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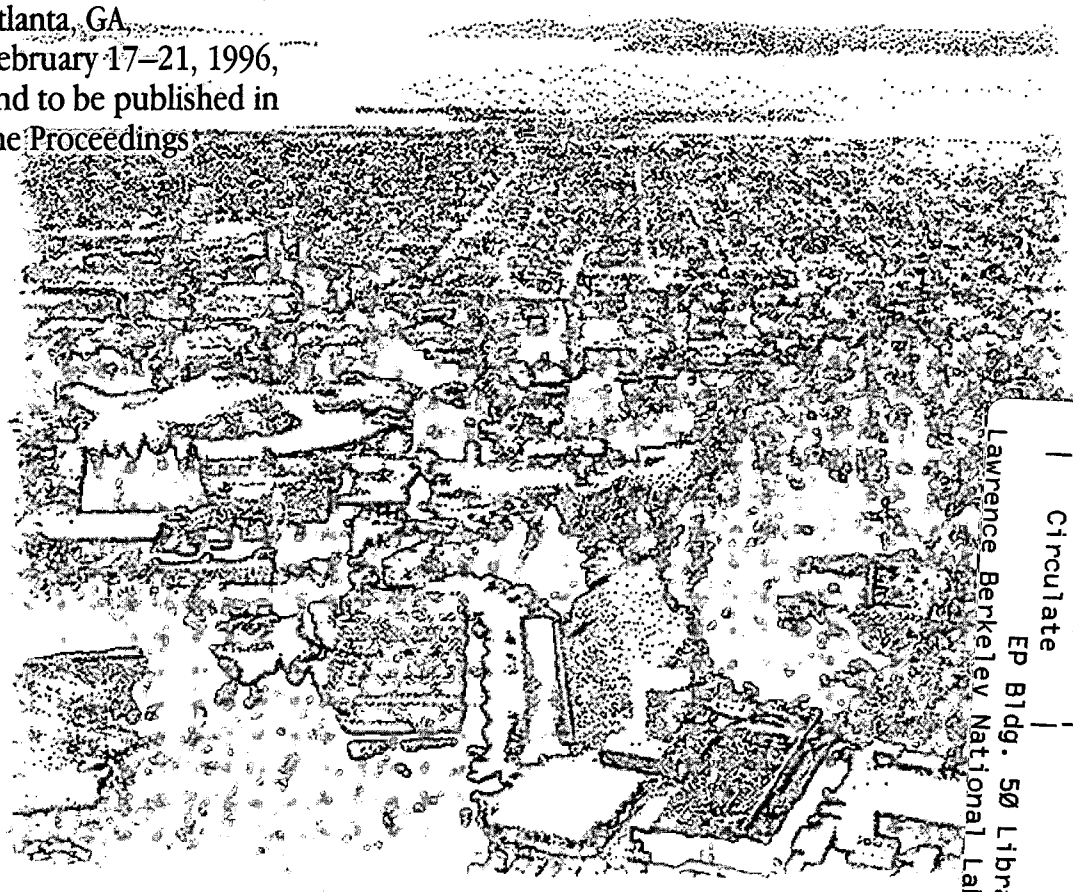

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Energy Use of Icemaking in Domestic Refrigerators

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ABSTRACT

This study was designed to develop and test a procedure to measure the electrical consumption of ice making in domestic refrigerators. The Department of Energy (DOE) test procedure was modified to include the energy used for icemaking in conventional refrigerators and those equipped with automatic icemakers. The procedure assumed that 500 grams of ice would be produced daily. Using the new test procedure and the existing DOE test (as a benchmark), four refrigerators equipped with automatic icemakers were tested for ice-making energy use. With the revised test, gross electricity consumption increased about 10% (100 kWh/yr) due to automatic icemaking but about 5% (55 kWh/yr) could be attributed to the special features of the automatic icemaker. The test also confirmed the feasibility of establishing procedures for measuring energy use of specific loads and other activities related to domestic refrigerators. Field testing and subsequent retesting revealed a 14% increase in energy use.

INTRODUCTION

Most large domestic refrigerators sold in the United States are equipped with an automatic icemaker or designed such that one can be easily added after sale. Laboratory and field monitoring studies have determined that refrigerators with automatic icemakers consume more electricity than similar models without them. The energy use of refrigerators with automatic icemakers was tested in the laboratory as part of a standards verification project in 1986 (BRL 1986). Electricity consumption increased 7% to 26% due to icemaking. A 1991 study of more than 80 refrigerators in southern California (QCI 1994) found that units with icemakers consumed about 8% more than their labeled value, while those without icemakers consumed about 5% less than the label. This suggests that refrigerators with automatic icemakers use roughly 13% more electricity than those relying on manual production of ice. A second monitoring study in northern California (Dutt and Proctor 1994) found that icemakers were also responsible for a 13% increase in electricity consumption, or about 74 to 104 kWh/yr for these 1991-vintage units. Some of the difference may be due to higher consumption of ice in homes with automatic icemakers, but no studies measured ice consumption.

There is nothing wrong or surprising that an additional feature increases energy use; however, this energy penalty is not reflected in the energy consumption labels affixed to new refrigerators or in official energy data, so consumers cannot make an informed purchase decision. In addition, utilities cannot accurately forecast electricity demand. (The energy consumption labels have historically been excellent indicators of actual consumption [Meier and Jansky 1993; AHAM 1988; Meier and Heinemeier 1988].) For these reasons, it is important that the energy test procedures produce accurate estimates of actual energy use. The goal of this investigation was to develop a modified energy test procedure for refrigerators that would include the electricity consumed by automatic icemakers and other new developments.[1] To verify the laboratory tests, the laboratory results for the same units were compared to field measurements in typical kitchens. We examined icemaking first because the automatic icemaking unit lends itself to the simplest modification of the existing DOE test procedures. In addition, icemakers function automatically, so laboratory tests are most likely to imitate field operation. The approach described here may be useful in establishing procedures for measuring energy use of other loads and activities related to domestic refrigerators.

A refrigerator's energy use is dominated by the compressor's work to remove conductive heat gains through the walls. The energy used for defrosting and anticondensation heaters is much smaller (ASHRAE 1988a). Heat gains from door opening are usually small but can climb to 25% of energy use when the doors are opened more than 100 times per day (Alissi et al. 1988). Another study, by Gage (1995), found that door openings can explain 9% to 55% of the variability in energy use. Measurements of heat gain caused by food loading and icemaking have not been undertaken, partly because they are dependent on the pattern of use. Recently, however, manufacturers have greatly increased the thermal resistance of the box and employed

1. The current U.S. energy test procedures for refrigerators were modified more than 15 years ago to incorporate the impact of the antisweat heaters. For comparison, the study by Dutt and Proctor estimated that the operation of the antisweat heater increased electricity use 16% to 17%.

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energy-saving designs for defrosting and anticondensation. These advances, along with more efficient compressors, have contributed to major reductions in refrigerator electricity use and have made the energy impacts of door opening, food loading, and icemaking relatively more important. This investigation of the energy use of automatic icemaking consisted of four steps:

- development of a test procedure,
- performance of the test procedure on several refrigerators,
- field monitoring of energy use, and
- retesting in the laboratory.

Ideally, the four steps should be iterative because experience gained from actual tests and field measurements can help shape the test procedure. Unfortunately, logistical and financial constraints permitted only one opportunity to develop the procedure and test it. Future work is anticipated to build upon these results.

DETAILS OF THE ICEMAKER

Designs for automatic icemaking units in different domestic refrigerators are all very similar. The major components are a water reservoir, motor/cam assembly, an ice mold, ejector blades and heater, a harvest basket, and a shut-off arm (WC 1987). Residential units all make cubes, which are then released through application of heat. The general procedure for icemaking is as follows.

1. Cycle begins when the need for more ice is sensed and water is allowed to enter the reservoir until it is full (controlled by a solenoid valve).
2. Water enters ice mold and begins cooling.
3. Thermostat senses that ice formation has finished (ice temperature is below about –8°C [17°F]).
4. Mold heater switches on, while motorized ejector blades press ice cubes out of mold into harvest basket.
5. Motor stalls when all cubes have been ejected and heater switches off.
6. Shut-off arm follows ice level and determines that basket is full and stops ice production.

A typical cycle converts 140 cc of water into eight crescent-shaped ice "cubes."[2] The elapsed time of one icemaking cycle depends upon the temperature setting of the refrigerator, but most modern automatic icemakers can produce at least 2,000 grams of ice per day (CR 1991). Thus, the maximum number of cycles is roughly 14 per day.

The automatic icemaker contains several heaters that add to the cooling requirements and make it use more energy than through manual production. The mold heater typically draws about 185 watts and usually operates less than two minutes per cycle. The energy contribution (per cycle) is shown for each process in Table 1. The motor (which presses ejector fingers against the cubes) is rated at about 3 watts and also operates two minutes per cycle. A solenoid controls the water valve; it draws about 20 watts and operates for about eight seconds per cycle. Together, these heaters and motors add 6 Wh per cycle of direct electricity use, plus about 6 Wh per cycle in compressor work to remove that heat. Finally, automatic icemakers will have higher rates of sublimation and add refrigeration load as lost ice is automatically replaced. This load appears to be negligible.[3]

TABLE 1 Engineering Estimates of Energy Engineering Estimates of Energy Contributions of Icemaking Features, Assuming COP = 1

Activity	Rated Power (W)	Per Cycle Amount (g)	Compressor Time (sec)	Compressor Energy (Wh)	Extra Work (Wh/cycle)	Total Energy Per Cycle (Wh)	Total Energy 500 grams (kWh/yr)
Fusion		140		13.0	13.0	26.0	33.7
Mold heater	185		120	6.2	6.17	12.3	16.1
"Motor, etc."	3		120	0.10	0.10	0.20	0.26
Chill-down (from 20°C to -10°C)		140		4.6	4.55	9.10	11.9
Totals				23.8	23.8	47.6	62.1

At the same time, automatic icemaking saves energy because the user does not need to open the freezer door as often. At 500 g/day production, this saves roughly two openings per day (depending on behavior). Using the data of Alissi et al. (1988) for the energy impact of 56 door openings per 24 hours, two door openings will increase energy use by less than 1%, or about 10 kWh per year.

Under *maximum* ice-harvesting conditions, the total energy devoted to icemaking (including chilling and freezing the water) is 248 kWh/yr, or about 25% of typical electricity use for these models of refrigerators. Under typical conditions, the additional load will be less. Figure 1 shows the results for 500 g/day, along with the amount of energy predicted to be due to each part of the process.

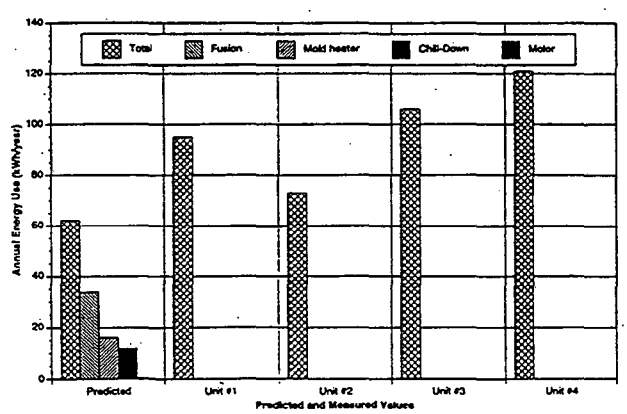

Figure 1 Predicted contribution for each icemaking feature (assuming COP = 1.0) compared to measured increase.

2. These cubes and trays are smaller than the typical cubes and trays used for manual icemaking.

3. Automatic icemakers typically maintain more ice than manual units, so ice loss through sublimation will be higher.

EXPERIMENTAL PROCEDURE

A test procedure is a compromise. A test procedure should be easy to perform and apply to a wide range of equipment. The procedures and conditions should be selected such that the results can be easily duplicated with high precision. Finally, the test procedure should be realistic and reflect how the device is typically operated. This final requirement often conflicts with the goal of easy testing and high accuracy in repeatability; almost any realistic test is also complex. A test procedure was sought here that resembled the existing DOE test procedure but retained a degree of realism while testing the efficiency of the icemaking equipment. As the existing DOE test procedure is familiar to manufacturers and testing laboratories, it was used as the baseline test (that is, the "no icemaking" condition).

As indicated, icemaking was not considered in AHAM's original energy-testing procedure or the Department of Energy's (DOE) subsequent modifications to it. The icemaking unit is switched off and the water supply line is left unconnected during the test. Internationally recognized test procedures for Japan (JSA 1986) and Europe also ignore the icemaker's contribution to energy use (though automatic icemaking is much less common in these regions). The International Standards Organization publishes a test procedure to measure icemaking capacity (ISO 1988, 1989), but it assumes that the ice is made by putting trays in a conventional refrigerator-freezer. An ASHRAE test procedure for testing commercial, stand-alone automatic icemakers already exists (ASHRAE 1988b), but it is clearly not appropriate for this situation.

The first, and most important, problem is to determine a reasonable baseline from which to measure the increased energy use of the automatic icemaker. The key issue is determination of typical domestic ice consumption by users of refrigerators with and without automatic icemakers. An extensive search revealed no measured data.[4] As a result, the authors arbitrarily selected a typical ice consumption of 500 g per day (this corresponds to about 3.5 trays/day). Discussions with experts in the industry suggest that this is reasonable, although actual use certainly fluctuates with climate, season, and number of people using the refrigerator. All automatic icemakers can easily produce this much ice; it also corresponds to about 25% of a typical icemaker's capacity. Thus the baseline from which to measure the automatic icemaker's energy penalty is the manual production of 500 g/day.

A second consideration in setting the procedure is to ensure that the energy required to make ice is significantly more than the uncertainty in the test procedure without icemaking. All measurements for the DOE test must be made with instrumentation exceeding specified tolerances. One estimate of the measurement uncertainty of the DOE test is ±2.5% (Abrahmson 1992). A later study (Meier et al. 1993) measured the energy use of several identical refrigerators. Such measurements overestimate uncertainty because they include both measurement uncertainty and variability among units. The coefficient of variation (standard deviation divided by the mean) was never more than 4.5% and usually was below 3%. Comparisons of differences in refrigerator energy use (of the same unit) should have much lower experimental error, probably around 1%. Thus, any energy test procedure for icemaking must lead to changes in energy use greater than 3%. A test procedure was developed and is described below. The principal feature is that it applies to all kinds of refrigerators, not just those with automatic icemakers.

Ice is made in essentially every refrigerator. The goal is to add the energy used for icemaking to the current test procedure, that is,

$$\text{Label Energy Use (kWh/yr)} = \{\text{DOE test}\}_{\text{existing}} + \{\text{Icemaking Load}\}.$$

All refrigerators make ice, so the icemaking contribution would apply to all models (not just those with automatic icemakers).

Procedure 1: Refrigerators Equipped with Icemakers

Only one test is performed. The other DOE conditions for a standard two-point test (with the antisweat switch turned on) are maintained except that the water line is connected. Halfway through the test (or eight hours, whichever occurs first), the icemaker is remotely triggered to make ice. Icemaking is allowed to continue until 500 grams of water have entered the unit and frozen. The supply water temperature must be above 20°C.

Procedure 2: Refrigerators Not Equipped with Icemakers

Two tests would be performed to determine the actual incremental electricity needed to make ice. This procedure is needed to avoid unduly penalizing refrigerators with automatic icemakers.

a. The standard DOE test with the antisweat heater on.

b. The standard DOE test, repeated with 500 g of water in the freezer. The water container would be manually inserted in the refrigerator eight hours into the test. The water container should be as light as possible and covered to prevent spills and evaporation.

The manual insertion of the water container (in the first procedure) introduces a small deviation from the standard DOE test. As noted earlier, a single door opening will not raise energy use more than 1%.

RESULTS

The tests were undertaken in a nationally recognized appliance testing laboratory (BRL 1991). The investigation was limited to four different high-efficiency refrigerators equipped with automatic icemakers. All refrigerators were purchased in 1991 and were among the most efficient available in their size and class. Three units were top freezers (TF) and one was a side-by-side (SS). The major characteristics of the refrigerators are given in Table 2.

Each of the four refrigerators underwent the conventional DOE energy test (with the antisweat heater on) and then the modified test to include use of the automatic icemaker (that is, procedure 1). A device to remotely trigger icemaking for the specified volume was developed to facilitate the project. The

4. Utility metering equipment typically used in load research projects cumulates energy use every 15 minutes and therefore cannot detect icemaking operation.

TABLE 2 Major Characteristics of the Tested Refrigerators

Unit	Nominal Capacity (liters)	Nominal Capacity (cu. feet)	Type	Label Energy Use (kWh/year)
1	597	21.1	Top Freezer	880
2	586	20.7	Top Freezer	836
3	563	19.9	Top Freezer	815
4	612	21.6	Side-by-Side: Equipped with through-the-door ice and water	1147

water line was connected to the icemaker input and the electrical connection to the icemaker was put in series with a set of contacts on a timer (normally set at open). Eight hours after the initiation of defrost, the timer automatically activated the icemaker and allowed sufficient water to enter so that 500 g of ice was made. The exact time allowed was determined through trial and error but ranged from 3.75 to 6.0 hours.

At the end of the defrost cycle, the water line was manually closed and the timer contact was briefly closed (typically two minutes). This allowed the icemaker motor to expel any ice remaining in the mold. The ice was weighed. The detailed results are shown in Table 3.

Comparison of Measured Energy Use and Label

While not a specific goal of this investigation, it is possible to compare measurements of a specific refrigerator's energy use to the labeled energy use for that model. Two refrigerators performed almost exactly at their labeled consumptions, while the other two (units 3 and 1) consumed 12% and 23% more than their labels. The most likely explanation for this discrepancy is that the DOE regulations allow the manufacturer to list either the average of two tests with the antisweat heater on and off or list one test with the heater on. The tests performed in this project were conducted with the antisweat heater switched on. The two refrigerators with higher energy consumption than labeled were probably tested by the manufacturer by averaging the heater on and off tests. The other two were probably tested by the manufacturer (for the label value) with the antisweat heater on.

Energy Use of Icemaking

Making exactly 500 g of ice proved difficult but actual harvests never diverged by more than 12% (and the standard deviation was only 5%). In each case, these deviations were not sufficient to change the number of icemaking cycles occurring during the test. Icemaking increased the electricity consumption of the four refrigerators by 8.8% to 11.8%—the average was 10%. This corresponds to 73 to 121 kWh/yr—the average was about 100 kWh/yr.

TABLE 3 Energy Test Results for the Four Refrigerators (with and without Icemaker)

	Unit #1				Unit #2			
	DOE		With Ice Maker		DOE		With Ice Maker	
Thermostat setting	M/M	W/W	M/M	W/W	M/M	W/W	M/M	W/W
Daily energy use (kWh)	2.91	2.29	3.14	2.44	2.58	2.23	3.07	2.42
Freezer temp. (°C)	-18.1	-12.3	-17.5	-12.6	-19.1	-14.3	-19.1	-14.6
Fresh food temp. (°C)	7.7	12.5	7.8	12.4	3.1	6.6	2.8	6.7
Defrost interval (minutes)	1176.8	1681.8	1110.1	1572.6	1227.8	1500.7	1054.7	1441.1
Ice production (g)	—		533	483	—		500	510
Time to make ice (hr)	—		6	7	—		5.5	9
Annual energy (kWh/yr)	2.97 x 365 = 1084		3.23 x 365= 1179		2.28 x 365= 832		2.48 x 365= 905	
Increase due to ice maker (%)	—		8.8		—		8.8	

	Unit #3				Unit #4			
	DOE		With Ice Maker		DOE		With Ice Maker	
Thermostat setting	M/M	W/W	M/M	W/W	M/M	W/W	M/M	C/C
Daily energy use (kWh)	2.78	2.16	3.08	2.3	3.17	2.5	3.3	3.86
Freezer temp. (°C)	-18.4	-11.1	-17.8	-10.4	-15.3	-9	-13.4	-18.7
Fresh food temp. (°C)	3.6	6.8	2.9	6.7	3.3	6.9	3.3	3.1
Defrost interval (minutes)	1105.6	1614.3	1038.4	1531.3	1080.3	1602.4	1058	823.6
Ice production (g)	—		542	492	—		500	474
Time to make ice (hr)	—		6	9	—		5	3
Annual energy (kWh/yr)	2.49 x 365= 909		2.78 x 365= 1015		3.14 x 365= 1146		3.47 x 365= 1267	
Increase due to ice maker (%)	—		11.7		—		10.6	

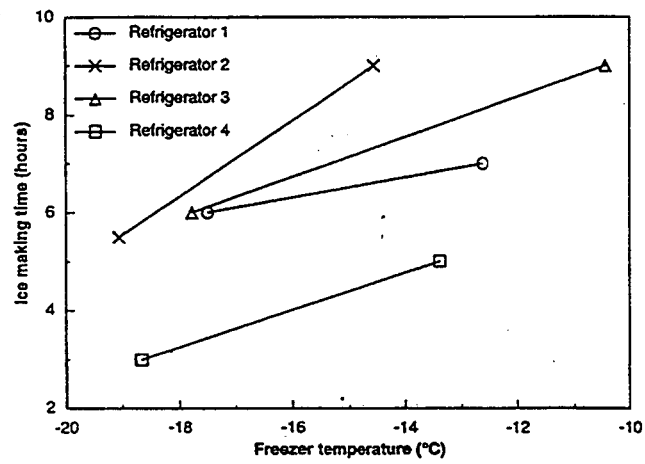

Figure 2 Impact of freezer temperature on icemaking times.

Icemaking Time

The time required to make 500 g of ice varied from three to nine hours. Recall that the DOE test procedure (and the modification to include icemaking) requires two tests to bracket the standard temperature. Thus, each refrigerator made ice at two temperatures. Figure 2 shows how icemaking time increased at higher freezer temperatures for every unit. Unit 4 behaved somewhat differently than the other three, probably because it is a side-by-side unit with through-the-door features. In addition, the thermostat setting had to be reduced to cold/cold to achieve an average temperature below the standard temperature.

Field Energy Use

The refrigerators were placed in typical homes in the Los Angeles (California) metropolitan area. The occupants were encouraged to use the refrigerator in the manner to which they were accustomed. Energy consumption was collected at 15-minute intervals. Monitoring continued for 18 to 31 months.

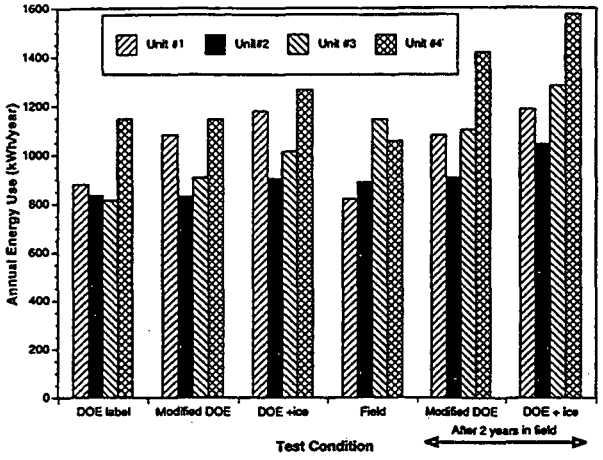

Figure 3 Energy use of the four refrigerators in the six different test conditions (data same as Table 4).

TABLE 4 Summary Data on Refrigerator Performance

	Unit #1	Unit#2	Unit #3	Unit #4
DOE label (from manufacturer)	880	836	815	1147
Modified DOE test (initial)	1084	832	909	1146
DOE test +ice maker (initial)	1179	905	1015	1267
Field monitoring	823	892	1146	1058
Modified DOE test (2 years later)	1083	910	1104	1419
DOE test + icemaker (2 years later)	1187	1043	1282	1574

Retesting

The units were brought back to the same facility for retesting. However, great care was taken to bring the units back in exactly the condition left by the users. In other words, the coils were not cleaned, ventilation grilles were not cleared of any obstructions, etc. All settings (except those needed to be adjusted for the test) were left in the user-set positions. The tests were then repeated using the same procedures described earlier. The results are summarized in Figure 3 and Table 4. The four units used an average of 14% more electricity in the modified DOE test and 16% more with the same icemaker test. Most of the increase was limited to two units (3 and 4), which used about 23% more electricity in the retests.

DISCUSSION

Procedure 1 was demonstrated to be feasible and capable of generating observable and consistent increases in electricity consumption. The refrigerators' gross electricity use increased about 10%, or 100 kWh/yr, due to operation of the automatic icemaker. The increases ranged from 73 to 121 kWh/yr (Figure 3).

The measured increase in energy use due to icemaking was roughly 60% greater than predicted from the calculations (Figure 1). The range in energy use is probably due to different lengths of mold heater operation. The measurements are consistent with a six-minute cycle rather than the two minutes assumed in the calculations. The mold heater's function is to facilitate ejection of the ice cubes from the mold, so small changes in thermostat settings or mold geometry could easily lengthen the mold heater runtime. (In retrospect, it would have been useful to monitor the elapsed time of mold heater operation.)

The discrepancy may also be due to lower compressor efficiencies than assumed. For example, an overall COP of 0.45 would be consistent with the 121-kWh/yr increase. Greatly differing COPs cannot explain the entire discrepancy because these refrigerators had similar (if not identical) compressors.

The energy penalty due to the icemaker is less than the gross energy increase because the energy required to make ice manually must be subtracted. At a COP of 1.0, the energy required to chill and freeze 500 g of ice is (33.7 + 11.9 =) 45 kWh/yr. Thus, the net energy difference (i.e., the energy penalty due to the automatic icemaker) is roughly (100 – 45 =) 55 kWh/yr. Put another way, the mold heaters, motors, etc., appear to add 55 kWh/yr to the average refrigerator's energy use in the laboratory. In retrospect, it would have been useful to repeat the test with the automatic icemaker switched off and 500 g of water allowed to freeze naturally (i.e, procedure 2). This procedure would have isolated the energy used by the automatic icemaker from that used to freeze the water.

The refrigerators used about 10% more electricity in actual kitchens than indicated in the laboratory. These results are consistent with two larger California studies for refrigerators of the same age (QCI 1994; Dutt and Proctor 1994; Alissi et al. 1988). At the same time, the four units used about 10% less electricity than predicted by the proposed test including icemaker energy. This is no surprise given the small sample size and the fact that no normalization for variation in ice use was attempted. Future field tests should let the occupants make ice manually for one monitoring period and compare that to a period where the ice is supplied automatically. These two periods would yield field data that could be compared to their counterpart laboratory tests (procedures 1 and 2).

When the laboratory tests were repeated after two years, three of the four refrigerators experienced 15% to 23% higher energy use and the fourth did not change (for an average of 14% increase in energy use). No attempt to restore the refrigerators to their new condition was made; indeed, we sought to preserve the dirt, obstructions, and settings left by the users. These results suggest that significant degradation of performance occurred during the first year of operation. It was impossible to identify the chief cause for the increased energy use, but dirty coils and obstructed ventilation paths may have played a role. This large impact of coil cleaning contradicts other field studies (Meier et al. 1993; Meier 1993) that found negligible savings from coil cleaning. The most likely additional explanation is gradual failure of specific components. A small deterioration in performance is to be expected, but the observed increase in energy use here seems higher than justified through normal wear. Anecdotal evidence from other studies suggests that icemaker malfunctions are responsible for a high fraction of refrigerator failures (CR 1991) and anomalous increases in energy use (Dutt and Proctor 1994). Thus, the increased energy use may be due to the icemakers.

CONCLUSIONS

This study showed that it was technically feasible to include automatic icemaker operation in a laboratory test of refrigerator energy use. Furthermore, the results were reproducible with only small error.

Inclusion of icemaking increased gross energy consumption of a typical modern refrigerator by 9% to 12%, corresponding to 73 to 121 kWh/yr. The range in energy use appeared to be due to differing lengths of mold heater operation. However, the energy penalty due to the icemaker is less than the gross increase because the energy required to make ice manually must be subtracted. The net energy difference, i.e., after subtracting the energy needed to make ice manually, is roughly 55 kWh/yr.

The refrigerators exhibited a surprisingly rapid deterioration in performance; they consumed about 14% more after two years in the field. This may be due to dirty coils and obstructed ventilation paths or other unidentified factors. This trend deserves further investigation, especially if the problem is linked to the automatic icemaker.

This modification of the DOE test procedure was relatively easy to undertake. Other modifications to increase its realism, such as for food loading, may be more difficult. Each modification needs to balance the demands for realism with the need to maintain a simple procedure with acceptable accuracy and precision. Careful testing, both in the laboratory and in the field, would also be necessary to ensure that the test applies to all common units.

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