A COMPARISON OF FIELD AND LABORATORY MEASUREMENTS OF RESIDENTIAL REFRIGERATOR ENERGY USE

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ABSTRACT

The laboratory-rated energy use of refrigerators is of interest to consumers, utility forecasters, and policy-makers. The laboratory test procedure does not attempt to simulate actual conditions, so it must be periodically validated as refrigerator configurations and technologies change. The test procedure has not been field-validated for at least 15 years in spite of significant improvements in refrigerator energy efficiency. In this study, the field energy use of 393 refrigerators were compared to these rated values (or "labels"). In this comparison, the laboratory test overestimated the typical refrigerator's annual field use by about 14 percent. The peak consumption is also important for forecasting; The peak monthly use was about 16 percent higher than the laboratory test expressed as average monthly use. Post-1982 refrigerators used about 22 percent less annual energy than their labels indicate, while the labels accurately predict the consumption of pre-1982 refrigerators.

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INTRODUCTION

Residential refrigerators in the United States consume the equivalent electrical output of 25 large electrical power plants. They are also the largest end use of electricity in most American homes. As a result, the energy use of refrigerators is important to both consumers and utilities.

A standard energy testing procedure was developed for U.S. refrigerators in the 1970s. In this test, the refrigerator is placed in an environmental chamber for 24 hours, while the ambient temperature is maintained at 32°C. The refrigerator doors are kept closed during the test, and no food loads are inserted. Adjustments and additional tests are required for refrigerators with special features.[1] The laboratory test procedure does not attempt to duplicate typical operating conditions. The higher ambient temperatures are used in place of heat gains from food loading and door opening. For this reason, it is essential to compare test procedure results with field measurements. This was in fact undertaken informally by the National Bureau of Standards about fifteen years ago. (The documentation has since then disappeared.)

Other test procedures have been developed with very different conditions in Europe and Japan.[2] Japanese test procedures take place at lower ambient temperatures and include door openings and food loading. However, these complications greatly increase the cost of the test and ability to duplicate results.

The test procedure results are used by the Federal Trade Commission for preparation of energy use labels which are affixed to every refrigerator sold in the U.S. It is hoped that the consumers will make better-informed purchasing decisions based on the label information. The recently-passed energy efficiency standards are also based on energy use as determined by this test procedure. The results are used in an aggregate form by energy demand forecasters. Trends in refrigerator energy use, as reflected in the tests, are incorporated in projections of future electricity demand. In general, the forecasters assumed that a model using the equivalent of 1200 kWh/year in the test, would also use 1200 kWh/year in a home.

Refrigerators have changed significantly since the test procedure was developed. Insulation levels and compressor efficiency have greatly increased. Evaporator designs and controls have also improved. These modifications should make the refrigerators more dependent on ambient temperature because standby losses have become a smaller fraction of total energy use. As a result, it is no longer certain that the test procedure provides a reliable estimate of field use, nor even that a model which uses less energy than another in the lab test will use less in the field. This could have implications for consumers, utility forecasters, and standards-setters. In addition, the peak electricity use of refrigerators has come under scrutiny. The relationship between the rated energy use and the field use during peak periods has not been examined.

We report here an updated correlation between the test values and field consumption for residential refrigerators. The test energy use was also correlated with the measured peak energy use. These correlations will assist utilities in making more accurate assessments of refrigerator energy use on baseload and peak demand.

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[1] FTC and DOE regulations allow manufacturers to "rate" products conservatively; therefore some manufacturers have given a "collection" of units the worst "rating" of all units in the group. This would be done most often for logistical reasons, i.e. to reduce the number of labels.)

[2] A. Meier, "Energy Use Test Procedures for Appliances: A Case Study of Japanese Refrigerators". *ASHRAE Transactions 93* (1987).

TECHNICAL APPROACH

Measured refrigerator energy use for individual refrigerators was obtained from six different field monitoring programs across the United States and numerous individual measurements (see Table I). Most were utility load-research programs, in which the refrigerators were monitored for over one year. Measurements were taken between 1981 and 1987. The minimum data requirement was annual energy consumption and model number for each refrigerator, although nearly all sources provided at least monthly energy use, and some studies measured energy use as frequently as each hour.

The rated (or "label") energy use for each refrigerator was taken from the Association of Home Appliance Manufacturers (AHAM) directories.[3] These directories have been published annually since 1975; however, publication lapsed for four years between 1977 and 1981. The directories also provided the age and some features of each refrigerator.

Despite the great amount of refrigerator field energy consumption data being collected in the United States, we found only six projects with data suitable for this project. Only these sources recorded the refrigerator model number. Even then, there were gaps due to meter failure or lapses in monitoring. If less than a year of data were available, the consumption was annualized for the annual comparisons. However, refrigerators monitored for less than nine months were rejected, since seasonal dependencies would make an accurate extrapolation impossible.

About half of the recorded refrigerator model numbers were not listed in the AHAM directories. The low matching rate was due to three factors:

- The refrigerator was purchased before 1975 (hence predating the directories), or during the 1979-81 gap in the directories.
- The refrigerator model number was incorrectly transcribed (such as a 'G' for a '6') by the energy auditor, and therefore could not be located in the directories.
- The directory model number either lacked or differed in the terminal digits or letters. Since there is no standard nomenclature methodology across manufacturers, these digits could either refer to irrelevant features such as color or door opening direction, or to presence of an icemaker or other features which have a significant effect on energy use. Refrigerators with model number transcription errors were deleted if the ambiguity led to a significant range in possible consumption.

As a result of these problems, only a fraction of the refrigerators that have been monitored in the United States could be included in this study. Table II summarizes how the potentially huge dataset was narrowed down to a much smaller number of units qualifying for this type of analysis.

COMPARISONS OF LABELED ENERGY USE WITH FIELD MEASUREMENTS

The annual energy data, and their sources are presented in Figure 1. The data represent 259 refrigerators taken from six major studies, and a few individual measurements. (A commentary describing each data set will be published in a forthcoming report.[4]) Each data point represents one refrigerator, except the PSE&G refrigerators where each point represents the average consumption of from 10 to 14 identical refrigerators. In the ORNL data, 41 refrigerators are shown, although they represent only two different models (so that all the points are in two vertical columns).[5] The data from a midwest refrigerator manufacturer represents up to five years of data for each of 35

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[3] Association of Home Appliance Manufacturers (AHAM), "1986 Directory of Certified Refrigerators and Freezers", 20 North Wacker Drive, Chicago, IL. (Similar directories were used for earlier years.)

[4] Alan Meier and Kristin Heinemeier, "A Comparison of Rated and Actual Energy Consumption in of Residential Refrigerators", Lawrence Berkeley Laboratory Report (forthcoming).

[5] The ORNL data set is unusual because the refrigerators consistently used more than predicted by the lab test. The design feature responsible for this behavior could not be determined by the researchers responsible for the data.

refrigerators.

A line of equal test and field energy consumption is drawn in this figure. If the two measurements agreed perfectly, then the points would lie along this line.

Annual Consumption

The average annual consumption of the 259 refrigerators in the compilation was 1254 kWh per year, with a standard deviation of 434 kWh.

The measured annual consumption was compared to the manufacturer's rating (based on the DOE laboratory test). The results are presented as a scatterplot in Figure 1. Most of the points lie close to the perfect-agreement line, indicating that the laboratory test procedure predicted field consumption quite well. In general, annual field energy use was lower than the laboratory test, but rarely by more than 20 percent. The equation of the best-fit line is:

$$\textit{Annual Field Energy Use} = 1.00 \times (\textit{Annual Label Use}) - 167$$

The correlation coefficient (0.62), however, was low. (See Table III). For a typical refrigerator, with a rated consumption of 1200 kWh per year, the label overpredicts field energy use by 14 percent.

Monthly Consumption

Monthly data for 213 refrigerators were compiled. A scatterplot of the data is shown in Figure 2. The highest, lowest, and average monthly field consumption are shown for each refrigerator. The monthly variation in consumption was high: it always exceeded 20 percent of the mean, and often exceeded 40 percent.

The peak monthly value for each refrigerator — which occurred most frequently in August — was significantly higher than the mean. In general, the peak month consumption was higher than the laboratory test consumption. The line best fitting the results was:

$$\textit{Peak Monthly Energy Use} = 1.14 \times \left[\frac{\textit{DOE Annual Label Use}}{12}\right] + 2.$$

The fit, however, was poor: the R^2 was 0.46. For a typical refrigerator, with a rated annual consumption of 1200 kWh per year (averaging 100 kWh per month), the peak month corresponds to roughly a 16 percent increase over the label.

Daily Variation

For those few refrigerators where daily data are available, it is interesting to observe how the daily consumption varies across the year. Figure 3 shows the average daily consumption for each day of the year, as well as the average daily consumption represented by the label annual consumption (= *Label*/365). These values are averaged across the 24 refrigerators for which this information is available. There is clearly a seasonal variation in demand; the average daily demand during mid-June to mid-August is 26% greater than that during the rest of the year. For this subset of refrigerators (and in contrast to our conclusion based on the larger set of refrigerators) the rated use is greater than the field use on all but a few days.

Vintage

Refrigerator efficiency has improved greatly in the last fifteen years. The annual energy data were examined to determine if the improved efficiency was apparent in field performance. Discussions with manufacturers indicated that the greatest changes occurred around 1982, so the data were partitioned into units sold before 1982 and those sold in 1982 or later. Figure 4 is a scatterplot of the refrigerators divided into the two age groups.

The newer refrigerators used on average less energy than the older units, 1044 versus 1374 kWh per year. No new units used more than 1660 kWh per year although the sample size is smaller (only 69 units). Lines best fitting the two groups were calculated and plotted in Figure 4. Based on the present data, it appears that new and old refrigerators have a different relationship between the rated and field use. Whereas an old unit's rated and field use will be almost identical, new refrigerators will use significantly less energy in the field than indicated by their label. For an old and new typical refrigerator, both having rated use of 1200 kWh per year, the old unit will use about 1185 kWh in the field, while the new unit will use about 923 kWh (or about 22 percent less).

SOURCES OF UNCERTAINTY

There are numerous sources of uncertainty in both the field and test energy data which could affect the validity and generalizability of the results. Some of these factors are described below.

The refrigerators in this compilation are not statistically representative. Some of the studies did seek to obtain a statistically representative group, but others used a group-of-convenience (usually company employees). Few refrigerators were monitored in the Southern part of the country. Few studies made any temperature measurements in the refrigerator, the kitchen, or even noted if the house was air conditioned. It was not known if the household had a second refrigerator (or if the monitored one was the primary unit) or a freezer. Refrigerators are often used in such unconventional ways that they have attracted the attention of anthropologists.[6] Lack of information regarding the occupants and the homes in which the units were located precludes any compensatory adjustments.

Many refrigerators have automatic icemakers. The presence of an icemaker does not always show on the model number because it is often an after-sale modification. One study measured the increased energy use from icemakers.[7] Energy use increased as much as 20 percent when the icemaker was included while conducting the DOE test. However, automatic icemakers are usually not operating, so this must be considered an upper limit. This error is usually less than 15 percent, but can be as great as 30 percent for certain units.[8] This study does not address this source of error.

We found that the results continue to fluctuate as new refrigerators are added. For example, in a previous version on this work, which examined fewer refrigerators, and a higher percentage of pre-1982 refrigerators, we found a much smaller difference between field and laboratory energy consumption.[9] Thus, we believe that the sample size is still too small and further data collection will be needed before we will be able to make conclusions with a high degree of confidence.

IMPLICATIONS FOR FORECASTING AND CONSERVATION PROGRAMS

Most electricity demand forecasting models have treated the electricity used for residential refrigeration as constant or only slightly varying. This study suggests that refrigerator energy use varies significantly across the seasons. Indeed, refrigerators are significant contributors to the summer peak. While the incremental summer increase

[6] Bruce Hackett and Loren Lutzenheiser, "Shelf Life: An Inquiry Into What — and Who — Can Be Found in Your Refrigerator", *Energy Auditor & Retrofitter*, May/June 1987.

[7] BR Laboratories. 1986. *Final Report on Laboratory Testing of Certified Refrigerators/Freezers*. Huntington Beach, CA: Prepared for the California Energy Commission, Agreement No. 400-84-011.

[8] BR Laboratories (see previous reference).

[9] Alan Meier and Kristin Heinemeier, "Energy Use of Residential Refrigerators: A Comparison of Laboratory and Field Use". *ASHRAE Transactions* 1988 (in press).

of one refrigerator is not a major load, the aggregate impact of 1.3 refrigerators per household may represent a significant fraction of the air conditioning load. (Indeed, some of the air conditioning peak is probably a refrigeration peak.) To our knowledge, load management technologies for refrigerators have never been seriously considered in the United States. Modifications of existing refrigerator designs to reduce peak energy use would certainly be worth investigating.

The correlation presented in this paper allows forecasters to more accurately estimate the contribution of new refrigerators to residential electricity demand without extensive monitoring. In its place, however, the utility must collect sales data on the shipment-weighted energy use of refrigerators in its service area.

Many utilities are considering rebate programs to encourage the purchase of energy efficient refrigerators. Most programs rely on the label to calculate the energy savings and cost effectiveness of the rebate programs. This study suggests that the labels overestimate refrigerator energy use for new refrigerators. On the other hand, the programs have rarely included the peak power savings. This study suggests that peak power savings will be substantially greater than indicated by the label.

CONCLUSIONS

The measured data on energy use of 259 refrigerators in six separate studies have been compiled and analyzed. Despite the large number of refrigerators being monitored, surprisingly few had sufficient data to permit a comparison with the label consumption.

The DOE energy test procedure appears to be a remarkably good predictor of field annual energy use. The best-fit line indicated that the label slightly overestimated field use, but by a constant amount. At a typical consumption of 1200 kWh per year, the field use was 14 percent less than the label. This suggests that consumer decisions and appliance standards can be based the DOE energy test procedure without introducing a large error.

There is significant month-to-month variation in energy use. August consumption was typically the highest, and the peak-month energy use of a typical unit was about 16 percent *above* the label. Utility forecasters should make this adjustment when predicting the refrigerator's contribution to the peak energy use.

New refrigerators have more insulation, higher-efficiency compressors, and better evaporators. These factors were expected to change the relationship between laboratory and field performance. Indeed, post-1982 refrigerators used about 22 percent less energy than their labels while older models conformed closely to the labels. Again, the sample sizes are small, so the results must be considered tentative.

ACKNOWLEDGEMENTS

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Table I. Sources of field monitored data.

Source	Loc.	Units	Interval	Notes
Consumer's Power Co.	MI	31	Monthly	
Oak Ridge National Lab	VA	50	Monthly	2 models: efficient and standard
	-	40	Monthly	2 compressor designs: efficient and standard
Pacific Gas & Electric Co.	CA	21	30 minutes	
Public Service Electric & Gas	NJ	100	Monthly	8 models: mean consumption for each model
Sierra Pacific Power Co.	NV	111	Daily	
Midwest manufacturer	IN	10	Monthly	Up to 4 years of data
		25	Quarterly	Up to 5 years of data
Miscellaneous	-	4	Annual	
Miscellaneous	-	2	Monthly	
TOTAL		**394**		**Some units not included due to insufficient data.**

Table II. Narrowing down of potential dataset.

Data Status	Number of Refrigerators
Unit was monitored,	5000+ (estimated)
and model number recorded,	394
and model number matched,	259
and at least 9 months data,	239
and monthly data,	213
and daily data,	24
and hourly data.	8

Table III. Regression data.

Energy Use	Best Fit Formula	R^2	Standard Error	Number of Units	Mean	Standard Deviation	Maximum
Annual (kWh/year)	$Field = 1.00 \times Label - 167.$	0.62	266	190	1254	431	2591
Peak month (kWh/month)	$Field = 1.14 \times (\frac{Label}{12}) + 2.$	0.46	34	130	125	46	272
Pre-82 annual (kWh/year)	$Field = 0.99 \times Label + 21.$	0.67	264	121	1374	456	2591
Post-82 annual (kWh/year)	$Field = 1.08 \times Label - 373.$	0.61	177	69	1044	280	1658

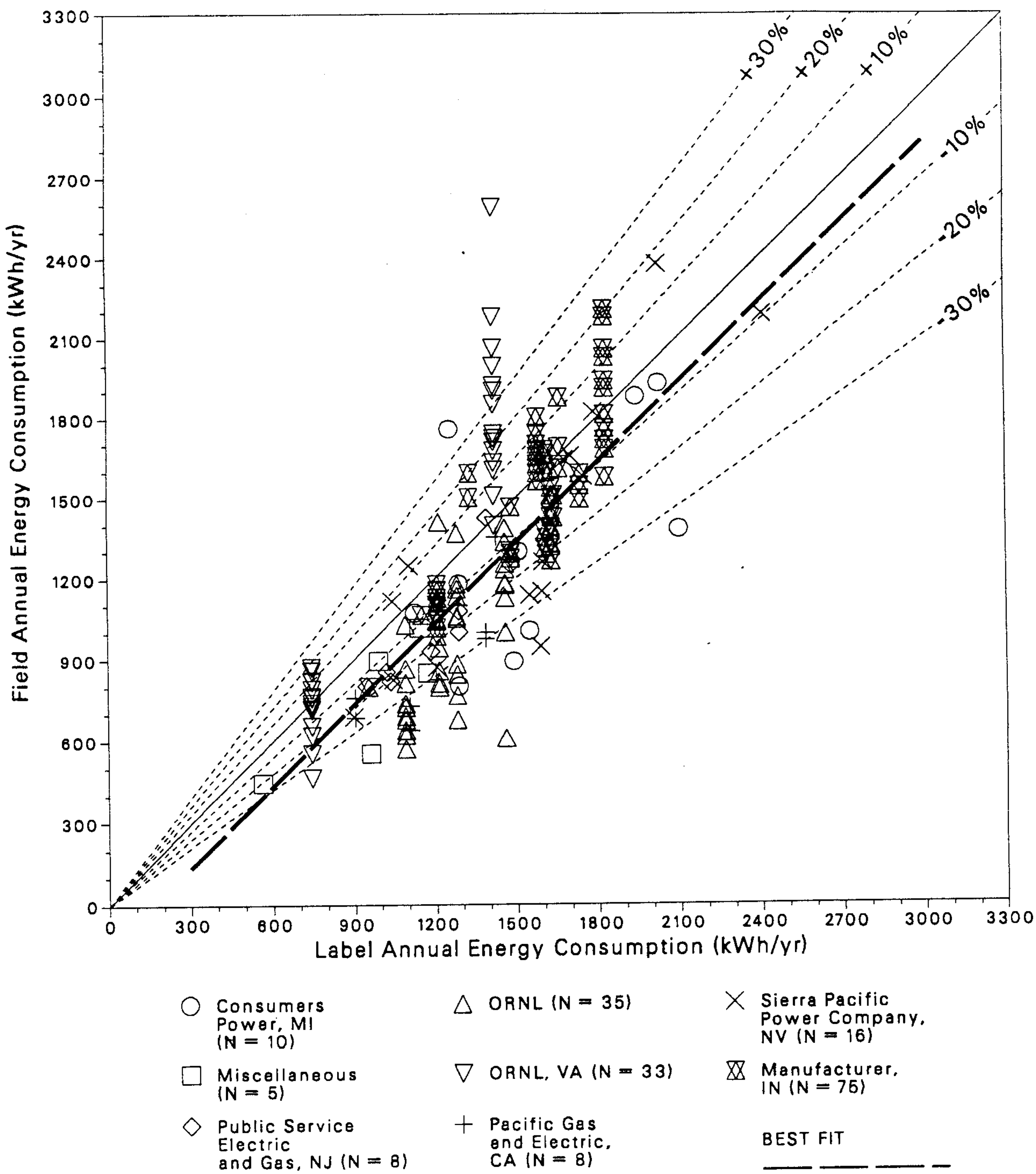

Figure 1. A scatterplot of DOE laboratory test ("label") consumption versus the measured annual field consumption. A line of perfect agreement is drawn for reference; units to the right of the line represent those with the label consumption greater than the field consumption. The field consumption of nearly all of the refrigerators was within 30 percent of the label. In general, the field consumption was less than the label. The columns of units (ORNL, PSE&G) represent groups of identical refrigerators.

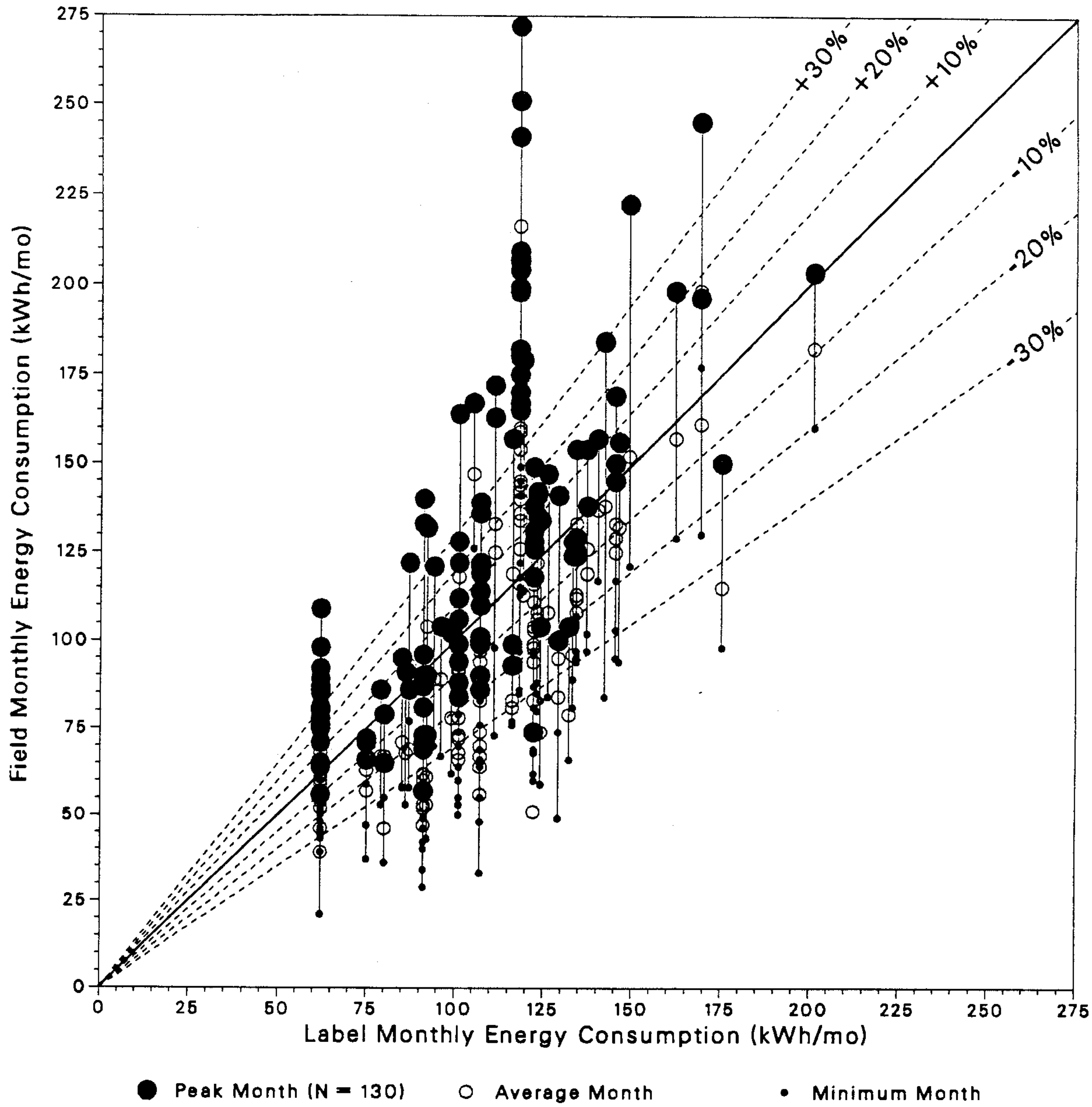

Figure 2. A scatterplot of DOE laboratory test ("label") monthly consumption versus the measured minimum, mean, and peak monthly field consumption. The range in monthly consumption was often greater than 30 percent. Peak consumption — most frequently in August — was generally above the label.

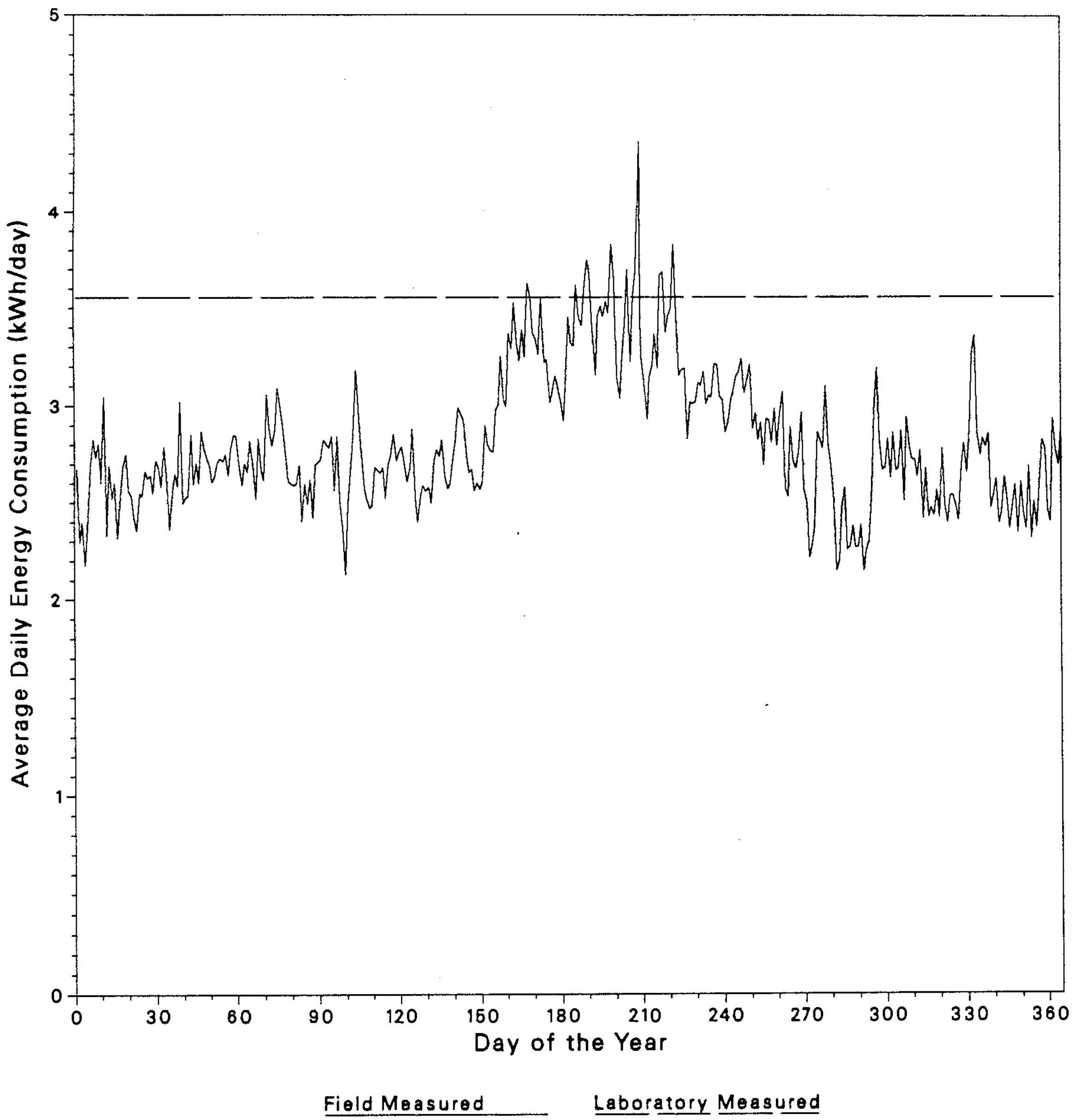

Figure 3. The average daily consumption for each day of the year, and the average daily consumption represented by the label annual consumption, averaged across the 24 refrigerators for which daily data are available. There is clearly a seasonal variation in demand; the average daily demand during mid-June to mid-August is 26% greater than that during the rest of the year.

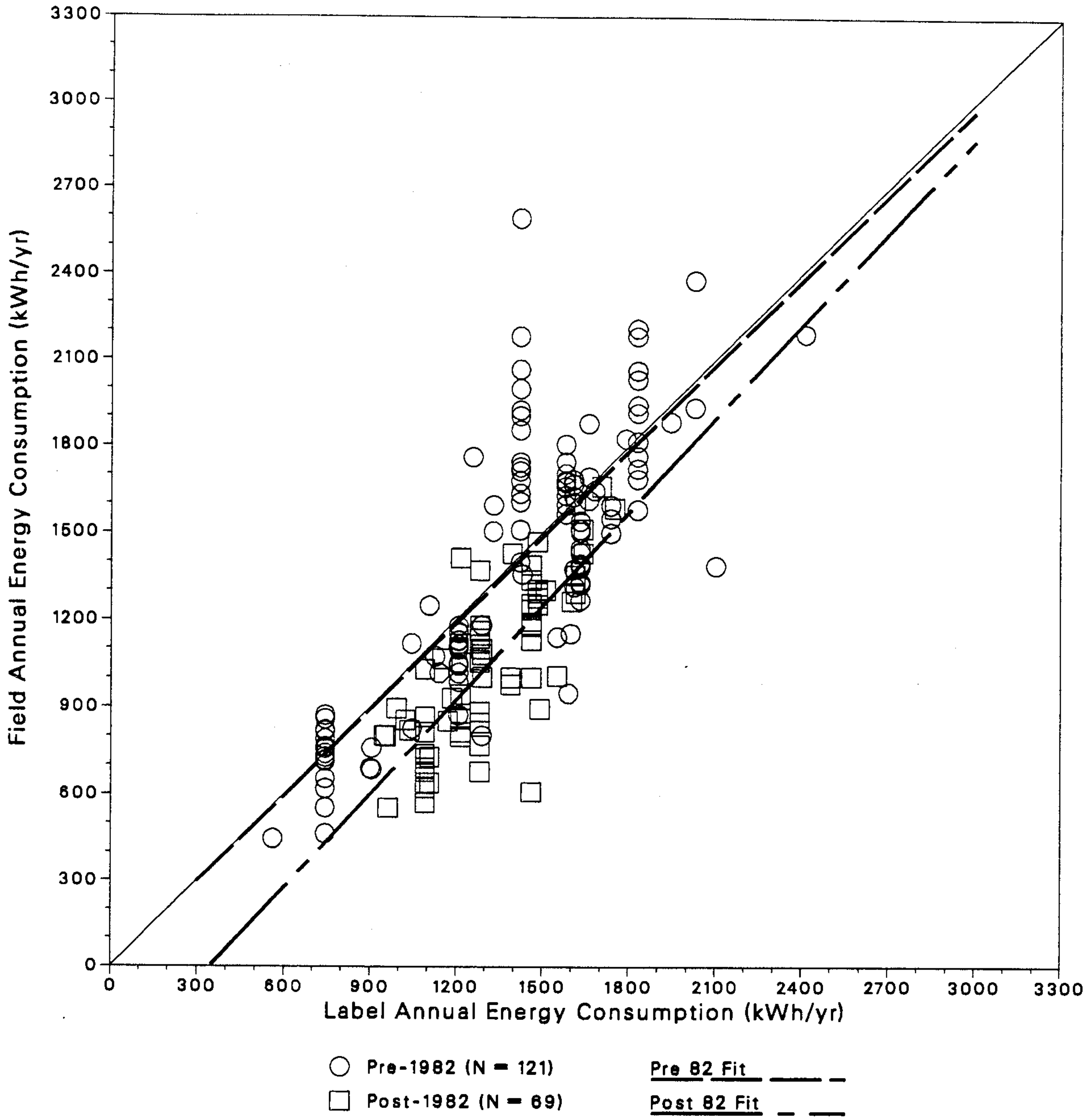

Figure 4. A scatterplot of DOE laboratory test ("label") annual consumption versus the measured annual field consumption for pre-1982 and post-1982 models. In this small sample, the post-1982 refrigerators (including 1982) used less energy than those sold before 1982. Moreover, the relationship between the test and field consumption is different for the two groups.