

National Weatherization Assistance Program Evaluation: Assessment of Refrigerator Energy Use



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March 2015

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Environmental Sciences Division

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Assessment of Refrigerator Energy Use**

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March 2015

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ACRONYMS AND ABBREVIATIONS

CSV	Comma Separated Value
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FDA	U.S. Food and Drug Administration
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
kWh	Kilowatt Hour
ORNL	Oak Ridge National Laboratory
OWIP	Office of Weatherization and Intergovernmental Program
USDA	U.S. Department of Agriculture
WAP	Weatherization Assistance Program

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ABSTRACT

This report assess the characteristics and performance of refrigerators found in a sample of homes eligible to receive services from the U.S. Department of Energy's Weatherization Assistance Program. The refrigerators studied for this research were located in homes that participated in a larger study of the impacts of weatherization on indoor air quality. The study primarily focuses on a set of 382 primary refrigerators and data collected about their operation pre-weatherization. The typical refrigerator found in the study homes was manufactured after the year 2000, has a capacity of 18 cubic feet, and has a top freezer. Only 27% of the primary refrigerators are located in kitchens and 34% are not located in conditioned spaces. Only 23% of the refrigerators had an energy-saver switch and of these, only 55% of the switches were observed to be in the on position. The preponderance of the refrigerators' inside temperatures was below the recommended 42 °F, though this threshold was exceeded the entire metering time for three refrigerators. The average annualized electricity consumption for a refrigerator in the sample was 756 kWh/year. The median was 651 kWh/year. The variation in consumption has many possible explanations, including: refrigerator capacity, age, indoor temperatures, location in unconditioned spaces, number of individuals in the household (e.g., influencing the number of door openings), number of operating options, and simple disrepair. It should be noted that the average electricity consumption of this set of refrigerators is possibly an underestimate given that the data were collected during the winter, the majority of the study houses are located in cold to very cold climates, and a large percentage of the refrigerators are located in unconditioned spaces. As expected, the age and capacity of refrigerators are positively and statistically related to annual energy use. Refrigerators that operate at unhealthy temperatures for much of the time use less energy on average.

The next section of this report describes the data that were collected and how the data were processed for analysis. Section 3 presents the results, beginning with characteristics of the refrigerators in the study and continuing with assessments of inside temperatures and energy consumed.

2. DATA COLLECTION AND PREPARATION

2.1 DATA COLLECTION

The bulk of the IAQ study was conducted during the winter of 2010-2011. Fieldwork for the IAQ study consisted of four site visits to each home. Visit 1 and visit 2 were before weatherization. During visit 1 the refrigerator temperature data were collected and the refrigerator power meter was installed. During visit 2, usually about 7 days later, the refrigerator power logger was retrieved. During visits 1 and 3, a detailed survey was conducted to record the general characteristics of the home and equipment including the characteristics of the primary refrigerator and secondary refrigerator, if present. In addition, all participants in the IAQ study were administered an extensive telephone survey, called the Occupant Survey³, covering a number of topics including basic demographics, indoor comfort, and health issues.

A logger recorded refrigerator temperature while the technician was on site during site visit number 1, typically less than two hours. Temperature data were collected on 159 refrigerators, all primary refrigerators. The temperature log files were combined into a single comma-separated value (CSV) file with 16,411 records. The one-minute records include site identifier, timestamp, and temperature in degrees Fahrenheit.

Refrigerator power data were collected for primary refrigerators and some secondary refrigerators during pre-weatherization and post-weatherization field visits. Refrigerator power loggers were installed during site visit 1 and retrieved during site visit 2 with duration of about one week. This process was repeated during visits 3 and 4 for selected refrigerators.

The logger files were combined into a single CSV file with almost five million records. The data fields are site identifier, refrigerator identifier, elapsed minutes, instantaneous watts, accumulated watt-hours, and a power cycle indicator (e.g., power outage). Table 2.1 shows the power data sample counts for the 405 sites with 459 refrigerators. This report will focus on the 382 primary refrigerators with data collected during the pre-weatherization visit.⁴

Table 2.1 Number of Refrigerators with Power Data

Refrigerator Sample	Frequency
Primary refrigerator, pre-weatherization	382
Secondary refrigerator, pre-weatherization	15
Primary refrigerator, post-weatherization	61
Secondary refrigerator, post-weatherization	1
Total	459

2.2 PREPARATION OF THE REFRIGERATOR TEMPERATURE DATA FOR ANALYSIS

Figure 2.1 shows a plot of temperature for a refrigerator operating normally. The site visit is too short to capture a full day of operation which would include time-of-day variations of refrigerator use and defrost cycle. Unfortunately, many of the recordings were too short to capture the maximum temperature, the minimum temperature, or both.

³ See Carroll et al. 2014 for a detailed description of the Occupant Survey

⁴ The project team was unable to revisit a substantial number of refrigerators post-weatherization, which is why this report focuses on data collected pre-weatherization.

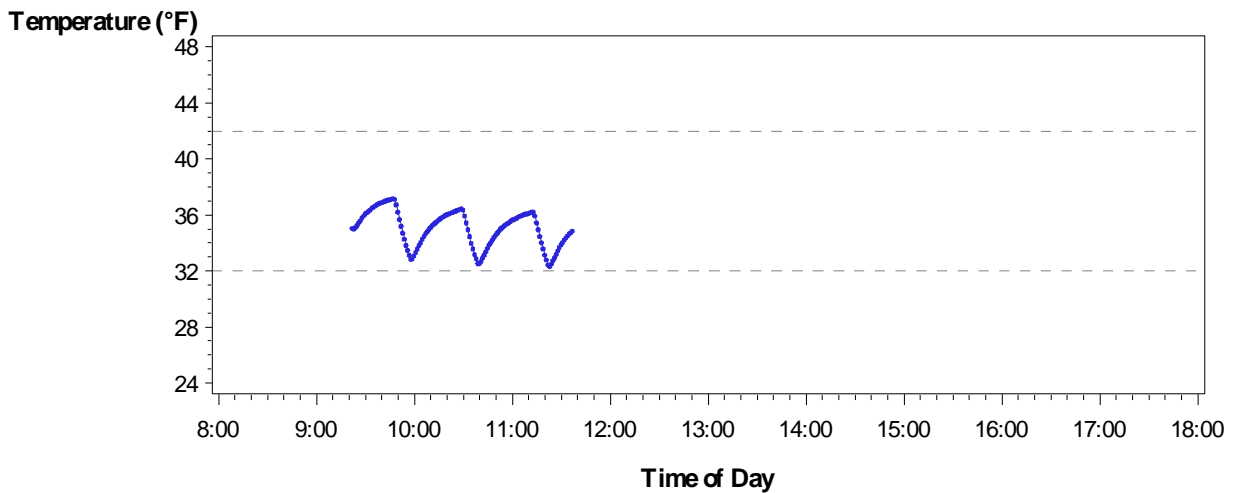


Figure 2.1 Typical Refrigerator Temperature

Data quality flags were created to identify the absence of recorded minimum temperature and maximum temperature and these filters were applied to statistical summaries of minimum temperature, maximum temperature, temperature range, and measures of healthy temperature. Table 2.2 shows that 112 (70 percent) of the temperature logs recorded both minimum temperature and maximum temperature.

Table 2.2 Number of Refrigerators with Minimum and Maximum Recorded

Minimum Temperature Recorded	Maximum Temperature Recorded		
	No	Yes	Total
No	24	23	47
Yes	0	112	112
Total	24	135	159

For those units where both maximum and minimum temperatures were observed, the average metering time was 1.7 hours. For those with incomplete range measurements, the average was about 1.3 hours.

2.3 PREPARATION OF THE REFRIGERATOR POWER DATA FOR ANALYSIS

Logger failures occurred resulting in loss of data. The meter contains a calibration table that was, on occasion, corrupted. As a result, 27 refrigerator files were deleted and 21 were truncated by data quality filters applied during preparation of the data for analysis.

Annual kWh was computed for each refrigerator as the average 1-minute watt-hours times 60 times 24 times 365 divided by 1000.

Figure 2.2 is a plot of instantaneous power for a selected refrigerator. Data points equal to 0 watts correspond to when the compressor is off and data points equal to approximately 100 watts correspond to when the compressor is one. The infrequent readings of approximately 380 watts correspond to when the defrost cycle is operating. Power levels consumed are low and the refrigerator compressor is often off while minimum temperature is maintained. However, there were tremendous variations among the sampled units in power levels and run times.

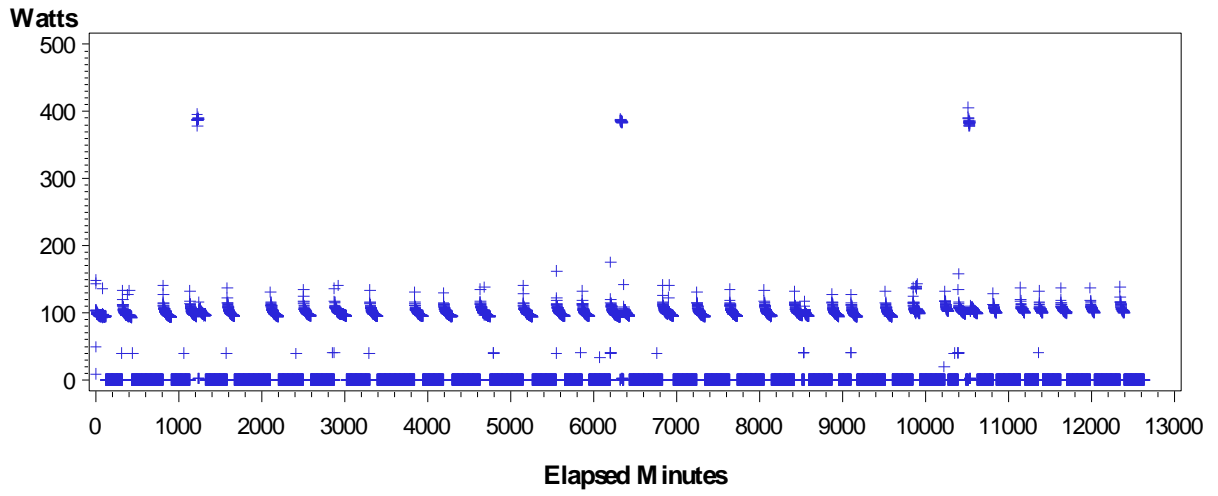


Figure 2.2 Example of Refrigerator Power (watts) Over Time (in minutes)

3. REFRIGERATOR CHARACTERIZATION AND PERFORMANCE

Table 3.1 describes the characteristics of the 382 primary refrigerators found in the IAQ study of homes pre-weatherization. Most have top freezers (67%) and almost all have automatic defrosters (96%). This set of refrigerators has fewer additional features, such as through the door water dispensers (26%) and anti-sweating technology (19%). Only 23% of the refrigerators had an energy saver switch and of these, the switch was set to on in only 55% of the cases. Also impacting refrigerator energy use is the fact that 34% of the refrigerators are not located in conditioned spaces, which could lead to reduced or increased energy consumption (e.g., if outside in winter or summer). Many refrigerators are located in basements (25%) and garages (18%). Forty five (9%) of the homes had a secondary refrigerator and 6 homes (1%) had a third refrigerator.

Figure 3.1 plots the dates that the primary refrigerators were manufactured. Almost 40% were manufactured between 2007 and 2010. Just over 25% were manufactured before the year 2000. One refrigerator was manufactured in the early 1970s. As indicated in Figure 3.2, most of the refrigerators have a capacity of about 18 cubic feet, though a fair number have higher capacities.

To protect family members from foodborne illness, the U.S. Department of Agriculture (USDA) recommends that the refrigerator temperature be 40 °F or below.⁵ Furthermore, the USDA recommends that food stored at temperatures above 40 °F for more than 2 hours should not be consumed due to a risk of food poisoning.⁶ Table 3.2 presents results from monitoring the temperature inside the primary refrigerators during the first IAQ study visit. On average, the refrigerators in the sample meet this requirement. However, upon closer inspection, of the 112 refrigerator meter files with both minimum and maximum temperature recorded, 25 (22%) had temperatures above 41 °F. Table 3.3 summarizes the characteristics of these two groups. Note that the temperature range is much wider for the refrigerators where the temperature rises above 41 °F.

A healthy refrigerator score was defined as the percentage of time that the metered temperature was below 42 °F. Figure 3.3 plots the distribution of refrigerators by this measure. Over 80% of the refrigerators scored a perfect 100%. It is surprising to see three refrigerators with a healthy score of zero. Figure 3.4 shows an example where the temperature meter captured four cooling cycles all above 41 °F.

⁵ http://www.fsis.usda.gov/wps/portal/food-safety-education/get-answers/food-safety-fact-sheets/safe-food-handling/refrigeration-and-food-safety/ct_index/lut/p/a1/jZFRT8IwEMc_DY_d3RwS8G1ZYmDKkBCI7IWUreuabO3SVqd-est8EQNK76l3v3979z_IgUKu2JsUzEmtWHO855M9rnESzhJMV7PwHhfZy3r1kCQ43dx6YPcHkEVX6i-cGP_TpId8cGOWyVJA3jFXE6kqDVRwR5iyPTcWaKV1SSyruPsgFSscsTXnzheOOTJUa6bKRioB1PDKSMHN4JB_oyQ_5EALt5eq5O-whfy0NQx9LLJoM56nWYSr8W_giHffwGVz_PSi0YdhUbtYHaKpH9N3yA03wavx6dq5zt6NcIR93wdCa9HwoNDtCM9Jam0dOFMSuvaZfj7Gc5RP7XZq4y8BE-W7/#4

⁶ National Occupant Survey (see Carroll et al. 2014 for a detailed description of this survey): 1.1% of treatment group respondents reported a household member suffered from food poisoning pre-weatherization during the previous year. This dropped to 0.3% post-weatherization. The results for a comparison group one year and two years post-weatherization are 0.2% and 0.2%, respectively. From the survey of IAQ households pre-weatherization, 0.6% of households reported a member suffered from food poisoning during the previous year.

Table 3.1 Primary Refrigerator Characteristics

Type of refrigerator	Bottom freezer	4%
	Side-by-side	29%
	Top freezer	67%
	Other	0%
Type of defroster	Auto	96%
	Manual	4%
Ice maker present	No	56%
	Yes	44%
Through the door water dispenser present	No	74%
	Yes	26%
Anti-sweat feature present	No	81%
	Yes	19%
Anti-sweat setting*	Off	52%
	On	48%
Energy-saver switch present	No	77%
	Yes	23%
Energy-saver setting*	Off	45%
	On	55%
Refrigerator location	Kitchen	27%
	Basement	25%
	Garage	18%
	Other living space	14%
	Hall	5%
	Porch	5%
	Other living space	5%
Refrigerator is in conditioned space	No	34%
	Yes	66%
Refrigerator is plugged in	No	12%
	Yes	88%
Have a secondary refrigerator	No	91%
	Yes	9%
Have a third refrigerator	No	99%
	Yes	1%

* For refrigerators with this setting

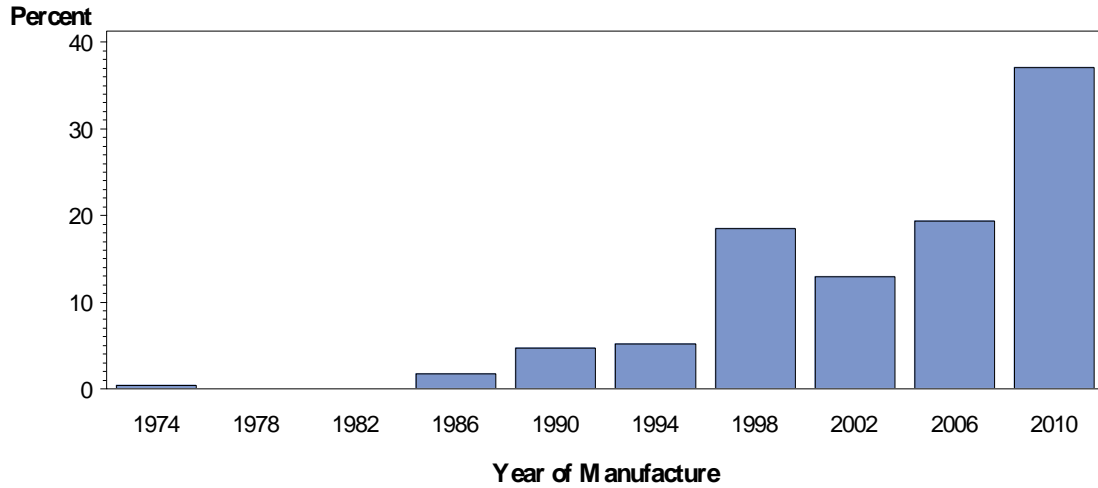


Figure 3.1 Year Primary Refrigerator Was Manufactured (in %)

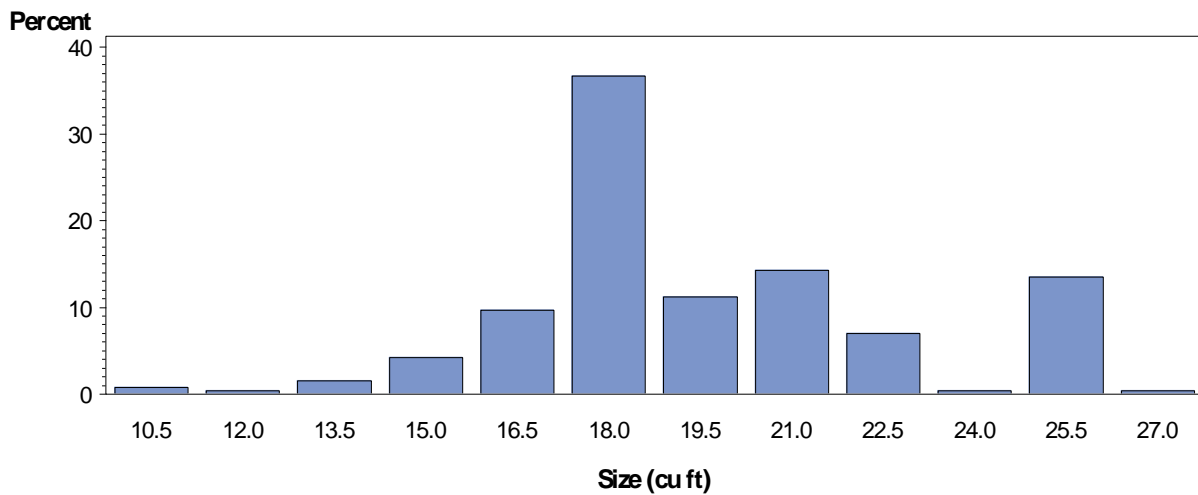


Figure 3.2 Primary Refrigerator Size (in %)

Table 3.2 Average Refrigerator Temperature Measurements

Average measurement of...	
Average temperature	37.7 °F
Minimum temperature	36.2 °F
Maximum temperature	39.4 °F
Temperature range	3.1 °F
Metering time	1.6 hours

Table 3.3 Characteristics of Refrigerators That Do and Do Not Maintain Temperature Less than 42 °F

	Temperature was observed to be above 42 °F	
	No	Yes
Average measurement of...		
Average temperature	36.6 °F	41.6 °F
Minimum temperature	35.2 °F	39.6 °F
Maximum temperature	37.9 °F	43.8 °F
Temperature range	2.7 °F	4.2 °F
Metering time	1.8 hours	1.8 hours

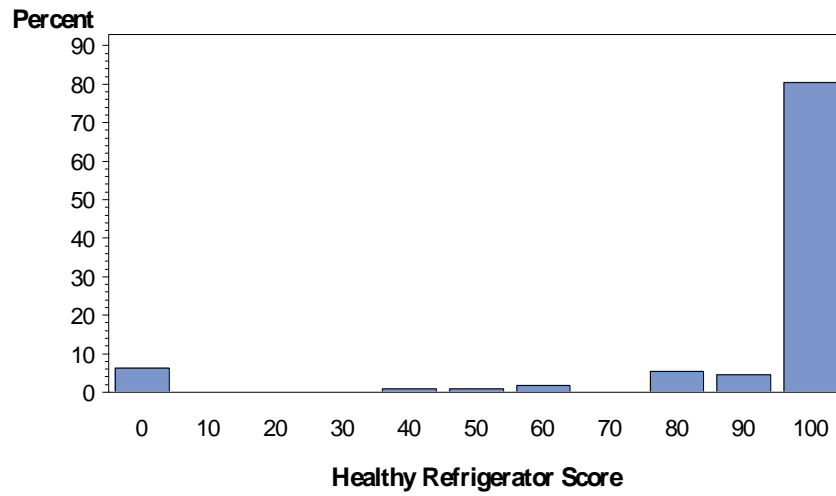


Figure 3.3 Distribution of the Healthy Refrigerator Score (in %)

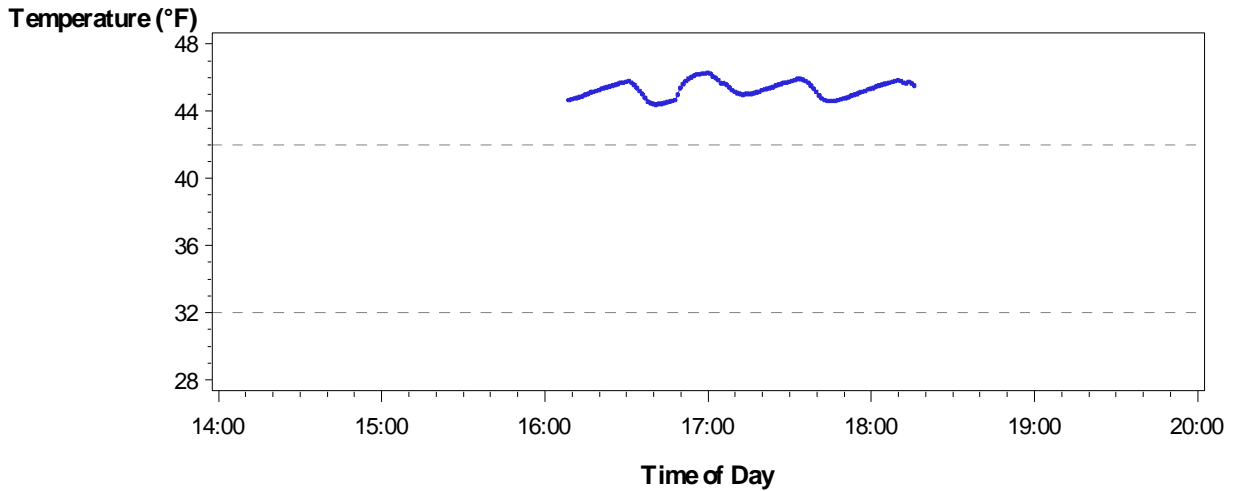


Figure 3.4 Example Where the Refrigerator Temperature was Always Above 42 °F

The average annualized electricity consumption for the set of primary refrigerators is 756 kWh/year. The median is 651 kWh/year. Figure 3.5 illustrates the skewed distribution of consumption, by the percentage of refrigerators in the sample. The variation in consumption has many possible explanations, including: different nameplate ratings, refrigerator capacity, age, indoor temperatures, location in unconditioned spaces, number of individuals in the household (i.e., influencing the number of door openings), number of operating options, and simple disrepair. It should be noted that the average electricity consumption of this set of refrigerators is possibly an underestimate given that the data were collected during the winter, the preponderance of the study houses are located in cold to very cold climates, and a large percentage of the refrigerators are located in unconditioned spaces.

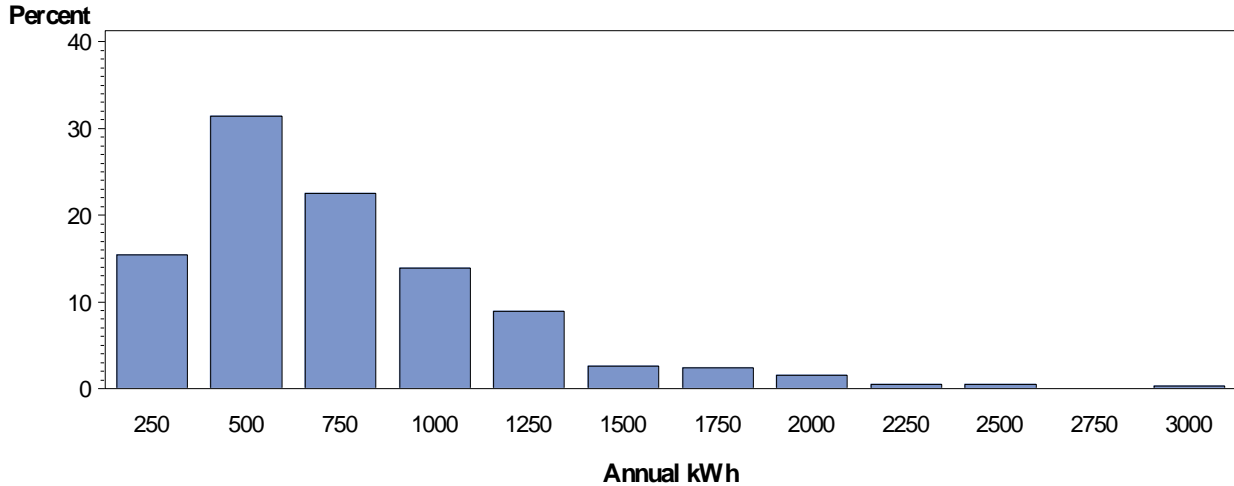


Figure 3.5 Annual Refrigerator Electricity Consumption (kWh/year)

A regression model was estimated to try to more formally explain the variation in annual power consumption across the set of primary refrigerators in the database. Table 3.4 presents the results. The most significant variable is refrigerator age. Not surprisingly, this result supports the more general observation that refrigerator efficiency has been improving markedly over time (See Figure 3.6). Conversely, and also not unexpected, energy use increases as the capacity of the refrigerator increases. Side-by-Side refrigerator-freezers consume more energy when compared to the other most common types, namely top-freezer refrigerators. An extra feature such as an ice maker does result in an increase in energy use, though this variable is insignificant. These four independent variables result in a model with a high adjusted R^2 (0.427) that is highly statistically significant. Variables that were tested in this model but were dropped due to being highly insignificant included: primary refrigerator located in a conditioned space; indoor temperature thermostat setting in the summer; indoor temperature thermostat setting in the winter; the presence of an energy saver switch; and the number of individuals in the household. It was somewhat unexpected that all of these variables would prove to be highly insignificant.

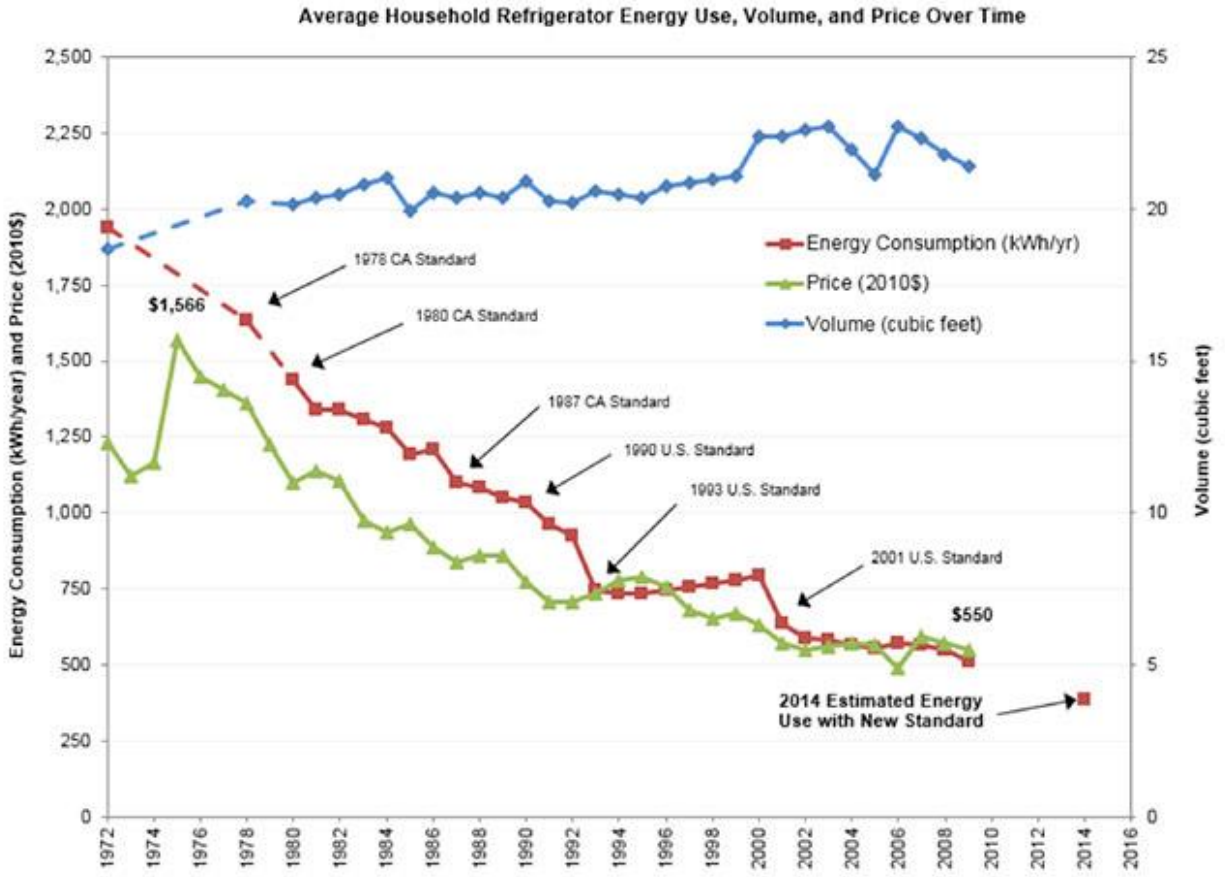


Figure 3.6 Average Household Refrigerator Energy Use, Volume, and Price Over Time⁷

Table 3.4 Refrigerator Regression Model: Dependent Variable Annual Energy Consumption

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-89.558	222.594		-.402	.688
Has Ice Maker	72.803	66.448	.110	1.096	.276
Refrigerator Age	23.436	3.894	.473	6.019	.000
Fridge Side by Side	188.692	82.723	.254	2.281	.025
Refrigerator size (ft ³)	23.201	11.923	.220	1.946	.055
R2=.452; ADJ. R2=.427, Sign. =.000					

⁷ (Source: <http://aceee.org/blog/2014/09/how-your-refrigerator-has-kept-its-co>)

The relationship between annualized energy use and healthiness was explored. This relationship was explored in two ways. First, the correlation between the annual energy use and the before-defined healthy refrigerator score was estimated. The Pearson Correlation (2-tailed) is 0.17 with a significance of 0.12, which is generally not considered to be statistically significant. Second, the energy consumption and healthy refrigerator scores were plotted, as shown in Figure 3.7. This figure indicates that refrigerators with largely unhealthy interior temperatures have relatively low energy consumption. In other words, instead of operating inefficiently by having longer on-cycles to try to get the temperatures down in the interior, these refrigerators actually use less energy. Potential explanations include mis-calibrated thermostats and problems causing compressors to short cycle. An indication that this phenomenon is appreciated by local weatherization crews is that the average healthy refrigerator score and annual energy consumption are low, 67 and 633, kWh, respectively, for primary refrigerators that were replaced for health reasons (i.e., non-energy conservation measures).

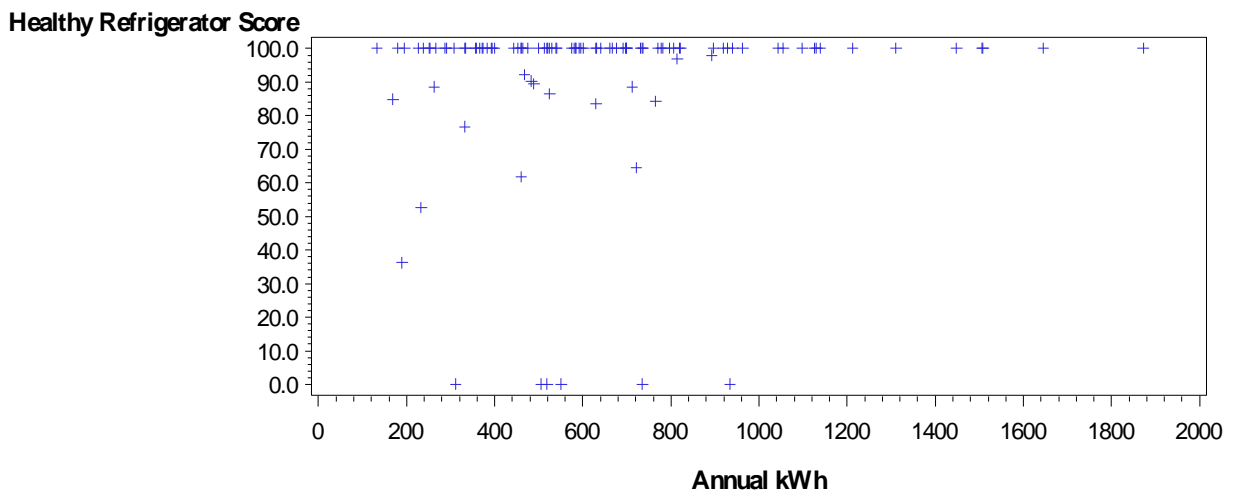


Figure 3.7 Annualized Refrigerator Energy Consumption by Healthy Refrigerator Score

The households that participated in the national IAQ study were administered an extensive occupant survey. The survey contained questions on household energy use behavior, demographics, and health. One health-related question that is pertinent to this study asked whether anyone in the household had suffered food poisoning in the previous year. Three households indicated that one or more household members had suffered from food poisoning. The annualized energy consumption for these three primary refrigerators was 311 kWh, 543 kWh, and 477 kWh, respectively, well below the national average energy consumption of 756 kWh. Unfortunately, data on the temperature inside these refrigerators was not collected. Also, it cannot be discerned from the survey the cause of the food poisoning (i.e., caused by food not sufficiently refrigerated). Thus, these results are illustrative of the types of data that could be collected by future research.

4. CONCLUSIONS

This report assesses the characteristics and performance of a set of refrigerators found in WAP eligible homes that participated in a national study of the impacts of weatherization on indoor environmental quality. The study primarily focuses on a set of 382 primary refrigerators and data collected about their operation pre-weatherization. The typical refrigerator found in the study homes was manufactured after the year 2000, has a capacity of 18 cubic feet, and has a top freezer. Only 27% of the primary refrigerators are located in kitchens and 34% are not located in conditioned spaces. Only 23% of the refrigerators had an energy-saver switch and of these, only 48% of the switches were observed to be in the on position, but the energy-saver feature was not found to correlate with lower energy use anyway. The preponderance of the refrigerators' inside temperatures was below the recommended 40 °F. The average annualized electricity consumption for a refrigerator in the sample was 756 kWh/year. The median was 651 kWh/year.

Most of the results were expected. For example, it was expected that most refrigerators found in this set of WAP eligible homes would be modest in size. It was certainly expected that the age and capacity of refrigerators would impact their annual energy use. It was somewhat unexpected that variables that describe refrigerators' surroundings (i.e., being in an unconditioned space, indoor temperature settings) were not significantly related to annual energy use. It was expected that refrigerators that exhibited unhealthy interior temperatures used relatively less energy. Lastly, it was unexpected that so many energy saver switches were found to be in the off position. This finding could be a point of emphasis in client energy education practiced by the Subgrantees.

There were a number of limitations to this study. The study was not able to monitor and meter new refrigerators installed by the weatherization program. Thus, this study was not able to estimate energy savings attributable to refrigerator replacement or the additional non-energy emission reduction benefits from refrigerator replacement. This study was not able to determine why energy-saver switches were seemingly ineffective. This study was not able to link unhealthy refrigerators to household health issues such as food poisoning due to the limitations of the occupant survey and the relatively small sample size relative to the reported frequency of this health issue. Future research could attempt to not only estimate the reduction in number of food poisoning events related to refrigerator replacement but also to monetize this benefit, as has been done for a number of other health-related benefits attributable to WAP such as reductions in asthma symptoms and thermal stress on occupants from exposure to extreme indoor temperatures (Tonn et al. 2014).

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