the ice maker is turned off. These results justify DOE's conclusion that ice maker energy consumption is significant and should be included in the refrigerator test procedure.

Our average ice maker energy consumption (43-61 kWh/year) is lower than AHAM's estimate of 83 kWh/year and falls below the range of 63-223 kWh/year estimated by NIST. Potential reasons for these discrepancies may include the following:

- AHAM's estimate of daily ice usage of 1.8 lbs/day may not be accurate under real-world conditions. Additional information or data would be required in order to assess the accuracy of AHAM's estimate.
- AHAM's measurements of energy consumption per pound of ice production may be skewed by the laboratory ambient conditions used for those tests (90 °F), which differs significantly from real-world ambient conditions (70 °F).
- The results for ice maker energy consumption obtained using our calculation method may not be totally attributable to ice making, since we did not control any other variables during our field test.
- Differences in household demographics between our field study and AHAM household samples may cause discrepancies in the results.
- Deficiencies may exist with our field test protocol, including the following:
  - Allowing households to consume stored ice during the "ice maker off" week could adversely affect the ice making that occurs during the following "ice maker on" week. For example, for volunteers who participated in a second session, the ice maker may have had to produce more ice than normal during the second "ice maker on" session in order to build up the ice reserves that were depleted during the previous "ice maker off" week.
  - One-week periods may be too short. More time may be required to collect data that is truly representative of average usage patterns.
  - Inconsistent household behaviors between the "ice maker on" and "ice maker off" weeks may affect the results.
- Study participants may have inadvertently deviated from their "normal" behavior during our field study.
- Our sample of refrigerator types/product classes may not represent the distribution of refrigerator types nationally.

14 Refrigerators - Recommendations

14.1 Annual Energy Consumption

Based on the conduct and results of our study, we propose the following recommendations for additional testing of real-world energy consumption:

- Use a large sample size. We recommend a minimum of around 50 households.
- Include a more varied range of household demographics.
- Capture year-round seasonality, spanning the coldest and warmest months of the year.
- Include more geographic household distribution, especially hot Southern climates.

14.2 Performance Degradation over Time

Our field study did not specifically measure refrigerator performance degradation over time, and during the summer session we noted a moderate correlation of refrigerator performance degradation with unit age. To study the effects of refrigerator performance degradation over time, we recommend measuring the real-world energy consumption of individual refrigerators over the course of 5-10 years, under roughly the same usage patterns each year. Alternatively, multi-year laboratory tests could be performed on individual units to monitor any performance degradation over time.

14.3 Ice Maker Energy Consumption

We propose the following recommendations for additional testing of ice maker energy consumption:

- Include ice maker energy consumption in the refrigerator test procedure as a measured parameter for each refrigerator, rather than a fixed value.
- Perform a comparison of ice maker energy consumption under laboratory conditions of both 90°F and 70°F to investigate the effect of ambient air temperature.
- Perform additional field studies to independently verify AHAM's estimates of average daily ice consumption.
- During field studies, measure the quantity of ice consumption (lb/day) in addition to ice maker energy consumption.
- Consider alternatives to the one-week-on, one-week-off methodology used in our study.
- Use the shortest time sampling intervals possible in the data logging system to enable identification of key signatures in the raw energy data.
- Use a larger sample size. We recommend a minimum of around 50 households.
- Include a more varied range of household demographics.
- Consider more geographic household distribution.

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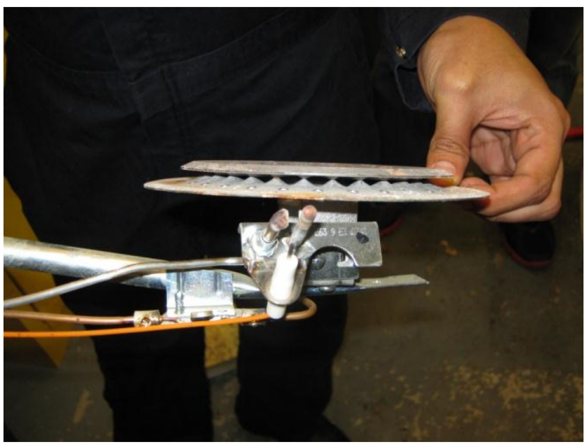
16 Appendix A – Water Heater Components

The photographs below, show the condition of water heater components observed during disassembly. The photographs also illustrate how we rated a ‘good’ component and a ‘poor’ component.

	GOOD	POOR
Combustion Chamber	 Unit 5	 Unit 12
Combustion Chamber	 Unit 5	 Unit 12

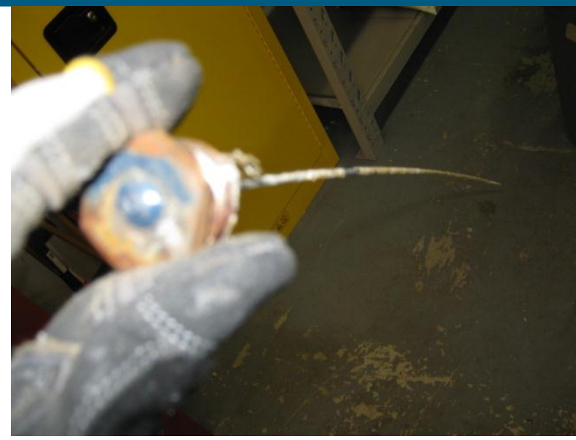
	GOOD	POOR
Burner	 Unit 5	 Unit 12
Burner	 Unit 4	 Unit 13

	GOOD	POOR
Interface (B/CC)	 Unit 13	 Unit 12
Interface (B/CC)	 Unit 6	 Unit 11
Interface (B/CC)	 Unit 2	 Unit 11

	GOOD	POOR
Spiral Heat Exchanger	 Unit 10	None
Spiral Heat Exchanger	 Unit 5	None

	GOOD	POOR
Upper Element	 Unit 3	 Unit 6
Lower Element	 Unit 3	 Unit 6

	GOOD	POOR
Insulation (top and side)	 Unit 2	 Unit 9
Insulation (CC)	 Unit 7	 Unit 13

	GOOD	POOR
Anti-corrosion Anode	 Unit 2	 Unit 11
Anti-corrosion Anode	 Unit 3	 Unit 6

	GOOD	POOR
Cold water dip tube	 Unit 2	None
Cold water dip tube	 Unit 5	None

	GOOD	POOR
Thermocouple	 Unit 2	 Unit 9
Thermocouple	 Unit 4	 Unit 11

17 Appendix B –Refrigerator Field Energy Monitoring Equipment

To record the energy consumption of each refrigerator, we used a Watts Up Pro power meter from Electronic Educational Devices[18]. This power meter has an accuracy of +/-1.5%. Memory storage depends on how many parameters are stored: 120,000 records can be stored if only logging Watts. In automatic mode with all parameters recorded, approximately 4,000 records can be stored.

We programmed each power meter to record data in 10-minute intervals. Each data point included voltage, instantaneous power draw in Watts, cumulative Watt-hours, and a timestamp. With these parameters and a 10-minute interval, we were able to store 8,147 records, or approximately 56 days of data.

We also recorded ambient air temperature and relative humidity conditions in each participant's kitchen using a USB Track-It Data Logger from Monarch Instrument[19]. This is a stand-alone compact data logger with an accuracy of +/- 3%. The loggers can store up to 64,000 records, and can sample at a rate as high as one sample every two seconds, or as low as one sample every 24 hours.

We programmed the temperature data loggers to record data in 10-minute intervals. At this interval, they can store up to 32,750 records each, or approximately 227 days worth of data. We attached magnets to each data logger and asked participants to place the data logger on the top or side of their refrigerator throughout the duration of the field study.

After one round of deployment (lasting two weeks), the equipment was returned to Navigant's office in Burlington, MA for downloading and analysis of the data. The empty data loggers and temperature sensors were then returned to some participants in the Burlington office for a second round of monitoring (lasting two weeks). At this time, participants in Boulder, CO and New York began their experiment. The Boulder and New York participants returned the equipment after one round of monitoring (lasting two weeks).

Figure 24 through Figure 27 show the Watts Up Pro power meter and the USB Track-It Data Logger and an example of installation in the field.

[18] Information on the Watts Up Pro power meters available at http://www.wattsupmeters.com.
[19] Information on the Track-It Data Logger available at http://www.monarchinstrument.com.

Figure 24. Watts Up Pro Power Meter and USB Track-It Data Logger

Figure 25. USB Track-It Data Logger

Figure 26. Installation of Watts Up Pro Power Meter

Figure 27. Installation of USB Track-It Data Logger

18 Appendix C – Refrigerator Raw Data from Field Study

			Spring Session #1					Spring Session #2					Summer Session				
Participant	Manufacturer	Model	Days On	Days Off	Total kWh On	Total kWh Off	Temp	Days On	Days Off	Total kWh On	Total kWh Off	Temp	Days On	Days Off	Total kWh On	Total kWh Off	Temp
Unit 1	Liebherr	C1650	6.9	8.2	5.8	6.2	68.1	7.7	7.0	7.0	6.0	N/A	10.2	14.3	12.9	15.1	76.2
Unit 2	Kitchen Aid	KSRS27FG5514	7.9	4.3	15.4	8.3	65.1	13.7	7.9	19.9	30.2	N/A					
Unit 3	General Electric	PDS22SCRBRSS	11.1	10.1	22.7	17.8	67.9	9.5	12.5	23.3	24.5	71.7	7.3	8.5	15.6	17.6	69.3
Unit 4	Maytag	PBF1951KEW	9.0	8.2	9.3	8.2	67.6	8.0	7.0	8.8	7.5	N/A	6.7	7.2	9.9	9.3	72.1
Unit 5	General Electric	GFSS6KKYASS	7.4	8.1	13.2	12.6	70.1										
Unit 6	Whirlpool	GD2SHAXLT00	7.5	8.6	13.9	15.6	70.0	8.0	7.2	16.1	13.4	NA	7.0	7.0	15.4	15.5	74.8
Unit 7	General Electric	GSH25JFXN BB	7.9	8.1	8.9	7.4	68.3	7.1	7.5	8.6	10.7	NA	21.0	12.5	31.7	15.3	73.1
Unit 8	General Electric	GTH22SHSARSS	8.0	8.1	10.8	8.7	70.1										
Unit 9	Bosch	B22CS30SNS/I	9.0	12.0	10.9	15.3	68.3	9.0	7.6	12.2	10.6	72.9	7.9	8.0	13.7	14.5	78.4
Unit 10	Whirlpool	W1TXEMMWS02	10.1	7.0	9.1	5.6	66.3										
Unit 11	Whirlpool	ED2PHEXNQ00	7.0	7.0	11.7	10.8	70.0						7.0	8.3	15.4	15.6	77.3
Unit 12	Frigidaire	GLHS68EEWO	6.6	7.4	12.0	12.5	72.6										
Unit 13	Kenmore	106.722062	8.2	10.9	7.6	10.4	63.7										
Unit 14	General Electric	PSS26MSWA	10.9	8.0	14.3	9.9	63.8										
Unit 15	General Electric	GSS25JEPH	8.4	20.6	17.3	39.2	73.2										
Unit 16	General Electric	TFH22PR	7.9	27.8	13.4	48.4	60.5										
Unit 17	Kenmore	106.953551	9.0	8.2	22.2	18.3	70.3										
Unit 18	General Electric	GSH25JSXJ SS											7.0	7.0	16.4	13.2	78.4
Unit 19	General Electric	TBX18IIDARWW											7.0	7.8	21.3	23.4	74.4

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